DOCTORAL THESIS

Legged Locomotion on Soft and Wet Terrains

Simon Pierre Godon

TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY
TALLINN 2025

TALLINN UNIVERSITY OF TECHNOLOGY
DOCTORAL THESIS
48/2025

Legged Locomotion on Soft and Wet Terrains

SIMON PIERRE GODON

TAL TECH PRESS

TALLINN UNIVERSITY OF TECHNOLOGY
School of Information Technologies
Department of Computer Systems

The dissertation was accepted for the defence of the degree of Doctor of Philosophy (Computer and Systems Engineering) on 26th June 2025

Supervisor: Pr. Maarja Kruusmaa,
Department of Computer Systems, School of Information Technologies
Tallinn University of Technology
Tallinn, Estonia

Co-supervisor: Dr. Asko Ristolainen,
Department of Computer Systems, School of Information Technologies
Tallinn University of Technology
Tallinn, Estonia

Opponents: Pr. Feifei Qian,
University of Southern California
Los Angeles, CA, USA

Pr. Kari Koskinen,
Tampere University
Tampere, Finland

Defence of the thesis: 30th June 2025, Tallinn

Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for any academic degree elsewhere.

Simon GODON

signature

European Union
European Regional
Development Fund

Investing
in your future

ISSN 2585-6901 (PDF)
ISBN 978-9916-80-332-5 (PDF)
DOI https://doi.org/10.23658/taltech.48/2025

Godon, S. (2025). *Legged Locomotion on Soft and Wet Terrains* [TalTech Press]. https://doi.org/10.23658/taltech.48/2025

TALLINNA TEHNIKAÜLIKOOL
DOKTORITÖÖ
48/2025

Jalgadel liikumine pehmel ja märjal maastikul

SIMON PIERRE GODON

TALTECH KIRJASTUS

Contents

Abstract
Legged locomotion on soft and wet terrains

Over the past decade, Unmanned Ground Vehicles (UGVs) have experienced rapid and continuous advancements. Improvements in motor power densities, battery storage densities, materials properties, and computing power have made it possible to take mobile robots out of constrained and predictable indoor environments. New applications include environmental monitoring, terrestrial and extraterrestrial exploration and mapping, agriculture, or search and rescue. These missions often need crossing environments that are soft, wet and deformable such as snow, sand or mud, in forests, estuaries, shores, rivers or fields.

So far, most of the aforementioned environments have been traversed by humans using heavy machinery with large power output, such as track-equipped excavators and tanks, or all terrain vehicles (ATVs) with large, studded, deflated wheels. However, these systems, often used for defense, resource exploitation or hobby purposes require large power outputs and damage the environments. In applications such as environmental monitoring or search and rescue, prolonged autonomy and preservation of the surroundings are instrumental.

Current robotic systems lack means to traverse these environments reliably, efficiently and without damaging the environment. The goal of this thesis is to provide solutions to those shortcomings by designing locomotion means, developing models of the ground substrate, control strategies or mechanical designs to help robots move on soft wet grounds.

The introduction of this thesis reviews the physics-based means of locomotion for moving on different unstructured grounds, both in the animal world and among the robots. It establishes the existence of two physics-based categories of locomotion means: static-based and dynamics-based, meaning that animals and robots mostly rely on either the frictional and hydrostatic-like properties of the ground, or on acceleration-related terms and try to preserve their momentum. Both categories are then subdivided into different contact patterns between the moving body and its environment. This introduction is based on a publication that reviews the latest research in biology and robotics on locomotion over soft, deformable ground. It classifies the locomotion methods used by both animals and robotic devices. Additionally, it presents a catalog of potential solutions to improve static and dynamic locomotion on such terrains. Several gaps were identified in this review, such as the relatively low amount of attention received by research on dynamics-based locomotion on soft grounds, or the lack of research on wet deformable grounds.

The rest of the thesis focuses on addressing the challenge of moving on soft wet grounds, and the author chose to explore it through the means of legged locomotion, because of the rapid advancements and potential of legged systems for tasks in natural environments. The author's second publication examines how soil with varying water content reacts to different stepping loads and models its behavior. The research demonstrated that the soil exhibits a near hydrostatic behavior when subjected to loading, and a non-linear response, with a suction force when retracting the intruder. It also demonstrated a strong dependence on water content, foot compliance, loading repetitions or speed.

Based on the knowledge gained from the experiments in the second publication, the thesis then explores two directions to solve the challenge of walking on soft wet grounds: a control approach and a mechanical design approach. As a first approach, a controller is presented. It takes advantage of the knowledge gained from soil modeling, to propose estimators for ground compliance and suction force, and a model-based center of mass (COM) positioning using proprioceptive information plus the estimated forces. The publication presents different versions of the controller to establish the contribution of each element of the controller to its overall performance.

Last, the thesis explores a mechanical solution for walking on soft wet grounds. The inspiration is drawn from a wild ungulate that walks with ease on diverse types of soft grounds: the moose. In this study, moose feet were mounted on an actuator to step on mud, demonstrating the contribution of the claws to locomotion in muddy terrain. Then, a silicone foot, inspired by the moose foot was designed and tested. This foot was compared to three reduced versions through experiments. The experiments demonstrated superior results for the designed foot, for all the metrics considered. Four of these feet were then installed on a quadruped robot using the controller developed in the previous publication. The robot was able to walk faster and more efficiently on different muddy grounds thanks to the moose-inspired silicone feet.

As a whole, this thesis provides contributions in reviewing, classifying and cataloging solutions for moving on soft grounds, as well as characterization and modeling of soil of different water content, and proposes a control approach and a mechanical solution for facilitating legged locomotion on wet deformable grounds. These results are useful to the research community, and to a wider audience as they push further the boundaries of the accessible areas for robots, helping to open diverse applications for UGVs. These results represent research directions and can be used as a starting point for future academic or industrial research to improve the capabilities of robotic systems in complex natural environments.

Kokkuvõte
Jalgadel liikumine pehmel ja märjal maastikul

Viimase kümnendi jooksul on mehitamata maismaasõidukid (UGV-d) teinud läbi kiire ja pideva arengu. Mootorite võimsustiheduse, akude energiasalvestuse tiheduse, materjaliomaduste ja arvutusvõimsuse paranemine on võimaldanud mobiilsete robotite kasutamist väljaspool piiratud ja etteaimatavaid siseolusid. Uued rakendused hõlmavad keskkonnaseiret, maapealset ja maavälist uurimist ja kaardistamist, põllumajandust ning otsingu- ja päästetöid. Need missioonid nõuavad tihti liikumist pehmetel, märgadel ja deformeeruvatel maastikel, nagu lumi, liiv või muda, samuti metsades, jõgede suudmealadel, kallastel, jõgedes või põldudel.

Senini on nimetatud keskkondi ületatud peamiselt raske tehnikaga, millel on suur võimsus, näiteks roomikutega ekskavaatorite ja tankidega või maastikusõidukitega (ATV-d) millel on pehmed suured ja sügava mustriga rehvid. Kuid sellised süsteemid, mida kasutatakse sageli kaitsetööstuses, loodusressursside ammutamisel või hobi eesmärkidel, nõuavad suurt võimsust ja kahjustavad keskkonda. Rakendustes, nagu keskkonnaseire või otsingu- ja päästetööd, on aga oluline nii pikem autonoomia kui ka keskkonna säilitamine.

Praegused robootikasüsteemid ei suuda neid keskkondi usaldusväärselt, tõhusalt ja keskkonda kahjustamata ületada. Selle doktoritöö eesmärk on pakkuda lahendusi nendele puudujääkidele, kavandades liikumismeetodeid, arendades pehmete pinnaste mudeliseerimist, juhtimisstrateegiaid ja mehaanilisi disaine, mis aitaksid robotitel liikuda pehmetel ja märgadel maastikel.

Töö sissejuhatus annab ülevaate füüsikalistest liikumismehhanismidest ebakorrapärasel pinnasel, uurides nii loomade kui ka robotite liikumist. Tuuakse esile kaks füüsikalist liikumisviisi: staatiline ja dünaamiline. See tähendab, et nii loomad kui ka robotid kasutavad kas maapinna hõõrdumis- ja hüdrostaatilisi omadusi või kiirendusel põhinevaid meetodeid, püüdes säilitada oma liikumishulka. Mõlemad kategooriad jagunevad omakorda erinevateks kontaktimustriteks liikuva keha ja keskkonna vahel. Antud sissejuhatus põhineb hiljutistel bioloogia- ja robootikauuringutel mis uurivad liikumist pehmetel ja deformeeruvatel pinnastel. Selles klassifitseeritakse nii loomade kui ka robotite kasutatavad liikumismeetodid ning esitatakse võimalikud lahendused staatilise ja dünaamilise liikumise parandamiseks nimetatud maastikel. Ülevaates tuvastati ka mitmeid lünki teadustöös, näiteks dünaamilise liikumise uurimise vähest tähelepanu pehmetele pinnastele ning vähene teadustööd märgade ja deformeeruvate pindade osas.

Ülejäänud doktoritöö keskendub liikumise arendamisele pehmetel ja märgadel pindadel. Autor valis selleks jalgadega liikumise uurimise, kuna viimastel aastatel on neljajalgsete süsteemide areng ja potentsiaal looduslikes keskkondades märkimisväärselt kasvanud. Antud töö autori teises teaduspublikatsioonis analüüsitakse, kuidas erineva veesisaldusega pinnas reageerib erinevatele sammukoormustele ning modelleeritakse selle käitumist. Uuring näitas, et pinnas käitub koormuse all peaaegu hüdrostaatiliselt ning sellele on iseloomulik mittelineaarne reaktsioon, sealhulgas imemisjõud jala eemaldamisel pinnasest. Samuti selgus, et pinnase reaktsioon sõltub tugevalt veesisaldusest, jala painduvusest, koormuse korduvusest ja kiirusest.

Nende eksperimentaalsete teadmiste põhjal uuriti kahte lähenemisviisi liikumise parandamiseks pehmetel ja märgadel pindadel: juhtimispõhist ja mehaanilist. Esiteks esitleti

kontrollerit, mis kasutab pinnasemudeli põhjal hinnanguid maapinna pehmuse ja imemisjõu kohta ning modelleerib massikeskme (COM) positsiooni roboti liigeste asendi ning hinnatud jõudude põhjal. Publikatsioonis võrreldi kontrolleri erinevaid versioone, et määrata iga kontrollkomponendi panus üldisele jõudlusele.

Lõpuks uuriti antud doktoritöös mehaanilist lahendust liikumise parandamiseks pehmetel ja märgadel pindadel. Inspiratsiooni lahendusele ammutati looduses liikuvatelt sõralistelt, täpsemalt põdralt, kes suudab kergesti liikuda erinevatel pehmetel maastikel. Uuringus paigaldati põdra jalad katsestendi, et analüüsida sõrgade mõju mudasel pinnasel liikumisele. Tulemuste põhjal disainiti ja testiti silikoonist jalalaba, mis imiteerisid põdra jala struktuuri. Seda võrreldi kolme lihtsustatud versiooniga ning katsete tulemused näitasid, et disainitud jalg oli kõigi mõõdetud parameetrite osas parem. Seejärel paigaldati neli sellist jalga neljajalgsele robotile, mis kasutas varem välja töötatud kontrollerit. Tänu põdrast inspireeritud silikoonjalgadele suutis robot liikuda kiiremini ja tõhusamalt erinevatel mudastel maastikel.

Kokkuvõttes, panustab antud doktoritöö pehmetel pinnaste liikumise analüüsi, klassifitseerimisse ning lahenduste katalogiseerimisse. Koos pinnase erineva veesisalduse modelleerimisega pakutakse välja juhtimispõhine ja mehaaniline lahendus jalgadega liikumise hõlbustamiseks märgadel deformeeruvatel pindadel. Käesoleva töö tulemused on kasulikud nii teadusringkondadele kui ka laiemale avalikkusele, sest need laiendavad robotite kasutusvõimalusi keerulistes looduslikes keskkondades, avades uusi rakendusvaldkondi mehitamata maismaasõidukitele. Lisaks annab antud doktoritöö aluse edasistele teadus- ja tööstusuuringutele, et täiustada robootikasüsteemide võimekust keerulistes keskkondades.

List of Publications

The present Ph.D. thesis is based on the following publications that are referred to in the text by Roman numbers.

I S. Godon, M. Kruusmaa, and A. Ristolainen. "Maneuvering on non-newtonian fluidic terrain: a survey of animal and bio-inspired robot locomotion techniques on soft yielding grounds". *Frontiers in Robotics and AI*, 10:1113881, 2023 (Appendix I)

II S. Godon, A. Ristolainen, and M. Kruusmaa. "An insight on mud behavior upon stepping". *IEEE Robotics and Automation Letters*, 7(4):11039–11046, 2022 (Appendix II)

III S. Godon, C. Prados, A. Chemori, A. Ristolainen, and M. Kruusmaa. Walking in mud: Modeling, control, and experiments of quadruped locomotion. *IEEE/ASME Transactions on Mechatronics*, pages 1–12 (early access), 2025 (Appendix III)

IV S. Godon, A. Ristolainen, and M. Kruusmaa. "Robotic feet modeled after ungulates improve locomotion on soft wet grounds". *Bioinspiration & Biomimetics*, 19(6):066009, 2024 (Appendix IV)

Other publications:

S. Godon, M. Kruusmaa, and A. Ristolainen. "Robotic foot design for enhanced locomotion on soft and wet grounds", Patent application P202400026, Nov. 2024

R. Gkliva, W. Remmas, S. Godon, J. Rebane, K. Ochs, M. Kruusmaa, and A. Ristolainen. "A multi-terrain robot prototype with archimedean screw actuators: design, realisation, modelling, and control". *IEEE Access*, 2024

C. Burlet, G. Stasi, S. Godon, R. Gkliva, L. Piho, and A. Ristolainen. "ROBOMINERS resilient reflectance/fluorescence spectrometers". In *EGU General Assembly Conference Abstracts*, pages EGU–12056, 2023

Author's Contributions to the Publications

- I In I, I was the main author, carried out the literature search, analyzed the results, prepared the figures and wrote the manuscript.
- II In II, I was the main author, designed and built the experimental setup, conducted the experiments, analyzed the results, prepared the figures, and wrote the manuscript.
- III In III, I was the main author, designed and built the experimental setup, wrote the software for controlling the robot and conducting the experiments, carried out simulations, conducted the experiments, analyzed the results, prepared the figures, and wrote the manuscript.
- IV In IV, I was the main author, designed and built the experimental setup, wrote the software to record and analyze data, designed and built the different foot prototypes, carried out experiments, analyzed the results, prepared the figures, wrote the manuscript.

Abbreviations

ATV	All Terrain Vehicle
COM	Center of Mass
MCoT	Mechanical Cost of Transport
MPC	Model Predictive Control
NESM	Normalized Energy Stability Margin
PID	Proportional-Integral-Derivative (controller)
PD	Proportional-Derivative (controller)
PD+FF	Proportional-Derivative + Feed-Forward (controller)
RL	Reinforcement Learning
UGV	Unmanned Ground Vehicle

1 Introduction: Motivations, Research Questions and contributions of the thesis

1.1 Background and Motivations

This thesis addresses the locomotion of legged robots on soft, wet grounds. The goal of this work is to provide a range of tools—from understanding the characteristics of yielding grounds to designing morphological features and controllers—to enable legged robots to navigate natural terrains covered with soft, yielding material.

Mobile robots have undergone a wide expansion in the past few decades. While low power density and low computational density first confined robots to factories, technological barriers were pushed further, and mobile robots are now expanding into a wide range of environments and carrying diverse tasks. Early mobile robots were mostly wheeled or tracked because these configurations allow for simple mechanical design, straightforward control, and stability on flat, hard terrains commonly found in man-made environments. However, the vast majority of the planet consists of natural environments where wheels or tracks are not the best choice due to obstacles and irregular or soft terrain. In particular, soft and wet yielding environments, such as wet forests, riversides, or seashores, are highly unpredictable and complex. In fact, these terrains are made of viscoplastic materials that dampen motion, deform when pressure is exerted on them, and do not regain their original shape after pressure is released. In those environments, animals walk, run, jump, crawl, or dig, as demonstrated in Publication I.

Publication I demonstrated that animals moving in yielding grounds use two different physics-based movement categories: static-based and dynamics-based movements. In the first case, they either move using discrete contact points with the medium (largely represented by walking), move while maintaining continuous contact with the ground (crawling or slithering), or dig through the medium. In the second case, that is, dynamics-based movements, only discrete contact or movement through the medium occurs, probably because continuous contact during dynamic motion is highly energy-inefficient. For each of these ways of locomotion, various research directions can be explored. Publication I demonstrated that both in biological and robotics research, little attention has been given to dynamic locomotion. Although the robotics literature has explored all static modes of locomotion on soft ground to a similar extent, the majority of research has focused on sand—particularly dry sand—leaving a gap in research on wet viscoplastic terrain, such as mud.

Advances in mobile robotics make it possible to foresee an increasing number of applications for robots in diverse environments. For example, [8] highlights the significant potential and interest in robotics-based environmental monitoring. Robot-based environmental monitoring enables high-resolution data collection, frequent surveying, and easy deployment. [9] demonstrates significant growth in robotics research aimed at incorporating mobile robots into agriculture. Robots are also going to be increasingly used for space exploration [10]. [11] explains how robots are essential in search and rescue to make operations safer, faster, and more effective at locating and rescuing victims of natural or man-made disasters.

Legged robots, and particularly quadruped robots have garnered increasing interest in recent years, and are well-suited for navigating complex natural environments due to their agility, versatility and endurance [12]. The number of legged animals moving in the wild is an indicator of the suitability of legs for natural environments. It is clear that quadruped robots are going to be increasingly involved in tasks that require agility, versatility, and endurance, especially in natural environments. Typical applications mentioned above are all applications for which quadruped robots are good candidates. Some of them are even already being investigated. Research is being done on quadruped robots for search and rescue [13, 14], agriculture [15], and extraterrestrial exploration [16, 17].

However, to traverse complex natural terrains, robots also need to traverse soft wet grounds, which are ubiquitous. Even though quadruped robots demonstrate superior ability to negotiate obstacles and unstructured terrains, they still struggle to traverse soft wet grounds, such as deep mud or deep snow. The reviews proposed in [8] and [9], highlight a striking lack of legged robots for both agriculture and environmental monitoring, likely due to the complex challenge of traversing some environments, such as wet deformable grounds.

As such, this thesis aims to address the gaps that hinder quadruped robot locomotion on soft yielding grounds. This work will approach the problem from different angles, including ground characterization and modeling, gait and controller design, and foot morphological design.

1.2 Research Questions

Building on the motivation above and the state-of-the-art gaps highlighted in Publication I, this thesis addresses the following core research questions:

1. **RQ1:** How do animals and robots achieve locomotion in soft, yielding terrains?
   - Answered in Publication I, presented in the introduction and summarized in Fig. 1.
2. **RQ2:** How does soil with varying water content behave under different feet compliance and stepping conditions, and how can this knowledge be used to inform robot design?
   - Answered in Publication II, discussed in Chapter 2 and summarized in Fig. 2.
3. **RQ3:** What type of control strategy allows quadruped robots to walk on soft, wet terrain?
   - Answered in Publication III, discussed in Chapter 3 and summarized in Fig. 3.
4. **RQ4:** How can foot design enhance locomotion performance in soft, wet grounds?
   - Answered in Publication IV, discussed in Chapter 4 and summarized in Fig. 4.

Relation of the introduction to RQ1

This introduction directly addresses RQ1: "How do animals and robots achieve locomotion in soft, wet terrains?". The insights presented here are drawn from Publication I, which offers a comprehensive survey and classification of locomotion strategies observed in both animals and robots in yielding environments. It categorized the locomotion strategies into static-based and dynamics-based locomotion, identified underexplored areas—particularly dynamic locomotion and wet viscoplastic terrains—and lays the foundation for the subsequent research questions. This lays the ground for the rest of the thesis, which tackles the problem from several angles: understanding the terrain, developing suitable control strategies for legged robots in soft, wet grounds, and designing effective feet for locomotion on these grounds.

1.3 Contributions and structure of the thesis

This thesis is structured around four core contributions, each corresponding to a core research question and supported by a dedicated publication:

- **Contribution I:** An overview and classification of the means of locomotion on soft yielding terrains, from both biological and robotics perspectives - Introduction, Publication I
- **Contribution II:** A characterization of soil behavior when subject to different stepping loads - Chapter 2, Publication II
- **Contribution III:** The development of a controller for locomotion in wet, yielding ground - Chapter 3, Publication III
- **Contribution IV:** The development of a bio-inspired foot for quadruped locomotion on soft ground - Chapter 4, Publication IV

The introduction is partly based on the results of the first publication, in Appendix I, which corresponds to the first contribution listed. Fig. 1 summarizes the first publication.

Introduction - Publication I

Objective: Review the existing means of locomotion both in nature and in the robotics literature, identify solutions to mimic, and research gaps

Materials and methods: Keywords search
Article collection
Article filtering
Abstraction of the locomotion means
Classification

Results: Classification of animals and robots physics-based locomotion means
Identification of research gaps
Catalogue of bio-inspired solutions for locomotion on soft yielding grounds

Figure 1: Overview of the first publication and its contribution to the introduction of the thesis

The remainder of this thesis is divided into three parts, focusing on each of the last three contributions listed above. Publication I highlighted that there is a lack of accurate models for legged locomotion on soft ground, because existing models rely on shearing stress or terrain-specific approaches, while the field of terramechanics focuses on wheeled and tracked vehicles [18]. For this reason, we investigated the response of soil to a variety of stepping loads, with varying water content and different foot types. Chapter 2 presents the results of this research and their contribution to the thesis. Fig. 2 provides an overview of the research outlined in Chapter 2.

Chapter 2 - Publication II

Objective: Identify the characteristic response of soil with different water content to a variety of loads, get a qualitative understanding and a model

Materials and methods: Linear rig experiment
Soil with different water content
Stepping with different feet, and different speeds
Repeated stepping in the same location
Force control on wet substrate

Results: Force vs sinkage curves for different speeds and different water content
Soil stiffness and impulse efficiency as a function of water content
Model of mud for intrusion
Force controller for stepping on mud

Figure 2: Overview of the second publication and its contribution to the second chapter of the thesis

With the knowledge gained from Chapter 2, we decided to develop a controller for quadruped robot locomotion on soft ground. This will constitute the control aspect of this thesis. In this research, described in Chapter 3, we develop a controller that uses results, both from publication I, where we gained insight into the strategies animals use when moving on soft ground, and publication II, where we understood that some of the challenges faced when moving on wet soil were related to varying stiffness of the ground, speed dependence of mud behavior and the suction forces. Fig. 3 provides an overview of this research and its contributions to the thesis.

Chapter 3 - Publication III

Objective: Develop a gait for locomotion on soft yielding ground taking inspiration from biological insights from publication I and the knowledge from publication II

Materials and methods: Test commercially available controller in nature and laboratory
Develop a controller able to traverse a track in the laboratory
Add features to the controller with an iterative approach
Demonstrate superior quantitative results of our controller
Demonstrate the controller in natural environments

Results: A controller enabling quadruped robots to traverse soft yielding grounds
Demonstration of the contribution of each part of the controller to the result

Figure 3: Overview of the third publication and its contribution to the third chapter of the thesis

The last core chapter of this thesis focuses on the mechanical design of the robot's interface with flowable materials, that is, the feet. Chapter 2 highlighted that when inserting and retracting a foot in mud, the properties of the foot, especially its stiffness, had an impact on the force profile during both phases. It also concluded that a foot with both compliance and anisotropic design could help address the challenge of stepping on soft, wet ground. Additionally, the introduction of this thesis presented results from Publication I, which demonstrated that animals use specific gaits, as well as morphological adaptations to aid locomotion on these terrains. For example, many animals use deformable or wider feet, or they have specific features such as long fingers or split hooves that can expand or retract during stepping. Therefore, we took inspiration from nature and used our knowledge from our rig experiments (Publication II) to design a bio-inspired, compliant, and anisotropic foot. Since we had developed a controller in Publication III to enable a robot to move in mud, we could test this foot on a Unitree Go1 quadruped robot using our own controller. These results and their contributions to the thesis are described in Fig. 4, and form the body of Chapter 4.

Chapter 4 - Publication IV

Objective: Develop an artificial, bio-inspired anisotropic foot that takes inspiration from biological insights in publication I, takes advantage of observations from publication II, and demonstrate it with the controller in publication III

Materials and methods: Perform rig experiments with an animal leg
Design a foot inspired from the animal leg
Evaluate the designed foot on a rig
Compare results on a quadruped robot with the designed feet

Results: Quantitative results on the contribution of digits of moose leg on mud
A bio-inspired anisotropic foot design
Demonstration of the new foot design on a quadruped robot traversing mud

Figure 4: Overview of the fourth publication and its contribution to the fourth chapter of the thesis

To summarize, Fig. 5 illustrates how the four journal articles build upon each other to form this thesis.

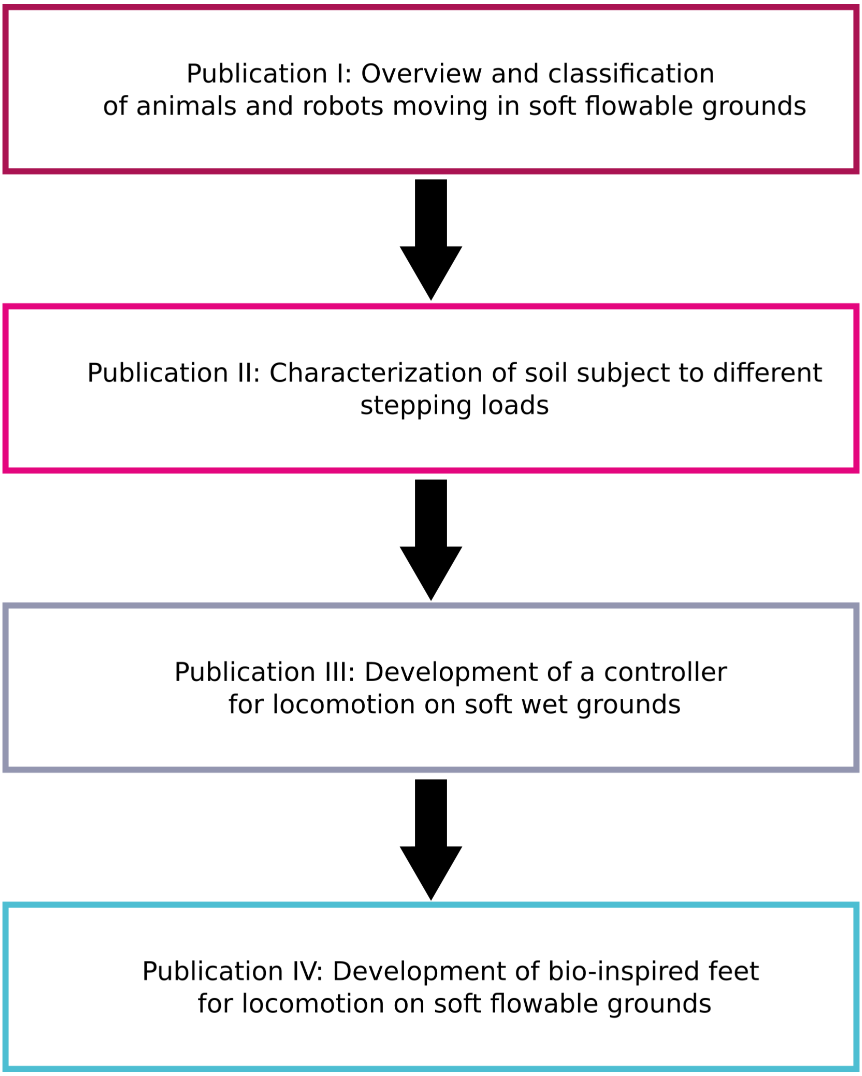

Figure 5: Sketch showing the flow of publications building upon each other to form this thesis

2 Characterization and modeling of a soft, wet ground subject to stepping

The primary challenge of soft, yielding grounds is their complex and unpredictable behavior. Although there are numerous rheological models for muds of different compositions, all of them have drawbacks. These include a lack of generalizability across different mud types, failing to account for dynamic changes, and reliance on parameters that are difficult to measure in real-world conditions. These limitations make the models impractical for applications such as locomotion, where the ground exhibits spatial and temporal heterogeneity. With every step, the foot can land on mud with different properties, further increasing the challenge.

Terramechanics is the study of interaction between mobile vehicles and deformable terrains [18]. It provides the tools to model and build wheeled and tracked vehicles to move on soft, yielding grounds. However, in legged locomotion, the challenges are different: rather than having a large surface deforming and shearing the ground, legged systems exert more concentrated and higher pressure, causing them to sink into the mud. The primary difficulty lies in sinkage depth, imbalance, and suction force hindering leg pullout rather than limitations in the traction due to shearing resistance of mud. Neither the terramechanics nor the legged robotics literature has addressed the issue of stepping on wet, yielding grounds. The motivation behind this research is therefore to improve our understanding of mud behavior under different stepping loads and provide an overview of the key parameters influencing legged locomotion on mud.

In publication II, we therefore decided to investigate the response of soil with different water contents to gain an insight on its characteristics and how they vary with the water content, and the type of stress. The experimental setup is shown in Fig. 6.

2.1 Results and discussions

The results outlined in Publication II contribute to building an understanding of the characteristics of stepping on mud. The investigation of mud behavior under stepping led to various conclusions regarding the mud's properties, its interactions with the foot, and the variability of these properties with water content and stepping speed.

The results in Publication II highlight that moving more slowly is more efficient for moving in mud. The ratio of impulse to work, which represents the amount of momentum gained per unit of energy spent on deformation, is inversely proportional to the intrusion speed. This indicates that stepping faster results in greater energy dissipation in the mud per unit of momentum gained.

Additionally, the experiments showed that moving more slowly provides an even greater advantage, as it allows for higher forces generation for the same sinkage depth. This means that robots or animals that move slower in mud would sink less, thereby, reducing energy expenditure on ground deformation and requiring lower step heights.

It was also found that the stiffness of the foot influences the force that can be generated. On the one hand, a foot of low stiffness deforms significantly, covering a smaller

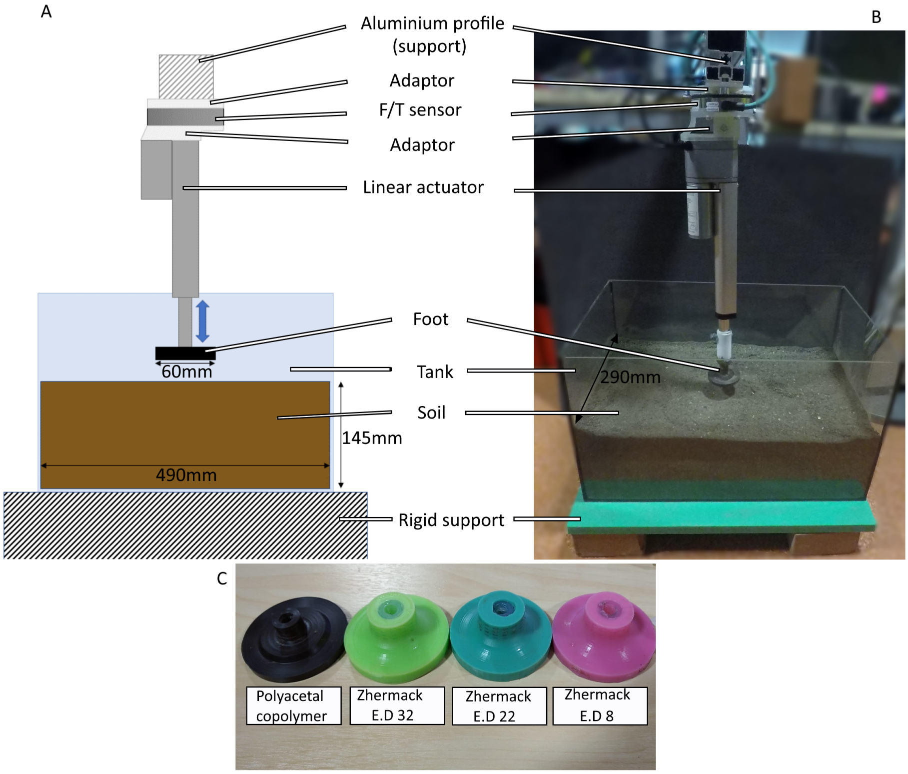

Figure 6: (A-B) The experimental setup used in our second publication. It consists of an aluminum support, on which a force sensor, a linear actuator, and the tested feet are rigidly mounted in series. Below the foot is a tank filled with soil, on which the linear actuator applies different loads (C). The different feet tested, all with the same surface area but different compliance.

surface area, which in turn increases pressure and sinkage. On the other hand, a foot of high stiffness leads to pressure concentration on its edges, which yields the mud and sinks deeper also [19]. Conversely, feet of intermediate stiffness allow reducing edge stress while maintaining their shape better, leading to a better distribution of pressure and allowing for the generation of higher forces overall for the same sinkage depth.

Experiments measuring the mud stiffness as a function of its water content revealed a non-linear relationship. Fig. 7 shows that when the soil is dry, up to when it contains 20% water, its stiffness remains constant. Beyond 20%, the stiffness decreases sharply, with mud approaching the consistency of water as the water content reaches 40%. However, the force vs. sinkage relationship during the intrusion phase can be considered nearly linear for all water contents (Fig. 8). The latter assumption is more accurate for lower water content, but still holds reasonably well for high water contents at least for locomotion applications. Finally, Fig. 8 shows that for intermediate water content a suction force develops under the foot during retraction, and gradually disappears when the foot gets lifted further.

Experiments evaluating the resistance of mud to repeated steps at the same location showed that each step reduces the mud's bearing capacity causing successive steps at the

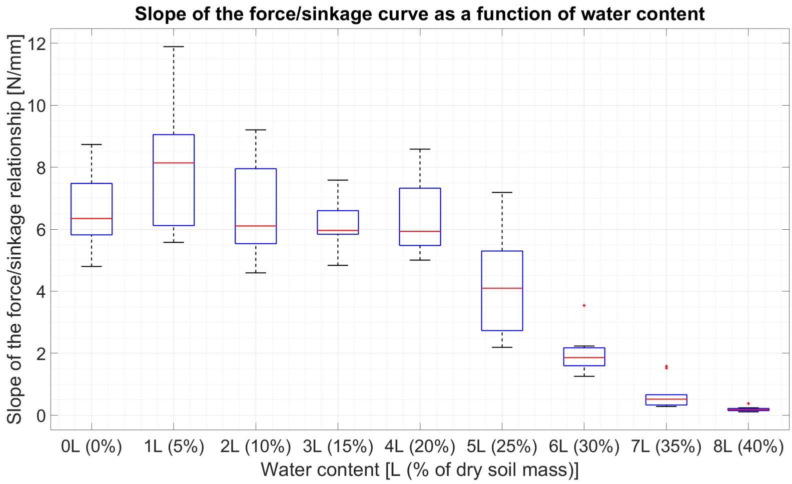

Figure 7: The slope of the force-sinkage relationship for varying water content in the soil. As shown, below 20% water, the slope of the force-sinkage curve remains relatively constant, but above 20%, the slope decreases sharply, approaching zero at 40% water relative to soil mass.

same spot to result in progressively deeper sinkage.

Finally, as discussed in some previous research, force control is a promising strategy for legged locomotion on soft terrains [20]. Based on our results, which show a linear force-sinkage relationship, we demonstrated that we could control force on wet, muddy grounds, by using a linear controller acting on the position of the actuator. This demonstration proved the feasibility of controlling force using a linear controller on mud. However, it also highlighted that, as can be expected from the above observation that the linear relationship is less and less true with increasing water content: the performance of the linear force controller degrades at higher water content (35%).

The results obtained in Publication II demonstrate various characteristics of the mud response to different linear loads. However, generating lateral motions requires generating lateral forces, which were not studied with this linear setup. Despite this, we argue that when walking in deep mud, the lateral forces are not a limiting factor, unlike wheeled, tracked, or legged locomotion on a thin layer of mud. In fact, when a legged system steps into deep mud, the foot becomes anchored in the substrate, preventing slippage. Publication I showed how several legged animals, when moving on yielding material, increased their step length because of the traction gained when the foot is sunk into deformable material. The similarity of the force-sinkage relationship observed in mud to that of other yielding materials hints that these results may be applicable to a wide range of mud compositions. The quantitative metrics for force, stress and sinkage depend on the material and the shape of the intruder, but the qualitative observations described here are certainly generalizable enough to help legged locomotion research on yielding terrains. The quantitative metrics can then be measured in real-time if deemed necessary, as determined by the controller.

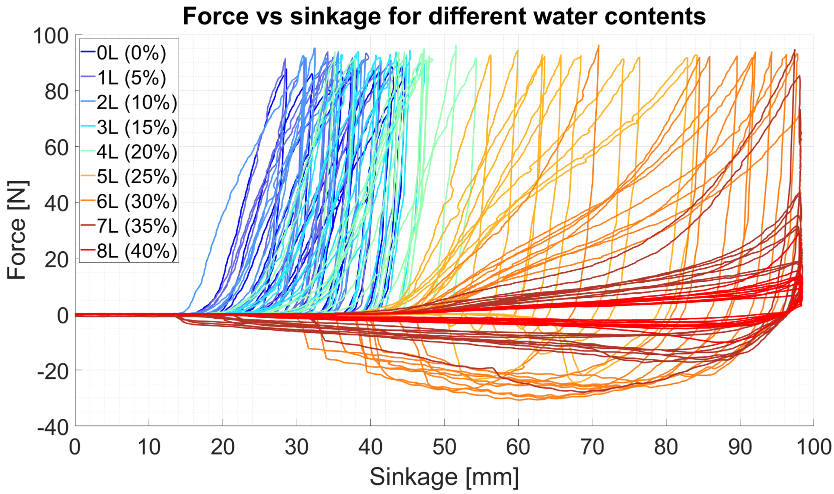

Figure 8: The force-sinkage curves for varying water content in the soil. This graph shows that higher water content results in a lower slope of the curve during the intrusion phase. During the extrusion phase, the suction force appears only at intermediate contents, with a maximum at 30% water content, where the suction force represents a fraction of the peak sinkage force.

2.2 Conclusions

The work presented in this section aimed to support our research on legged locomotion on soft grounds by providing an initial characterization of muddy terrains. This research revealed that mud has some unique characteristics that must be considered when developing robots or controllers to walk on such soft deformable terrains. Some key findings include that moving more slowly increases impulse and force generation, that foot stiffness significantly influences the force-sinkage relationship, that repeated stepping in the same location weakens the mud, and that above 20% water content, the mud's bearing capacity declines rapidly. Lastly, a particularly notable phenomenon, seemingly specific to wet cohesive media such as mud, is the emergence of suction forces during foot withdrawal at intermediate water content. This suction force is absent for low water content, where the mud behaves as a solid, and when the water content is high and the mud behaves as a fluid. This aligns with Barnes' description that the soil exhibits a viscoplastic behavior only at intermediate water content [19].

Relation to RQ2. This chapter directly addresses RQ2: "How does soil with varying water content behave under different feet compliance and stepping conditions, and how can this knowledge be used to inform robot design?". Through the experiments performed in mud with varying water content, we quantified how mud's response to stepping loads change, particularly how its stiffness and how suction force are impacted. We also characterized how compliance of the foot affects loading, and showcased how a foot of intermediate stiffness balances stress concentration and shape retention. Next, we highlighted how different stepping conditions, such as repeated loading, or variable speed, influence force generation. We found that stepping in the same location decreases the mud's stiffness, and that slower stepping allows for higher force generation. These results inform robot design in both control and mechanical aspects. From a control perspective, it allows for the incorporation of the mud model in the control scheme and advocates for lower stepping speeds in soft, wet terrains. From a mechanical perspective, it highlighted the need for tuned foot compliance and the need for incorporating solutions to counteract the suction force.

3 Controller for quadruped locomotion on soft, wet grounds

The first study on which this thesis is based, presented in Publication I explores different strategies for locomotion on soft grounds and demonstrated that the use of static-based locomotion with discrete contacts was one of the most widely used approaches in robotics. This can be explained by the wide applicability of legged systems, and particularly quadruped robots in natural environments. The second work, presented in Publication II examined key soil characteristics with varying amounts of water. Building on these insights, we worked on Publication III, which incorporates the diverse characteristics of mud behavior to design a controller for a quadruped robot walking in deep mud. In our research, the mud is considered deep as it reaches 56% of the tibia length.

The controller developed in publication III for locomotion in deep mud is shown in Fig. 9. This controller was built iteratively, and each of the six versions of this controller is presented in the figure. Additionally, Table 1 details the specific features that vary between controller versions, namely, the leg speed adaptation when the leg is in the mud, the stability criterion of the body, or the definition of the leg trajectory. We compared the different versions of this controller with the commercially available trotting gait controller, which is one of the most commonly used gaits for quadruped robots.

Table 1: Summary of controller versions with their leg trajectory speed, stability criterion, and trajectory definitions

Version	Leg speed	Stability	Leg trajectory
v_0	1 fixed speed	NESM	Bézier
v_1	2 speeds, RMSE threshold	NESM	Bézier
v_2	2 speeds, Force threshold	NESM	Bézier
v_3	2 speeds, Force threshold	Model	Bézier
v_4	2 speeds, Force threshold	Model	Polynomial
v_5	Proportional to Force	Model	Polynomial

We began with a controller containing only commonly used components, namely, a static gait controller using a Normalized Energy Stability Margin (NESM) stability criterion, impedance control for gravity compensation, trajectory planning based on Bézier curves, attitude, altitude, and heading control. First, we demonstrate that this controller can walk through mud blindly, albeit at a highly conservative speed. Then, we present five additional versions of the controller, each incorporating a single new feature to highlight its contributions (Tab. 1, Fig. 9). Each added feature is designed based on insights gained from Publication II to mitigate for the different adverse effects of mud, such as anisotropy, suction forces or prior disturbances.

Each version of our controller was initially developed in the Gazebo simulator using ROS (Robot Operating System), and later tested in our experimental setup. Our experimental setup consists of a corridor filled with a 12 cm deep layer of mud, with an overhead rail system to secure the robot from falling into the mud. The setup is shown in Fig. 10. Our results demonstrate that each new feature improves the overall speed of the robot. While some features also reduce the mechanical cost of transport (MCoT) of locomotion in deep mud, others increased speed at the expense of increased MCoT.

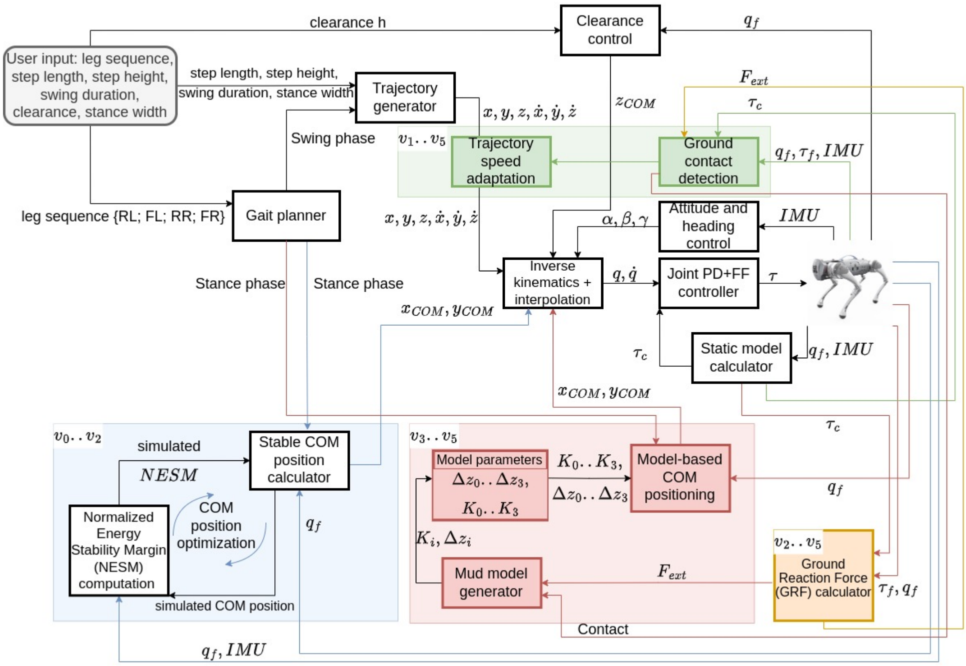

Figure 9: The controller proposed in Publication III, with its different versions. The first version of the control architecture includes only the blocks with a white background, while all subsequent versions of our controller use the ground contact detection and trajectory adaptation blocks (green blocks). The third version introduces the Ground Reaction Force (GRF) estimator (orange block) and utilizes it to feed the ground contact detection block, instead of using the RMSE between the feedback torque τ_f and the gravity compensation torque τ_c. The last three versions of our controller replace the blue area with the red area for center of mass (COM) position calculation. In all cases, the main loop runs at 500Hz. The clearance control block maintains the height of the body at the input clearance h. The attitude and heading control block is responsible for maintaining the robot attitude and heading, and provides desired rotations as Euler angles α, β, γ to the inverse kinematics block. τ_f and q_f represent the feedback torque and position of all the motors of the robot, respectively. $x, y, z, \dot{x}, \dot{y}, \dot{z}$ are the commanded position and velocity of the swinging foot, x_{COM}, y_{COM} are the coordinates of the next position of the center of mass of the robot, $q, \dot{q}$ are the position and velocity commands of the motors, F_{ext} is the external force acting on the swinging foot, Δz_i are the foot depths in mud, and K_i are the estimated mud stiffness under the feet.

3.1 Results and discussions

Publication III presents a comparison between a commercially available dynamic-gait controller, and a series of six controllers specifically developed for quadruped locomotion in deep mud. While the dynamics-based controller is based on a trotting gait, in which the two pairs of diagonally opposed legs alternate high frequency stepping, our controllers are all statics-based, ensuring that three legs remain in contact with the ground at all times, forming a support polygon. This research demonstrated that the commercially available,

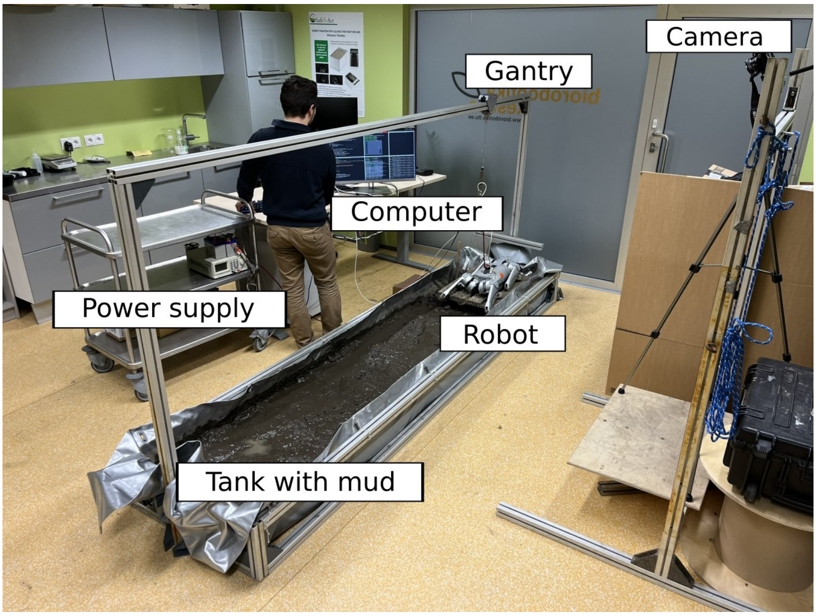

Figure 10: The experimental setup used in our third publication. It consists of a 3 m $\times$ 0.8 m tank filled with 12 cm of mud, which the robot traversed. The robot is secured by cables attached to a pulley on a gantry. Power is supplied externally to allow for emergency cutoffs and extended runtime. High-level commands are issued and data is recorded by an off-board computer. A camera captures the scene for post-processing the robot's movements.

dynamics-based controller is not suitable for deep-mud locomotion as it fails after a short distance. This failure can be attributed to the inadequacy of this type of gait for deep mud. The trotting gait is widely used in quadruped robotics due to its stability, simplicity, and adaptability to different terrains. However, in the case of mud, and unlike on rigid terrains, a foot in mud continue to sink under load and cannot be considered as a support when it hits the ground. The sinkage can reach different depths for different feet, adding to the complexity of control and making the trotting gait even more unstable. An additional challenge is that the trotting gait follows a highly rhythmic pattern, alternating support between diagonally opposed leg pairs. In mud, lifting a leg becomes difficult due to the suction force resisting foot extraction. This resistance can vary between feet, potentially causing imbalance.

The controllers developed in publication III are therefore all based on a static gait where the controller ensures that a leg is supporting the robot before initiating the next step. However, even in this case, lifting a leg from the mud can be challenging. To address this, we developed a controller using the widely known NESM in which the robot positions its center of mass within a stable region of the support polygon. As such, this placement makes the robot highly resistant to instability. NESM imposes certain constraints on the controller, as stability is limited by the maximum stability vertex located at the in-center of the support polygon. Consequently, leg motion has to be performed slowly enough so that it does not generate more suction force (or torque along the edge of the support polygon) than the center of mass could counterbalance at the in-center of the support polygon. Accounting for this limitation and slowing down the leg motion, we verified that this gait could successfully traverse our experimental mud track. However, the traversal speed remained slow.

With the first controller, the robot was unaware of the terrain it was traversing. In the second version, our goal was to increase the robot's speed by utilizing proprioceptive feedback, enabling it to better perceive its environment. To achieve this, we added a mud contact observer, allowing the robot to estimate whether a leg is in mud, based on the instantaneous root-mean-square error (RMSE) between the measured torque at the joints and the expected torque due to gravity. The estimation relies on an empirically determined threshold designed to filter out disturbances caused by mud sticking to the foot, friction, or neglected dynamics terms. Using this information, the second version of our controller increases the speed of the swinging leg while it is outside the mud. This modification results in a higher locomotion speed, and a slight decrease of the MCoT.

The RMSE-based mud contact observer used in our second controller version provided a reasonably accurate determination of when the leg was inside the mud. However, to improve both the accuracy and intuitiveness of the measurements, we incorporated the ground reaction force (GRF) exerted by mud on the foot, and used it as a new metric to inform the mud contact observer. This enhancement allowed for a clearer distinction between the positive and negative vertical forces, enabling more precise filtering of disturbances. While this modification resulted in only a marginal speed increase, it laid the foundation for broader use of GRF for our model-based center of mass (COM) positioning in our fourth version.

The third version of our controller was able to increase the speed of the foot while in the air thanks to a GRF-based mud contact observer, but the speed was remained constrained by the maximum stability the in-center of the support polygon could provide. The NESM is a stability criterion designed for hard ground, but it does not account for cases where forces are applied to a leg being lifted off the ground. To overcome this limitation, we developed a stability criterion based on the equilibrium of torques around the critical edge of the support polygon, defined as the edge formed by the two adjacent feet to the moving foot ((M_1, M_2) in Fig. 11). The controller computes the distance at which the robot has to place its COM from the critical edge of the support polygon, ensuring that the torque generated by the suction force on the lifting leg is counterbalanced by the sum of the torque due to the robot's weight on the opposite side and the suction force exerted by the diagonally opposed foot, see Fig 11. This new criterion increased the allowable force generation by the foot and enabled a higher swing speed. As a result, this controller enabled the robot to traverse the mud track more quickly, and with a reduction of the MCoT.

In the first four first versions of our controller, we used Bézier curves for generating the feet trajectories. An example Bézier curve is shown in Fig. 12. These curves present the advantage of being very simple in their implementation, and they have a low computational cost. However, they exhibit high velocity and acceleration at the end points, which is suboptimal in muddy conditions, as these points correspond to the highest insertion force and suction force in mud. To address this issue, we replaced Bézier curves with polynomial curves, which precise control of the position, velocity, acceleration, and liftoff angle, see Fig. 12. This adjustment enabled us to increase the overall swing speed, while maintaining low velocity toward the trajectory endpoints. As a result, the robot was able to traverse the track more quickly, with virtually no impact on the MCoT.

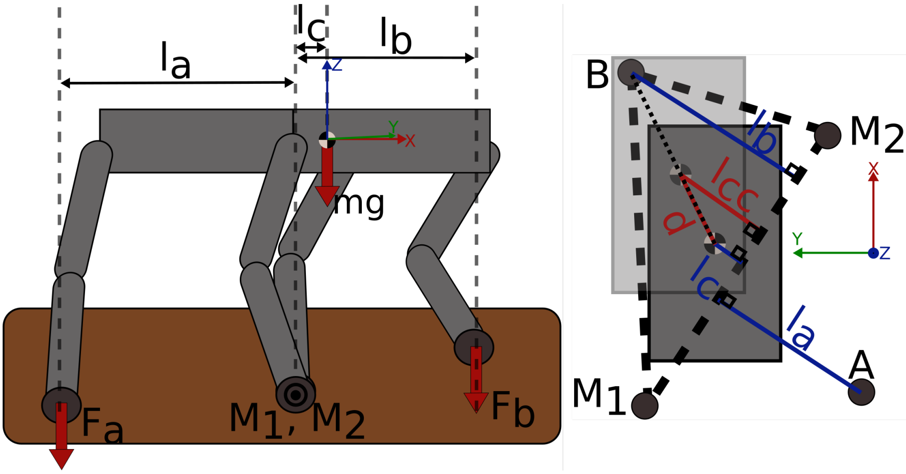

Figure 11: Illustration of the forces involved for model-based COM positioning in a muddy substrate. M_1, M_2 are the two feet defining the critical edge of the support polygon. l_a is the projection on the z-axis of the orthogonal distance between the foot to lift A and the edge M_1, M_2. l_b is the same for the diagonally opposed foot B. F_a, F_b are the corresponding forces at these feet, l_c is the projection on z of the orthogonal distance between the COM and the polygon edge M_1, M_2. l_{cc} represents the critical distance at which the COM should be positioned relative to M_1, M_2, and d indicates the displacement of the COM. The left diagram shows a side view, and the right diagram presents a top view.

Finally, in previous versions, we had up to two predefined speeds for the swing trajectory, each tuned to allow the robot to remain stable in all conditions. However, when the leg sinks less into the mud, the suction force is lower, and the speed could therefore be increased. To eliminate the need for empirical speed tuning, we introduced a speed multiplier that varies between 0 and 1, proportional to the force margin, defined as the ratio between the maximum stabilizing force predicted by our model and the actual force measured at the foot. This final modification significantly increased the speed of our controller, but came at the cost of increased MCoT compared to the fifth version. Ultimately, this last version achieved more than 6 times the speed of our first version, with a reduction of the MCoT by 6%.

In summary, the controllers we developed in this research all use a static gait, with a large step length of 53% body length, and a slow swing speed while in the mud, both during intrusion and extraction of the foot. A higher step height than that of the commercially available controller further reduced the portion of the swing phase occurring in the mud. Each enhancement to our initial version, including the mud contact observer and model-based stability criterion, more precisely controlled polynomial curve, and speed varying proportionally to the force margin, enabled faster and slightly more efficient traversal. Overall, contrary to the trotting gait controller, all our controllers successfully traversed the deep layer of mud without failures, achieving four times greater efficiency. The MCoT of our controllers is comparable to previous research on other types of resistive terrain, and, as expected, remains an order of magnitude higher than locomotion on hard ground.

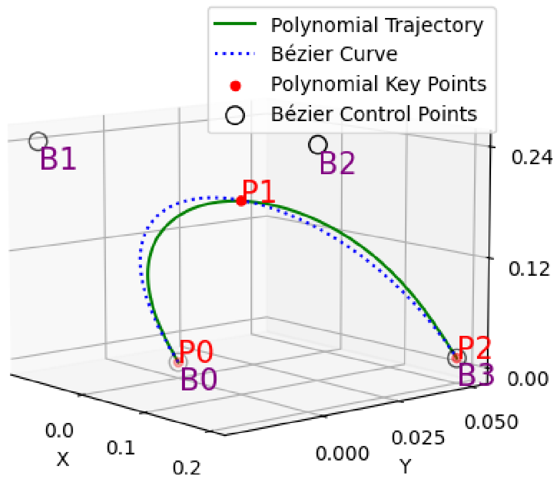

Figure 12: Bézier curve path of each leg (first four versions of the controller) and polynomial curve (last two versions). The control points and key points are determined based on the target foot position. The figure illustrates that both trajectory types are similar, particularly in achieving comparable touchdown and liftoff angles.

3.2 Conclusions

Legged locomotion is a promising means of locomotion in natural environments, as evidenced by the wide diversity of legged animals. Soft, yielding terrain are common in nature, and present challenges for standard controllers used in quadruped robots. Our research developed a controller that enables quadruped robots to traverse muddy terrains unlike the commercially available trotting gait controller, which is ill-suited for such conditions.

Trotting-gait controllers are well adapted to locomotion in a wide range of environments, but the suction force, damping, and anisotropy of mud introduce step uncertainty, disrupt momentum conservation, and ultimately make trotting gaits unsuitable for wet, yielding terrains. The trotting gait was used as our baseline due to its commercial availability, but more generally, no existing controller is specifically designed for quadruped locomotion in deep yielding grounds, and developing one remained a challenge.

Most recent approaches to control of quadruped locomotion on complex terrains rely on Reinforcement Learning (RL), but this approach requires a high number of trials, typically conducted in simulation. In the case of mud, no simulator to date can generate realistic simulations of mud, while trial-and-error learning in real conditions is impractical due to the harsh and potentially damaging environment.

Instead of relying on RL, our controller builds on well-established quadruped locomotion control frameworks, integrating features specifically tailored for locomotion in deep mud, inspired by findings obtained in publications I and II. Our controller is designed around a static gait, incorporating gravity compensation, a large step length, swing speed monitoring, and COM positioning based on estimated suction forces in the mud and the position of each leg. All these features make the robot well-suited for muddy terrain, enabling stable navigation through muddy tracks and other natural environments without tumbling. Additionally, it achieves a MCoT comparable to that reported in other studies on locomotion in resistive ground. The primary downside of this gait is its slow pace. Even though our controller was also successfully tested on hard ground, the slow pace makes it inadapted to long distances. As a result, it would be most useful as a specialized gait for traversing mud fields before switching to a dynamic gait on firmer terrain. Alternatively, future work could focus on optimizing the controller to increase its speed while maintaining stability.

Some future steps could help improve this research. One possible approach is to increase the gait speed through more active COM positioning. Instead of maintaining a fixed position, the COM could be initially placed using our model and then dynamically adjusted toward the next anticipated position, while always remaining within the static stability region. This would promote a faster and more natural gait. Additionally, sharp transitions between different environments could impose challenges. These could be better managed by incorporating active COM positioning also during the insertion phase, accounting for force also during the insertion phase of the swing trajectory. Further advancements could involve incorporating our model in more advanced modern controllers such as model predictive control (MPC) or MPC-RL hybrid controllers, or even explore the feasibility of model-free controllers for wading through deep mud. Finally, since a controller's performance is inherently limited by its hardware, another research direction is to develop improved robotic hardware to enhance legged locomotion in deep mud. This is the direction we decided to explore in the following section. There, we propose a novel foot design aimed at increasing force generation, reducing sinkage, and enabling walking on thinner mud, pushing the boundaries of quadruped robot locomotion in soft terrains.

Relation to RQ3. This chapter directly addresses RQ3: "What type of control strategy allows quadruped robots to walk on soft, wet terrain?". The results presented in this chapter demonstrate that traditional trotting gait controllers are ill-suited for soft, wet grounds. These dynamic gait controllers rely on predictable GRF to maintain stability and conserve momentum, assumptions that break down in terrains such as mud that are yielding and dissipative, and introduce variable suction forces that further disrupt the rhythmic pattern. We showed that a statics-based gait, combined with tailored adaptations such as mud detection, mud-aware trajectory planning, and suction-aware COM positioning enables a stable and efficient traversal of deep mud. These findings point to the necessity of specialized, terrain-aware control strategies for quadruped locomotion in soft, wet terrain.

4 Bio-inspired foot design for quadrupedal locomotion on soft, wet grounds

Our research in Publication III demonstrated that using a controller designed to address the different challenges of locomotion in mud -outlined in Publication II- can enable a quadruped robot to traverse a track of deep mud. However, a controller's effectiveness is inherently limited by the hardware it operates. If the terrain contains mud that is too fluid and deep to support the robot's weight, there is nothing the controller can do, and the robot must avoid such areas. To extend the robot's accessible range, we explored hardware-based solutions identified in Publications I and II.
Publication I shows that most legged animals walking on soft, deformable ground have adapted feet, with, for example, long fingers, finger webs, viscoelastic cushions, or split expandable hooves. The latter adaptation is used by many ungulates whose natural habitat often includes wet, deformable grounds. These animals likely benefit from the anisotropic properties of their feet: the feet expand when they want to generate propulsive force, and retract while minimizing resistance from the substrate during foot recovery.

Building on these findings, in this chapter, we investigate how a bio-inspired anisotropic foot design, inspired from ungulates' split hooves, and appropriately tuned compliance can improve locomotion on a muddy terrain.

To conduct this research, we used the moose as a model; a large ungulate with split hooves that is particularly well adapted to live in wet conditions, with wet snow, swamps and mud being part of its natural habitat. We took moose legs and attached them to a linear actuator to investigate how their split hooves contribute to facilitate locomotion on a soft, wet ground (Fig. 13). A picture of the moose legs is visible in Fig. 14.A-B.

We then designed a bio-inspired artificial foot, inspired from the foot of the moose (Fig. 14.C-D). The foot is made with silicone digits on its sides, that passively expand and retract, providing anisotropic behavior in soft deformable grounds.

As demonstrated in publication II, the stiffness of the foot has a role on the generated force on the ground. Thus, we tuned the stiffness of the digits to provide the maximum resistance to intrusion in different muds. The tuning process was a conducted iteratively, combining Finite Element Analysis (FEA) with prototyping.

We tested the effectiveness of the bio-inspired anisotropic foot in muds with varying water content, and compared its performance to three simplified versions of the foot (Fig. 14.E-J). Our performance metrics were sinkage during intrusion in mud, maximum suction force during extraction, and total work over a full cycle.

Fig. 15 illustrates our experimental setup. The left panel shows the experimental setup used to compare the performance of our bio-inspired artificial foot with its simplified versions. The second panel shows the experimental setup where we evaluated the speed and MCoT of the Unitree Go1 robot equipped with four of our bio-inspired artificial feet, or with its original feet.

4.1 Results and discussions

In Publication IV we demonstrate soft anisotropic feet, inspired by the split-hooves of ungulates, such as moose. These animals have hooves composed of multiple digits that expand when stepping into mud and retract when lifting the foot. As we show in our re-

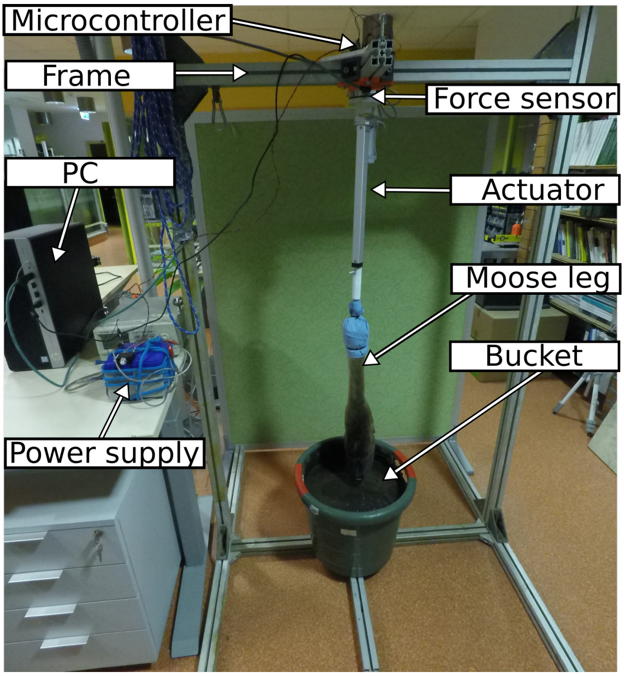

Figure 13: The experimental setup used in our fourth publication, where we mounted the moose legs on a linear actuator. It consists of an aluminum frame on which we fixed the force sensor, the actuator, and the moose leg in series. Below the frame, a bucket of mud rests on the bottom. High-level commands are sent from the PC, while real-time low-level control and data collection are managed by a microcontroller.

search, this effect is at least partly passive.

To investigate the effects of split hooves on locomotion in mud, we installed moose legs on a test rig, and compared insertion in mud with digits either free or fastened. Our results demonstrated that the passive extension and retraction of the moose digits help reduce the suction force when the leg is pulled out of the mud. However, contrary to our expectations, we did not find a reduction in sinkage depth or a reduction of the energy expenditure due to mud deformation. This absence of significant effects could be attributed to several factors, such as to the phenomenon not being entirely passive, limitations in our experimental setup—such as the restricted range of motion of our actuator or the confinement to a single water content—or simply that split hooves do not inherently reduce sinkage and energy consumption.

Motivated by these findings, we investigated whether a controlled bio-inspired foot design could more effectively reduce sinkage, suction, and energy consumption. We designed bio-inspired feet, modeled after the moose's foot structure, and tested their performance in mud with varying water content. The feet featured a ball-shaped sole similar to the original Go1 feet, surrounded by compliant digits. Our experiments measured the force, sinkage, and energy dissipated for the bio-inspired anisotropic foot in mud with low, medium, and high water content, corresponding to water-to-soil ratios of 0.21, 0.25, and 0.27, respectively. To isolate the contribution of the digits, we also compared the bio-inspired anisotropic foot with three reduced versions: one with fully extended digits,

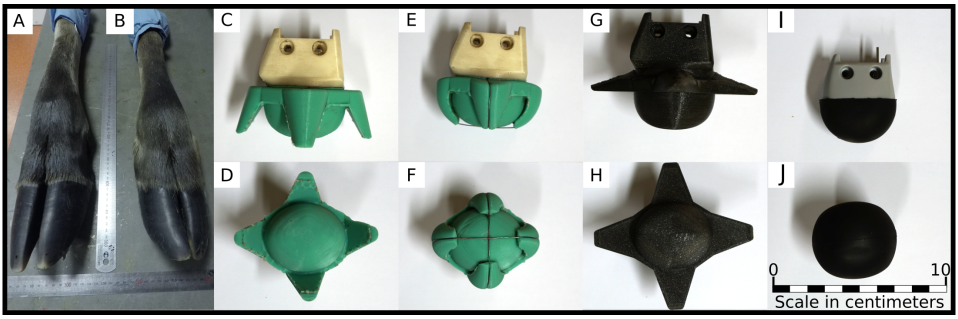

Figure 14: The different feet tested in our fourth publication. (A-B) moose front and back legs, used to test the hypothesis that split hooves facilitate locomotion in mud. (C-D) The proposed bio-inspired anisotropic foot developed for walking on mud. It features a ball-shaped sole similar to most quadruped robot feet, surrounded by flexible silicone digits that passively expand in soft deformable grounds, and retract when removing the foot from the medium. (E-F) The proposed bio-inspired anisotropic foot with fastened digits, used to isolate the contribution of the digits during the intrusion phase. (G-H) A rigid version of the foot with the digits fully extended. It was used to show, by contrast, the contribution of the passive retraction of the digits during the extrusion phase. (I-J) The original commercially available Go1 foot, used as a baseline for comparison. (C-J) are at the same scale, displayed in (J)

one with fastened digits, and one without digits (the original commercially available robot foot). The different foot types we tested are illustrated in Fig. 14.

With this new experiment, we expected to find at least similar performance to the moose feet, or even surpass them on our metrics, since the smaller dimensions of our feet did not limit our experimental conditions.

The results showed a reduction in suction force, sinkage, and energy expenditure in all three conditions tested, namely, low, medium and high water-to-soil ratio. More precisely, the bio-inspired anisotropic foot we proposed reduces suction force by 21% to 47.6%, sinkage depth by 37.4% to 46.3% and energy expenditure by 40.3% to 70.4% in the medium and high water content conditions. Under the low water content condition, suction force, sinkage depth and energy expenditure are respectively reduced by 82.1%, 18.4%, and 19.1%. While the low water content condition showed notable improvements, the commercially available foot already performed well in such conditions, making further improvements less significant.

The comparisons with the rigid foot with extended digits and the foot with fastened digits highlighted the contributions of the anisotropic foot for the different stages of the step. First, the bio-inspired anisotropic foot exhibited less sinkage than the foot with fastened digits, demonstrating the role of digit extension in reducing the sinkage. It also generated a lower suction force than the foot with rigid extended digits during retraction, showing that digit retraction helps break the suction and reduce resistance to withdrawal. In summary, our bio-inspired anisotropic foot allowed for less sinkage, reduced suction force, and lower energy expenditure overall. Moreover, since the digits remain off the ground on firm surfaces, the bio-inspired foot does not introduce any disadvantages when walking on hard terrain.

Finally, after confirming the effectiveness of the bio-inspired feet in a controlled test

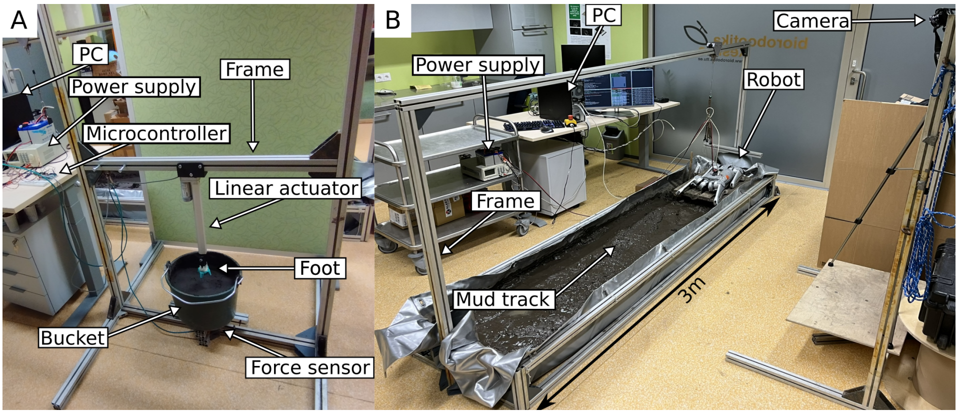

Figure 15: The experimental setup used in our fourth publication. (A) Setup for testing the artificial feet mounted on a linear actuator. The setup is similar to the one used for testing with the moose legs (Fig. 13). The artificial foot is mounted on the linear actuator, itself fixed to an aluminum frame. On the bottom, a force sensor is positioned beneath a bucket of soil to measure ground reaction forces. A microcontroller handles low-level control and data acquisition, while high-level commands and recording are managed by the PC. (B) The mud track used to test the quadruped robot with and without the bio-inspired artificial feet. It consists of a 3m x 0.8m track filled with a 12cm layer of mud, overhung by a gantry. The gantry prevents the quadruped robot from falling into the mud. Power is supplied externally for extended runtime and quick shutdown. High level commands and recording are done through the PC. A camera captures the scene for analyzing movements in postprocessing.

rig, we mounted them on a quadruped robot to assess their impact on actual locomotion performance in mud. Our results on the quadruped robot corroborated the results obtained from the test rig: the MCoT of the quadruped robot was drastically reduced, in a manner consistent with the findings from the test rig. Additionally, the robot's speed was significantly increased thanks to the reduced sinkage.

These results demonstrate the applicability and effectiveness of our new bio-inspired anisotropic feet. It is also important to note that the robotics experiments were conducted using the controller developed in Publication III, without any modifications. This suggests that adding these feet to a quadruped robot for traversing mud provides advantages and practicality, without introducing downsides. A patent application has been submitted for this foot design.

4.2 Conclusions

In the introduction of this thesis, we demonstrated that animals employ both different gaits and distinct anatomical features to enable locomotion on soft, deformable grounds. The first chapter then focused on characterizing the different responses of mud under various stepping loads. Then, while the second chapter focused on the development of a gait tailored for locomotion in mud, in this third chapter, we proposed to address the challenge of locomotion in mud from an anatomical perspective. To this end, we drew inspiration from nature, where ungulates with split hooves are able to traverse muddy terrains. We first demonstrated that the split hooves of the moose indeed provide a distinct advantage in mud, by reducing the suction force when the foot is retracted from the mud.

We then designed an artificial foot, inspired by the feet of the moose, featuring soft digits along its circumference, which imparted properties of compliance and anisotropy. Testing this foot on our test rig demonstrated that it reduces sinkage, suction force, and overall energy cost of a step in mud.

Contrary to our expectations, our experiments on moose feet did not show that split hooves reduce sinkage or save energy. However, the bio-inspired anisotropic feet did achieve these reductions, suggesting that similar results might have been observed in moose feet if our experimental conditions had not been limiting.

After demonstrating that our bio-inspired artificial feet provided significant advantages in various mud conditions, we showcased the applicability and practicality of our solution by mounting four of these feet on a quadruped robot. The resulting experiments demonstrated that the feet enabled to increase speed and decrease MCoT, all without the need to modify the robot's controller.

As Marc Raibert stated during ICRA 2023, "hardware is just as important as software". This solution serves as a hardware counterpart to complement the software approach presented in the previous chapter.

Relation to RQ4. This chapter directly addresses RQ4: "How can foot design enhance locomotion performance in soft, wet grounds?". The results demonstrated that a bio-inspired anisotropic foot design can significantly improve locomotion on soft, wet grounds such as mud. The foot we presented, inspired from the hooves of ungulates, significantly reduced sinkage, suction force, and energy expenditure caused by mud deformations across varying mud conditions. These improvements are enabled by the foot's compliance, the passive expansion of the digits during the intrusion phase, and their passive retraction during withdrawal. Further experiments on a quadruped robot confirmed the energy savings and also demonstrated an increased locomotion speed enabled by lower sinkage. These findings highlight the importance of foot design in complementing and enhancing the role of a dedicated controller for locomotion in soft, wet grounds.

4.3 Societal impact

Publication IV has garnered significant media attention. As of the writing of this thesis, it has been featured in at least 55 news sites, blog posts, or journal publications, accross 12 different languages. Notable international coverage includes the *Wall Street Journal*, *Yahoo News*, *MSN News*, *The Daily Star*, *Eurekalert!*, or *Interesting Engineering*. In Estonia, the work was highlighted in major outlets such as in *Postimees*, *ERR* public boradcasting radio, *Horizont* magazine, and *Research in Estonia*. Some examples of media coverage are shown in Fig. 16.

In addition, the patent application #P202400026 [5] was filed to protect the invention described in Publication IV. This step underscores the practical relevance and potential societal value of the research, as it paves the way for future commercialization and broader real-world applications.

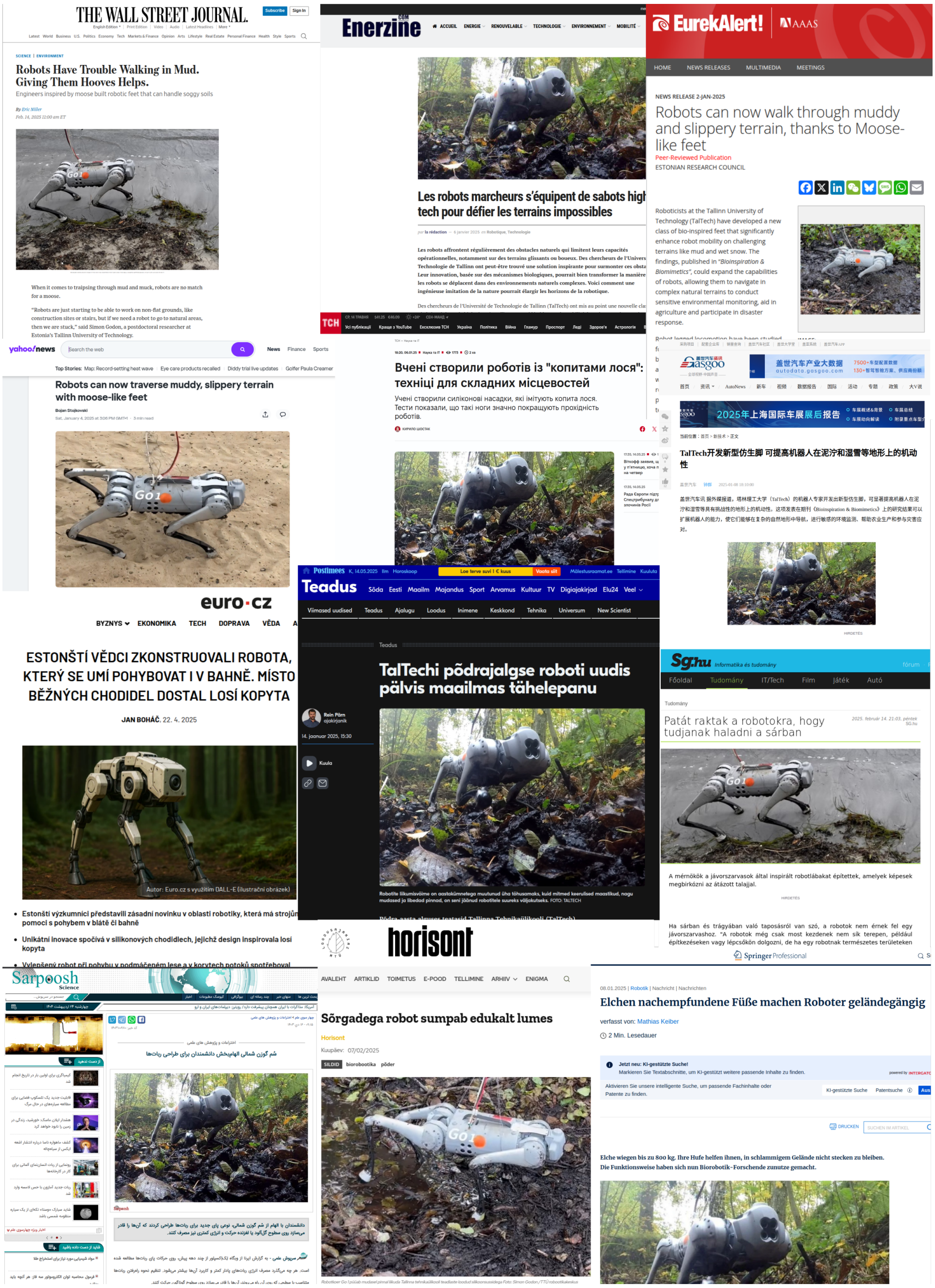

Figure 16: Collage of some of the media coverage of Publication IV.

5 Conclusions and future work

This thesis presented contributions to the review of locomotion techniques, soil modeling, quadruped control, and mechanical design of feet for quadruped robots locomoting on soft, yielding grounds.

Locomotion on soft yielding ground is challenging because of the diverse and hard to predict behaviors of yielding grounds such as deformation, variable stiffness, yielding stress, and suction force. However, such grounds are ubiquitous in nature, and enabling robots to traverse them would provide substantial benefits for operations such as search and rescue, exploration, environmental monitoring, and agriculture.

Legged robotics is emerging as a preferred solution for the applications mentioned above, because legged robots, and quadrupeds in particular, present a good combination of versatility, agility and endurance. Nonetheless, research on quadruped robots has only recently gained enough maturity to allow locomotion on anything other than hard flat grounds. Research aimed at enabling these robots to walk in complex terrains almost exclusively focuses on sand, debris or accidented terrains. The study of legged robot locomotion on soft yielding grounds has been little explored, and when it has been studied, it has mostly focused on dry granular media. Locomotion on other types of yielding grounds has been extensively studied in the field of terramechanics [18], but the teachings from this field, which focuses on wheeled and tracked vehicles, are only marginally applicable to legged locomotion, where the main challenges are related to sinkage and stability, rather than traction and shearing forces of wheels or tracks. Our research thus represents one of the first works addressing legged locomotion on soft wet grounds.

The introduction and publication I presented the work on soft ground modeling and the challenges inherent to locomotion on soft, yielding grounds. The different physics-based principles of locomotion in both animals and robots are then reviewed and classified into statics-based and dynamics-based locomotion means. Each of these categories is further sub-classified based on how these physics-based principles are implemented from an anatomical perspective. The outcomes of this research are a classification of the locomotion means of animals and robots on soft yielding ground, an analysis of the amount of work and gaps in both robotics and biology literature, and finally a catalogue of solutions for bio-inspiration in designing robots or vehicles moving on soft yielding grounds.

To address the challenge of legged locomotion on soft, yielding ground, we first needed to investigate the gap in understanding how these substrates respond to stepping loads. Chapter 2 and publication II highlight this thesis's contribution to bridging this gap. This work shows how the behavior of a soil changes with varying water content, and explores the stiffness of the ground, the ratio of impulse-to-work, or the dependence of the generated force on the stiffness of the foot and on repeated stepping. We found that mud exhibits a linear force-sinkage relationship during the intrusion phase, though the stiffness varies non-linearly with water content. Additionally, the speed of intrusion plays a role in both the intrusion and extrusion phases of the step. During the latter, a suction force appears, but only for moderate water contents. Finally, this work demonstrates that a linear force controller can be used to perform a step on mud, with better results at low water contents, where the linear force-sinkage relationship is more accurate. Overall, this research provides insights into the important characteristics of mud and the effect of parameters such as the foot stiffness, suction force and the model of the force-sinkage relationship.

After developing an understanding of mud behavior, we proceeded to tackle higher-level aspects of legged locomotion. As previously mentioned, most research on legged locomotion in challenging environments has focused on terrains such as dry sand or uneven ground. However, quadruped locomotion in deep mud remains largely unexplored. Our aim was thus to start investigating this aspect of terrestrial locomotion and propose the first controller for quadruped locomotion in deep mud.
Chapter 3 and publication III present this thesis' contribution to the control of quadruped robot locomotion in deep mud. This work proposes a gait inspired by those observed in publication I, and leverages the knowledge gained in Chapter 2 and publication II about mud behavior and modeling. The controller proposed in this thesis is based on a newly developed model-based stability criterion, bio-inspired gait, and several adjustments to the leg motion to account for the resistive nature of the mud. This work demonstrated that the controller we proposed, in contrast to a commercially available dynamics-based trotting gait controller, enabled reliable traversal of a deep track of mud while consuming less mechanical energy.

The work presented in Chapter 3 and in publication III yielded notable results and appears promising from a control perspective. However, the software is limited by the capabilities of the hardware. Legged locomotion in mud is strongly influenced by leg sinkage and the suction force when withdrawing the foot from the mud. As demonstrated in Chapter II, a compliant foot can reduce sinkage when exerting pressure on soft ground, and an anisotropic design can lower suction force and the work exerted during a step. We therefore took inspiration from nature once again, using solutions cataloged in publication I, and investigated the contribution of split hooves, which are found in the legs of many large mammals, to locomotion on soft ground. The results from the animal leg experiments were promising but were later surpassed by experiments with our bio-inspired anisotropic foot design. Our foot is mechanically simple, easy to manufacture, and offers advantages in sinkage depth, suction force reduction, and work spent in deforming the mud. Finally, the proposed foot does not impede locomotion on hard grounds and can therefore be kept on at all times during a mission, even when soft, wet grounds are only a portion of the covered area.

To conclude, the work presented in this thesis is the first of its kind as no previous research has focused on quadrupedal robotic locomotion on wet, yielding ground such as mud. Consequently, we consider this as foundational work, with the research directions explored in this thesis serving as a starting point for further advancements, ultimately enabling broader deployment of quadruped robots in natural environments.

The work presented in publication II provided an understanding of the mud under different stepping conditions but was limited to low stepping speeds, and higher speeds could therefore be investigated. One of the most promising future directions for expanding on this work lies in the control aspect. The controller in publication III demonstrates the feasibility of traversing a mud track using a static gait with a model-based stability criterion and several adaptations to leg trajectories, allowing for walking in mud while limiting suction and resistive effects. However, this controller results in relatively slow locomotion speeds, which could limit its applicability to certain real-world applications in its current state. Additionally, while the controller has been demonstrated in real-world conditions, those conditions were limited to flat, mostly homogeneous terrain. Future work could explore ways to increase locomotion speed by combining different motions or implementing force control during swing leg interactions with the mud. A broader direction for future research involves applying Physics-Informed Machine Learning by integrating MPC with RL, where MPC incorporates the mud model and stability criterion developed in our research to ensure global motion stability, while RL refines foot interactions using real-world data, optimizing for velocity and energy efficiency through reward functions. Alternatively, Residual RL could enhance the existing model-based controller by learning only the necessary corrections to foot trajectories, ensuring robust handling of mud's resistive and suction effects. These approaches could significantly improve locomotion speed, robustness, and adaptability to highly inhomogeneous and inclined terrains.

Another research direction is the mechanical design aspect of our research. In publication IV, we demonstrated a foot that improves locomotion on soft, yielding ground. This foot was directly inspired by a moose' foot, with the digits surrounding it analogous to the split hooves of the moose. However, this represents only an initial step toward designing feet adapted to locomotion on soft, wet grounds. Future work could explore how varying the shape, stiffness, and orientation of the digits can further improve locomotion on wet, yielding grounds.

Finally, our work represents an effort to develop a field analogous to Terramechanics for legged systems. Through the four publications presented in this thesis, we proposed solutions relating to the control, mechanical design, or modeling of soft, yielding grounds. As such, a third promising research direction we foresee lies in pursuing the work done in publication II, expanding the types of stepping loads, the types of terrains, and mechanical properties of the end effectors. This would contribute to building a theory of legged locomotion on soft deformable grounds, bridging with Terramechanics.

List of Figures

List of Tables

References

[1] S. Godon, M. Kruusmaa, and A. Ristolainen. "Maneuvering on non-newtonian fluidic terrain: a survey of animal and bio-inspired robot locomotion techniques on soft yielding grounds". *Frontiers in Robotics and AI*, 10:1113881, 2023.

[2] S. Godon, A. Ristolainen, and M. Kruusmaa. "An insight on mud behavior upon stepping". *IEEE Robotics and Automation Letters*, 7(4):11039–11046, 2022.

[3] S. Godon, C. Prados, A. Chemori, A. Ristolainen, and M. Kruusmaa. Walking in mud: Modeling, control, and experiments of quadruped locomotion. *IEEE/ASME Transactions on Mechatronics*, pages 1–12 (early access), 2025.

[4] S. Godon, A. Ristolainen, and M. Kruusmaa. "Robotic feet modeled after ungulates improve locomotion on soft wet grounds". *Bioinspiration & Biomimetics*, 19(6):066009, 2024.

[5] S. Godon, M. Kruusmaa, and A. Ristolainen. "Robotic foot design for enhanced locomotion on soft and wet grounds", Patent application P202400026, Nov. 2024.

[6] R. Gkliva, W. Remmas, S. Godon, J. Rebane, K. Ochs, M. Kruusmaa, and A. Ristolainen. "A multi-terrain robot prototype with archimedean screw actuators: design, realisation, modelling, and control". *IEEE Access*, 2024.

[7] C. Burlet, G. Stasi, S. Godon, R. Gkliva, L. Piho, and A. Ristolainen. "ROBOMINERS resilient reflectance/fluorescence spectrometers". In *EGU General Assembly Conference Abstracts*, pages EGU–12056, 2023.

[8] M. Dunbabin and L. Marques. "Robots for environmental monitoring: Significant advancements and applications". *IEEE Robotics & Automation Magazine*, 19(1):24–39, 2012.

[9] C. Cheng, J. Fu, H. Su, and L. Ren. "Recent advancements in agriculture robots: Benefits and challenges". *Machines*, 11(1):48, 2023.

[10] D. Goldsmith and M. Rees. *"The end of astronauts: Why robots are the future of exploration"*. Harvard University Press, 2022.

[11] K. Tong, Y. Hu, B. Dikic, S. Solmaz, F. Fraundorfer, and D. Watzenig. "Robots saving lives: A literature review about search and rescue (sar) in harsh environments". In *2024 IEEE Intelligent Vehicles Symposium (IV)*, pages 953–960. IEEE, 2024.

[12] M. Tranzatto, T. Miki, M. Dharmadhikari, L. Bernreiter, M. Kulkarni, F. Mascarich, O. Andersson, S. Khattak, M. Hutter, R. Siegwart, et al. "Cerberus in the darpa subterranean challenge". *Science Robotics*, 7(66):eabp9742, 2022.

[13] C. Bellicoso, M. Bjelonic, L. Wellhausen, K. Holtmann, F. Günther, M. Tranzatto, P. Fankhauser, and M. Hutter. "Advances in real-world applications for legged robots". *Journal of Field Robotics*, 35(8):1311–1326, 2018.

[14] B. Lindqvist, S. Karlsson, A. Koval, I. Tevetzidis, J. Haluška, C. Kanellakis, A. Aghamohammadi, and G. Nikolakopoulos. "Multimodality robotic systems: Integrated combined legged-aerial mobility for subterranean search-and-rescue". *Robotics and Autonomous Systems*, 154:104134, 2022.

[15] L. Milburn, J. Gamba, M. Fernandes, and C. Semini. "Computer-vision based real time waypoint generation for autonomous vineyard navigation with quadruped robots". In *2023 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC)*, pages 239–244. IEEE, 2023.

[16] H. Kolvenbach, P. Arm, G. Valsecchi, N. Rudin, and M. Hutter. *Legged Systems for Exploration*, pages 135–156. Springer Nature Switzerland, Cham, 2024.

[17] P. Arm, G. Waibel, J. Preisig, T. Tuna, R. Zhou, V. Bickel, G. Ligeza, T. Miki, F. Kehl, H. Kolvenbach, et al. "Scientific exploration of challenging planetary analog environments with a team of legged robots". *Science robotics*, 8(80):eade9548, 2023.

[18] J Y Wong. *Terramechanics and off-road vehicle engineering: terrain behaviour, off-road vehicle performance and design*. Butterworth-heinemann, 2009.

[19] Graham Barnes. *Soil mechanics*. Bloomsbury Publishing, 2017.

[20] C. Hubicki and J. Hurst. "Running on soft ground: Simple, energy-optimal disturbance rejection". In *Adaptive Mobile Robotics*, pages 543–547. World Scientific, 2012.

Acknowledgements

The journey toward completing this PhD has been incredibly rich in experiences, learning opportunities, and personal and professional growth. I am deeply thankful to all the people and organizations that made this journey possible and as rewarding as I could have ever expected.

First and foremost, I would like to express my sincere gratitude to my supervisor, Prof. Maarja Kruusmaa, for giving me the opportunity to join her lab and embark on the journey of a PhD candidate. Through her invaluable expertise, guidance, unwavering support, and trust in me, she allowed me to carry out my research independently and pursue the research directions I desired.

I would also like to thank my co-supervisor, Dr. Asko Ristolainen, for his technical expertise and insights into my research, as well as for his academic and personal support throughout this journey.

My heartfelt thanks go to all my colleagues at the Centre for Biorobotics, who became not only collaborators but also good friends. Their support, skills, and the positive work atmosphere they fostered made cooperation both natural and fruitful. In particular, I am grateful to Roza, Jaan, and Andres for always being ready to share their time and expertise. I also extend my thanks to Laura, Yuya, and Javier, with whom teaching was a pleasure as we shared knowledge, exchanged ideas, and supported each other. Special thanks to Jeff and Gert for our lengthy discussions on countless topics, to Jaanus for the enjoyable discussions, but also for handling administrative matters and allowing me to focus on my research, and to all the other lab members who made the lab feel like a second home.

Lastly, I would like to thank my friends and family for their constant support. Most importantly, I am deeply grateful to my wife, Eléonore, who stood by me throughout this journey and made my life infinitely brighter. Finally, to my son, Louis-Etienne, whose birth gave me an extra push to complete this work and added a sweet and tender challenge to writing this thesis.

Finally, I acknowledge the financial support that made this research possible:

- The European Union’s Research and Innovation programme Horizon 2020 project ROBOMINERS (grant agreement 820971),
- The Estonian Research Council "Multiscale Natural Flow Sensing for Coasts and Rivers" (grant agreement PRG1243)

Appendix 1

I

S. Godon, M. Kruusmaa, and A. Ristolainen. "Maneuvering on non-newtonian fluidic terrain: a survey of animal and bio-inspired robot locomotion techniques on soft yielding grounds". *Frontiers in Robotics and AI*, 10:1113881, 2023

TYPE Review
PUBLISHED 06 June 2023
DOI 10.3389/frobt.2023.1113881

Check for updates

OPEN ACCESS

EDITED BY
Andre Rosendo,
Worcester Polytechnic Institute, United States

REVIEWED BY
Andras Karsai,
Northrop Grumman, United States
Alvo Aabloo,
University of Tartu, Estonia

*CORRESPONDENCE
Simon Godon,
✉ simon.godon@taltech.ee

RECEIVED 01 December 2022
ACCEPTED 18 May 2023
PUBLISHED 06 June 2023

CITATION
Godon S, Kruusmaa M and Ristolainen A (2023), Maneuvering on non-Newtonian fluidic terrain: a survey of animal and bio-inspired robot locomotion techniques on soft yielding grounds.
Front. Robot. AI 10:1113881.
doi: 10.3389/frobt.2023.1113881

Maneuvering on non-Newtonian fluidic terrain: a survey of animal and bio-inspired robot locomotion techniques on soft yielding grounds

Simon Godon*, Maarja Kruusmaa and Asko Ristolainen

Centre for Biorobotics, Department of Computer Systems, Institute of Information Technologies, Tallinn University of Technology, Tallinn, Estonia

Frictionally yielding media are a particular type of non-Newtonian fluids that significantly deform under stress and do not recover their original shape. For example, mud, snow, soil, leaf litters, or sand are such substrates because they flow when stress is applied but do not bounce back when released. Some robots have been designed to move on those substrates. However, compared to moving on solid ground, significantly fewer prototypes have been developed and only a few prototypes have been demonstrated outside of the research laboratory. This paper surveys the existing biology and robotics literature to analyze principles of physics facilitating motion on yielding substrates. We categorize animal and robot locomotion based on the mechanical principles and then further on the nature of the contact: discrete contact, continuous contact above the material, or through the medium. Then, we extract different hardware solutions and motion strategies enabling different robots and animals to progress. The result reveals which design principles are more widely used and which may represent research gaps for robotics. We also discuss that higher level of abstraction helps transferring the solutions to the robotics domain also when the robot is not explicitly meant to be bio-inspired. The contribution of this paper is a review of the biology and robotics literature for identifying locomotion principles that can be applied for future robot design in yielding environments, as well as a catalog of existing solutions either in nature or man-made, to enable locomotion on yielding grounds.

KEYWORDS

multiphase environment, soft grounds, yielding grounds, animals, robots, bio-inspiration, locomotion, non-Newtonian fluid

1 Introduction

The last decades have witnessed a rapid advancement of robotics applications from well-structured and defined industrial environments into an unstructured and dynamic external environment (Bruzzone and Quaglia, 2012; Rubio et al., 2019). Robots in the real world can move on solid ground as well as in the air and water, and consequently, researchers and engineers have developed terrestrial, aerial, and underwater robots (Aguilar et al., 2016). However, robots still cannot access all types of natural environments (Bruzzone and Quaglia, 2012; Aguilar et al., 2016; Rubio et al., 2019).

Soft yielding substrates are materials that significantly deform under the application of stress and do not recover their original shape when stress is released. These materials can present a yield stress under which they do not undergo plastic deformation, but once pressure exceeds the yield stress, the material flows and undergoes irrecoverable, plastic deformation (Balmforth et al., 2014; Coussot, 2014). Such materials are common in nature: soils are a mixture of different particles such as gravels, sands, silts, and clays (depending on the particle size) mixed with air, water, and organic matter (Barnes, 2016). Mud is such a medium with high water content. Sand, snow, and leaf litter are other examples of such materials with varying properties (Wong, 2009; Balmforth et al., 2014; Barnes, 2016).

The problem of locomotion in deformable grounds is important to solve because it would facilitate new robotic applications such as search and rescue in wet forests, muddy fields, avalanches, and mudslides (Schneider and Wildermuth, 2016); for the agricultural vehicles operating on wet soils (e.g., rice fields) (Duckett et al., 2018; Oliveira et al., 2021); for exploration or excavation of materials (e.g., wood and ore) with a minimal environmental impact (Billingsley et al., 2008; Lopes et al., 2020); for environmental monitoring in high-biodiversity areas (e.g., river estuaries, bogs, and shores) (Dunbabin and Marques, 2012); or for extra-terrestrial exploration (Li and Lewis, 2022).

The field of terramechanics (Bekker, 1960; Wong, 2009) covers interactions between vehicles and natural grounds from a traction perspective. It covers the theory of vehicles moving with wheels or tracks on mud, sand, or soil. However, as we demonstrate in this article, there are very different ways of moving on soft deformable grounds, and terramechanics covers only one of these, which is the method used by all wheeled and tracked vehicles.

Well-known manned vehicles and some robots use wheels and tracks to move in these environments up to a limit (Bruzzone and Quaglia, 2012). Usually, they are large and heavy enough to deform the medium and gain traction from the solid bottom under the loose substrate if the medium is non-homogeneous and from the unyielded buried substrate, otherwise. Yet, this can fail if the medium is too deep and weak because actuators cannot generate sufficient tangential forces to move a potentially buried body. Some robot prototypes are addressing the challenge of traversing yielding terrains. Some quadruped (Raibert et al., 2008; Bagheri et al., 2017) or hexapod robots with rigid (Li et al. (2013); Li et al. (2009)) or adaptable legs (Liang et al., 2012) have been shown to be capable of negotiating those terrains. The SeaDog robot uses spoke wheels, which combine some advantages of wheels and legs (Klein et al., 2012), and the ePaddle robot uses wheels with expandable paddles (Shen et al., 2018). Undulatory robots mimicking worms (Sfakiotakis et al., 2016), snakes (Marvi et al., 2014), or lizards (Maladen R. D. et al., 2011) are other examples. Unstructured environments have also been negotiated by crawling robots such as a sea-turtle robot (Mazouchova et al., 2013) and a mudskipper robot (McInroe et al., 2016). A razor clam robot was designed, capable of digging through mud (Winter et al. (2014)). Some researchers designed screw-based robots, having either two screws (Nagaoka et al., 2010b) or four (Lugo et al., 2017). Recently, some robots were designed to challenge the granular lunar terrain (Shrivastava et al., 2020) by combining wheels and walking gaits. On a different scale, a sperm-inspired robot has been built, moving at low Reynolds numbers (Khalil et al., 2016). Aguilar et al. (2016) introduced the field of robophysics which consists of studying the motion of moving systems by complementing the study of complex robots with simplified robotics experiments and simple theoretical models. It provides a review of research that has already helped with the understanding of unstructured environments.

Bioinspiration and biomimetics seems to be the most commonly used paradigm for developing robots for yielding environments: the majority of the aforelisted examples explicitly claim to be inspired by animal locomotion. Typically, they mimic a specific animal or an aspect of the locomotion of a specific animal. Bio-inspired robotics can be used in two ways: one can take inspiration from a known working solution taken from nature to make a robot particularly well-suited for an environment, thereby benefiting robotics. It can also be used the other way around: one can make a robot that mimics a living being to understand some of its working principles, thereby benefiting biology (Gravish and Lauder, 2018). The concept of biomimetics and bioinspiration is a specific case of a problem-solving technique called design-by-analogy (Verhaegen et al., 2011) and often has its focus on biomechanics (Goel et al., 2017). The analogy between biology and engineering can be derived at different levels, but the decisive phase is the mapping from the problem domain to the solution domain using the most appropriate level of abstraction (Vincent et al., 2006; Verhaegen et al., 2011). It is critical to find an appropriate abstraction level for the task when using biomimetics (Nagel et al., 2010), and a higher level of abstraction allows for the creation of links between different principles that are independent of the form or behavior of biological entities (Mak and Shu, 2004). When abstract principles have been derived, they can be transposed to technology and the abstraction level can be lowered to reach technological solutions for which direct mimicry of biology–technology may not be feasible (Baumeister et al., 2013; Fayemi et al., 2017).

A majority of the robotics literature we analyzed chose to mimic the anatomy of an animal, its locomotion, or a feature of its body or behavior. Through mathematical modeling, some researchers have begun to unify these principles of locomotion in dry granular media. For example, Astley et al. (2020) reviewed the principles and mathematical modeling of limbless locomotion in dry sand, Zhang and Goldman (2014) demonstrated the applicability of resistive force theory (RFT) in dry granular media, and Hosoi and Goldman (2015) proposed a mathematical modeling technique for digging and burrowing in granular media and described four regimes based on the size of the animal and the inertial number. Other works also address different media. For example, Dorgan (2015) established the mechanisms of subterranean locomotion in dry and cohesive media, and Aguilar et al. (2016) proposed using mathematical modeling, simulations, and experimental validation as a systematic approach to locomotion in a variety of environments such as air, water, hard ground, or cluttered environments and goes beyond the field of yielding media. There, locomotion in yielding materials is treated from an anatomical point of view and describes the modes of locomotion as a legged, flipper-based, sand-swimming, or two-anchor mechanism.

The very active work on modeling presented previously is a necessary effort to understand the mechanisms of locomotion in yielding media. However, while reviewing the research work on biology, we found that, in the vast majority of cases, mathematical modeling of the animals' locomotion was not available. To enable their study, we propose turning to a higher abstraction level where locomotion can be studied from a qualitative point of view, such as the higher level prescribed by the biomimetics methodology.

In this paper, we review biology literature addressing locomotion in soft, deformable environments and propose some general principles for designing robots for those terrains. We use abstraction at the level of general mechanical principles of the deformable medium to derive engineering goals. We also categorize the existing robotics literature and demonstrate that some of those principles have been explicitly or implicitly already used in robots or other vehicles, and since they are sufficiently general, the resultant design does not necessarily need to be explicitly bio-inspired. This overview aims to offer a systematic approach, general guidelines, and design targets for developing better vehicles for soft yielding environments. The higher abstraction level used in this overview enables drawing parallels between locomotion strategies that may, at first, seem distant from each other. As discussed previously, the use of a high abstraction level such as the one we chose is advocated by the biomimetics methodology. With this paper, we aim at providing future researchers in this field with a tool to pass from the problem domain to the solution domain and find an adapted solution for their application related to locomotion in yielding environments. In addition to this engineering tool, we believe this classification can aid in the discovery of links between locomotion strategies and provide hints for future research into the unification of locomotion theories in soft yielding materials. Last, the present paper will be a useful catalog of possible sources of inspiration for locomotion in soft media. The principles and strategies of locomotion presented in this paper could be further modeled and experimented with using and extending the theories presented previously, for example, through the robophysics framework.

2 Background on non-Newtonian, yielding materials

Yielding materials are a subset of non-Newtonian fluids, which are fluids that exhibit shear stress that is not proportional to the shear rate. Over the last century (Alderman (1997); Denn (2004) for overviews), researchers have identified a wide range of complex behaviors exhibited by non-Newtonian fluids, including shear-thinning, shear-thickening, Bingham plastics, and viscoplastic fluids (Bingham (1917; 1922); Herschel and Bulkley (1926); Oldroyd (1947); Metzner and Reed (1955); Metzner (1956); Schowalter (1960)). Rheology, which is the study of the flow and deformation of matter, is a fundamental discipline that bridges the study of non-Newtonian fluid mechanics and the theory of plasticity (Barnes et al., 1989; Larson, 1999). It provides a framework for understanding and quantifying the complex behaviors of non-Newtonian fluids, as well as other complex materials beyond fluids, such as polymers, gels, pastes, and muds. This understanding of complex materials is essential to comprehend the behavior of soil, which is a complex substrate made up of four components: minerals, air, water, and organic matter. These components can be present in varying proportions depending on precipitation, proximity to water bodies, or compression of the material. Depending on the particle size of minerals, the soil particles can be classified as clay (smallest), silt, sand, or gravel (largest). When the water content is very high, the soil behaves as a liquid. When the water content decreases, the soil behaves as a plastic or viscoplastic material and is solid when the water content is low (Barnes, 2016). The plastic behavior means that above a certain stress, called yield stress, the material deforms and does not return to its original shape. The smaller the particles, the lower the permeability to water, and the more prominent the plastic behavior is.

The stress applied on the material can be computed with the von Mises criterion (1):

$$\sigma = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}, \tag{1}$$

where σ_i denotes the stresses in each principal direction and is calculated as in Eq. 2, and σ denotes the von Mises stress. Above a certain value called "yield stress," the material will undergo plastic deformation and flow. For non-cohesive materials like sand or dust, the yield stress is negligible, and the material starts to flow as soon as it is pressed upon.

$$\sigma_i = \frac{F_i}{S_i}. \tag{2}$$

In Eq. 2, F_i is the force in direction i, and S_i is the contact area in the same direction. Forces can be either due to the weight of the body or due to acceleration.

Viscoplastic behavior exhibits both solid and fluid properties, and material deformation is also affected by the rate of stress (Kutter and Sathialingam, 1992; Balmforth et al., 2014; Coussot, 2014). A large selection of models exists for muddy/clayey/sandy soils, but a unifying model is still to be found (Liingaard et al., 2004; Karim and Gnanendran, 2014). Soft yielding grounds are manifold and can present different properties, depending on whether they are cohesive, such as mud and wet sand, or not cohesive, such as dust or dry sand. More specifically, contrary to non-cohesive yielding grounds, cohesive grounds have a yield stress and are viscous (Augustesen et al., 2004; Omidvar et al., 2012; Mishrai et al., 2016; Yang et al., 2017).

To move, a body must exert forces on the environment. The environment, in turn, generates a counter-reaction force that propels the body. On a solid flat ground, if the body stands still, the force on the ground, called the ground reaction force, has only a normal component to compensate for the weight of the body. When the body moves, it must exert a force parallel to the ground, which is the horizontal component of the ground reaction force and is limited by the friction coefficient of the ground/body couple. When the ground is soft, it can deform under the weight of the body, and the maximum force is also limited by its shear resistance. The deformation of the material causes energy losses that make locomotion more difficult as more work is required (Lejeune et al., 1998). The work W exerted on a deforming medium is defined as in Eq. 3, where z is the depth of intrusion and F the force as a function of z.

$$W = \int F dz. \tag{3}$$

The body will move forward when it generates sufficient forces F in the direction of movement over some time t (mechanical impulse I) to move its mass m at a certain speed v (to gain momentum):

$$I = \int F dt = m\Delta v. \tag{4}$$

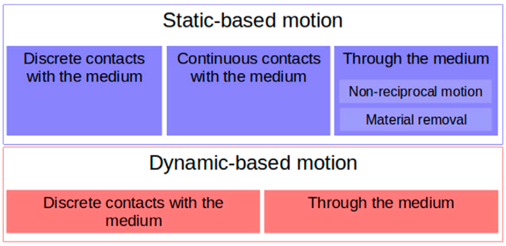

FIGURE 1
Classification of the principles and strategies of locomotion in yielding grounds.

When the soil is yielding, the applied force is limited by the yield force in the direction of movement, reducing the impulse and slowing the body down. To reduce sinkage into the media, robots or animals have to apply reduced pressure. When sinkage already occurred, the animals or robots have to deal with moving in a deformable material, where, depending on the material, stress, rate of stress, and depth of insertion can all play a role (Terzaghi et al., 1996).

Given that soft yielding materials exhibit different behaviors depending on how one interacts with them, there are two different ways of moving in/on them. When moving on a yielding substrate, frictional hydrostatic forces dominate at low speeds, while the inertial hydrodynamic response of the material dominates at high speeds (Qian et al., 2012). There are, thus, two ways to move on or through a yielding material: using the material's static properties or using its dynamics properties (**Figure 1**).

There are primarily two ways to move using the static properties of the medium, as shown in the top part in **Figure 1**. The first way is to not exceed the yield stress of cohesive materials or deform them plastically so that the resulting surface can be used as a static support against which to generate thrust. When we do not consider dynamics, the vertical equilibrium is maintained between hydrostatic-like pressure on the immersed volume of the body and weight. We refer to hydrostatic-like pressure as a pressure that increases proportionally with depth (Aguilar and Goldman, 2016). It has been shown that different flowable materials, when stepped upon, generate a reaction force that is almost proportional to the depth of intrusion (Sharpe et al., 2013; Godon et al., 2022; Ma et al., 2022). In the horizontal direction, thrust can be generated by relying on the cohesion and adhesion of the medium particles with the body. Additionally, if plastic deformation is carried out, the body can push horizontally against the unveiled surface of the material.

In the second case, the moving body uses the dynamic fluid properties of the medium (see the bottom part of **Figure 1**). To move dynamically on/in a fluid, a body has to transfer momentum to the fluid so that the fluid reacts by providing thrust, as per the principle of the conservation of momentum. There are three main momentum transfer mechanisms in fluids: drag (pressure and friction drags), lift, and acceleration reaction forces. However, in friction-dominated media, lift cannot be used for propulsion (Webb, 1988), and pressure drag is another manifestation of inertial forces (Vogel, 2020). This leaves two mechanisms for movement through a frictional fluid. The first, friction drag, can be used in static locomotion and is also a necessary component of pressure-drag-induced inertial forces. The second, acceleration-related force, takes advantage of propelling fluid particles in the opposite direction of the desired thrust. In nature, this is usually performed in the fluid by oscillations or undulations of the body and appendages in fish, ducks, or seals (Sfakiotakis et al., 1999; Vogel, 2020), but can also be performed at the surface by slapping the fluid. In this rapid motion regime, the forces exerted by the fluid depend quadratically on velocity. We refer to this as the hydrodynamic-like principle (Aguilar and Goldman, 2016) because of its similarities to the hydrodynamic principles of propulsion exerted in fluids (Webb, 1988; Sfakiotakis et al., 1999; Vogel, 2020).

As opposed to moving on a deformable soft media, dynamic motion through such medium is hindered by high friction drag and form drag. One solution to reduce drag is to use fluidization. Fluidization is the process by which material particles are given a sufficient velocity so that the granular material (cohesive or not) behaves as a fluid. This can be performed by injecting a fluid through the materials, which will generate a form drag on the particles and reduce the interparticle stress. Fluidization can also be enhanced by vibrations in a granular material (Zik et al., 1992; Xu and Zhu, 2006). Fluidization is mostly used to move through the substrate to facilitate progression and is hence typically observed in animals digging or burrowing in granular media (Hosoi and Goldman, 2015).

Thus, locomotion on non-Newtonian yielding ground is different from that on solid ground or in water. To move on/through such materials, animals have developed a wide range of locomotion strategies. These strategies are explored and categorized in this paper, and existing robots are categorized accordingly.

3 Methods

This paper aims at answering the following questions:

- How to classify the modes and mechanisms of locomotion in natural, yielding environments?

- What physical principles are present in nature for locomotion in yielding environments?

- Do those modes and mechanisms share any common physical principles that are abstract enough to be applied to robots including non-bio-inspired robots?

To answer these questions, we conducted a review of biology research, focusing at first on animal locomotion in soft yielding environments. We identified relevant research papers and classified them based on material behavior and locomotion mechanisms. We have also mapped existing robots into the presented principles, demonstrating that successfully developed solutions are designed implicitly or explicitly against those principles and suggesting that defining those principles as design targets will help develop better vehicles faster and easier.

Our integrative literature review on the biology of locomotion in deformable environments used established methodologies outlined in Torraco (2005); Snyder (2019). We utilized relevant keywords associated with the themes of locomotion, animals, and soft

TABLE 1 Keywords used for the literature search.

About the animal/action	About the environment
Amphibious, animal, benthic, boring, burrowing, crawling, fish, fossorial, legged, locomotion, motion, semi-terrestrial, walking	Clay, flowable, ground, intertidal, low resistance, mangrove, mud, multiphase, sand, slurry, substrate, soft, unstructured, viscoplastic, weak ground, wet granular media, yielding, yield stress

environments (Table 1) to search various online databases such as Google Scholar, IEEExplore, ACM Digital Library, Science Direct, Web of Science, Wiley Online Library, Scopus, CiteSeerX, SpringerLink, PNAS, and PLOS One. Our search terms involved combining at least one word from the first column with at least one word from the second column in Table 1 to create different keyword combinations (e.g., "animal locomotion in multiphase environments," "walking fish on mud," and "legged locomotion on low resistance ground"). Additional papers were identified from the references in the documents. To ensure inclusiveness, all papers mentioning any of the selected keywords were selected at first. Then, analysis of the main topic of the documents led to keeping only those addressing locomotion from a mechanical perspective. For instance, documents discussing the evolution of the genome, neural control, muscle control, fish swimming near the surface, or an evolutionary analysis of anatomy were excluded. The documents were then divided into categories based on the main topic, and some categories were disregarded as being out of scope for this literature review (e.g., addressing the effect of viscosity on swimming or the burrowing patterns of crustaceans). The most representative documents of each category constitute the corpus of this article and were organized based on the mechanical principles and locomotion strategies employed by the animals they describe. Papers relating to robotic analogs were included at a later stage.

We, then, analyzed the locomotion used by each species and robot and abstracted it to understand how and where the forces are generated. We discovered that even when forces were generated using different body parts, motions, speeds, and material properties, they could be classified into two categories based on whether they used the static or dynamic properties of the yielding media. Then for each mechanical principle, the interaction type could be generated using different strategies, which mainly differed depending on the nature of the contact between the body and the medium. Furthermore, under this second level, we discuss the animals' specific means of locomotion, describing which body parts are used, how they are used, and the special features facilitating the means of locomotion.

In the next sections, the locomotion strategies classified according to the mechanical principle will be more closely described, along with a description of the specific animal locomotion patterns and references to the existing robotic analogs.

In the following sections, the animals' and robots' means of locomotion on soft yielding grounds will be categorized into the two following interaction types: those using the static properties of the material, mainly using friction-based hydrostatic pressure, and those using the dynamic properties, mainly inertia.

4 Statics-based movements

Statics-based movements use the hydrostatic-like pressure in the medium to counter gravity, friction forces, and material cohesion to generate forward impulse. We observed that the highest level of distinction that could be made was based on the spatial distribution of the contact between the body and the media. Three different strategies were observed:

- Discrete contacts with the medium
- Continuous contact at the surface of the medium
- Immersion through the medium

The two first strategies imply compensating the body's vertical and forward momentum on the ground by achieving static equilibrium between the deformable material and the body. There are two possibilities: the stresses exerted by the body on the medium are less than or equal to the medium's yield stress. In most cases, unless the animal is very light-weighted, or the ground is almost solid, the material first yields, and then solidification occurs when pressure drops below the yield stress: at first contact, only a minor portion of the body, for example, a foot, touches the ground, and the pressure is very high. The surface yields, the foot sinks into the soil until a sufficient surface area touches the substrate to distribute the efforts, and the relative pressure is reduced to the yield stress. Resistive force increases linearly with depth: the deeper the appendage sinks into the substrate, the higher the pressure, and the more the substrate resists intrusion. Only when solidification has occurred, the animal can use the substrate as a static support. Yet, at this stage, the material has deformed, required work, and made locomotion harder. There are two different possibilities to reduce sinkage: reduce the pressure exerted on each weight-bearing body part and reduce acceleration-related forces.

Animals use different strategies to achieve such results: using a large number of legs, using large feet surface areas, lying on a large portion of the trunk, using the tail to increase the contact area, or reducing forces by moving slower. In the third strategy, through the medium, the body is inside the substrate, and hydrostatic-like pressure does not need to compensate for the weight of the body outside the material. There, the challenge is rather to generate forces using non-reciprocal movements because the friction-dominated environment dissipates energy, and therefore inertia (Purcell, 1977; Vogel, 2020).

4.1 Animal locomotion

4.1.1 Discrete contacts with the medium

Ungulates (large mammals with hooves) step on yielding substrates with hooves. The relatively small surface area of the hoof is initially insufficient for compensating their weight without yielding the substrate. As a result, the yield stress of the material is exceeded and the leg starts to sink; the foot of the animal sinks into mud until it encounters something harder or until the hydrostatic-like pressure compensates for the weight. One interesting feature observed in ungulates is the passive enlarging of their feet when stepping on yielding material. Not only do the different toes move apart from each other, but also in some cases, digits are located higher at the back of the foot. The rear digits also passively extend outward when the leg sinks into the yielding substrate and passively retract when the leg is removed from the substrate. Two studies were found in the literature about locomotion of cows in slurry or sand (Phillips and Morris, 2000; Telezhenko and Bergsten, 2005). When in a not too deep layer of slurry, cows reduce their stride frequency to compensate for the difficulty of penetrating and retracting the leg through the slurry. Simultaneously, they increase their stride length because the risk of slipping is reduced when the animal has a strong foothold in the slurry (Phillips and Morris, 2000). The same increase in stride length was observed when walking in sand compared to hard ground (Telezhenko and Bergsten, 2005). The foothold providing additional traction has been experimentally studied on a test bed in granular materials (Yeomans et al., 2013).

Similarly, it was found that in the case of hermit crabs, bigger individuals ran faster on beach sand by increasing stride length, but not frequency (Herreid and Full, 1986). Other research showed that basilisk lizards also increase their speed on sand by solely increasing their stride length (Bagheri et al., 2017). Salamanders use undulations of their body to take larger steps (Edwards, 1989) and walk on mud using a gait (Aydin et al., 2017) which keeps three legs on the ground to reduce the pressure on the substrate. Tiger salamanders additionally increase the surface area of their feet contacting the ground when the medium is compliant, but it is not clear whether this is a passive process due to surface softness or an active mechanism (Vega and Ashley-Ross, 2020). The same phenomenon was observed in hatchling turtles using the alternating gait in which diagonally opposed flippers push on the media. During the stroke, the plastron is lifted off the ground to reduce drag, and the flippers are oriented perpendicularly to the propulsive force to decrease soil deformation. An illustration of the hatchling turtles using the alternating gait is shown in **Figure 2A**. The Uma lizard has fringed toes that may facilitate locomotion on sand. These fringes increase the surface area, which, in turn, increases frictional forces and decreases pressure (Carothers, 1986). However, a more recent study disagrees and reveals that these fringes have an advantage in burrowing (Zheng et al., 2020). Generally, it has been shown that lizards living in sandy areas have longer feet relative to their size (Kohlsdorf et al., 2001). Additionally, lizards with larger feet could passively reduce their penetration ratio and maintain better performance on flowable grounds. For many lizard species running on sand, it was demonstrated that the acceleration was lower on sand than on less compliant surfaces (Vanhooydonck et al., 2015). The same observation has been made on humans. It can be explained in part by the mechanical work lost when deforming the sand, and in part by decreased muscle and tendon efficiency in positions reached by the feet (Lejeune et al., 1998). Moreover, similar to what was observed for cows, lizards, and crabs, humans increase their stride length on very compliant surfaces (McMahon and Greene, 1979). **Figure 2B** depicts a human stepping on yielding mud.

Other large animals, such as elephants or camels, also increase the surface area of their feet when stepping. Fat pads in camels exhibit viscoelastic behavior and expand more as more pressure is exerted on them. This pressure-dependent expansion enables pressure on the ground to be independent of velocity. It also acts as a dampener, reducing the loading rate and peak force. Additionally, fat pads reduce localized pressure build-up, which enables traversing rocky terrains without damaging the foot (Clemente et al., 2020). Similarly, elephants can also walk on the waterside or desert sand thanks to their fat pads (Weissengruber et al., 2006), which have viscoelastic properties and enable them to absorb shocks and adapt to the ground (Panagiotopoulou et al., 2012).

Many light-weighted legged animals are also described walking on deformable grounds. For these animals, their weight is low enough or their feet surface area is sufficient to reduce the stress exerted on the ground, hence reducing deformations. For example, arthropods are lightweight and have six to hundreds of legs. They are often found in areas where the ground is soft, for examples, crabs on the seaside, scorpions in the sand, and centipedes in forest soils (Foxon, 1936; Trueman, 1983; Faulkes and Paul, 1997; Herreid, 2012; Kuroda et al., 2014). Caterpillars (Trimmer et al., 2006) and inchworms (Plaut, 2015) are also very light-weighted animals that use several pairs of paws moving in an undulating pattern. Even though such larvae's natural habitat is not directly mud or sand, they can often be found moving with ease on such substrates. An illustration of the caterpillar gait can be found in **Figure 2C**

One common feature we can notice in all these animals is the presence of mechanisms to reduce foot pressure: large paws, spreading/retracting digits (anisotropy), long fingers or a large number of legs, soft feet absorbing shocks, and spreading weight or gait lowering pressure on feet. It is worth noting that many animals we find in the desert or along the watersides have webbed feet or long fingers, increasing the surface area: Gila monster, shovel-snouted lizard, web-footed Namib dune gecko, ducks, beavers, and otters. For animals walking in such media, keeping a relatively low speed was observed to be a consistent behavior. This could be to reduce frictional losses as well as acceleration-related forces that could further yield the substrate and plunge appendages deeper into it (Li et al., 2012).

4.1.2 Continuous contacts at the surface of the medium

The strategy presented in this section consists of keeping the main body constantly in contact with the ground. Crawling animals use a large part of their body to lie down on the ground and use appendages or undulations of the body to generate forces parallel to the ground.

Crawling is a mode of locomotion often used by animals living in water and occasionally venturing onto the shore. This suggests that this mode of locomotion is unlikely to be optimized for land locomotion, but rather a way for bodies adapted to aquatic environments to move on land. A large number of these animals are fish. Fish move in water using axial undulations. Some evolved limbs and invaded land over time (Amaral and Schneider, 2018), resulting in locomotion strategies that combine body undulations and limbs. For example, *Polypterus senegalus* is a fish which uses its fins along with longitudinal rotations of its body to generate motion, while the body is resting on the ground (Standen et al., 2016). Climbing perches, lungfishes, and *Clarias* all use a similar crawling-based locomotion on land: they all lay their entire body on the ground, distributing their weight over a large surface area, and then anchor a part of their body by plastically deforming the ground. Then, they apply lateral force to this anchor to propel themselves. The climbing perch uses this principle by planting the detachable sub-operculum into the ground to use it as a pivoting point for propelling its body forward (Davenport and Matin, 1990). Using the same strategy,

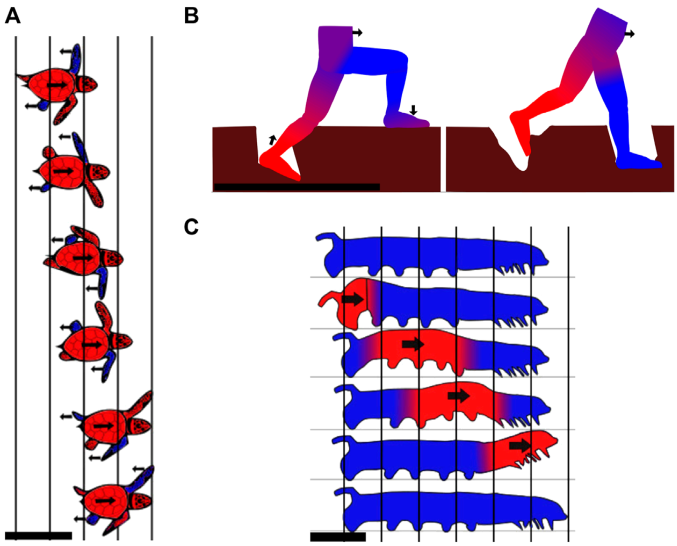

FIGURE 2
Example gaits of animals using static-based locomotion with discrete contacts. **(A)** Stepping pattern of a quickly moving hatchling turtle using only its four appendages. The blue parts are the flippers that are supporting against the ground, while the red parts are those moving forward. Two flippers are pushing backward/downward against the sand at the same time, while the other two are in the recovery motion and brought forward in the air. Top view, scale bar is 5 cm. Drawn according to Lutz and Musick (1996). **(B)** Illustration of a person walking through mud. One leg sinks and deforms mud until the hydrostatic pressure compensates for the human's weight. When the leg is bearing the entire weight, the other leg is retracted and placed further. The mud undergoes plastic deformation and does not fully recover its original shape. The blue parts are flippers supporting against the ground, while the red parts are those moving forward. Side view, scale bar is 1 m. **(C)** Movement cycle of the caterpillar. The moving parts are highlighted in red and the static parts in blue. Progression of the body happens outside of the medium while the feet make discrete contacts with the ground to generate the reaction forces. Side view, scale bar is 1 cm.

the *Clarias* plant their fin (Johnels, 1957) and the lungfish plant their crane (Horner and Jayne, 2014). **Figure 3A** presents *Clarias* moving on land using this strategy, and **Figure 3B** presents the crane anchoring of lungfish. In all those cases, the plastic properties are used to plant the anchor into the mud, and the frictional properties are used when pulling. This way of combining appendages and body undulations is described as axial-appendages; one of the three modes of locomotion of fish on land (Pace and Gibb, 2014), the other two being undulations or appendages only. These locomotion patterns are probably the most primitive ways of moving on soft media as they have been adopted by the first fishes invading land (Amaral and Schneider, 2018).

When crawling, animals such as the mudskipper (HARRIS, 1960; Van Dijk, 1960; Pace and Gibb, 2014) or hatchling turtles during their symmetric gait (crawling simultaneously with both front flippers) (Mazouchova, 2012) propel themselves by pushing backward/downward with their flippers, while leaving a large part of their body dragging on the ground. In the propulsion phase of the mudskipper, the fins are placed flat on the surface of the ground to obtain the maximum traction possible and take advantage of friction to exert lateral forces. During the hatchling turtle's propulsion phase, sand is solidified by positioning the flipper normal to the direction of efforts, increasing the effective surface area, and then used to propel the body. While the limbs are in a swing phase (moving without touching the ground to prepare for another stroke), the animal lies on a larger portion of the body, which enables the material to not significantly deform. The larger portions of the body used are the pectoral and caudal fins for the mudskipper and the carapace for the turtle. The crawling locomotion pattern of the mudskipper is shown in **Figure 3C**.The mudskipper has been observed to use its tail more and more as the steepness of the incline increases (McInroe et al., 2016). This mechanism also prevents back slippage.

The remaining crawling animals found in the literature move on soft ground by undulating their bodies. Gastropods move on such substrates while not yielding them (Trueman, 1983). Their light weight, together with the large surface area of their foot, enables very little pressure to be exerted on the substrate. The body of gastropods continuously stays in contact with the ground, and peristaltic-like undulations of the foot generate propulsion forces. Snakes use different locomotion patterns, all consisting of undulations of different sorts. Their locomotion patterns consist of keeping a large part or all of the body on the ground, and then they slide the body by pushing on natural obstacles or lumps of sand that they formed themselves during sidewinding locomotion by deforming and solidifying the sand surface (Wake, 2001). In the more challenging case when no obstacles are available to push against and the substrate is too hard to be deformed, scale anisotropy and weight distribution help snakes to move on a substrate (Hu et al., 2009); this is used in concertina and rectilinear locomotion patterns (Jayne, 1986; Wake, 2001).

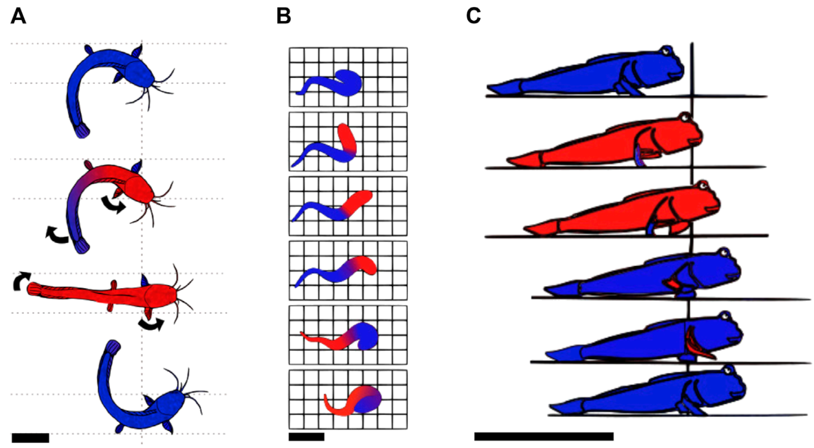

FIGURE 3
Example gaits of animals using a static-based locomotion with continuous contact. **(A)** Locomotion of the *Clarias* on land according to Johnels (1957). The red parts are those progressing, while the blue parts are those pushing against the ground or are static. The *Clarias* anchors one pectoral fin in the ground and uses its tail to pivot its body around the anchored fin. It then anchors the second pectoral fin and repeats the cycle on the other side. Top view, scale bar is 10 cm. **(B)** Representation of the locomotion pattern of the lungfish on land. The red parts represent those that are progressing, while the blue ones represent those that are pushing/pulling on the soil. The lungfish propels its head by pushing on its tail and anchors its head in the ground. Then, it brings the tail closer to the head, using the head as an anchor and starts a new cycle. Top view, scale bar is 10 cm. Drawn according to Horner and Jayne (2014). **(C)** Locomotion pattern of the mudskipper using the alternating tripod system. The red parts are moving forward while the blue ones are not. The mudskipper uses its pectoral fins to generate lateral forces on the ground and rests on the pelvic fins during the recovery motion of the pectoral fins. Throughout the entire locomotion cycle, the tail is trailing on the ground. Side view, scale bar is 10 cm. Drawn based on HARRIS (1960).

Leeches and worms on mud use peristaltic undulations, where the parts in contact with the ground are large enough so that friction resists backward movement while the rest of the body is moving forward (Dorgan, 2010; Kristan, 2019). The polychaete *Nereis virens* also uses body undulations from the back to the front in combination with a rowing pattern of the legs (La Spina et al., 2007).

Seals are the only example found in the literature of a large animal moving on such substrates (sand and gravel) using undulations (O'gorman 1963). The seal's entire body is in contact with the ground and undulates in the sagittal plane at slower speed and in the frontal plane at greater speeds. Similar to all animals in this section, keeping a large portion of the body always on the ground reduces the seal's sinkage.

4.1.3 Through the medium

In this third static-based strategy, animals move through the media. There are two ways to do this: either by deforming the body and using non-reciprocal motion or by removing the material, thereby removing the frontal motion resistance.

4.1.3.1 Non-reciprocal motion

In a low Reynolds number regime, the viscous forces dominate the inertial forces. In this case, locomotion cannot rely on the principle of giving momentum to a fluid because viscous forces dampen any inertia, and animals have to use locomotion strategies based on non-reciprocal motion (Purcell, 1977; Pak et al., 2015). Sperms use flagella while moving in low Reynolds number environments. To break the symmetry and enable propulsion at low Reynolds numbers, the flagella oscillates from side to side, bending in a chiral shape (Friedrich et al., 2010). This strategy is also typically used by clams, which move through the medium using a dual-anchor mechanism in which a part, either the shell or the foot, is shrunk and pushed through the medium, while the other is expanded and *vice versa*. This strategy of changing the shape of different body parts during the motion or the anchoring phase creates a non-reciprocal motion that enables one to move without making use of the medium's inertia. This behavior can be observed in **Figure 4A**.

Burrowing eels have been observed to burrow into the bottoms of water bodies using a high slip factor (ratio of undulation wave speed to locomotion speed). This means that the undulating wave of the body travels at almost the same speed as the body and that the substrate behaves as a solid. Consequently, little energy is lost in substrate deformations (Herrel et al., 2011). This can be explained by two different phenomena. First, by concentrating stresses and deforming the material in front, the wedge-shaped head reduces form drag. Second, when the eels dig, they use smaller wavelength undulations, resulting in more distributed forces in the direction of motion, and reducing stresses on the substrate. Similarly, sand lances use their wedge-shaped nose to enter the substrate via plastic deformation and then use the lateral portion of their body to undulate and push against the sand with little deformation (Gidmark et al., 2011). The same principle applies to worms using peristaltic motion: the body anchors at several places, using the substrate as a solid to provide traction, while some body parts are shrunk and pushed forth (Dorgan et al., 2016). Worms use crack propagation to move inside the ground, especially when the soil is not too soft. Peristaltic waves end with the enlarging of the tip of

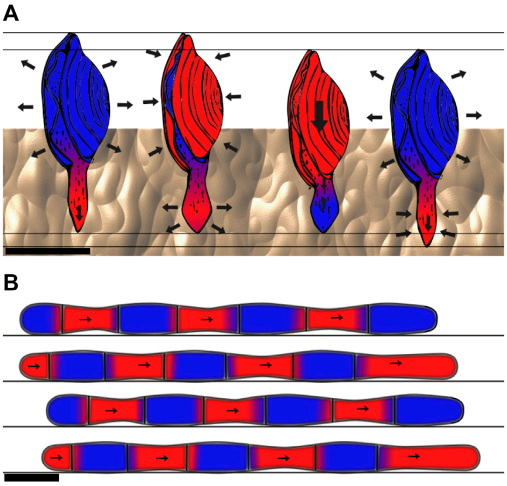

FIGURE 4
Example movements of animals using non-reciprocal static-based locomotion. **(A)** Locomotion cycle of a clam. The moving parts are specified with red color and the static ones with blue. The digging pattern of the clam is based on a dual-anchor: the shell is expanded and applies forces on the surrounding medium, which anchors the shell in place. Then, the foot, shaped in a thin, elongated form, penetrates the substrate further. The foot is then expanded and the shell closes so the foot becomes the anchor, and the foot pulls the shell. Then, the shell is expanded again for a new cycle. Side view, scale bar is 1 cm. Schematics is based on Dorgan (2015); Trueman (1983). **(B)** Worm using peristaltic motion. The red parts are those progressing, while the blue ones are anchored to the soil. The peristaltic motion consists of waves of contraction and release of circular and longitudinal muscles. Parts of the body are expanding and generating forces against the ground, while the body parts that do not touch the substrate are progressing. Side view, scale bar is 1 cm.

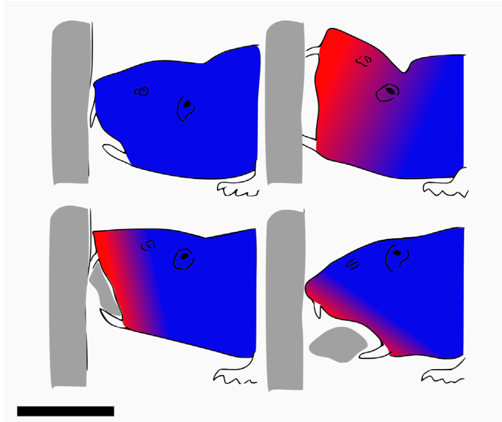

FIGURE 5
Mole rat digging a tunnel with his teeth. Red parts are the moving parts. Side view, scale bar is 3 cm. Drawn after Van Wassenbergh et al. (2017).

the front end of the worm, which acts as a wedge to crack the soil (Murphy and Dorgan, 2011; Grill and Dorgan, 2015). This wedge appears to reduce the form drag by reducing the worm's frontal area. If the soil is too soft, it deforms rather than cracking when subjected to high stresses, and the worm moves by plastic rearrangement of the grains (Dorgan et al., 2016). To grip the soil more firmly, some worms also have chaetae on their segments, which protract during the stance phase to increase friction and retract during the forward movement (Foxon, 1936; Crane and Merz, 2017), creating a friction anisotropy. **Figure 4B** presents the worms' peristaltic motion.

Mole crabs are using their legs to dig into the substrate and burrow themselves. For this purpose, they use four pairs of legs to scrape the material off the ground. During the digging motion, legs are successively extended or retracted, hence creating motion anisotropy and enabling the body to burrow (Trueman, 1970; Faulkes and Paul, 1997; Treers et al., 2022). This animal is also suspected of using fluidization, which will be described later.

4.1.3.2 Material removal

This strategy entails digging a tunnel to eliminate form drag on the body as it travels through the media. It cannot be used in a purely fluidic or solid medium and is, therefore, specific to soft plastic grounds. Some examples of animals using this strategy are moles (Yalden, 1966; Scott and Richardson, 2005), mole rats (Jarvis and Sale, 1971; Van Wassenbergh et al., 2017) (**Figure 5**), mole crickets (Zhang et al., 2011), and the arthropod *Nebalia bipes* (VANNIER et al., 1997). These animals make use of different methods of digging. Moles use their arms equipped with large paws to plastically deform the substrate and eventually remove it from the front. So do the mole crickets, while the mole rats dig using their teeth. The *Nebalia bipes* digs into unconsolidated mud by scraping the surface with its paws. Additional anisotropy is created by a microscale structure on its shell, facilitating progression through mud while hindering backward motion (VANNIER et al., 1997).

As it was seen in this section, animals progressing statically through the media are all using anisotropy, either through oscillations, surface features like chaetae, or microscales or body deformation. Some animals also take extra steps to reduce the form drag of the media, either by removing it, or by plastically deforming it using a wedge-shaped frontal end of the body.

4.2 Robotic analogs

As we will see in this section, the technologies used for locomotion in robotics can be classified using the same categories as the strategies derived for animals. The abstraction of the principles helps understand how technologies that may at first seem very different, can be brought together under the same principle.

Most of the robots that used discrete contacts with the medium were not designed to move on soft yielding media, but they were shown to walk on sand or mud with varying degrees of success.

The most common legged robots demonstrated on yielding substrates are hexapods. The AmphiHex (Liang et al., 2012), RHex (Li et al., 2013), and SandBot (Goldman et al., 2009) robots are all hexapods, which enable them to reduce the pressure on a single foot. However, as observed in some of the experiments (Li et al., 2009; Zhong et al., 2018), the small area and length of the feet relative to the robot's weight do not allow an effective motion as the robot struggles in deformable media. Experiments using the SandBot (Li et al., 2009; Qian et al., 2015) showed that for very weak grounds, increasing the step frequency too much and/or reducing the material compaction leads to dramatic performance losses. The performance drop is probably due to an increase in acceleration-related vertical ground support force that leads to deeper sinkage of the legs (Li et al., 2009; Qian et al., 2012). The BasiliskBot was designed to study the effects of substrate properties on the locomotion parameters and showed that a higher sand saturation level led to increased stride length, which, in turn, increased velocity (Bagheri et al., 2017). Similar velocity drops were observed at higher stepping frequencies. A crab-like robot was built to investigate how crab dactyls could improve sand anchoring (Graf et al., 2021). It was found that, despite a clear increase in the generated anchoring forces, the use of pointed, curved dactyls reduced the locomotion speed on yielding media. Some quadruped robots were also used in yielding media: Lee et al. (2020a) demonstrated the quadruped robot ANYmal treading over natural terrains. Even though the robot hardware is not well-adapted for locomotion in these deformable terrains, robust control enables the robot to traverse ground coated with mud or snow. Using the same principle and similar hardware, the BigDog robot was demonstrated walking in mud and snow (Raibert et al., 2008).

Other experiments used a bottom–up approach, investigating how different materials or actuation strategies could affect forces and sinkage. For example, an experiment using a variable stiffness jamming foot was built to prove that using a soft deformable foot allows for less deceleration, sinkage, and pull-out forces when interacting with sand due to increased surface area and internal work (Chopra et al., 2020). Additionally, stiffening the foot after sinkage allows for more shear force to be generated. Another experiment tested different stepping parameters on muds and found that foot compliance increased the generated force on mud, and that lower speeds lead to higher forces (Godon et al., 2022).

Other robots maintained continuous contact with the ground. In Baines et al. (2022), a turtle-inspired robot that can change the shape of its appendages was designed. The appendages can be changed from legs to flippers to either walk, crawl, or swim. The turtle robot uses the crawling gait on yielding media to ensure stability and avoid stress concentration. It was shown that the cost of transport is correlated with the friction coefficient of the shell and negatively correlated with the friction coefficient of the appendages. Additionally, crawling on four flippers was more efficient than that on two flippers, showing that bio-inspired robots can be capable of outperforming their biological inspiration. A sea-turtle robot (Mazouchova et al., 2013) has been designed to mimic some aspects of the crawling locomotion on sand. It was demonstrated that crawling with a flexible wrist helped locomotion by reducing the work done on the material, and that flipper-induced lift enabled to reduce drag on the body. Additionally, a similar mudskipper robot (McInroe et al., 2016) showed how the tail could improve crawling on low-yield substrates, especially on inclines where limbs alone are not sufficient to provide thrust. A *Nereis* robot was created to explore undulatory locomotion on sand, aided with elastomer appendages (Sfakiotakis et al., 2016). This robot could move on sand thanks to the distribution of its mass over a large body. Appendages were providing the propulsive force, aided by body undulations. It was observed that, even though the joint compliance between segments reduced the average velocity, this enabled the robot to pass all the presented obstacles.

A snake robot has been created to study sidewinding locomotion (Marvi et al., 2014). Analogous to the animal, this robot deforms the sand to create lumps of sand, which then solidify and serve as a static support.

The ePaddle robot was designed to incorporate a wheel-paddle mechanism to negotiate both unstructured and yielding grounds as well as water and solid plane ground (Shen et al., 2018). On sand, the paddles dig into the ground to obtain more traction and reduce slippage.

More generally, man-made ground vehicles fit in this category. Examples include wheeled vehicles (the Sherp ATV (SHERP, 2022) and Burlak (BURLAK, 2022)) which use large, deflated wheels to spread the weight on a large surface area to reduce soil vertical deformations. In addition, the tires of these vehicles incorporate large studs to gain traction on the soil. Other examples include tracked vehicles (Ripsaw tank (RIPSAW, 2022) and the Tinger track (TINGER, 2022)), which are designed to increase friction and distribute weight. Yet, this strategy can only work if the layer of the yielding medium is shallow, or the yield stress is very high, because these vehicles do not have the buoyancy that the wheeled vehicles take advantage of. Screw-propelled vehicles have been proposed, built, and proven reliable in muddy and sandy surfaces (MudMaster (PHIBION, 2022) and RUA (Fales et al., 1971)). Typically, on a solid soil, the helix will yield the substrate and then push on it without yielding it further. On very soft ground, like dry sand or very thin and wet mud, or even water, its behavior will look more like a paddle inside a fluid.

Now let us analyze the robot prototypes using static locomotion through the medium.

A few robots have been built to move using non-reciprocal motion. For example, a sperm-inspired robot was built, mimicking the flagella oscillations of sperm and enabling locomotion in a friction-dominated medium (Khalil et al., 2016). The sandfish lizard robot has been designed to mimic the high rate undulations of the animal, and that has enabled the robot to swim in a granular substrate (Maladen R. et al., 2011). Even though studies on the animal demonstrated granular fluidization (see next section), the robot appears to take advantage only of non-reciprocal motion in a dense frictional flow. The RoboClam is inspired by the razor clam (Winter et al., 2014) and uses the clam's dual-anchor mechanism to dig efficiently through unconsolidated media. Ortiz et al. (2019) shows a worm-inspired robot that uses peristaltic motion to move through dry granular media. Similarly, Liu et al. (2019) demonstrated a worm-inspired robot with a patterned skin that increases traction during the anchoring phase of the peristaltic movement and is retracted during the advance. A robot for planetary subsurface exploration was created and tested in a regolith simulant (Zhang et al., 2019). The robot uses a dual-anchor mechanism that enables anisotropy, similar to the alternating anchoring/forward motion observed in earthworms. When one anchor is pushing on the walls, the other one is retracted and moved in the direction of motion with a pushing module between the anchors. This motion is combined with material removal and is described in the next paragraph. A similar burrowing robot was designed and tested in soil (Omori et al., 2012). The main difference with the robot in Zhang et al. (2019) lies in the presence of four propulsion sub-units that mimic the peristaltic motion of earthworms, thereby creating motion anisotropy.

Some robots use the material removal technique to move through the medium; for example, Kobayashi et al. (2011) created a mole-inspired burrowing robot capable of moving through soft yielding soil by plastic deformation of the ground, resulting in a tunnel. The material is not dug out when boring a tunnel but rather pushed aside. The arms, using an anisotropic motion, are perpendicular to the material while progressing and parallel to the body during the swing phase. In Treers et al. (2022), a mole crab-inspired robot was built, able to dig itself through the sand by statically moving the sand from below to the top. To create larger forces during the digging phase than during the recovery motion, the legs are retracted, hence creating frictional anisotropy. Lee et al. (2020b) developed a mole rat robot that was inspired both by the mole rat's teeth-scraping for the digging mechanism and by the mole for material removal. On top of the non-reciprocal motion, the underground drilling robot mentioned in the previous paragraph (Zhang et al., 2019) uses material removal. The body of the robot consists of an excavation module and a propulsion module, connected by a propulsion module. All three modules are screw-shaped to allow transport from the front of the robot to the back, thereby eliminating form drag. The similar reddish soil-burrowing robot (Omori et al., 2012) also uses material removal through a screw-based excavation unit. The main difference is that in the latter prototype, the material is conveyed through the body. Another lunar subsurface explorer was designed and tested on sand (Nagaoka et al., 2010a). The robot consists of a cylindrical body with a contra-rotor screw drill (CSD). The CSD is a cone on which two contra-rotating sections are responsible for loosening the regolith material and pushing it backward. The propulsion force is generated by backward displacement of the material.

As seen in this section, animals and robots use a large diversity of techniques and technologies to move through soft deformable media using its static properties. Now, let us observe the second mechanical principle used to move through such environments, dynamics-based motion.

5 Dynamics-based movements

To move using the dynamic properties of the medium, a body has to rely on the medium's inertia to exert a sufficient force. To facilitate locomotion on/through a yielding material, a body can make it behave as a fluid, thereby reducing its resistance. Analogous to what was observed in the statics-based interactions, two different strategies were observed:

- Discrete contacts with the medium
- Go through the medium

We did not find any examples of dynamics-based locomotion using continuous contact with the medium in the robotics or biology literature. However, some man-made vehicles use this strategy. Examples are a full-throttle dirt bike going over a mudflat or a propeller-propelled boat powerful enough to generate thrust in mud. Although the reason for the absence of this strategy in nature or robotics could not be identified in the literature, we believe it does not provide any benefits that would justify its usage. As we will see in this section, the use of dynamics-based motion requires making use of the medium's inertia with discrete, powerful strokes or fluidizing it. A dynamic locomotion based on continuous contact may not benefit from form drag reduction with fluidization since the major part of the body lies outside of the yielding material. This type of locomotion may not benefit from having a continuous, frenetic movement at the interface between air and yielding media either, as this would likely require substantial power to continuously expel material backward/downward. While animals sometimes use power-intensive locomotion strategies for mating, escaping, or preying, they generally tend to use energy-efficient locomotion strategies (Schmidt-Nielsen, 1997; Alexander, 2003). It is, thus, not surprising that no animal was discovered using this inefficient strategy nor that no bio-inspired robot was discovered using it, or any robot, particularly given the generally inefficient locomotion of robots (Kashiri et al., 2018).

5.1 Animals' locomotion

Similar to the previous section, we will first look at locomotion strategies in animals and then at their robotic analogs.

5.1.1 Discrete contacts with the medium

The basilisk lizard uses high-rate deformations to move on water and along watersides. Even though water cannot be considered a yield-stress material, the basilisk lizard shows how using high-rate deformations enables it to stay on top of a fluid. By stepping very quickly on the fluid with long digits and increasing the surface area, the lizard takes advantage of the dynamic properties of fluids. Stepping quickly on a fluid causes a column of fluid to move beneath the foot's surface. The inertial resistance of this column of fluid enables some force to be applied on it (Hsieh and Lauder, 2004). On top of the inertial effect, hydrostatic pressure and shear resistance of the fluid, i.e., the friction induced between layers of fluid because of its viscosity, contribute to the reaction force. The latter is negligible at high Reynolds numbers such as for the basilisk lizard on water (Bush and Hu, 2006; Park et al., 2008). **Figure 6** depicts the leg of a basilisk lizard during the slap and stroke phases. These forces (inertial, hydrostatic, and viscous forces) can enable animals to run on fluids. The higher the fluid density and the higher its viscosity, the easier it is to stay on the surface. This same principle can be applied to moving on soft flowable media such as mud or sand. The basilisk lizard has been observed to balance and avoid sinking into a flowable substrate by reducing its stride length as the surface hardness diminishes (Bagheri et al., 2017). *Callisaurus* lizards have been observed on sand using their foot as a paddle to generate force when sinking into the flowable material. The energy lost during frictional dissipation in the yielding material is compensated for by the upper hind muscles (Li et al., 2012). Paddling through a fluidizing medium is based on the momentum given to elements of fluid, in the same way one propels with a paddle on a boat.

Other animals are also using a similar effect to move on flowable materials. To propel itself, the worm *Theristus caudasaliens* makes

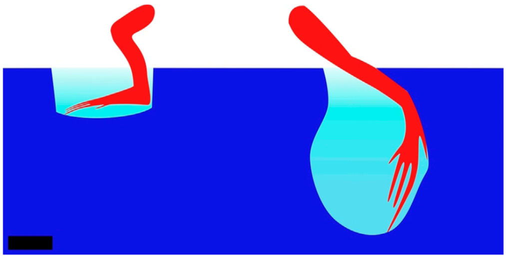

FIGURE 6
Basilisk lizard leg during the slap (left) and stroke (right) phases or a step. During the slap, the inertia of the column of water under the foot and the hydrostatic pressure generated by the column of displaced fluid above the foot generate reaction force, which enables the lizard to not sink and gain forward momentum. During the stroke phase, the same principles apply, but force is directed forward. The leg is then retracted from the water before the created air pocket collapses. Side view, scale bar is 1 cm. Drawn after Hsieh and Lauder (2004).

short and powerful strokes on the ground (Adams and Tyler, 1980). An illustration is provided in **Figure 7**. Some blennies similarly hit the soil with their tails to jump forward (Hsieh, 2010). They also orient the wide lateral surface of their tails toward the soil to get more grip. The larger surface area leads to a larger column of fluid being pushed and also leads to distributed efforts to reduce the pressure. The arthropod *Nebalia bipes* also uses short strokes of the tail for propulsion while digging into mud. Additionally, the microscale structure on its shell is suspected to improve hydrodynamics by degenerating turbulence close to the surface of the animal, which, in turn, helps progression through mud (VANNIER et al., 1997).

5.1.2 Through the medium

Some animals use high-rate deformation to fluidize the material. This strategy is used by the sandfish lizard, for example, which undulates its body to transform the sand into a fluid-like material, enabling it to swim inside the sand (Maladen et al., 2009; Goldman, 2014). The razor clam has also been described as using the fluidization of the water bottoms to burrow at depths where the forces required to dig are higher than what it produces. By agitating its shell at high speed, the clam creates pressure drops that break the walls of the tunnel, make the mud behave as a fluid, and reduce the required force to dig itself into the substrate (Trueman, 1983; Winter et al., 2012).

Worms like *Scalibregma inflatum* have also been described as using fluidization of the sand underwater by moving their bodies and appendages (Dorgan et al., 2016).

Montana et al. (2015) shows how the octopus *Kaurna stranks* digs itself into the ground using fluidization by jetting water into saturated sand. It also secretes mucus to solidify the walls of the tunnel. The octopus shown in **Figure 8** uses fluidization to dig itself into the sand.

Trueman (1970) showed the digging behavior of sand crabs in saturated sand, and it is speculated that the sand passes into a fluid-like state when the crabs give a high velocity to the sand particles.

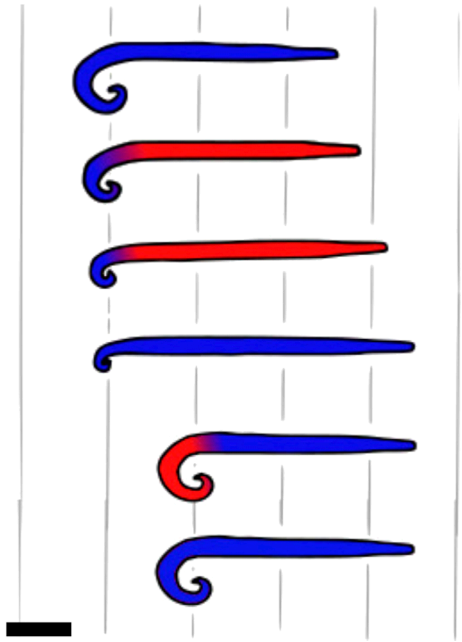

FIGURE 7
Hopping pattern of *Theristus caudasaliens*. The red parts are moving forward, while the blue ones are not. The worm jumps by bending its tail and rapidly releasing it to generate a short and powerful stroke on the medium. Top view, scale bar is 0.1 mm. Drawn after Adams and Tyler (1980).

5.2 Robotic analogs

Similar to what was observed in statics-based locomotion, robotic analogs were found using dynamics-based locomotion.

Two examples of robots were found in literature using the dynamic properties of the sand with discrete contacts. Both are hexapods using one-degree-of-freedom rotary legs. The SandBot was the first legged robot to demonstrate fluidization with rotary legs (Li et al., 2009). Experiments using this robot showed that an increase in the stride frequency and/or a decrease in soil compaction can lead to a dramatic loss of speed on a flowable substrate, probably due to its fluidization (Li et al., 2009). In this case, this was an undesired effect as it decreased the speed and efficiency. Zhang et al. (2013) demonstrated that DynaRoach, a similar rotary-leg, cockroach-inspired walking robot, that is lighter and has wider legs than the SandBot, uses static-like forces at low speeds, but transitions to hydrodynamic-like forces when legs' rotation frequency increases, thereby increasing its locomotion speed. This means that contrary to low speeds, where hydrostatic forces balance the weight and enable sufficient tangential forces to be applied for moving, high speeds are dominated by particles' inertia, where the robot generates forces by accelerating sand particles in the opposite direction. DynaRoach could benefit from the inertia of the particles because its wider legs enable it to increase the amount (and therefore,

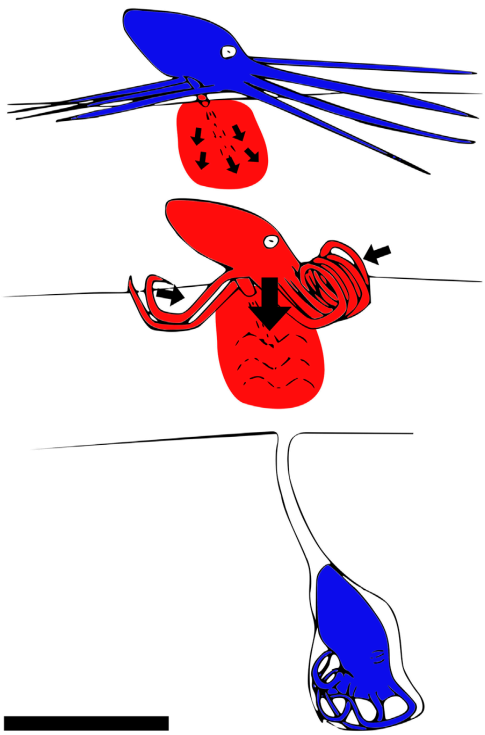

FIGURE 8
How the octopus *Kaurna stranks* digs itself under the saturated sand by using fluidization. The moving parts are shown in red. The octopus first injects water into the sediments, thereby fluidizing the medium. Then, it inserts itself into the fluidized sediment and creates a mucus-covered chimney with its tentacles to breathe. Side view, scale bar is 10 cm. Drawn after Montana et al. (2015).

mass) of particles being given momentum, and its lighter body requires less momentum to gain velocity. These two examples, and particularly the latter, where the locomotion benefited from the hydrodynamic-like behavior of the medium, show how inertia can be used to step quickly on a yielding medium and accelerate particles in the opposite direction to obtain enough momentum to move. However, these examples also show us, similar to the basilisk lizard, that low weight, wide appendages, and high speeds are required. The combination of lightweight, high instantaneous power, and a large surface contact area is technically challenging and leaves few design options for a robot using this locomotion strategy. This is probably limiting the strategy's ability to scale.

Robots making use of fluidization to move through the medium were also rare in the literature. The RoboClam has been created to mimic the razor clam's locomotion and manages to dig with decreased energy expenditure thanks to high-rate agitations of the shell that fluidize the mud (Winter et al., 2014). Similar to the animal, the RoboClam creates pressure drops in the fluid surrounding the walls of the burrow, which leads to the fluidization of the material and reduces its resistance. It was also demonstrated that using only the fluidization motions without using the dual-anchoring motions enabled the robot to burrow under its own weight. Naclerio et al. (2018) created a robot that advances by extending its body, inspired by plant root growth. The robot grows from the tip, reducing skin friction drag because the rest of the body remains immobile relative to the ground. It also fluidizes the sand to reduce form drag by blowing air in the direction of motion. The fluidization enables the robot to reduce the penetration force into the sand by an order of magnitude, especially for higher air flows. The two examples previously mentioned show robotic devices that use fluidization to reduce penetration resistance into yielding materials, in a similar way to animals using fluidization through the medium. This differs from robots or animals using discrete, dynamic contacts with the medium, where the objective is to use the fluid's inertia to generate thrust. In the two cases shown here, the robots were demonstrated to reach depths they could not reach without the use of fluidization. This strategy could also be used to move horizontally through the medium while using less energy. Last, the sandfish lizard robot was demonstrated to swim in the sand using mainly frictional forces (Maladen R. et al., 2011), but it appears to use fluidization locally at the tail and head, even though the contribution of this fluidization to locomotion may be limited (Ding et al., 2012).

6 Physical principles to move on soft deformable grounds: analyses, gaps, and discussion

The locomotion mechanisms described in previous sections often share common physical principles that facilitate the animal to negotiate yielding terrains. Those principles can be used by animals regardless of their anatomy or locomotion pattern and are, therefore, common to many species. A summary of this classification can be found in **Table 2**. Next, we classified the robots accordingly. This can be found in **Table 3**.

6.1 Current state of research and research gaps

Table 3 shows that robots have been primarily developed for using the static-based ways of locomotion. Dynamic-based locomotion alone has been marginally used for robot locomotion. Of course, swimming robots have been developed for underwater environments, but no evidence has been found that they would be capable of swimming in yielding materials. Indeed, using dynamics-based locomotion in yielding materials can mean hitting it very quickly to stay on the surface. It can also mean to fluidize it with frenetic oscillations or fluid projection, both of which require a high power output.

Both discrete and continuous ground contacts have been extensively studied in statics-based locomotion strategies. This does not imply that the problem of locomotion in these environments has been solved. Indeed, the large majority of the robots presented here are not fully working solutions but instead were intended to study a specific aspect of locomotion. Each robot contributes to the comprehension of locomotion on yielding substrates. Some of these robots, for example, were aimed at testing models of

TABLE 2 Modes of locomotion used by animals: arthropods (Foxon, 1936; Trueman, 1983; Herreid and Full, 1986; Faulkes and Paul, 1997; Herreid, 2012; Kuroda et al., 2014), basilisk lizard (Bagheri et al., 2017), blennies (Hsieh, 2010), burrowing eels (Herrel et al., 2011), caterpillars (Trimmer et al., 2006), *Callisaurus lizard* lizard (Li et al., 2012), *Clarias* (Johnels, 1957), climbing perch (Davenport and Matin, 1990), cows (Phillips and Morris, 2000), (Telezhenko and Bergsten, 2005), elephants (Weissengruber et al., 2006; Panagiotopoulou et al., 2012), gastropods (Trueman, 1983), hatchling turtles (Mazouchova, 2012), humans (Lejeune et al., 1998), (McMahon and Greene, 1979), inchworms (Plaut, 2015), leeches (Dorgan, 2010), lizards (Carothers, 1986; Kohlsdorf et al., 2001; Vanhooydonck et al., 2015), lungfishes (Horner and Jayne, 2014), mole crab (Trueman, 1970; Faulkes and Paul, 1997; Treers et al., 2022), mole crickets (Zhang et al., 2011), moles (Yalden, 1966), mole rats (Van Wassenbergh et al., 2017), mudskipper (HARRIS, 1960; Van Dijk, 1960; Pace and Gibb, 2014), *Nebalia bipes* (VANNIER et al., 1997), *Nereis virens* (La Spina et al., 2007), octopus (Montana et al., 2015), *Polypterus senegalus* (Standen et al., 2016), razor clams (Trueman, 1983; Winter et al., 2012), salamanders (Edwards, 1989; Aydin et al., 2017; Vega and Ashley-Ross, 2020), sandfish lizard (Maladen et al., 2009; Goldman, 2014), sand lances (Gidmark et al., 2011), seals (O'gorman 1963), snakes (Jayne, 1986; Wake, 2001), sperm cells (Friedrich et al., 2010), *Theristus caudasaliens* (Adams and Tyler, 1980), and worms (Foxon, 1936; Grill and Dorgan, 2015; Dorgan et al., 2016; Crane and Merz, 2017)

	Static-based				Dynamic-based	
Animal	Discrete C.	Cont. C.	Through N-recip.	Through Exc.	Discrete C.	Through
Arthropods	x					
Basilisk lizards	x					
Blennies					x	
Burrowing eels			x			
Caterpillars	x					
Clarias		x				
Climbing perch		x				
Cows	x					
Elephants	x					
Gastropods		x				
Hatchling turtles	x	x				
Humans	x					
Inchworms	x					
Leeches	x					
Lizards	x					
Lungfish	x					
Mole crab				x		X
Mole crickets				x		
Moles				x		
Mole rats				x		
Mudskipper		x				
Nebalia bipes				x		X
Nereis virens			x			
Octopus						X
P. senegalus		x				
Razor clams			x			X
Salamanders	X					
Sandfish lizard						X
Sand lances			x			
S. inflatum						X
Seals		x				
Snakes		x				
Sperm cells			x			
T. caudasaliens					x	
Worms			x			

TABLE 3 Bio-inspired modes of locomotion used by robots: AmphiHex (Liang et al., 2012), amphibious robot turtle (Baines et al., 2022), BasiliskBot (Bagheri et al., 2017), BigDog (Raibert et al., 2008), crab-like robot (Graf et al., 2021), CSD robot (Nagaoka et al., 2010a), dynaRoACH (Zhang et al., 2013), ePaddle robot (Shen et al., 2018), inchworm robot (Zhang et al., 2019), mole crab robot (Treers et al., 2022), mole-inspired robot (Kobayashi et al., 2011), mole rat robot (Lee et al., 2020b), mudskipper robot (McInroe et al., 2016), NASA's mini rover (Shrivastava et al., 2020), *Nereis* robot (Sfakiotakis et al., 2016), planetary subsurface explorer (PSE) (Omori et al., 2012), RHex (Li et al., 2013), RoboClam (Winter et al., 2014), sandfish robot (Maladen R. et al., 2011; Ding et al., 2012), screw-drive rover (Nagaoka et al., 2010b), SeaDog (Klein et al., 2012), sea turtle robot (Mazouchova et al., 2013), sidewinding rattlesnake robot (Marvi et al., 2014), sperm-shaped robot (Khalil et al., 2016), tetrad-screw robot (Lugo et al., 2017), tip-extending burrowing robot (Naclerio et al., 2018), and worm-inspired robot (Liu et al., 2019; Ortiz et al., 2019). Brackets describe an undesired effect.

	Static-based				Dynamic-based	
Animal	Discrete C.	Cont. C.	Through N-recip.	Through Exc.	Discrete C.	Through
AmphiHex	X					
Amphib. turtle		x				
BasiliskBot	X					
BigDog	X					
Crab-like r.	X					
CSD r.				x		
dynaRoACH	X				x	
ePaddle		x				
Inchworm r.			X	x		
Mole crab				x		
Mole r.			X			
Mole rat r.				x		
MudskipperBot		x				
NASA's rover	X	x				
Nereis r.		x				
PSE r.			x	x		
RHex	X					
RoboClam			x			x
SandBot	X				(x)	
Sandfish r.			x			x
Screw-drive r.		x				
SeaDog	X					
Sea turtle r.		x				
Sidewinding r.		x				
Sperm-shaped r.			x			
Tetrad-screw r.		x				
Tip-extending r.			x			x
Worm-inspired r.			x			

yielding materials, others were testing a specific hardware or kinematic feature of a robot, while others aimed at understanding a phenomenon observed on an animal. We can also see that animals digging/burrowing statically are much less explored. This can probably be explained by the reduced fields of applicability of such robots compared to robots moving above the ground. It is also worth noting that no animals or robots are using a dynamic-based continuous contact locomotion strategy. One possible reason might be that this locomotion strategy combines high velocity with continuous drag, resulting in what appears to be a very inefficient, energy-demanding, and potentially ineffective solution.

It is important to note that not all the robots analyzed in Table 3 are explicitly bio-inspired. Indeed, some robots using principles such as force distribution or increased friction have been exploited for a long time, even in the automotive industry, and can be achieved by other means than copying the solutions from nature, for example, fat tires, tracks, and screws. Nonetheless, the abstraction level we proposed, based solely on physics-based interactions on the higher level and the nature of contacts on the second level, allows one to bring together solutions such as the crawling gait of the mudskipper and Archimedean screw-based robots' locomotion, demonstrating the classification's potential for use in biomimetics.

6.2 Discussion

This paper's main contribution is a review of biology and robotic literature to identify locomotion principles that can be used in robot design in yielding environments. The principles are classified at two different levels, one considering the mechanical principle, the other considering the locomotion strategies to exploit that principle. The higher levels of abstraction also allow expanding the ontology to non-bio-inspired robots. It is worth noting that using abstract language and non-technical terms to describe a problem is a well-known systematic problem-solving technique proposed to avoid tunnel vision and early fixation (Al'tshuller 1999). The abstraction level used in this review proposes to classify locomotion strategies regardless of animal or robot morphology. As it is common in the biomimetics methodology, the resulting classification can, thus, assist researchers or engineers interested in locomotion on yielding grounds to easily pass from the problem domain to the solution domain (Vincent et al., 2006; Verhaegen et al., 2011; Fayemi et al., 2017). This process widens the range of potential solutions and prevents early zeroing in on a solution directly mimicked from nature, which may be suboptimal or impossible to implement. In the current case, it can assist the designer in defining the problem and proposing more diverse solutions for the problem of motion in low-yield environments by understanding general physics-based principles.

The results described in this paper have some limitations. First of all, we observed that biology literature strictly addressing the biomechanics of animals in yielding environments is very scarce, especially when compared to the papers generally addressing legged locomotion, flying biomechanics, swimming biomechanics, etc. Even in the identified papers, the focus of the paper was often on some other aspects (e.g., the behavior of the animal), and biomechanics was only very briefly described. Even when the papers focused on bio-locomotion, they often used biology terminology and methods rather than those of physics and mechanics, for example, the locomotion mechanisms were descriptive rather than mathematically formulated, and physical quantities were not measured. This lack of mathematical modeling, necessary for robotics, probably explains the frequent tendency of bio-inspired robotics research to incorporate bio-locomotion research as a preamble in the same paper. This represents an additional difficulty for roboticists trying to develop bio-inspired robots. Recently, robophysics research has started to address such topics with a more mechanics-based approach (Aguilar et al., 2016). In some cases, due to the lack of mathematical modeling in research papers, our interpretations of the physical principles are partly speculative. For example, the effect of stress timing and duration on yielding environments has received little attention in the biology literature. In such cases, we had to make assumptions on the motions of some animals based on drawings or verbal descriptions, and these assumptions could be proven inaccurate. However, the principles used for the classification follow the known laws of physics; we, therefore, believe that even if an animal was misclassified, this does not question the main contributions of this research: the general, abstracted locomotion principles, and the catalog of bio-inspired solutions. This work can still serve as inspiration and a general theoretical framework for someone who wants to design robots or understand animal locomotion principles.

The developed ontologies indicated several research gaps and opportunities for improvement. First of all, some strategies (e.g., dynamics-based discrete contacts) are scarcely addressed in the biology literature, which also limits the research opportunities in bio-inspired robotics. Principles using the static properties of yielding substrates are most commonly used by robots, and among those walking mechanisms, discrete contacts have been most widely addressed. Although continuous contact motion-based robots are developed for terrestrial and underwater environments, they are often tested on a single yielding medium in a laboratory environment. This offers the possibility of expanding the research problems using already existing robot platforms or already developed methods. Finally, because the ontologies' higher level of abstraction is physics-based, there is no need to focus on bio-inspiration. We believe that it offers some guidelines for developing useful robots and vehicles using state-of-the-art technologies. Furthermore, recent years have witnessed advances in the modeling of interactions between the locomotors and yielding materials, particularly in dry granular materials, through the use of RFT or geometric mechanics, as discussed earlier. We hope the classification proposed here will help researchers in the field to explore similarities between different locomotion strategies and further develop the theories of locomotion in yielding environments.

Author contributions

AR, MK, and SG conceived the format of the review. SG searched, analyzed, and organized the existing literature. SG contributed with figures. AR, MK, and SG contributed to the writing of the manuscript. AR, MK, and SG performed final proofreading and revision. All authors contributed to the article and approved the submitted version.

Funding

This research has been supported by the project ROBOMINERS which received funding from the European Commission's Horizon 2020 Research and Innovation Program under the grant agreement No. 820971.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors, and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Adams, P. J., and Tyler, S. (1980). Hopping locomotion in a nematode: Functional anatomy of the caudal gland apparatus ofTheristus caudasaliens sp. n. *J. Morphol.* 164, 265–285. doi:10.1002/jmor.1051640304

Aguilar, J., and Goldman, D. I. (2016). Robophysical study of jumping dynamics on granular media. *Nat. Phys.* 12, 278–283. doi:10.1038/nphys3568

Aguilar, J., Zhang, T., Qian, F., Kingsbury, M., McInroe, B., Mazouchova, N., et al. (2016). A review on locomotion robophysics: The study of movement at the intersection of robotics, soft matter and dynamical systems. *Rep. Prog. Phys.* 79, 110001. doi:10.1088/0034-4885/79/11/110001

Alderman, N. (1997). *Non-Newtonian fluids: Guide to classification and characteristics*. London: ESDU.

Alexander, R. M. (2003). *Principles of animal locomotion*. New Jersey, United States: Princeton University Press.

Al'tshuller, G. S. (1999). *The innovation algorithm: TRIZ, systematic innovation and technical creativity*. Worcester, Massachusetts: Technical innovation center, Inc.

Amaral, D. B., and Schneider, I. (2018). Fins into limbs: Recent insights from sarcopterygian fish. *genesis* 56, e23052. doi:10.1002/dvg.23052

Astley, H. C., Mendelson, J. R., III, Dai, J., Gong, C., Chong, B., Rieser, J. M., et al. (2020). Surprising simplicities and syntheses in limbless self-propulsion in sand. *J. Exp. Biol.* 223, jeb103564. doi:10.1242/jeb.103564

Augustesen, A., Liingaard, M., and Lade, P. V. (2004). Evaluation of time-dependent behavior of soils. *Int. J. Geomech.* 4, 137–156. doi:10.1061/(asce)1532-3641(2004)4:3(137)

Aydin, Y. O., Chong, B., Gong, C., Rieser, J. M., Rankin, J. W., Michel, K., et al. (2017). "Geometric mechanics applied to tetrapod locomotion on granular media," in *Conference on biomimetic and biohybrid systems* (Berlin, Germany: Springer), 595–603.

Bagheri, H., Taduru, V., Panchal, S., White, S., and Marvi, H. (2017). "Animal and robotic locomotion on wet granular media," in *Conference on biomimetic and biohybrid systems* (Berlin, Germany: Springer), 13–24. doi:10.1007/978-3-319-63537-8_2

Baines, R., Patiballa, S. K., Booth, J., Ramirez, L., Sipple, T., Garcia, A., et al. (2022). Multi-environment robotic transitions through adaptive morphogenesis. *Nature* 610, 283–289. doi:10.1038/s41586-022-05188-w

Balmforth, N. J., Frigaard, I. A., and Ovarlez, G. (2014). Yielding to stress: Recent developments in viscoplastic fluid mechanics. *Annu. Rev. Fluid Mech.* 46, 121–146. doi:10.1146/annurev-fluid-010313-141424

Barnes, G. (2016). *Soil mechanics: Principles and practice*. London: Macmillan International Higher Education.

Barnes, H. A., Hutton, J. F., and Walters, K. (1989). *An introduction to rheology*, 3. Amsterdam, Netherlands: Elsevier.

Baumeister, D., Tocke, R., Dwyer, J., Ritter, S., and Benyus, J. (2013). Biomimicry resource handbook: A seed bank of knowledge and best practices. *Missoula Biomimicry* 3.

Bekker, M. G. (1960). *Research and development in terramechanics*. Brisbane, Queensland: University of Queensland.Off-the-road locomotion.

Billingsley, J., Visala, A., and Dunn, M. (2008). *Robotics in agriculture and forestry*, 46. Berlin, Germany: Springer, 1065–1077.

Bingham, E. C. (1917). *An investigation of the laws of plastic flow*, 278. D.C., United States: US Government Printing Office.

Bingham, E. C. (1922). *Fluidity and plasticity*, 2. New York, United States: McGraw-Hill.

Bruzzone, L., and Quaglia, G. (2012). Review article: Locomotion systems for ground mobile robots in unstructured environments. *Mech. Sci.* 3, 49–62. doi:10.5194/ms-3-49-2012

BURLAK, 2022. The Burlak. Available at: https://burlakoffroad.com, (Accessed November 25, 2022).

Bush, J. W., and Hu, D. L. (2006). Walking on water: Biolocomotion at the interface. *Annu. Rev. Fluid Mech.* 38, 339–369. doi:10.1146/annurev.fluid.38.050304.092157

Carothers, J. H. (1986). An experimental confirmation of morphological adaptation: Toe fringes in the sand-dwelling lizard uma scoparia. *Evolution* 40, 871–874. doi:10.2307/2408475

Chopra, S., Tolley, M. T., and Gravish, N. (2020). Granular jamming feet enable improved foot-ground interactions for robot mobility on deformable ground. *IEEE Robot. Autom. Lett.* 5, 3975–3981. doi:10.1109/lra.2020.2982361

Clemente, C. J., Dick, T. J., Glen, C. L., and Panagiotopoulou, O. (2020). Biomechanical insights into the role of foot pads during locomotion in camelid species. *Sci. Rep.* 10, 1–12. doi:10.1038/s41598-020-60795-9

Coussot, P. (2014). Yield stress fluid flows: A review of experimental data. *J. Newt. Fluid Mech.* 211, 31–49. doi:10.1016/j.jnnfm.2014.05.006

Crane, R., and Merz, R. (2017). Mechanical properties of sediment determine burrowing success and influence distribution of two lugworm species. *J. Exp. Biol.* 220, 3248–3259. doi:10.1242/jeb.156760

Davenport, J., and Matin, A. A. (1990). Terrestrial locomotion in the climbing perch, anabas testudineus (bloch) (anabantidea, pisces). *J. Fish. Biol.* 37, 175–184. doi:10.1111/j.1095-8649.1990.tb05938.x

Denn, M. M. (2004). Fifty years of non-Newtonian fluid dynamics. *AIChE J.* 50, 2335–2345. doi:10.1002/aic.10357

Ding, Y., Sharpe, S. S., Masse, A., and Goldman, D. I. (2012). Mechanics of undulatory swimming in a frictional fluid. *PLoS Comput. Biol.* 8, e1002810. doi:10.1371/journal.pcbi.1002810

Dorgan, K. (2010). Environmental constraints on the mechanics of crawling and burrowing using hydrostatic skeletons. *Exp. Mech.* 50, 1373–1381. doi:10.1007/s11340-010-9399-2

Dorgan, K. M., D'Amelio, C., and Lindsay, S. M. (2016). Strategies of burrowing in soft muddy sediments by diverse polychaetes. *Invertebr. Biol.* 135, 287–301. doi:10.1111/ivb.12131

Dorgan, K. M. (2015). The biomechanics of burrowing and boring. *J. Exp. Biol.* 218, 176–183. doi:10.1242/jeb.086983

Duckett, T., Pearson, S., Blackmore, S., and Grieve, B. (2018). *Agricultural robotics. Tech. Rep.* EPSRC UK-RAS Network.

Dunbabin, M., and Marques, L. (2012). Robots for environmental monitoring: Significant advancements and applications. *IEEE Robot. Autom. Mag.* 19, 24–39. doi:10.1109/mra.2011.2181683

Edwards, J. L. (1989). Two perspectives on the evolution of the tetrapod limb. *Am. Zool.* 29, 235–254. doi:10.1093/icb/29.1.235

Fales, W., Amick, D. W., and Schreiner, B. G. (1971). *The riverine utility craft (RUC)*. Tech. rep., SAE Technical Paper.

Faulkes, Z., and Paul, D. (1997). Digging in sand crabs (decapoda, anomura, hippoidea): Interleg coordination. *J. Exp. Biol.* 200, 793–805. doi:10.1242/jeb.200.4.793

Fayemi, P.-E., Wanieck, K., Zollfrank, C., Maranzana, N., and Aoussat, A. (2017). Biomimetics: Process, tools and practice. *Bioinspir. Biomim.* 12, 011002. doi:10.1088/1748-3190/12/1/011002

Foxon, G. (1936). XL.-Observations on the locomotion of some Arthropods and annelids. *Ann. Mag. Nat. Hist.* 18, 403–419. doi:10.1080/00222933608655210

Friedrich, B. M., Riedel-Kruse, I. H., Howard, J., and Jülicher, F. (2010). High-precision tracking of sperm swimming fine structure provides strong test of resistive force theory. *J. Exp. Biol.* 213, 1226–1234. doi:10.1242/jeb.039800

Gidmark, N. J., Strother, J. A., Horton, J. M., Summers, A. P., and Brainerd, E. L. (2011). Locomotory transition from water to sand and its effects on undulatory kinematics in sand lances (ammodytidae). *J. Exp. Biol.* 214, 657–664. doi:10.1242/jeb.047068

Godon, S., Ristolainen, A., and Kruusmaa, M. (2022). An insight on mud behavior upon stepping. *IEEE Robot. Autom. Lett.* 7, 11039–11046. doi:10.1109/lra.2022.3194667

Goel, A. K., Tuchez, C., Hancock, W., and Frazer, K. (2017). "Is biologically inspired design domain independent?," in *Design computing and Cognition'16* (Berlin, Germany: Springer), 157–171. doi:10.1007/978-3-319-44989-0_9

Goldman, D. I. (2014). Colloquium: Biophysical principles of undulatory self-propulsion in granular media. *Rev. Mod. Phys.* 86, 943–958. doi:10.1103/revmodphys.86.943

Goldman, D., Komsuoglu, H., and Koditschek, D. (2009). March of the sandbots. *IEEE Spectr.* 46, 30–35. doi:10.1109/mspec.2009.4808384

Graf, N., Behr, A., and Daltorio, K. A. (2021). *Dactyls and inward gripping stance for amphibious crab-like robots on sand*. United Kingdom: Bioinspiration & Biomimetics.

Gravish, N., and Lauder, G. V. (2018). Robotics-inspired biology. *J. Exp. Biol.* 221. doi:10.1242/jeb.138438

Grill, S., and Dorgan, K. M. (2015). Burrowing by small polychaetes - mechanics, behavior and muscle structure of Capitella sp. *J. Exp. Biol.* 218, 1527–1537. doi:10.1242/jeb.113183

Harris, V. A. (1960). ON the locomotion of the mud-skipper periophthalmus koelreuteri (pallas): (GOBIIDAE). *Proc. Zoological Soc. Lond.* 134, 107–135. doi:10.1111/j.1469-7998.1960.tb05921.x

Herreid, C. F., and Full, R. J. (1986). Locomotion of hermit crabs (coenobita compressus) on beach and treadmill. *J. Exp. Biol.* 120, 283–296. doi:10.1242/jeb.120.1.283

Herreid, C. F. (2012). *Locomotion and energetics in arthropods*. Berlin, Germany: Springer Science & Business Media.

Herrel, A., Choi, H. F., Dumont, E., De Schepper, N., Vanhooydonck, B., Aerts, P., et al. (2011). Burrowing and subsurface locomotion in anguilliform fish: Behavioral specializations and mechanical constraints. *J. Exp. Biol.* 214, 1379–1385. doi:10.1242/jeb.051185

Herschel, W. H., and Bulkley, R. (1926). Konsistenzmessungen von Gummibenzollösungen. *Kolloid-Zeitschrift* 39, 291–300. doi:10.1007/bf01432034

Horner, A. M., and Jayne, B. C. (2014). Lungfish axial muscle function and the vertebrate water to land transition. *PloS one* 9, e96516. doi:10.1371/journal.pone.0096516

Hosoi, A., and Goldman, D. I. (2015). Beneath our feet: Strategies for locomotion in granular media. *Annu. Rev. fluid Mech.* 47. doi:10.1146/annurev-fluid-010313-141324

Hsieh, S.-T. T. (2010). A locomotor innovation enables water-land transition in a marine fish. *PloS one* 5, e11197. doi:10.1371/journal.pone.0011197

Hsieh, S. T., and Lauder, G. V. (2004). Running on water: Three-dimensional force generation by basilisk lizards. *Proc. Natl. Acad. Sci. U.S.A.* 101, 16784–16788. doi:10.1073/pnas.0405736101

Hu, D. L., Nirody, J., Scott, T., and Shelley, M. J. (2009). The mechanics of slithering locomotion. *Proc. Natl. Acad. Sci. U.S.A.* 106, 10081–10085. doi:10.1073/pnas.0812533106

Jarvis, J. U., and Sale, J. B. (1971). Burrowing and burrow patterns of East African mole-rats Tachyoryctes, Heliophobius and Heterocephalus. *J. Zoology* 163, 451–479. doi:10.1111/j.1469-7998.1971.tb04544.x

Jayne, B. C. (1986). Kinematics of terrestrial snake locomotion. *Copeia* 1986, 915–927. doi:10.2307/1445288

Johnels, A. G. (1957). The mode of terrestrial locomotion in clarias. *Oikos* 8, 122–129. doi:10.2307/3564996

Karim, M. R., and Gnanendran, C. T. (2014). Review of constitutive models for describing the time dependent behaviour of soft clays. *Geomechanics Geoengin.* 9, 36–51. doi:10.1080/17486025.2013.804212

Kashiri, N., Abate, A., Abram, S. J., Albu-Schaffer, A., Clary, P. J., Daley, M., et al. (2018). An overview on principles for energy efficient robot locomotion. *Front. Robot. AI* 5, 129. doi:10.3389/frobt.2018.00129

Khalil, I. S., Tabak, A. F., Hosney, A., Mohamed, A., Klingner, A., Ghoneima, M., et al. (2016). "Sperm-shaped magnetic microrobots: Fabrication using electrospinning, modeling, and characterization," in Proeedings of the 2016 IEEE International Conference on Robotics and Automation (ICRA), Stockholm, 16-21 May 2016 (IEEE), 1939–1944. doi:10.1109/icra.2016.7487340

Klein, M. A., Boxerbaum, A. S., Quinn, R. D., Harkins, R., and Vaidyanathan, R. (2012). "Seadog: A rugged mobile robot for surf-zone applications," in Proceedinigs of the 2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), Rome, Italy, 24-27 June 2012 (IEEE), 1335–1340. doi:10.1109/biorob.2012.6290759

Kobayashi, T., Tshukagoshi, H., Honda, S., and Kitagawa, A. (2011). Burrowing rescue robot referring to a mole's shoveling motion. *Proc. 8th JFPS Int. Symposium Fluid Power*, 644–649.

Kohlsdorf, T., Garland Jr., T., Jr, and Navas, C. A. (2001). Limb and tail lengths in relation to substrate usage inTropidurus lizards. *J. Morphol.* 248, 151–164. doi:10.1002/jmor.1026

Kristan, W. (2019). Control of locomotion in annelids. *Oxf. Handb. Invertebr. Neurobiol.*, 450–470. doi:10.1093/oxfordhb/9780190456757.013.22

Kuroda, S., Kunita, I., Tanaka, Y., Ishiguro, A., Kobayashi, R., and Nakagaki, T. (2014). Common mechanics of mode switching in locomotion of limbless and legged animals. *J. R. Soc. Interface.* 11, 20140205. doi:10.1098/rsif.2014.0205

Kutter, B. L., and Sathialingam, N. (1992). Elastic-viscoplastic modelling of the rate-dependent behaviour of clays. *Géotechnique* 42, 427–441. doi:10.1680/geot.1992.42.3.427

Larson, R. G. (1999). *The structure and rheology of complex fluids*, 150. New York: Oxford University Press.

Lee, J., Hwangbo, J., Wellhausen, L., Koltun, V., and Hutter, M. (2020a). Learning quadrupedal locomotion over challenging terrain. *Sci. Robot.* 5, eabc5986. doi:10.1126/scirobotics.abc5986

Lee, J., Tirtawardhana, C., and Myung, H. (2020b). " Development and analysis of digging and soil removing mechanisms for mole-bot: Bio-inspired mole-like drilling robot," in Proceedings of the 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (IEEE), 7792–7799. doi:10.1109/iros45743.2020.9341230

Lejeune, T. M., Willems, P. A., and Heglund, N. C. (1998). Mechanics and energetics of human locomotion on sand. *J. Exp. Biol.* 201, 2071–2080. doi:10.1242/jeb.201.13.2071

Li, C., Hsieh, S. T., and Goldman, D. I. (2012). Multi-functional foot use during running in the zebra-tailed lizard (callisaurus draconoides). *J. Exp. Biol.* 215, 3293–3308. doi:10.1242/jeb.061937

Li, C., and Lewis, K. (2022). The need for and feasibility of alternative ground robots to traverse sandy and rocky extraterrestrial terrain. *Adv. Intell. Syst.* doi:10.1002/aisy.202100195

Li, C., Umbanhowar, P. B., Komsuoglu, H., Koditschek, D. E., and Goldman, D. I. (2009). Sensitive dependence of the motion of a legged robot on granular media. *Proc. Natl. Acad. Sci. U.S.A.* 106, 3029–3034. doi:10.1073/pnas.0809095106

Li, C., Zhang, T., and Goldman, D. I. (2013). A terradynamics of legged locomotion on granular media. *science* 339, 1408–1412. doi:10.1126/science.1229163

Liang, X., Xu, M., Xu, L., Liu, P., Ren, X., Kong, Z., et al. (2012).The amphihex: A novel amphibious robot with transformable leg-flipper composite propulsion mechanismProceedings of the 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems(IEEE), 3667–3672. doi:10.1109/iros.2012.6386238

Liingaard, M., Augustesen, A., and Lade, P. V. (2004). Characterization of models for time-dependent behavior of soils. *Int. J. Geomech.* 4, 157–177. doi:10.1061/(asce)1532-3641(2004)4:3(157)

Liu, B., Ozkan-Aydin, Y., Goldman, D. I., and Hammond, F. L. (2019). Kirigami skin improves soft earthworm robot anchoring and locomotion under cohesive soil. In Proceedings of the 2019 2nd IEEE International Conference on Soft Robotics, 14-18 April 2019, Seoul, Korea, (IEEE), 828–833. doi:10.1109/robosoft.2019.8722821

Lopes, L., Bodo, B., Rossi, C., Henley, S., Žibret, G., Kot-Niewiadomska, A., et al. (2020). Robominers - developing a bio-inspired modular robot-miner for difficult to access mineral deposits. *Adv. Geosci.* 54, 99–108. doi:10.5194/adgeo-54-99-2020

Lugo, J. H., Ramadoss, V., Zoppi, M., and Molfino, R. (2017). Conceptual design of tetrad-screw propelled omnidirectional all-terrain mobile robotProceedings of the 2017 2nd International Conference on Control and Robotics Engineering (ICCRE) (IEEE), 13–17. doi:10.1109/iccre.2017.7935033

Lutz, P., and Musick, J. (1996). *The Biology of sea turtles. No. V. 1*. CRC Marine Science (Taylor & Francis).

Ma, X., Wang, G., Liu, K., Chen, X., Wang, J., Pan, B., et al. (2022). Granular resistive force theory extension for saturated wet sand ground. *Machines* 10, 721. doi:10.3390/machines10090721

Mak, T., and Shu, L. (2004). Abstraction of biological analogies for design. *CIRP Ann.* 53, 117–120. doi:10.1016/s0007-8506(07)60658-1

Maladen, R. D., Ding, Y., Umbanhowar, P. B., and Goldman, D. I. (2011a). Undulatory swimming in sand: Experimental and simulation studies of a robotic sandfish. *Int. J. Robotics Res.* 30, 793–805. doi:10.1177/0278364911402406

Maladen, R. D., Ding, Y., Li, C., and Goldman, D. I. (2009). Undulatory swimming in sand: Subsurface locomotion of the sandfish lizard. *science* 325, 314–318. doi:10.1126/science.1172490

Maladen, R. D., Ding, Y., Umbanhowar, P. B., Kamor, A., and Goldman, D. I. (2011b). Mechanical models of sandfish locomotion reveal principles of high performance subsurface sand-swimming. *J. R. Soc. Interface.* 8, 1332–1345. doi:10.1098/rsif.2010.0678

Marvi, H., Gong, C., Gravish, N., Astley, H., Travers, M., Hatton, R. L., et al. (2014). Sidewinding with minimal slip: Snake and robot ascent of sandy slopes. *Science* 346, 224–229. doi:10.1126/science.1255718

Mazouchova, N. (2012). *Principles of fin and flipper locomotion on granular media*. Ph.D. thesis. United States: Georgia Institute of Technology.

Mazouchova, N., Umbanhowar, P. B., and Goldman, D. I. (2013). Flipper-driven terrestrial locomotion of a sea turtle-inspired robot. *Bioinspir. Biomim.* 8, 026007. doi:10.1088/1748-3182/8/2/026007

McInroe, B., Astley, H. C., Gong, C., Kawano, S. M., Schiebel, P. E., Rieser, J. M., et al. (2016). Tail use improves performance on soft substrates in models of early vertebrate land locomotors. *Science* 353, 154–158. doi:10.1126/science.aaf0984

McMahon, T. A., and Greene, P. R. (1979). The influence of track compliance on running. *J. biomechanics* 12, 893–904. doi:10.1016/0021-9290(79)90057-5

Metzner, A. (1956). "Non-Newtonian technology: Fluid mechanics, mixing, and heat transfer," in *Advances in chemical engineering* (Amsterdam, Netherlands: Elsevier), 1, 77–153. doi:10.1016/s0065-2377(08)60311-7

Metzner, A., and Reed, J. (1955). Flow of non-Newtonian fluids-correlation of the laminar, transition, and turbulent-flow regions. *AIChE J.* 1, 434–440. doi:10.1002/aic.690010409

Mishrai, S., Chakraborty, T., and Basu, D. (2016). "High strain rate stress-strain response of soils-a review," in *International workshop on geotechnics for resilient infrastructure* (Japan: The Second Japan-India Workshop), 80–85.

Montana, J., Finn, J. K., and Norman, M. D. (2015). Liquid sand burrowing and mucus utilisation as novel adaptations to a structurally-simple environment in octopus kaurna stranks, 1990. *Behav* 152, 1871–1881. doi:10.1163/1568539x-00003313

Murphy, E. A., and Dorgan, K. M. (2011). Burrow extension with a proboscis: Mechanics of burrowing by the glycerid hemipodus simplex. *J. Exp. Biol.* 214, 1017–1027. doi:10.1242/jeb.051227

Naclerio, N. D., Hubicki, C. M., Aydin, Y. O., Goldman, D. I., and Hawkes, E. W. (2018). "Soft robotic burrowing device with tip-extension and granular fluidization," in Proceedings of the 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems, Madrid, Spain, 01-05 October 2018 (IEEE), 5918–5923. doi:10.1109/iros.2018.8593530

Nagaoka, K., Kubota, T., Otsuki, M., and Tanaka, S. (2010a). Experimental analysis of a screw drilling mechanism for lunar robotic subsurface exploration. *Adv. Robot.* 24, 1127–1147. doi:10.1163/016918610x501255

Nagaoka, K., Otsuki, M., Kubota, T., and Tanaka, S. (2010b). "Terramechanics-based propulsive characteristics of mobile robot driven by archimedean screw mechanism on soft soil," in Proceeding of the 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, Taipei, Taiwan, 18-22 October 2010 (IEEE), 4946–4951. doi:10.1109/iros.2010.5651010

Nagel, J. K., Nagel, R. L., Stone, R. B., and McAdams, D. A. (2010). Function-based, biologically inspired concept generation. *Aiedam* 24, 521–535. doi:10.1017/s0890060410000375

O'gorman, F. (1963). Observations on terrestrial locomotion in Antarctic seals. *Proc. Zoological Soc. Lond.* 141, 837–850.

Oldroyd, J. G. (1947). A rational formulation of the equations of plastic flow for a bingham solid. *Math. Proc. Camb. Phil. Soc.* 43, 100–105. doi:10.1017/s0305004100023239

Oliveira, L. F., Moreira, A. P., and Silva, M. F. (2021). Advances in agriculture robotics: A state-of-the-art review and challenges ahead. *Robotics* 10, 52. doi:10.3390/robotics10020052

Omidvar, M., Iskander, M., and Bless, S. (2012). Stress-strain behavior of sand at high strain rates. *Int. J. impact Eng.* 49, 192–213. doi:10.1016/j.ijimpeng.2012.03.004

Omori, H., Murakami, T., Nagai, H., Nakamura, T., and Kubota, T. (2012). Development of a novel bio-inspired planetary subsurface explorer: Initial experimental study by prototype excavator with propulsion and excavation units. *IEEE/ASME Trans. Mechatronics* 18, 459–470.

Ortiz, D., Gravish, N., and Tolley, M. T. (2019). Soft robot actuation strategies for locomotion in granular substrates. *IEEE Robot. Autom. Lett.* 4, 2630–2636. doi:10.1109/lra.2019.2911844

Pace, C., and Gibb, A. C. (2014). Sustained periodic terrestrial locomotion in air-breathing fishes. *J. Fish. Biol.* 84, 639–660. doi:10.1111/jfb.12318

Pak, O. S., Lauga, E., Duprat, C., and Stone, H. (2015). "Theoretical models of low-Reynolds-number locomotion," in *Fluid-structure interactions in low-Reynolds-number flows* (London, United Kingdom: Royal Society of Chemistry), 100–167. doi:10.1039/9781782628491-00100

Panagiotopoulou, O., Pataky, T. C., Hill, Z., and Hutchinson, J. R. (2012). Statistical parametric mapping of the regional distribution and ontogenetic scaling of foot pressures during walking in Asian elephants (elephas maximus). *J. Exp. Biol.* 215, 1584–1593. doi:10.1242/jeb.065862

Park, H. S., Floyd, S., and Sitti, M. (2008). IEEE, 3101–3107. Dynamic modeling of a basilisk lizard inspired quadruped robot running on waterProceedings of the 2008 IEEE/RSJ International Conference on Intelligent Robots and SystemsNice22-26 September 2008.

PHIBION. The mudmaster. 2022, Available at: https://www.phibion.com/the-mudmaster, (Accessed November 25 2022).

Phillips, C., and Morris, I. (2000). The locomotion of dairy cows on concrete floors that are dry, wet, or covered with a slurry of excreta. *J. dairy Sci.* 83, 1767–1772. doi:10.3168/jds.s0022-0302(00)75047-8

Plaut, R. H. (2015). Mathematical model of inchworm locomotion. *Int. J. Non-Linear Mech.* 76, 56–63. doi:10.1016/j.ijnonlinmec.2015.05.007

Purcell, E. M. (1977). Life at low Reynolds number. *Am. J. Phys.* 45, 3–11. doi:10.1119/1.10903

Qian, F., Zhang, T., chen, Li, Hoover, A., Masarati, P., Birkmeyer, P., et al. (2012). Walking and running on yielding and fluidizing ground. *Proc. Robotics Sci. Syst.*, 345–553. doi:10.15607/rss.2012.viii.044

Qian, F., Zhang, T., Korff, W., Umbanhowar, P. B., Full, R. J., and Goldman, D. I. (2015). Principles of appendage design in robots and animals determining terradynamic performance on flowable ground. *Bioinspir. Biomim.* 10, 056014. doi:10.1088/1748-3190/10/5/056014

Raibert, M., Blankespoor, K., Nelson, G., and Playter, R. (2008). Bigdog, the rough-terrain quadruped robot. *IFAC Proc. Vol.* 41, 10822–10825. doi:10.3182/20080706-5-kr-1001.01833

RIPSAW. 2022, The Ripsaw tank. Available at: http://www.ripsawtank.com/, (Accessed November 25, 2022).

Rubio, F., Valero, F., and Llopis-Albert, C. (2019). A review of mobile robots: Concepts, methods, theoretical framework, and applications. *Int. J. Adv. Robotic Syst.* 16, 1–22. doi:10.1177/1729881419839596

Schmidt-Nielsen, K. (1997). *Animal physiology: Adaptation and environment*. Cambridge, United Kingdom: Cambridge University Press.

Schneider, F. E., and Wildermuth, D. (2016). Assessing the search and rescue domain as an applied and realistic benchmark for robotic systemsProceedings of the 2016 17th International Carpathian Control Conference (ICCC) (IEEE), 657–662. doi:10.1109/carpathiancc.2016.7501177

Schowalter, W. R. (1960). The application of boundary-layer theory to power-law pseudoplastic fluids: Similar solutions. *AIChE J.* 6, 24–28. doi:10.1002/aic.690060105

Scott, R. G., and Richardson, R. C. (2005). "Realities of biologically inspired design with a subterranean digging robot example," in Proceedings of the 6th IASTED International Conference on Robotics and Applications, Cambridge, MA, USA, 226–231.

Sfakiotakis, M., Lane, D. M., and Davies, J. B. C. (1999). Review of fish swimming modes for aquatic locomotion. *IEEE J. Ocean. Eng.* 24, 237–252. doi:10.1109/48.757275

Sfakiotakis, M., Chatzidaki, A., Evdaimon, T., Kazakidi, A., and Tsakiris, D. P. (2016). Effects of compliance in pedundulatory locomotion over granular substrates. In Procceedings of the 2016 24th Mediterranean Conference on Control and Automation (MED) 21-24 June 2016, Athens, Greece, (IEEE), 532–538. doi:10.1109/med.2016.7536061

Sharpe, S. S., Ding, Y., and Goldman, D. I. (2013). Environmental interaction influences muscle activation strategy during sand-swimming in the sandfish lizard scincus scincus. *J. Exp. Biol.* 216, 260–274. doi:10.1242/jeb.070482

Shen, Y., Zhang, G., Tian, Y., and Ma, S. (2018). Development of a wheel-paddle integrated quadruped robot for rough terrain and its verification on hybrid mode. *IEEE Robot. Autom. Lett.* 3, 4062–4067. doi:10.1109/lra.2018.2862431

SHERP. The Sherp ATV. 2022, Available at: https://sherpa.eu/(Accessed November 25 2022).

Shrivastava, S., Karsai, A., Aydin, Y. O., Pettinger, R., Bluethmann, W., Ambrose, R. O., et al. (2020). Material remodeling and unconventional gaits facilitate locomotion of a robophysical rover over granular terrain. *Sci. Robot.* 5. doi:10.1126/scirobotics.aba3499

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *J. Bus. Res.* 104, 333–339. doi:10.1016/j.jbusres.2019.07.039

Spina, G., Sfakiotakis, M., Tsakiris, D. P., Menciassi, A., and Dario, P. (2007). Polychaete-like undulatory robotic locomotion in unstructured substrates. *IEEE Trans. Robot.* 23, 1200–1212. doi:10.1109/tro.2007.909791

Standen, E. M., Du, T. Y., Laroche, P., and Larsson, H. C. (2016). Locomotor flexibility of polypterus senegalus across various aquatic and terrestrial substrates. *Zoology* 119, 447–454. doi:10.1016/j.zool.2016.05.001

Telezhenko, E., and Bergsten, C. (2005). Influence of floor type on the locomotion of dairy cows. *Appl. Animal Behav. Sci.* 93, 183–197. doi:10.1016/j.applanim.2004.11.021

Terzaghi, K., Peck, R. B., and Mesri, G. (1996). *Soil mechanics in engineering practice*. New Jersey, United States: John Wiley & Sons.

TINGER. The Tinger track. 2022, Available at: http://tingeratv.com/model/tr/, (Accessed November 25, 2022).

Torraco, R. J. (2005). Writing integrative literature reviews: Guidelines and examples. *Hum. Resour. Dev. Rev.* 4, 356–367. doi:10.1177/1534484305278283

Treers, L. K., McInroe, B., Full, R. J., and Stuart, H. S. (2022). Mole crab-inspired vertical self-burrowing. *Front. Robotics AI*, 263. doi:10.3389/frobt.2022.999392

Trimmer, B. A., Takesian, A. E., and Sweet, B. M. (2006). "Caterpillar locomotion: A new model for soft-bodied climbing and burrowing robots," in *International symposium on technology and the mine problem*, B457–B467.

Trueman, E. (1983). "Locomotion in molluscs," in *The mollusca* (Amsterdam, Netherlands: Elsevier), 155–198. doi:10.1016/b978-0-12-751404-8.50012-8

Trueman, E. (1970). The mechanism of burrowing of the mole crab, emerita. *J. Exp. Biol.* 53, 701–710. doi:10.1242/jeb.53.3.701

Van Dijk, D. (1960). Locomotion and attitudes of the mudskipper, periophthalmus, a semi-terrestrial fish. *South Afr. J. Sci.* 56, 158–162.

Van Wassenbergh, S., Heindryckx, S., and Adriaens, D. (2017). Kinematics of chisel-tooth digging by african mole-rats. *J. Exp. Biol.* 220, 4479–4485. doi:10.1242/jeb.164061

Vanhooydonck, B., Measey, J., Edwards, S., Makhubo, B., Tolley, K. A., and Herrel, A. (2015). The effects of substratum on locomotor performance in lacertid lizards. *Biol. J. Linn. Soc. Lond* 115, 869–881. doi:10.1111/bij.12542

Vannier, J., Boissy, P., and Racheboeuf, P. R. (1997). Locomotion in nebalia bipes: A possible model for palaeozoic phyllocarid crustaceans. *Lethaia* 30, 89–104.

Vega, C. M., and Ashley-Ross, M. A. (2020). Tiger salamanders (ambystoma tigrinum) increase foot contact surface area on challenging substrates during terrestrial locomotion. *Integr. Org. Biol.* 2, obaa029. doi:10.1093/iob/obaa029

Verhaegen, P.-A., D'hondt, J., Vandevenne, D., Dewulf, S., and Duflou, J. R. (2011). Identifying candidates for design-by-analogy. *Comput. Industry* 62, 446–459. doi:10.1016/j.compind.2010.12.007

Vincent, J. F., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., and Pahl, A.-K. (2006). Biomimetics: Its practice and theory. *J. R. Soc. Interface.* 3, 471–482. doi:10.1098/rsif.2006.0127

Vogel, S. (2020). *Life in moving fluids: The physical biology of flow-revised and expanded*. Second Edition. New Jersey, United States: Princeton university press.

Wake, M. H. (2001). Tetrapod limbless locomotion. *LS*. doi:10.1038/npg.els.0001864

Webb, P. W. (1988). Simple physical principles and vertebrate aquatic locomotion. *Am. Zool.* 28, 709–725. doi:10.1093/icb/28.2.709

Weissengruber, G., Egger, G., Hutchinson, J., Groenewald, H. B., Elsässer, L., Famini, D., et al. (2006). The structure of the cushions in the feet of african elephants (loxodonta africana). *J. Anat.* 209, 781–792. doi:10.1111/j.1469-7580.2006.00648.x

Winter, A. G., Deits, R. L., and Hosoi, A. E. (2012). Localized fluidization burrowing mechanics ofEnsis directus. *J. Exp. Biol.* 215, 2072–2080. doi:10.1242/jeb.058172

Winter, A., V, R., Deits, D., Dorsch, A., Slocum, A., and Hosoi, A. E. (2014). Razor clam to roboclam: Burrowing drag reduction mechanisms and their robotic adaptation. *Bioinspir. Biomim.* 9, 036009. doi:10.1088/1748-3182/9/3/036009

Wong, J. Y. (2009). *Terramechanics and off-road vehicle engineering: Terrain behaviour, off-road vehicle performance and design*. Oxford, United Kingdom: Butterworth-heinemann.

Xu, C., and Zhu, J. (2006). Parametric study of fine particle fluidization under mechanical vibration. *Powder Technol.* 161, 135–144. doi:10.1016/j.powtec.2005.10.002

Yalden, D. (1966). The anatomy of mole locomotion. *J. Zoology* 149, 55–64. doi:10.1111/j.1469-7998.1966.tb02983.x

Yang, R., Chen, J., Yang, L., Fang, S., and Liu, J. (2017). An experimental study of high strain-rate properties of clay under high consolidation stress. *Soil Dyn. Earthq. Eng.* 92, 46–51. doi:10.1016/j.soildyn.2016.09.036

Yeomans, B., Saaj, C. M., and Van Winnendael, M. (2013). Walking planetary rovers - experimental analysis and modelling of leg thrust in loose granular soils. *J. Terramechanics* 50, 107–120. doi:10.1016/j.jterra.2013.01.006

Zhang, T., and Goldman, D. I. (2014). The effectiveness of resistive force theory in granular locomotion. *Phys. Fluids* 26, 101308. doi:10.1063/1.4898629

Zhang, T., Qian, F., Li, C., Masarati, P., Hoover, A. M., Birkmeyer, P., et al. (2013). Ground fluidization promotes rapid running of a lightweight robot. *Int. J. Robotics Res.* 32, 859–869. doi:10.1177/0278364913481690

Zhang, W., Li, L., Jiang, S., Ji, J., and Deng, Z. (2019). Inchworm drilling system for planetary subsurface exploration. *IEEE/ASME Trans. Mechatronics* 25, 837–847.

Zhang, Y., Huang, H., Liu, X., and Ren, L. (2011). Kinematics of terrestrial locomotion in mole cricket gryllotalpa orientalis. *J. Bionic Eng.* 8, 151–157. doi:10.1016/s1672-6529(11)60013-9

Zheng, P., Liang, T., An, J., and Shi, L. (2020). Morphological function of toefringe in the sand lizard Phrynocephalus mystaceus. *Sci. Rep.* 10, 1–10. doi:10.1038/s41598-020-79113-4

Zhong, B., Zhang, S., Xu, M., Zhou, Y., Fang, T., and Li, W. (2018). On a cpg-based hexapod robot: Amphihex-ii with variable stiffness legs. *IEEE/ASME Trans. Mechatron.* 23, 542–551. doi:10.1109/tmech.2018.2800776

Zik, O., Stavans, J., and Rabin, Y. (1992). Mobility of a sphere in vibrated granular media. *Europhys. Lett.* 17, 315–319. doi:10.1209/0295-5075/17/4/006

Appendix 2

II

S. Godon, A. Ristolainen, and M. Kruusmaa. "An insight on mud behavior upon stepping". *IEEE Robotics and Automation Letters*, 7(4):11039–11046, 2022

An Insight on Mud Behavior Upon Stepping

Simon Godon, Asko Ristolainen, and Maarja Kruusmaa

***Abstract*—In this research we show a characterization of mud behavior under vertical stepping. We showed that mud stiffness can vary 45-fold and the energy spent to generate equivalent impulse can vary 2-fold depending on the mud water content, but also that stepping faster on mud leads to lower peak forces and higher energy consumption. Next, we showed that the peak force generated can be increased by 33% by changing the foot stiffness, but is reduced by 18% if stepping is repeated on the same spot. We then demonstrated how force control can be used to achieve identical force profiles on very different muds. These results will help to design mechanical parts or control strategies for legged robot locomotion on mud.**

***Index Terms*—Field robot, force control, flowable ground, legged robot, mud.**

I. Introduction

Wet cohesive materials are ubiquitous in nature (forest soils, mudflats, marshes, littorals, estuaries, wet fields) and are challenging to traverse. The ability to traverse these environments is of particular interest in robotic missions such as search and rescue in forests, muddy fields, and mudslides; for agriculture on wet soils (e.g. rice fields); for exploration or excavation of materials with a minimal environmental impact, or for monitoring biodiverse environments. Currently, the only machines at our disposition to access such environments are large machinery like tractors, ATVs, or tracked vehicles which are heavy and have continuous contact with the ground. To reduce the impact on natural environments, and to easier access to unstructured areas, it is thus necessary to develop tools that are lightweight and agile to avoid and preserve natural obstacles. Legged robots are particularly well suited for that as they are lighter than human-driven vehicles, the legs enable nondestructive discrete contact points with the environment and the compaction resistance of soft material piling up in front of wheels/tracks can be avoided. It was shown that legged robots combine the most advantages for traversing natural environments but present shortcomings in soft grounds compared to tracked robots [1]. Indeed, legged robotics research has mostly focused on hard flat terrains, and only recently addresses locomotion on rough/uneven terrains (debris, rocky slopes) [1]. Locomotion on soft grounds is seldom an object of robotics research and focuses primarily on sand or other granular media [2]. Wet, cohesive materials are rarely studied in the context of robotics research and even less in legged locomotion. One possible explanation is the increased locomotion complexity these environments present: as we demonstrate in this letter, they are cohesive, resist extrusion of the foot, are plastically deformable, and their behaviors depend on water content. In this letter, we aim at reducing the shortcomings legged robots have on wet flowable grounds, by investigating the behavior of mud upon stepping using a vertical foot/mud intrusion setup (Fig. 1, supplementary video). This work aims at providing an insight into the topic to help the design of robot legs and their control for efficient and/or effective locomotion on mud.

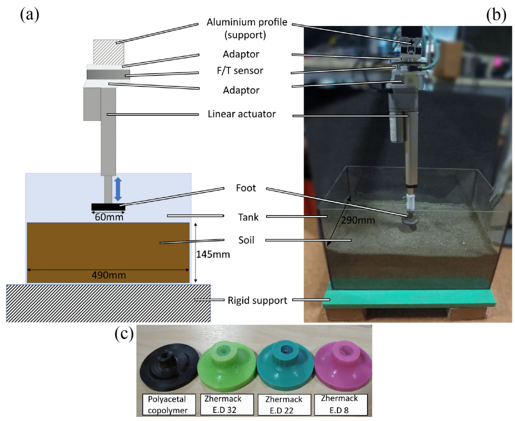

Fig. 1. (a) Schematics of the experimental setup. (b) Photo of the experimental setup. (c) The four different feet used. Foot stiffness increases from right to left.

Manuscript received 24 February 2022; accepted 10 July 2022. Date of publication 28 July 2022; date of current version 25 August 2022. This letter was recommended for publication by Associate Editor N. Kottege and Editor P. Pounds upon evaluation of the reviewers' comments. This work was supported in part by the European Union's Horizon 2020 research and innovation programme ROBOMINERS under Grant 820971, and in part by the Estonian Research Council under Grant PRG1243 Multiscale Natural Flow Sensing for Coasts and Rivers. *(Corresponding author: Simon Godon.)*

The authors are with the Centre for Biorobotics, Tallinn University of Technology, 12618 Tallinn, Estonia (e-mail: simon.godon@taltech.ee; asko.ristolainen@taltech.ee; maarja.kruusmaa@taltech.ee).

This letter has supplementary downloadable material available at https://doi.org/10.1109/LRA.2022.3194667, provided by the authors.

Digital Object Identifier 10.1109/LRA.2022.3194667

II. Related Work

Legged locomotion on flowable soils is a complex and energy-consuming activity for humans and animals alike. It is even more for legged robots, which rather recently started to demonstrate agile locomotion on hard grounds [3], [4]. In general, as we will demonstrate, neither terramechanics nor legged robotics have solved the challenge of stepping on a wet, cohesive flowable material. Terramechanics [5], which studies the interaction between soil and wheeled/tracked vehicles takes a traction perspective, and its applicability is limited to wheeled/tracked vehicles, which only slightly sink into the soil, have continuous contact with the ground, are heavy, and reach high tangential velocities compared to an animal walking on mud. These use cases make its principles unsuitable for legged robots which are lighter, with discontinuous contacts, and move at lower speeds where traction and slippage play a smaller role than sinkage. Yet, terramechanics derived some pressure-sinkage models, such as Bernstein's [6], Bekker's [7] or Reece's [8]. These are useful to model different materials but require several parameters, making them more accurate, but complex and terrain-specific. [9] reviews the soil models and parametrization methodologies, but is aimed at wheels/tracks-terrain interaction, and, underlines the high variability in the models obtained for soil characterization. This demonstrates the complexity of deriving a soil model, and shows the emphasis terramechanics research put on tracked/wheeled vehicles. The variety and complexity of soil models are obstacles to their applicability to mobile robots, which may traverse environments in which each step will be different.

On the other hand, legged robotics research rarely covers interactions with wet, cohesive, flowable soils. The review on locomotion robophysics reviews a wide range of robot models and experiments aiming at understanding principles of locomotion and largely focuses on dry granular media [2]. Legged robot locomotion on dry sand, for example, was studied [10] [11], but the derived principles are applicable to dry granular media, which are cohesionless. Terrain classification studies also were done on dry materials, where a robot can classify the type of soil [12]. Some attempts were made to have robots walk on mud, but they were either made on a shallow layer of mud, where the solid ground under it is used as support [3], or based on high-speed strokes of rotating legs. A range of robots based on this principle was developed, stemming from the RHex hexapod structure with 1 degree of freedom (DoF) per leg [10], with end effectors evolved into Whegs [13], reconfigurable legs/flippers [14], [15], Ninjalegs [16], or variable stiffness legs [17]. Some of these robots demonstrate an ability to traverse mud, but the locomotion based on rapidly rotating 1 DoF actuators doesn't allow advanced gait planning or step placement to pass obstacles or preserve the environment. More complex and versatile robots with several DoF per leg represent a great opportunity to overcome more challenging terrains and to preserve the traversed environment. However, adding several DoF per leg also increases control complexity, which is even more challenging in muddy environments.

Most legged robotics research on soft terrains addresses control of robots, especially gait control using one of two approaches: control using a soil model, or using a model-free controller. For example, a soil model assuming that force increases with sinkage following a power law was used on a hexapod walking robot which corrected its attitude using force information [18]. Similarly, active compliance was used on a six-legged robot where the body orientation was kept fixed and leg sinkage was controlled [19]. More recently, a genetic algorithm was used to simulate the gait generation of a quadruped robot on sand using a non-linear model for intrusion forces in sand [20]. Model-free controllers, are also mostly based on force control, for example, in [21], a simple model-free force controller enabled a robot to balance on a variety of grounds. Simulations on a hopping system suggest that impulse control permits motion on terrains with unknown properties, including dissipative grounds [22]. Also, [23] demonstrates a model-free reinforcement learning controller able to maneuver a four-legged robot through unstructured environments, including a shallow layer of mud, which allows support on the solid underlayer, contrary to deep mud. In [24], a hybrid ground learning and active compliance control was developed to enable a robot to walk on both wood and sponge, but was not demonstrated on cohesive media. As shown here, most research on legged locomotion on soft grounds dealt with stabilization or attitude control applied at the whole-body level. However, whole-body locomotion encompasses complex control problems which would benefit from a better understanding of foot/ground interactions. We hence propose to focus on simplified setups investigating foot/ground interactions.

Contrary to whole-body locomotion research, some studies investigate a single control or mechanical parameter. [25] analyzed the cost of transport (CoT) and velocity of two gaits in a fluidized sand bed and found that retracting the leg out of the flowable material was the most effective and efficient way of running. [26] suggests that using a circular, flat-bottomed foot on sand enables to reach higher force. For these reasons, in our experiment, we will use flat-bottomed, circular feet.

In the above literature review, little research investigated the behavior of mud upon stepping. Most research in terramechanics focuses on wheels or tracks interaction with soil, and legged robotic research mainly focuses on robot stability on different soils. Some of the above approaches demonstrate good results in terms of stability, however, few showcased locomotion on flowable soils, and none attempted characterization of wet soil or used agile locomotion strategies. The contribution of this letter is the characterization of the behavior of mud upon stepping and the investigation of parameters having an impact on bearing capacity, but also the demonstration that a simple force controller, based on qualitative knowledge of mud behavior can be used to traverse different muds. These results will be useful to develop an understanding of the mud behavior and bolster the design of mechanical parts and controllers to develop robots for agriculture, environmental monitoring, search and rescue, exploration, and resource extraction.

III. Materials and Methods

Mud has properties changing in space and time, due to its infinite number of possible compositions (percentage of clay, silt, sand, gravels, organic matter, water, compaction). Therefore, a general model for mud is complex to develop and probably unpractical. Hence our approach staved off deriving an accurate and general model and instead analyzed the qualitative behaviors which could be generalizable to different muds. We performed experiments intruding circular feet into muds: intrusion at constant speed on two different soils, with different feet, at constant speed with different water content, and force-controlled steps on soils with different water content (Table I). For each

TABLE I
OVERVIEW OF THE EXPERIMENTS PERFORMED

Exp. #	Parameter varied	Values of parameter varied	Const. parameters	Num of experiments	Goal
1	Speed of intrusion	[10, 20, 30, 40, 50] mm/s	Water content, foot	10 per condition (total: 50)	Investigate whether the speed of intrusion impacts the maximum achievable force
2	Speed of intrusion	[2, 3, 3.8, 4.3, 8, 14, 20, 34, 48] mm/s	Water content, foot	10 per condition (total: 90)	Similar to exp.1, with higher water content, to see whether the speed of intrusion impacts muds with different water contents differently.
3	Foot material	Polyacetal copolymer, ZED 8,22,32	Water content, speed	10 per condition (total: 40)	Investigate whether foot stiffness impacts the maximum achievable force.
4	Water content	[0, 5, 10, 15, 20, 25, 30, 35, 40]% dry soil mass	Speed, foot	10 per condition (total: 90)	Investigate the evolution of the soil stiffness and retraction force with water content.
5	Repeated stepping	3 steps	Speed, foot, water content	10	Investigate whether mud's bearing capability is reduced after stepping, and by how much.
6	Water content	[0, 20, 30, 35]% dry soil mass	Foot, force controller (only in experiment 6)	18 per condition (total: 72)	Demonstrate the feasibility of force control on different muds using the same model-free controller.

experiment, the measurements of interest are the sinkage and force.

For these experiments (see Fig. 1), a linear actuator Firgelli FA-PO-35-12-6" was used to step on mud. Four feet of different stiffness (rigid plastic (polyacetal copolymer) as well as silicones Zhermack Elite Double- ZED 8, 22, and 32) were mounted on the actuator (Fig. 1(c)). Each foot is circular with a diameter ϕ 60 mm (28.3 cm^2). The silicone feet were cast with a rigid mesh in the upper part to allow a rigid connection between the foot and the actuator. The mud was garden soil saturated with water. Control was implemented on an Arduino Uno (Arduino AG) and data was recorded using Matlab Simulink (MathWorks inc). Force was recorded using an ATI Serial Axia Force/Torque (F/T) sensor. For each experiment, we recorded the position, vertical force, and calculated power. Moments and lateral forces were measured and considered negligible.

When the speed of intrusion was studied (Figs. 4 and 5), we saturated the soil with water and intruded the foot at different speeds until a set sinkage. Experiments 1 and 2 were performed on muds with different water contents because the actuator's limitations prevented very low speeds on harder soil. For investigating the effect of feet stiffness on the force/sinkage relationship, we use a PID velocity controller with position condition intruding the foot to a predefined depth at a constant speed, to compare the required force for intrusion at identical depth.

For investigating the effect of water content on bearing capacity, the soil was first dried on the ground for 5 days and then sieved with a 4 mm sieve. 20 kg (20.6 L) of dry soil was then placed into the tank and slightly compacted by placing a 4 kg weight (with 44 cm^2 surface area, leading to a 8.9 kPa pressure). We then shuffled the upper part of the soil to reduce the surface compaction. For each experiment, the foot was penetrated into the soil at a constant speed (10 mm/s). Between experiments, the soil was mixed, compacted, shuffled, and evened out. Altogether we performed 10 experiments per water content, in 9 different conditions (Table I). After each addition of water, the soil was mixed to have homogeneous properties. A 90 N threshold was set to protect the experimental setup.

The 1 DoF experiment did not allow generating lateral forces, responsible for the forward motion of a legged device. However, we argue in this letter that on mud, slower locomotion is preferable. Since slower locomotion generates lower lateral forces, the limitations of the setup do not play a significant role. Additionally, in deformable grounds, legs sink and are laterally supported by a column of mud. This reduces the risk of slippage, as observed in cows which reduced speed and increased step length and leg inclination at contact in deep mud [27].

Following the mud characterization, we performed stepping experiments on the mud by controlling force of the leg, using the ZED 22 foot because of its higher performances in other experiments. To simulate the profile of the vertical Ground Reaction Forces in legged locomotion, the positive half cycle of a sinusoidal wave was commanded, with a 4 s duration and 30 N amplitude. This controller (see Fig. 2) allows generating the three phases of the step: landing, support, and lift-off. When in the force mode, two different PID controllers are used for the two nearly-linear behaviors of mud; one with a steep slope for decreasing force, and one with more moderate slope for increasing force (see Figs. 4, 7, and 8). Then, the gain adaptation block varies the gains of each force controller depending on the derivative of force command by a multiplying factor computed as in (1).

$$\alpha = \frac{arctan(\dot{u} - 1) + \pi}{2} \tag{1}$$

The adaptation of gains enables to complement the shift of PIDs by making PID 2 less aggressive as the command flattens, and on the contrary, making PID 3 less aggressive when the command sharpens toward negatives. This way, despite the high variability of soil stiffness, we can achieve smooth force increase, and prevent any excessive reaction when force command decreases, especially when the slope of force/sinkage relationship is very steep.

IV. Results and Discussion

A. Going Slower is More Efficient

Experiments 1 and 2 (see Table I) investigated the effect of speed of intrusion on forces generated on mud. The impulse of

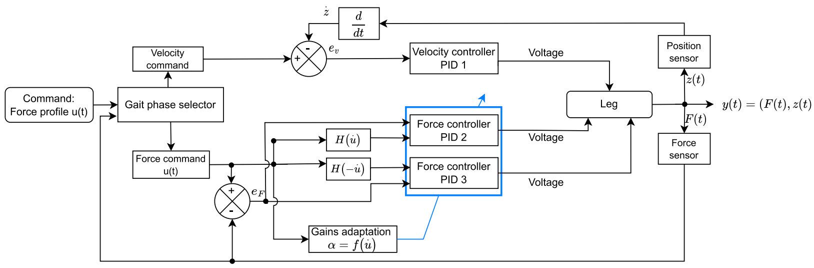

Fig. 2. Step controller. The gait phase selector decides whether the step is before landing, during support or lift-off of the foot based on a force threshold (1 N), and outputs a velocity command or a force command. First, a downward velocity command is sent, then, if force is higher than the threshold, the force profile is commanded, and when force goes below the threshold again, an upward velocity command is sent. The velocity PID controller is following the set velocity command until the force controller relays (landing phase) or until a position is reached (lift-off phase). When in force command mode, two Heaviside blocks activate PID 2 or 3 depending on whether the force command is increasing or decreasing. Additionally, each controller's gains are adapted based on the derivative of the force command.

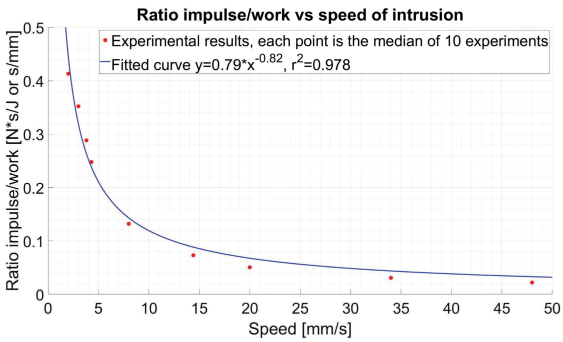

Fig. 3. Ratio impulse/work vs speed. The ratio was computed by dividing the impulse (Newton-Cotes integration of force overtime, only during the movement phases) by work (Newton-Cotes integral of force over sinkage).

a step onto the soil is defined as the integral of force overtime. Work, which represents the energy lost in the deformation of soil (and is, contrary to solid, elastic deformations, irrecoverable), is computed as the integral of force over sinkage. If we want to maximize the vertical momentum while minimizing the energy lost in soil deformation, we may want to increase the following ratio:

$$\frac{Impulse}{Work} = \frac{\int F dt}{\int F dz} \tag{2}$$

which has the unit of s/m, or inverse of speed. In equation (2), z is the distance between the current position and the position where the first non-zero force was detected (similarly for t). Let us consider the intrusion phase. As shown in Section II, there exist a variety of soil models. Despite being accurate, these models are complex and therefore harder to apply, especially on a natural ground where the material parameters may vary. For these reasons, we chose to simplify the model as much as possible to both increase its generalizability and to simplify its parameter estimation, at the cost of reduced accuracy. One of the simplest models is Bernstein's, i.e., $F(z) = k \cdot z^n$, where F(z) is the force as a function of sinkage, k and n are constants depending on the soil [6]. Observing Figs. 4(a) and (b), 7, 8 and Table II, we can notice that during the intrusion phase, the relationship between force and sinkage is almost linear. Hence the model can be simplified to

$$F(z) = k \cdot z \tag{3}$$

Since we use a constant speed of intrusion, and force increases linearly with depth (3), force increases linearly with time:

$$Impulse = F_{max} \cdot \frac{t}{2} \approx \frac{kzt}{2} = \frac{kz^2}{2v_z} \tag{4}$$

where $v_z = \frac{z}{t}$ is the vertical speed, and we have

$$Work = F_{max} \cdot \frac{z}{2} \approx \frac{kz^2}{2} \tag{5}$$

which gives

$$\frac{Impulse}{Work} = \frac{1}{v_z} \tag{6}$$

This relation is also observed in our experiments, as witnessed in Fig. 3. This result can be understood as follows: being static on mud requires no energy (no work) and still generates impulse, driving (6) to infinity. The same impulse can be generated by several intrusions at the same depth, deforming soil on each step. To keep a constant altitude, a robot must compromise between stepping frequency and energy efficiency, at least for what concerns mud deformation. Note that this applies if we withdraw the foot as soon as it reaches the maximum force. On a mobile robot bearing its own weight, the efficiency could even get better at very low speeds. Indeed, as witnesses Fig. 5, after the movement has stopped (at peaks), the force suddenly drops. The slower the leg sinks, the smaller the difference between the peak force and the steady-state force. If we let the robot sink under its own weight (case when the speed is excessively slow), no mechanical power is required, but also, we don't have any 'excess' peak force, which is otherwise wasted mechanical work. When pulling the leg out of the mud, some energy is still required, the other legs are bearing more weight and sinking deeper.

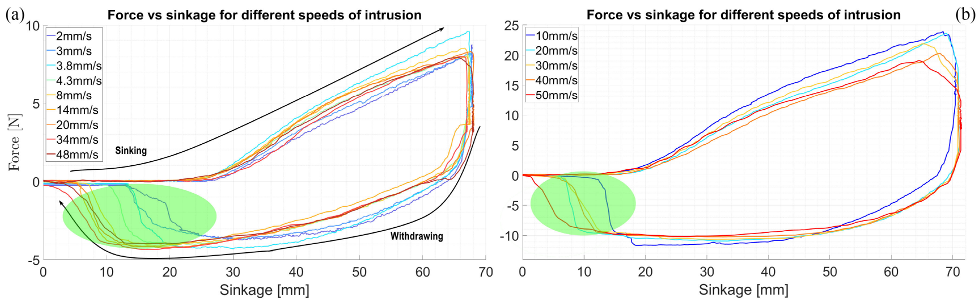

Fig. 4. (a) Force vs sinkage for speeds from 2 mm/s to 48 mm/s. The graph is read clockwise: sinking leads to positive forces (left to right) up to the peak force and withdrawing leads to negative forces (from right to left). The green area marks the breakage of the suction effect. Each curve is the median of a set of 10 curves. Interquartile ranges (IQR) were omitted for readability. (b) Similar experiment with lower water content, in steps of 10 mm/s.

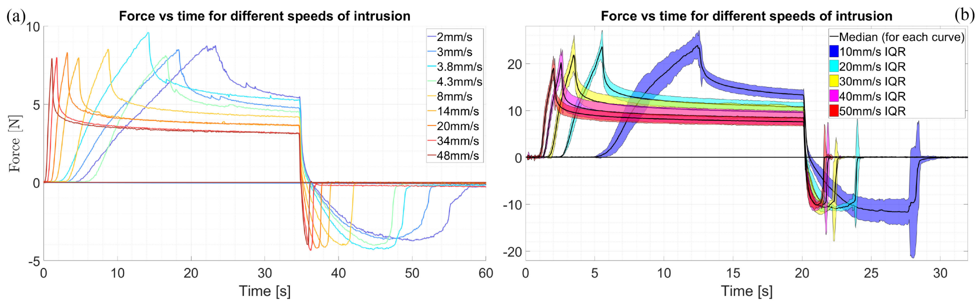

Fig. 5. (a) Force vs time for speeds from 2 mm/s to 48 mm/s, corresponding to Fig. 4(a). It consists of intrusion at a constant speed, a pause until the 35th second, and retraction retraction. Each curve is the median of 10 experiments. IQRs were omitted for readability. (b) Force vs time for speeds from 10 mm/s to 50 mm/s, corresponding to Fig. 4(b). The experiment consists of intrusion at a constant speed, a pause the 20th second, and retraction. Each curve is the median of a of 10 experiments.

B. Going Slower Increases Forces

Fig. 4 shows the force vs sinkage for different speeds. Experiments in Fig. 4(a) were performed on mud with more water than those in Fig. 4(b). Both figures show a higher force for the lower intrusion speed (shear-thinning), and Fig. 4(b) shows that the mud with a lower water content resists intrusion more, and its resistance is more dependent on speed. While withdrawing, we can see that force first drops to zero with little movement because of the plastic deformation of the mud. Then, withdrawing further creates a suction under the foot which leads to negative, pulling forces. When the air gets under the foot, the suction is broken and force abruptly returns to zero (green areas in Fig. 4). For the two water contents tested we observe an absolute ratio of 2 both between the maximum intrusion force and suction force. However, the suction continues across a longer extrusion when the water content is higher (Fig. 4(a)).

This result complements the previous one: on top of decreasing the energetic cost of locomotion on mud, lower speeds also lead to higher forces, reducing further the mechanical work spent on deforming the soil. If the goal of a mud walking robot is efficiency or reduced environment deformation, reducing velocity appears to be a promising strategy. Nevertheless, legged robots need to maintain base torque (and power) in their motors to stand still. Thus, decreasing the robot's speed increases the time a robot takes to perform a task and will in turn lead to higher energy consumption. Further experiments studying the CoT on a legged platform are needed to find an optimum.

C. Stiffness of the Foot Matters

As can be seen in Fig. 6, the feet with the average stiffness (ZED 22 and 32 feet) generate higher forces for the same sinkage. More precisely, the ZED 22 foot reaches 33% higher force than the ZED 8 (37.6 N vs 28.2 N). However, this advantage is mitigated by the higher force required when withdrawing the foot. The feet that create the highest force during sinkage also require more force when withdrawing from the mud (Fig. 7).

A possible explanation for the force dependence on stiffness is that, compared to the rigid foot, the ZED 32 and 22 feet deform more under the application of force, hence avoiding high-pressure concentrations that cause the failure of the mud. When the foot is too soft (ZED 8), the deformations are so large that the projected surface area of the foot decreases significantly and the pressure is higher, causing failure of the mud. This new finding adds to previous findings relating to the shape of the

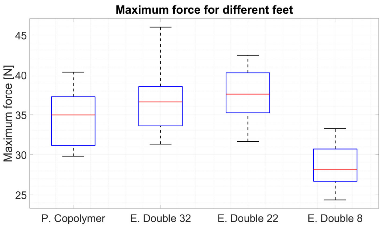

Fig. 6. Maximum force generated by the feet for a same step. Each box represents (top to bottom) the upper adjacent, 75th percentile, median, 25th percentile and lower adjacent for the maximum forces reached in Fig. 7.

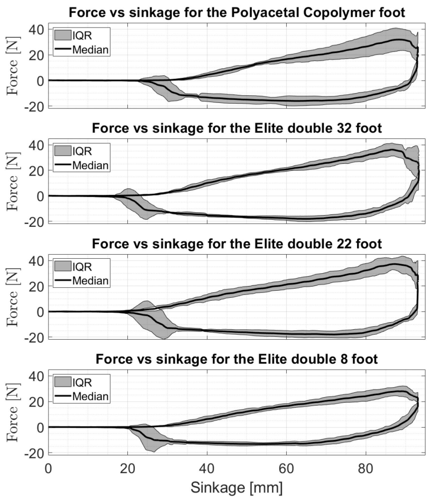

Fig. 7. Force vs sinkage for the four feet. Each curve is the median of 10 similar experiments.

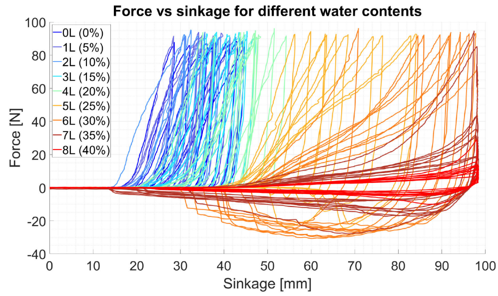

Fig. 8. Force/sinkage curves for different water contents.

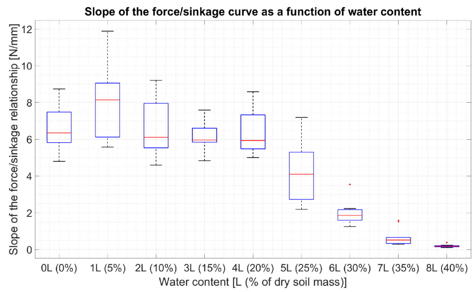

Fig. 9. Slope of the force/sinkage relationship vs water content. Each box represents (top to bottom) the upper adjacent, 75th percentile, median, 25th percentile and lower adjacent of the slopes extracted from Fig. 8. To compute the slope, we fitted a linear model between the point where 1 N is reached and the maximum force.

TABLE II
R^2 FOR THE LINEAR MODEL FITTING OF THE CURVES IN FIG. 8 COMPUTED AS THE AVERAGE OF THE 10 SIMILAR CURVES

Water(%)	0	5	10	15	20	25	30	35	40
R^2	0.993	0.982	0.976	0.9501	0.956	0.992	0.937	0.908	0.907

foot [26] for determining the intrusion force. When a robot is intended to walk on soft grounds attention should be paid to foot stiffness. It is known that on hard grounds, low foot/tire stiffness results in more energy to move. It is consequently advisable to adjust the foot stiffness depending on the ground the robot walks on.

D. Higher Water Content Reduces Mud's Bearing Capacity

The force/sinkage curves for different water contents are displayed in Fig. 8. The slopes of these curves, assuming a linear relationship (3) are plotted in Fig. 9, and the coefficients of determination (R^2) are presented in Table II. When water weights 0 to 20% of the soil mass, the soil gradually reduces its bearing capacity with (median) slopes between 8.1 and 5.9 N/mm, but with higher water content, the stiffness drops to 0.18 N/mm for 40% water content, 1/45th of the stiffness for 2 L of water. We can see from Table II that the linear model fits very well for up to 25% water content ($R^2 > 0.95$). For higher water contents, the linear model derives marginally from the experimental observations but is still a good fit ($R^2 > 0.9$). This result suggests that linear controllers could be used for the landing phase.

The suction force appears after 5 L of water (25% dry soil mass), reaches its maximum at 6 L (30%), and then decreases as the mud fluidizes (Fig. 8). This suction could be minimized by an anisotropic design, i.e., a foot with a different shape for intrusion and extrusion. On a legged robot, suction from the retraction of one foot would further increase the load and sinkage of the other feet. Gaits and feet design preventing the suction force are hence important to consider.

Finally, Fig. 10 shows that the ratio impulse/work is lower for completely dry soil, is relatively constant for water contents from 1 L to 5 L (from 5% to 25% of soil mass), and then sharply halves. This result shows that moving on dusty soil is less energy efficient than on slightly wet and cohesive soil, but efficiency collapses when water content is high.

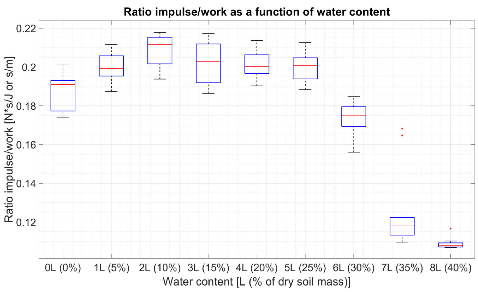

Fig. 10. Impulse/work vs water content. Each box represents (top to bottom) the upper adjacent, 75th percentile, median, 25th percentile and lower adjacent. The ratio was computed by dividing the impulse (Newton-Cotes integration of force overtime during the movement phases) by work (Newton-Cotes integral of force over sinkage).

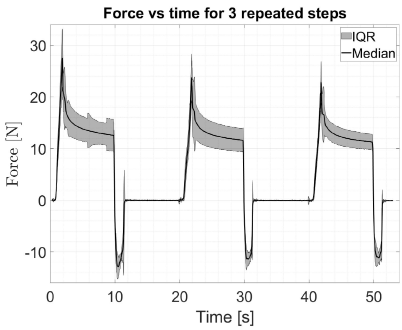

Fig. 11. Repeated steps on the same spot, at the same depth. The second step reaches a much lower force than the first, and the third reaches a slightly smaller force than the second. The black curve represents the median and the shaded area the IQR, for a set of 10 experiments.

E. Repeated Stepping Weakens the Mud

Fig. 11 shows a succession of three subsequent steps at the same depth. It can be observed that at the second and third steps the force decreases. More precisely, the median for the third peak (22.6 N) is 18% lower than for the first peak (27.5 N). This means that stepping on mud reduces its bearing capacity. It follows that for a walking robot in a natural muddy environment, gaits using new foot placement for each consecutive leg are to favor.

F. An Adaptive PID Controller Can Adapt to Varying Soils

Fig. 12 shows that the proposed stepping controller can follow the commanded force profile for most mud conditions. The controller was able to perform a step on every mud without retuning any gains, despite very different characteristics of the muds. This suggests that the qualitative model we used to design this controller is sufficient to control stepping on mud, despite the high variability in mud behavior with water content. However when the mud is too soft, the controller's performance is decreased (Root Mean Square Error, RMSE = 4.67 N, see Fig. 12). This shows the limitation of the assumption of a

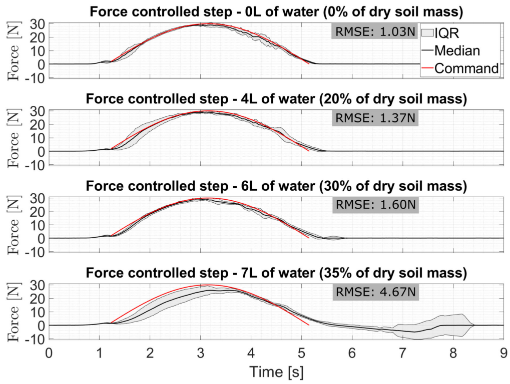

Fig. 12. Output of the step controller depending on the water content of the mud. First the foot is velocity-controlled (PID 1) up to contact, then force-controlled with PID 2 up to the peak force, then force-controlled with PID 3 until force reaches 1 N, and then is velocity controlled with PID 1. The RMSE is computed between the median curve and the command.

linear force-sinkage relationship for high water content, where a faster-reacting controller would be able to follow the command. These errors could lead to variations in the robot's attitude which could be problematic or not depending on the application.

G. Generalizability

The 1 DoF leg setup did not allow lateral forces generation, but we argue that for efficiency and environmental preservation purposes, slower locomotion, which reduces lateral forces, is preferable in muddy environments. Additionally, in deep mud, the sinked foot is anchored and prevents slippage. Therefore, we believe that lateral forces are incidental to leg-mud interaction and their absence from this study does not impede the applicability of these results to a leg with more DoF. Also, our experiments used the same soil in which the water content was varied. Interestingly, the force/sinkage relationship for intrusion is similar to that observed in sand [11], [26], loams, and muskegs [5] (linear or power function with a power close to one). However, it seems that the suction force is a particularity of mud. Mud properties are time and location-dependent and an accurate model is unpractical for a mobile robot. The qualitative behavior of mud, however, is important. Similarly, to terramechanics characterization techniques, e.g., penetrometer, bevameter [5], the method used here can be used on different muds and the observations on the dependence of the force on speed, water content and stiffness of the foot, and the weakening of mud after re-stepping are likely to be generalizable to a large variety of mud compositions. The magnitude of the variations however will likely be different in each mud. For this reason we aimed at deriving a general qualitative model instead of an accurate, terrain-specific model. Our observations can be used on legged robots, and in-situ measurement of ground stiffness or retraction force are needed to adapt the gait, using the knowledge this letter provides on the general behavior.

V. Conclusion

This experimental study unveiled results that can inform future work on robotic legged locomotion on mud:

- The relation between sinkage and bearing force can be approximated by a linear relationship, whose slope depends both on the intrusion speed and water content.
- The vertical impulse/work ratio is inversely dependent on speed, which means that to go faster on mud, more energy is spent per unit distance.
- Lower intrusion speeds lead to higher force, and this is more pronounced for mud with lower water content.
- A too stiff or too soft foot doesn't provide as much support force as feet with intermediate stiffness.
- At a water content of 25-35%, re-stepping in the same spot decreases mud's bearing capacity due to plasticity.
- In mud, vacuum appears below the foot and resists withdrawing until some air gets under the foot. This phenomenon appears when the water content is high enough, but lessens when the water content is too high.
- Soil stiffness collapses at high water content.
- A controller with variable gains can enable stepping on muds with different properties, with degraded performance for very fluid mud.

The 1 DoF experiment restricted variables to speed, foot materials, mud compositions, or controlling force. Future work using more DoF could vary loading strategies and explore lateral forces. Additionally, experiments on a mobile robot could focus on gaits compensating for sinkage, measure the CoT, investigate how gravity may be used to sink passively or hinder locomotion during withdrawal, when the load is relocated on the other feet. Future work could also investigate ways to cancel the suction force possibly with an anisotropic design of the foot.

References

[1] L. Bruzzone and G. Quaglia, "Review article: Locomotion systems for ground mobile robots in unstructured environments," *Mech. Sci.*, vol. 3, no. 2, pp. 49–62, Jul. 2012.

[2] J. Aguilar et al., "A review on locomotion robophysics: The study of movement at the intersection of robotics, soft matter and dynamical systems," *Rep. Prog. Phys.*, vol. 79, no. 11, 2016, Art. no. 110001.

[3] M. Raibert, "BigDog, the rough-terrain quadruped robot," *IFAC Proc. Volumes,* vol. 17, no. 1 PART 1, pp. 6–9, 2008.

[4] K. Kaneko, K. Harada, F. Kanehiro, G. Miyamori, and K. Akachi, "Humanoid robot HRP-3," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2008, pp. 2471–2478.

[5] J. Y. Wong, *Terramechanics and Off-Road Vehicle Engineering: Terrain Behaviour, Off-Road Vehicle Performance and Design*. London, U.K.: Butterworth-Heinemann, 2010.

[6] R. Bernstein, "Probleme zur experimentellen motorpflugmechanik," *Der Motorwagen*, vol. 16, no. 9, pp. 199–206, 1913.

[7] M. G. Bekker, "Mechanics of off-the-road locomotion," *Proc. Inst. Mech. Eng.: Automobile Division*, vol. 16, no. 1, pp. 25–44, 1962.

[8] A. R. Reece, "Principles of soil-vehicle mechanics," *Proc. Inst. Mech. Eng.: Automobile Division*, vol. 180, no. 1, pp. 45–66, 1965.

[9] R. He, C. Sandu, A. K. Khan, A. G. Guthrie, P. Schalk Els, and H. A. Hamersma, "Review of terramechanics models and their applicability to real-time applications," *J. Terramechanics*, vol. 81, pp. 3–22, Feb. 2019.

[10] C. Li, T. Zhang, and D. I. Goldman, "A terradynamics of legged locomotion on granular media," *Science*, vol. 339, no. 6126, pp. 1408–1412, 2013.

[11] L. Ding et al., "Foot-terrain interaction mechanics for legged robots: Modeling and experimental validation," *Int. J. Robot. Res.*, vol. 32, no. 13, pp. 1585–1606, Nov. 2013.

[12] H. Kolvenbach, C. Bartschi, L. Wellhausen, R. Grandia, and M. Hutter, "Haptic inspection of planetary soils with legged robots," *IEEE Robot. Automat. Lett.*, vol. 4, no. 2, pp. 1626–1632, Apr. 2019.

[13] M. A. Klein, A. S. Boxerbaum, R. D. Quinn, R. Harkins, and R. Vaidyanathan, "SeaDog: A rugged mobile robot for surf-zone applications," *Proc. IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatron.*, 2012, pp. 1335–1340.

[14] G. Dudek et al., "AQUA: An amphibious autonomous robot," *IEEE Computer*, vol. 40, no. 1, pp. 46–53, Jan. 2007.

[15] X. Liang et al., "The AmphiHex: A novel amphibious robot with transformable leg-flipper composite propulsion mechanism," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2012, pp. 3667–3672.

[16] B. B. Dey, S. Manjanna, and G. Dudek, "Ninja legs: Amphibious one degree of freedom robotic legs," in *Proc. IEEE Int. Conf. Intell. Robots Syst.*, 2013, pp. 5622–5628.

[17] B. Zhong, S. Zhang, M. Xu, Y. Zhou, T. Fang, and W. Li, "On a CPG-Based hexapod robot: AmphiHex-II with variable stiffness legs," *IEEE/ASME Trans. Mechatron.*, vol. 23, no. 2, pp. 542–551, Apr. 2018.

[18] M. Kaneko, K. Tanie, and M. N. M. Than, "A control algorithm for hexapod walking machine over soft ground," *IEEE J. Robot. Autom.*, vol. 4, no. 3, pp. 294–302, Jun. 1988.

[19] D. M. Gorinevsky and A. Y. Shneider, "Force control in locomotion of legged vehicles over rigid and soft surfaces," *J. Robot. Res.*, vol. 9, no. 2, pp. 4–23, 1990.

[20] J. Hulas and C. Zhou, "Improving quadrupedal locomotion on granular material using genetic algorithm," in *Proc. UKRAS20 Conf.: "Robots Real World"*, 2020, vol. 3, pp. 33–34.

[21] J. White, D. Swart, and C. Hubicki, "Force-based control of bipedal balancing on dynamic terrain with the Tallahassee Cassie robotic platform," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2020, pp. 6618–6624.

[22] D. Koepl and J. Hurst, "Impulse control for planar spring-mass running," *J. Intell. Robot. Syst.: Theory Appl.*, vol. 74, no. 3–4, pp. 589–603, 2014.

[23] J. Lee, J. Hwangbo, L. Wellhausen, V. Koltun, and M. Hutter, "Learning quadrupedal locomotion over challenging terrain," *Sci. Robot.*, vol. 5, no. 47, Oct. 2020.

[24] D. Zhou and K. H. Low, "Combined use of ground learning model and active compliance to the motion control of walking robotic legs," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2001, vol. 3, pp. 3159–3164.

[25] S. Gart, R. Alicea, W. Gao, J. Pusey, J. V. Nicholson, and J. E. Clark, "Legged locomotion in resistive terrains," *Bioinspiration Biomimetics*, vol. 16, no. 2, 2021, Art. no. 025001.

[26] D. Han, R. Zhang, H. Zhang, Z. Hu, and J. Li, "Mechanical performances of typical robot feet intruding into sands," *Energies*, vol. 13, no. 8, 2020, Art. no. 1867.

[27] C. J. Phillips and I. D. Morris, "The locomotion of dairy cows on concrete floors that are dry, wet, or covered with a slurry of excreta," *J. Dairy Sci.*, vol. 83, no. 8, pp. 1767–1772, 2000.

Appendix 3

III

S. Godon, C. Prados, A. Chemori, A. Ristolainen, and M. Kruusmaa. Walking in mud: Modeling, control, and experiments of quadruped locomotion. *IEEE/ASME Transactions on Mechatronics*, pages 1–12 (early access), 2025

Walking in Mud: Modeling, Control, and Experiments of Quadruped Locomotion

Simon Godon, Carlos Prados, Ahmed Chemori, *Senior Member, IEEE*, Asko Ristolainen, and Maarja Kruusmaa

***Abstract*—Soft wet grounds such as mud, sand, or forest soils, are difficult to navigate because it is hard to predict the response of the yielding ground and energy lost in deformation. In this article, we address the control of quadruped robots' static gait in deep mud. We present and compare six controller versions with increasing complexity that use a combination of a creeping gait, a foot–substrate interaction detection, a model-based center of mass positioning, and a leg speed monitoring, along with their experimental validation in a tank filled with mud, and demonstrations in natural environments. We implement and test the controllers on a Go1 quadruped robot and also compare the performance to the commercially available dynamic gait controller of Go1. While the commercially available controller was only sporadically able to traverse in 12 cm deep mud with a 0.35 water/solid matter ratio for a short time, all proposed controllers successfully traversed the test ground while using up to 4.42 times less energy. The results of this article can be used to deploy quadruped robots on soft wet grounds, so far inaccessible to legged robots.**

***Index Terms*—Control architecture, experiments, legged robotics, mud, yielding grounds.**

Fig. 1. The Unitree Go1 robot used in this research. The IMU is located at the center of the trunk, and each leg has three motors: one for the hip joint, one for the thigh joint, and one for the tibia joint. See also Fig. 2.

I. Introduction

LEGGED locomotion has evolved as a versatile solution for traveling on natural, uneven terrains [1]. Although quadruped robot locomotion research is making quick progress, demonstrating high agility, stability, and adaptiveness in natural environments, challenges still persist. Soft, yielding, and flowing grounds are particularly challenging for animals and robots alike [2]. At the same time, these conditions can be found everywhere in a natural environment, for example, lowlands and wetlands, snowy landscapes, littoral zones, river basins, etc. Robots, reliably moving in those environments can assist humans in many applications, such as search and rescue, agriculture, or environmental monitoring [3].

In recent years, several attempts have been made to investigate quadruped locomotion in complex, partially flowable terrains. For example, Angelini et al. [3] demonstrated the ANYmal robot walking in sandy, rocky, and vegetated grounds. Arm et al.[4] presented a team of quadruped robots able to walk on sand, slopes, and rocks. In [5], model-based reinforcement learning (RL) is used to get a quadruped robot to learn to move on sand, hard grounds, and soft synthetic grounds. Fahmi et al.[6] presented a whole body controller capable of estimating ground compliance, allowing the robot to adapt to grounds of different compliance. In [7], a terrain classifier is developed and used to adapt the controller to foam and different hard grounds. Other works focus on the hardware design of the foot to allow it to adapt to sandy, rocky, or muddy surfaces [8], [9], [10].

None of the works on control above appear to address mud and other wet media, probably because it is a particularly complex environment. First, mud has always variable properties, depending on the changing water content and particle size. Second,

Received 29 November 2024; revised 27 February 2025; accepted 4 April 2025. Recommended by Technical Editor S. Ibaraki and Senior Editor Y.-J. Pan. This work was supported in part by the European Union's Horizon 2020 research and innovation programme ROBOMINERS under Grant 820971, and in part by the Estonian Research Council under Grant PRG1243 Multiscale Natural Flow Sensing for Coasts and Rivers, and PHC PARROT French-Estonian joint project. *(Corresponding author: Simon Godon.)*

Simon Godon, Asko Ristolainen, and Maarja Kruusmaa are with the Centre for Biorobotics, Tallinn University of Technology, 12618 Tallinn, Estonia (e-mail: simon.godon@taltech.ee; asko.ristolainen@taltech.ee; maarja.kruusmaa@taltech.ee).

Carlos Prados is with the Universidad Politécnica de Madrid, 28012 Madrid, Spain (e-mail: c.prados@upm.es).

Ahmed Chemori is with the LIRMM, University of Montpellier, CNRS, 34095 Montpellier, France (e-mail: Ahmed.Chemori@lirmm.fr).

This article has supplementary material provided by the authors and color versions of one or more figures available at https://doi.org/10.1109/TMECH.2025.3560588.

Digital Object Identifier 10.1109/TMECH.2025.3560588

unlike other soft grounds such as sand or foam, a wet cohesive yielding ground exerts suction force on the extruding foot. As the water content of mud varies, so does the suction force, and this makes modeling and control of foot–ground interaction more complicated [2], [11]. Finally, if the mud is deep, the resistive and suction forces enhance the nonlinearities and uncertainties of foot–ground interaction. Rather than walking on the mud, the animal walks in the mud: wading.

Some experiments were conducted using simple robot models to understand different aspects of the interaction between mud/resistive grounds and robots [11], [12], [13], [14]. A RL approach was even successfully tested in shallow mud using a quadruped robot [15]. None of those attempts consider wading in deep mud.

In this article, we introduce a control architecture for a quadruped walking in mud and test it using a Unitree Go1 platform (see Fig. 1). Analogous to biological systems [16], our control architecture relies solely on proprioceptive information, such as an Inertial Measurement Unit (IMU), encoders, and motor current.

Contrary to all the other works mentioned above, our controller uses a static gait where the robot is constantly stable. The rationale behind the use of a static gait is that mud is highly dissipative, making it hard if not impossible to rely on momentum. Also, since mud's properties are highly variable from one step to the other, they are hard to predict, and an estimation error could lead to falling, getting stuck, or damaging the robot. Therefore, we prioritized stability and adopted a static gait, following the same strategy as quadruped animals moving in mud [2] (see accompanying video.[1]).

Our controller is different from previously developed static gait controllers for locomotion on hard surfaces, because it includes features specifically developed for locomotion on muddy grounds, such as ground stiffness measurement, leg trajectory adaptation, suction force estimation, and Center of Mass (COM) positioning taking into account mud's estimated properties. Besides, to the best of our knowledge, this is the first successful attempt to make a quadruped robot walk in deep mud.

The rest of this article is organized as follows: in Section II, the materials and methods are described with the robot platform and kinematic model, the control architecture, and the experimental setup. Our findings are presented in Section III and discussed in Section IV. Finally, Section V concludes this article.

II. Materials and Methods

A. Robot Platform

The Unitree Go1 robotic platform was used in this study for experimental validation of control strategies (see Fig. 1). Each leg is equipped with three Quasi Direct Drive (QDD) actuators, and an IMU is embedded in the main body. Each QDD actuator provides comprehensive feedback encompassing position, velocity, and torque parameters. The robot parameters are summarized in Table I. The letters between brackets represent the location of the link in Fig. 2.

[1]The supplementary video is available at https://youtu.be/TidYdtmdEr4

TABLE I
Summary of Robot Parameters

Parameter	Value
mass	12 kg
trunk length	0.3762 m
trunk width	0.0935 m
shoulder length (OA)	0.08 m
thigh length (AB)	0.213 m
tibia length (BC)	0.213 m

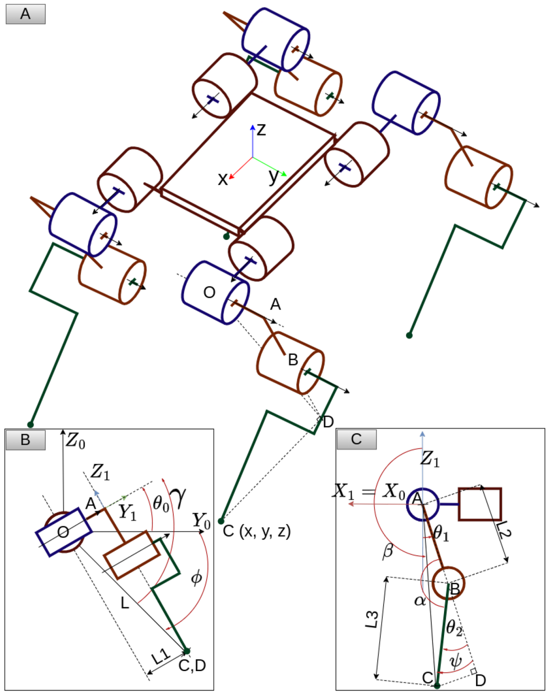

Fig. 2. Kinematic diagram of the quadruped robot Unitree Go1.

B. Robot Kinematics

The kinematic model of the robot is presented in Fig. 2. The inverse kinematic model calculates the angles of all three joints of each leg given the desired foot position, as:

$$\boldsymbol{Q}(t) = \mathrm{IK}(\boldsymbol{P}(t))$$
$$= \begin{bmatrix} a\tan 2(\frac{z}{y}) + \frac{\pi}{2} \pm \left(\frac{\pi}{2} - acos(\frac{L_1}{\sqrt{y^2+z^2}})\right) \\ a\tan 2\left(\frac{x}{-\sqrt{y^2+z^2-L_1^2}}\right) - a\tan 2\left(\frac{L_3\sin(\theta_2)}{L_2+L_3\cos(\theta_2)}\right) - \pi \\ acos\left(\frac{L_1^2+L_2^2+L_3^2-x^2-y^2-z^2}{2L_2L_3}\right) - \pi \end{bmatrix} \quad (1)$$

where $\boldsymbol{P}(t) \rightarrow \mathrm{IK}(\boldsymbol{P}(t))$ is a function that computes the required angles $\boldsymbol{Q}(t) = [\theta_0(t), \theta_1(t), \theta_2(t)]^T$ given a desired foot position $\boldsymbol{P}(t) = [x(t), y(t), z(t)]^T$.

Then, to compute the required joint velocity given a Cartesian foot velocity, we use the Jacobian $\boldsymbol{J}(\boldsymbol{Q}(t))$ as in (2)

TABLE II
SUMMARY OF CONTROLLER VERSIONS WITH THEIR LEG TRAJECTORY SPEED, STABILITY CRITERION, AND TRAJECTORY DEFINITIONS

Version	Leg speed	Stability	Leg trajectory
v_0	1 fixed speed	NESM	Bézier
v_1	2 speeds, RMSE threshold	NESM	Bézier
v_2	2 speeds, Force threshold	NESM	Bézier
v_3	2 speeds, Force threshold	Model	Bézier
v_4	2 speeds, Force threshold	Model	Polynomial
v_5	Proportional to Force	Model	Polynomial

and (3) with $L_1 = 0.08$m for right legs, $L_1 = -0.08$m for left legs, $L_2 = L_3 = 0.213$m, $c_i = \cos(q_i(t))$, $s_i = \sin(q_i(t))$, $c_{ij} = \cos(q_i(t) + q_j(t))$, $s_{ij} = \sin(q_i(t) + q_j(t))$.

$$\dot{\boldsymbol{Q}}(t) = \boldsymbol{J}(\boldsymbol{Q}(t))^{-1}\dot{\boldsymbol{P}}(t) \tag{2}$$

with

$$\boldsymbol{J}(\boldsymbol{Q}(t)) = \begin{bmatrix} 0 & -L_2c_1 - L_3c_{12} & -L_3c_{12} \\ c_0\left(L_2c_1 + L_3c_{12}\right) + L_1s_0 & -s_0\left(L_2s_1 + L_3s_{12}\right) & -L_3s_0s_{12} \\ s_0\left(L_2c_1 + L_3c_{12}\right) - L_1c_0 & c_0\left(L_2s_1 + L_3s_{12}\right) & L_3c_0s_{12} \end{bmatrix} \tag{3}$$

C. Control Architecture

We present six incremental versions of our controller using a creeping gait (gait in which at least three legs are in contact with the ground at all times), summarized in Table II, where each version has leg speed, stability criterion, or leg trajectory definition modified compared to the previous one:

1) $\boldsymbol{v_0}$: A creeping gait controller with the Normalized Energy Stability Margin (NESM) [17], and using Bézier curves for leg trajectory generation.
2) $\boldsymbol{v_1}$: Builds upon $\boldsymbol{v_0}$ by integrating a mud-foot contact observer based on monitoring the instantaneous Root Mean Square Error (RMSE) between the commanded torques and the feedback torques, enabling leg trajectory speed adaptation depending on contact with mud.
3) $\boldsymbol{v_2}$: Keeps the same elements as $\boldsymbol{v_1}$, but the RMSE-based observer is replaced by a Ground Reaction Force (GRF)-based observer.
4) $\boldsymbol{v_3}$: Further enhances the controller by using the GRF estimator to generate a mud model for each step, and replaces the NESM-based COM positioning with a model-based approach.
5) $\boldsymbol{v_4}$: Replaces the Bézier curves for leg trajectory generation with a polynomial definition, thus allowing more precise control on the velocity profile of the foot.
6) $\boldsymbol{v_5}$: Monitors the speed of the leg to limit the suction force to the maximum force allowed by the model.

Fig. 3 presents the proposed controller versions. These controllers and their main blocks will be presented in the subsequent sections. The proposed controller versions are compared to a *baseline controller*, the commercially available (co.) controller of Go1.

In the following, the gait, static model, and impedance control, common to all the versions of our controller, and the unique features of each controller version will be presented.

1) Gait: In nature, moving with legs on mud is preferably done using a tripod gait, where three legs are always on the ground while the fourth is moving [18], supplementary video.[1] This ensures maximum static stability. It also reduces the pressure exerted on any single foot, as the load is always distributed among at least three feet [2]. The gait we used repeats the leg sequence Rear-Left (RL), Front-Left (FL), Rear-Right (RR), and Front-Right (FR). As shown in Fig. 4, this gait alternates between 8 phases: 4 phases where 3 legs are supporting and one is swinging, and 4 phases with 4 supporting legs which prepare for the next phase by shifting the COM of the robot.

2) Static Model and Impedance Control: In static gaits, the joints of the robot have low speed and acceleration. Thus, the inertial and centrifugal components of the dynamic model (4) can be neglected with respect to the components of the gravitational and external forces. This problem simplification leads to the static model of the system (5), where only the forces and torques produced by the action of gravity and the reaction forces appear. In (4), $\boldsymbol{\tau}$ is the vector of torques applied to the joints, $\boldsymbol{M}(\boldsymbol{q})$ is the mass matrix, $\boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})$ is the Coriolis and centripetal matrix, $\boldsymbol{g}(\boldsymbol{q})$ is the vector of gravitational forces, $\boldsymbol{J}(\boldsymbol{q})$ is the Jacobian matrix, and $\boldsymbol{F}_{\text{ext}}$ is the vector of external forces applied to the system.

$$\boldsymbol{\tau} = \boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{J}(\boldsymbol{q})^{\boldsymbol{T}}\boldsymbol{F}_{\text{ext}} \tag{4}$$

$$\boldsymbol{\tau} = \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{J}(\boldsymbol{q})^{T}\boldsymbol{F}_{\text{ext}} \tag{5}$$

The Go1 robot is equipped with force sensors on the feet, which compute force based on the pressure exerted on a deformable polymer membrane. However, locomotion on a very soft ground does not deform the membrane as the force is not concentrated on the sole of the foot. For that reason, the force distribution problem is solved using the method proposed in [19], [20], which assumes that the torque at the contact point is practically zero. To comply with this premise, we consider that the point of contact between the foot and the environment remains static during the stance phase [21]. While faster methods exist for solving the force distribution problem [22], [23], the static gait does not require such fast computation.

Based on [24], we use the Newton–Euler method to calculate the components of gravitational and external forces. This method has been proven to cut the computational cost by half compared to the classical method that uses the transposed Jacobian matrix. Thus, the torques required to compensate for the existing forces are calculated for each joint in (6). This equation calculates the torque required at a joint to counteract the forces acting on the system and maintain static stability, based on the amount of force applied $\boldsymbol{F} \in \mathbb{R}^{3\times1}$, at a distance $\boldsymbol{r} \in \mathbb{R}^{3\times1}$. The unitary vector $\boldsymbol{u_q} \in \mathbb{R}^{3\times1}$ serves to project the torque on the joint axis. Thus, for each weight of the link and each reaction force, we find the joint torque $\tau_c(i)$ that makes our system static and stable:

$$\tau_c(i) = \boldsymbol{u_q} \cdot (\boldsymbol{r} \times \boldsymbol{F}) \tag{6}$$

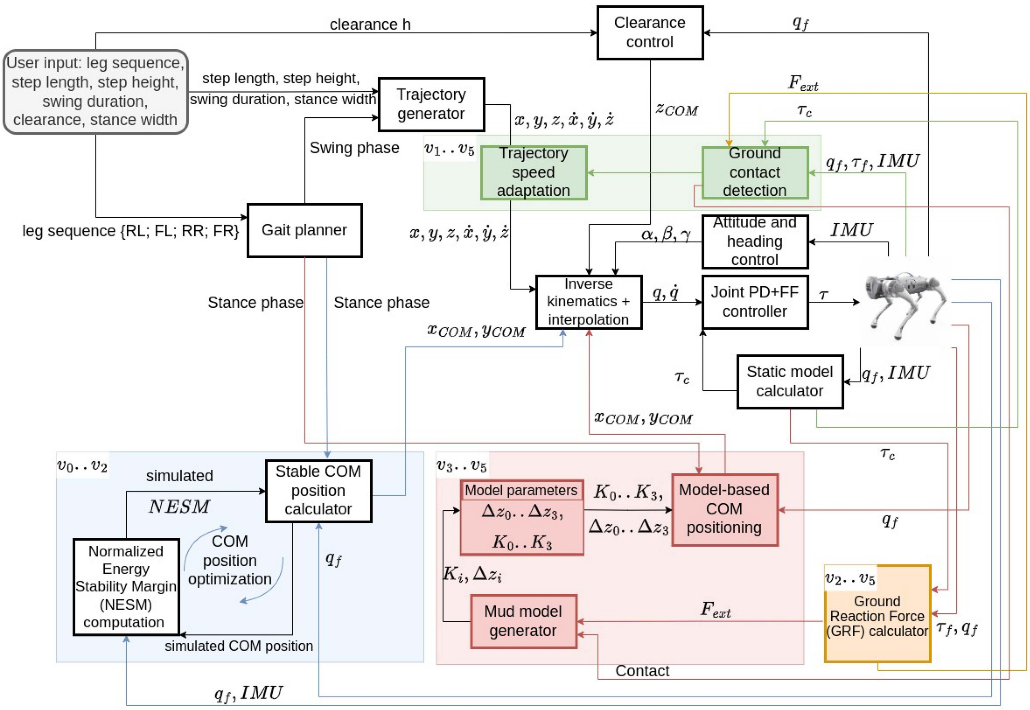

Fig. 3. The different control architectures used in our research. The first version of the control architecture (v_0) includes only the blocks with a white background, while all the other versions of our controller (from v_1 to v_5) use the ground contact detection and trajectory adaptation blocks (green blocks). v_2 adds the Ground Reaction Force (GRF) estimator (orange block) and uses it to feed the ground contact detection block, instead of using the RMSE between the feedback torque τ_f and the gravity compensation torque τ_c. The last versions of our controller (from v_3 to v_5) replace the blue area with the red area for COM position calculation. In all cases, the main loop runs at 500Hz. The clearance control block is responsible for maintaining the height of the body at the input clearance h. The attitude and heading control block is responsible for maintaining the robot attitude and heading, and gives desired rotations as Euler angles α, β, γ to the inverse kinematics block. τ_f and q_f are respectively the feedback torque and position of all the motors of the robot. $x, y, z, \dot{x}, \dot{y}, \dot{z}$ are the commanded position and velocity of the swinging foot, $x_{\text{COM}}, y_{\text{COM}}$ are the coordinates of the next position of the COM of the robot, $q, \dot{q}$ are the position and velocity commands of the motors, F_{ext} is the external force acting on the swinging foot, Δz_i are the foot depths in mud, and K_i are the estimated mud stiffness under the feet.

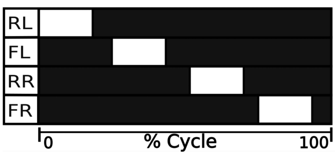

Fig. 4. Diagram of the gait used by the proposed controllers. Dark and light areas represent respectively stance and swing phases. RL, FL, RR, FR refer to Rear Left, Front Left, Rear Right, and Front Right legs.

We use a proportional derivative (PD) + Feed-Forward controller with gravity compensation for the low-level control of each motor, using the computed torque (6) for the Feed-Forward term:

$$\boldsymbol{\tau} = \boldsymbol{\tau_c} + \boldsymbol{K_p}\left(\boldsymbol{q_d} - \boldsymbol{q}\right) + \boldsymbol{K_d}\left(\dot{\boldsymbol{q}}_{\boldsymbol{d}} - \dot{\boldsymbol{q}}\right) \tag{7}$$

where $\boldsymbol{\tau}, \boldsymbol{\tau_c} \in \mathbb{R}^{12\times1}$ are the vector of input joint torques and gravity compensation torques $\tau_c(i)$, $\boldsymbol{q_d}$, $\dot{\boldsymbol{q}}_{\boldsymbol{d}} \in \mathbb{R}^{12\times1}$ are the desired position and velocity vectors, $\boldsymbol{K_d}$, $\boldsymbol{K_p} \in \mathbb{R}^{12\times12}$ are the diagonal matrices of derivative and proportional gains.

3) Controller v_0: includes the white blocks in Fig. 3. The main components will be detailed in the following paragraphs.

a) Stability: As we chose to use a static gait in which at least three legs are always on the ground, we decided to use the NESM in $v_0 - v_2$ to assess the robot stability [17]. It is an energy-efficient and reliable stability criterion as it takes into account the inclination of the robot, as well as the height of its COM [25]. The NESM was the only criterion considered because of its high stability, and was replaced in the v_3 of our controller. Intuitively speaking, if the robot is virtually rotated around an edge of its support polygon, the NESM calculates the height the COM would have to rise before tipping over to the other side of the polygon's edge. To determine the next position of the COM, we used an iterative method that simulates the next position of the COM and computes a simulated NESM with the fictive COM position (blue region in Fig. 3). Based on the computed fictive NESM, the next simulated COM position is shifted toward a region of higher NESM until the chosen stability margin is reached. The satisfactory Cartesian position of the COM is then fed into the controller.

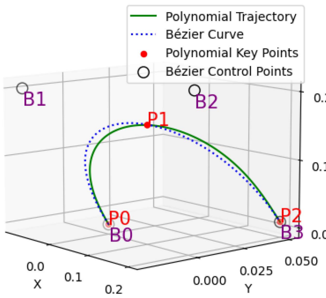

Fig. 5. Bézier curve of each leg ($v_0 - v_3$) and polynomial curve ($v_4 - v_5$). The control points and key points depend on the goal position of the foot. This shows that the two curves are similar, and in particular that both achieve a similar touch-down and lift-off angle.

b) Swing leg trajectory: The trajectory of each leg for $v_0 - v_3$ is controlled by a cubic Bézier curve generator using the following four points (see Fig. 5):

$$
\begin{aligned}
B_0 &= (x, y, z) \\
B_1 &= \left(x - \frac{dx}{2}, y - \frac{dy}{2}, z + h\right) \\
B_2 &= \left(x + \frac{dx}{2}, y + \frac{dy}{2}, z + h\right) \\
B_3 &= (x + dx, y + dy, z + dz)
\end{aligned}
$$

In these point definitions and Fig. 5, B_0 is the initial location of the foot in the body frame, and B_3 the goal position, h is the step height, dx, dy, and dz the commanded displacements along their respective axes. dx is calculated to place the foot half a step length in front of the contralateral foot. In this research, we used a step length of 0.2 m which is close to half the body length and experimentally determined as the upper limit of the kinematically reachable step length, chosen to reduce the number of steps the robot had to take, and thereby reduce the work exerted on mud, dy is calculated to maintain the foot at half the desired input stance width (half the distance between two contralateral feet) and $dz = 0$. The particularity of this curve that makes it well suited for a muddy environment is the identical angle to land on and lift the foot off the substrate, reducing the force required to remove the foot out of the sticky medium: as demonstrated in previous research [11], freshly disturbed mud is easier to deform. In addition, given the configuration of the Go1 robot's legs, where the knee points backward, the path taken by the foot is along the tibia direction, where there is less mud to be disturbed.

The commanded foot position, for $t \in [0; T]$, where T is the swing period, is therefore $\boldsymbol{P}(t) \in \mathbb{R}^{3\times1}$:

$$
\boldsymbol{P}(t) = \begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix} = \begin{bmatrix} x_A & x_B & x_C & x_D \\ y_A & y_B & y_C & y_D \\ z_A & z_B & z_C & z_D \end{bmatrix} \boldsymbol{s}(t) \quad (8)
$$

with

$$
\boldsymbol{s}(t) = \left[\left(1 - \tfrac{t}{T}\right)^3 \quad 3\left(1 - \tfrac{t}{T}\right)^2 \tfrac{t}{T} \quad 3\left(1 - \tfrac{t}{T}\right)\left(\tfrac{t}{T}\right)^2 \quad \left(\tfrac{t}{T}\right)^3 \right]^T \quad (9)
$$

Similarly, the commanded velocity is $\dot{\boldsymbol{P}}(t) \in \mathbb{R}^{3\times1}$:

$$
\dot{\boldsymbol{P}}(t) = \begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{z}(t) \end{bmatrix} = \begin{bmatrix} x_B - x_A & x_C - x_B & x_D - x_C \\ y_B - y_A & y_C - y_B & y_D - y_C \\ z_B - z_A & z_C - z_B & z_D - z_C \end{bmatrix} \dot{\boldsymbol{s}}(t) \quad (10)
$$

with

$$
\dot{\boldsymbol{s}}(t) = \frac{3}{T} \left[\left(1 - \tfrac{t}{T}\right)^2 \quad 2\left(1 - \tfrac{t}{T}\right) \tfrac{t}{T} \quad \left(\tfrac{t}{T}\right)^2 \right]^T \quad (11)
$$

For the control of the position of the leg trajectory, we feed the discretized foot positions $\boldsymbol{P}(t)$ (8) into the inverse kinematics solver and obtain discretized joint angles $\boldsymbol{Q}(t) \in \mathbb{R}^{3\times1}$ (1). For the velocity command, we use (10) and (2) to compute the commanded joint velocities in the joint space.

4) Controller v_1: This controller is an enhancement of v_0 with additions in green boxes in Fig. 3. The two following paragraphs describe the two green blocks in Fig. 3.

a) Ground contact detection through torque error: To enhance the locomotion speed, the swing trajectory speed can be increased when the leg is out of mud, while still keeping the same trajectory speed when the leg is inside the substrate. In v_1, we detected contact using the torque error in the swinging leg. During the swing trajectory, the torques in the swing leg are still computed using (7), where $\boldsymbol{\tau_c}$ is computed to compensate gravity, and the subsets of $\dot{\boldsymbol{q}}_{\boldsymbol{d}}$ and $\boldsymbol{q_d}$ relating to the swinging leg are computed according to (1) and (2). When the leg is in swing phase, the instantaneous RMSE between the gravitational compensation torque and the feedback torque in the actuators is monitored, and if the instantaneous RMSE becomes larger than a threshold, ϕ_τ, the leg is considered in contact (12) with the mud (first green block in Fig. 3). ϕ_τ is experimentally determined to filter out inaccuracies due to neglecting the acceleration and Coriolis terms, noise, and added mass of the mud sticking to the leg. In (12), $\boldsymbol{\tau}_{\boldsymbol{c}_{\text{leg}}}$ and $\boldsymbol{\tau}_{\boldsymbol{f}_{\text{leg}}} \in \mathbb{R}^{3\times1}$ denote subsets of $\boldsymbol{\tau_c}$ and $\boldsymbol{\tau_f}$ where only the three motors corresponding to the leg are kept.

$$
\text{Contact} = \left(\text{RMSE}\left(\boldsymbol{\tau}_{\boldsymbol{c}_{\text{leg}}}, \boldsymbol{\tau}_{\boldsymbol{f}_{\text{leg}}}\right) > \phi_\tau\right) \quad (12)
$$

b) Trajectory speed adaptation: Using the contact information from the contact observer, the next green block in the control diagram (see Fig. 3) adapts the speed of the leg based on whether the leg is estimated to be inside the mud or in the air. When the leg is in the air, the trajectory speed is multiplied by an arbitrary factor of 8 by modifying (9) and (11). This way, we can increase the speed of the swing leg while it is out of the substrate, while keeping the slow motion inside the substrate to prevent too high suction forces.

5) Controller v_2: In v_2, we kept the improvements made for controller v_1, and added a GRF estimator to inform the contact detection block based on external force on the foot, instead of basing it on RMSE monitoring. The following paragraphs describe the GRF estimator (orange block in Fig. 3) and the modifications made to the contact observer (right green block).

a) GRF estimator: In the version v_2 of our controller, we used the simplified linear model of the mud and estimated it using the static model and the actuators torque feedback:

$$\boldsymbol{F}_{\text{mud}} = \left(\boldsymbol{J}_{\text{leg}}{}^{T}\right)^{-1}\boldsymbol{\tau}_{\text{mud}} = \left(\boldsymbol{J}_{\text{leg}}{}^{T}\right)^{-1}\left(\boldsymbol{\tau}_{\boldsymbol{c}_{\text{leg}}} - \boldsymbol{\tau}_{\boldsymbol{f}_{\text{leg}}}\right) \quad (13)$$

From this model, we calculate the vector of the GRF exerted by the mud on the foot $\boldsymbol{F}_{\text{mud}} \in \mathbb{R}^{3\times1}$, using the torque at the joints due to the action of mud at the joints $\boldsymbol{\tau}_{\text{mud}} \in \mathbb{R}^{3\times1}$, defined as the difference between the commanded torque $\boldsymbol{\tau}_{\boldsymbol{c}_{\text{leg}}}$ and the feedback torque $\boldsymbol{\tau}_{\boldsymbol{f}_{\text{leg}}} \in \mathbb{R}^{3\times1}$, and $\boldsymbol{J}_{\text{leg}} \in \mathbb{R}^{3\times3}$ is the subset of $\boldsymbol{J}$ corresponding to the three joints of the leg. $\boldsymbol{\tau}_{\text{mud}}$ and $\boldsymbol{F}_{\text{mud}}$ are also affected by acceleration related terms, but these are neglected due to the slow movements of the leg. If mud infiltrated the joints, this can result in increased friction that can alter the accuracy of the measurements. We mitigated this risk by cleaning the robot joints in between experiments.

b) Ground contact detection through force feedback: Using our GRF calculator, we set a threshold for the vertical GRF, $F_{\text{z,mud}}$ and the leg was considered in contact with the mud if $F_{\text{z,mud}}$ was out of a range between 0 and ϕ_F:

$$\text{Contact} = \left(\left|F_{\text{z,mud}} - \frac{\phi_F}{2}\right| > \phi_F\right) \quad (14)$$

Similar to ϕ_τ, the threshold ϕ_F is used to compensate for the inaccuracies due to neglecting the acceleration related terms in (13), inaccuracies due to the added mass of mud stuck on legs or mud entering the joints and causing resistance. Compared to the previous RMSE-based contact observer, this observer presents the advantage of using a more tangible criterion, and of relating the error in each joint to its position relative to the foot through the use of the Jacobian, resulting in increased detection accuracy.

6) Controller v_3: This version of the controller replaced the blocks in the blue region with the three red blocks in Fig. 3. They are described in the three next paragraphs.

a) Mud model generator and model parameters: Based on the contact observer and the GRF calculator, the mud model generator estimates two parameters for each step: the depth of insertion Δz_i and the mud stiffness K_i. When the foot is considered in contact with the mud, the model generator records the position of the foot and considers its z position as the surface of the mud. Each subsequent position and GRF (13) are stored and used to generate a model of the mud online, using a linear regression to solve the following:

$$\boldsymbol{Z}K = \boldsymbol{F_z} \quad (15)$$

where $\boldsymbol{Z}$ is a column vector containing all the recorded positions Δz_i of the foot since contact was detected, K is a real number representing the mud stiffness, and $\boldsymbol{F_z}$ is a column vector containing all the recorded vertical components of the GRF since contact was detected. Once the leg terminates its swinging phase, the latest depth Δz_i and mud stiffness K are stored alongside the depths and stiffnesses of the other legs and are ready to be used by the model-based COM positioning block.

b) Model-based COM positioning: Contrary to locomotion on other soft grounds such as sand, foam, or leafs, locomotion on mud presents an additional complication: the suction force that resists retraction of the foot from the mud. To take this into account, we developed a novel COM positioning criterion that computes the required position of the COM so that the robot remains stable by taking into account the suction force on each leg. In our previous research, we showed that the intrusion force into mud can be approximated with a hydrostatic-like model whose stiffness coefficient (described in the previous paragraph) depends on the water content [11]. The suction force can also be estimated from the stiffness of the mud and the depth of insertion. In our previous research, we found that the suction force represents a fraction of the insertion force, varying linearly with depth, but depending nonlinearly on the water content. The mud only provides suction force at intermediate water contents: below 25%, no suction force happens, and above 40%, mud becomes fluid, with null stiffness, and stops resisting extrusion as well. In between, the data from [11] shows that the suction force has a shape of an upside-down quadratic function, with roots at 0, and K_{25}, which is the stiffness measured at water-to-soil ratio of 0.25. Therefore, the suction force on one of the robot's legs can be estimated with (16), (see also Fig. 6), where K is the stiffness measured under the foot, Δz is the current foot depth, and $\alpha < 0$ is a scaling factor depending on the foot form:

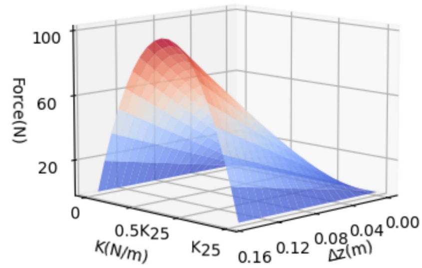

Fig. 6. Plot of the estimated suction force as a function of the leg sinkage Δz and the mud stiffness K.

$$F_{\max} = \begin{cases} \alpha K(K - K_{25})\Delta z & if K < K_{25} \\ 0 & \text{otherwise.} \end{cases} \quad (16)$$

Then, when one leg is to be lifted, the controller computes the critical length l_{cc} to place the COM in a stable position (17). l_{cc} is the projection normal to z of the orthogonal distance of the safe position of the COM to the considered edge of the polygon, see Fig. 7.

$$l_{cc} = \frac{\tau_m + F_a l_a - C_u F_b l_b}{mg} \quad (17)$$

l_a, l_b, F_a, F_b are defined in Fig. 7, τ_m is the desired torque margin, and $C_u \in [0 : 1]$ is a coefficient of uncertainty, determined empirically from previous experiments, to account for estimation errors in F_b, due to model simplifications, added mass on the feet, measurements errors, or mud infiltrating the joints. A lower C_u means reduced impact from F_b on the l_{cc}, resulting in increased safety but higher mechanical cost of transport (MCoT) and reduced speed. The motion direction of the COM is chosen to be toward the opposed foot, so that the COM stays within the support polygon (see Fig. 7, right panel). The resulting motion

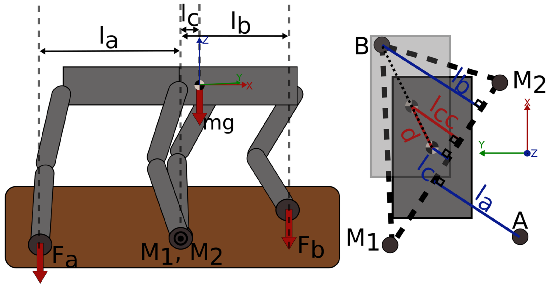

Fig. 7. Illustration of the forces involved in model-based COM positioning in a muddy substrate. M_1, M_2 are the two feet that define the critical edge of the considered support polygon. l_a is the projection normal to the z-axis of the orthogonal distance from foot A (the foot to be lifted) to the edge M_1M_2. l_b is the same for the diagonally opposed foot B. F_a and F_b are the corresponding forces at these feet. l_c is the projection normal to z of the orthogonal distance between the COM and the polygon edge M_1M_2. l_{cc} is described in (17), and d is the displacement that the COM will undergo. Left panel: side view. Right panel: top view.

of the COM is along d in Fig. 7, right panel which is computed so that the COM is at a distance l_{cc} from the line M_1M_2.

7) Controller v_4: The Bézier curve trajectory presents the advantage of being simple and easy to compute. However, the Bézier curve has high velocities and accelerations at the ends of the curve, which is problematic in mud, since it coincides with the deepest sinkage. To account for the critical speeds at the ends, the whole trajectory needed to be slower. In v_4, we replaced the Bézier curve by a degree six polynomial curve. The curve is presented in green in Fig. 5 along with the three points where constraints are defined. The degree of the curve was chosen to impose seven constraints, i.e., positions at P_0, P_1, P_2, lift-off and touch-down velocities (and angles) at P_0 and P_2 so that it follows the Bézier curve, and low accelerations at P_0 and P_2. This modification allowed us to increase the overall swing speed by precisely controlling the velocities at the ends of the curves.

8) Controller v_5: In the previous version of our controller, the suction force was estimated, and the COM was positioned in a position so that even at the peak of the suction force, the robot would not tumble over if the leg was maintained at a lower speed. Instead, the speed could be monitored continuously so it is the highest possible at all times, ensuring both a higher overall speed, and safety, by not allowing the force to exceed the suction force estimated by the model. In v_5, the speed of the leg is multiplied by a factor ρ defined as follows:

$$\rho = 1 - \frac{F_{z,\text{mud}}}{F_{\text{max}}} \tag{18}$$

9) Baseline Controller: The commercially available baseline controller uses a dynamic trotting gait in which the two opposed diagonal feet are swinging at the same time and alternating with the other pair of diagonally opposed legs. The stepping frequency is 4Hz and the distance covered per step (step length) varies with the desired speed. In our trials, we tested different speeds and found that independently of the locomotion speed, the commercially available baseline controller would fail to traverse the track by making the robot fall after a short amount of time. The reported numbers in the results section are based on the slowest speed available (0.2 m/s), which gave the best results. The faster speeds resulted in immediate failure, see Sections III-A and IV, and supplementary video.

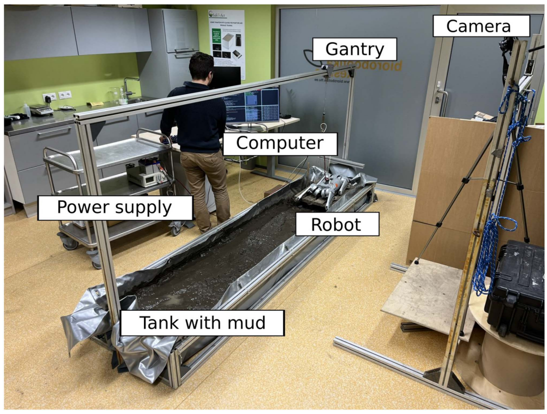

Fig. 8. View of our experimental setup and its main components.

D. Experimental Setup

Given the harsh environment that causes high loads on the motors and the risks of corrosion or damage to electrical circuits in wet environments, we first created the various controllers and extensively tested them in the Gazebo simulation environment using the Robot Operating System (ROS). To ensure that the simulation-to-reality transfer was successful, we regularly tested our code on the physical robot on hard ground and, later, on mud. The simulation environment could not simulate mud, in particular suction forces, limiting simulation-based development to hard or elastic surfaces.

Our experimental setup can be observed in Fig. 8. It consists of a 3 m long and 0.8 m wide track, in which we placed a 12 cm high layer of mud (56% of the robot's tibia length). To ensure consistency, the mud was mixed manually before each experiment using a shovel. The ratio of water to solid matter in the mud is $R_w = 0.35$, where R_w is defined in (19), with M_w the water mass and M_{ds} the dry soil mass. R_w was computed by measuring the soil mass before and after heat drying.

$$R_w = \frac{M_w}{M_{ds}} \tag{19}$$

Our experimental platform Go1 is not designed to work in wet and abrasive matter. Therefore, the robot was secured by a trolley that freely rolls on a rail above the tank, attached to the robot with steel cables. Also, walking in mud implies exerting much higher forces and torques at the joints than normal. We therefore kept the number of trial runs as low as possible and as high as necessary to reliably assess the controllers' performance.

A camera was tracking the robot with the help of a marker placed on the robot's body. The robot was powered externally

Fig. 9. Time-lapse of the different controller versions, and the commercially available controller over a 120 s period of time. The commercially available baseline controller fails after 6 seconds, and the robot falls. All the proposed controller versions managed to traverse the track without failure. Each subsequent version of the controller enables the robot to traverse the track faster than the previous one.

TABLE III
MEDIAN SPEED (BODY LENGTH/MIN) AND MCOT (DIMENSIONLESS) FOR THE COMMERCIALLY AVAILABLE CONTROLLER AND THE VERSIONS OF OUR PROPOSED CONTROLLER

Controller Version	Speed	MCoT
Co. controller	$10.8_{\pm 0.74}$	$9.02_{\pm 0.67}$
v_0	$0.27_{\pm 0.01}$	$2.42_{\pm 0.03}$
v_1	$0.64_{\pm 0.02}$	$2.23_{\pm 0.04}$
v_2	$0.67_{\pm 0.01}$	$2.45_{\pm 0.01}$
v_3	$1.09_{\pm 0.01}$	$2.04_{\pm 0.02}$
v_4	$1.27_{\pm 0.01}$	$2.05_{\pm 0.01}$
v_5	$1.72_{\pm 0.01}$	$2.27_{\pm 0.01}$

to enable longer runtime and allow quick power cut-off. An Ethernet cable was also connected to the robot to provide reliable communication with the PC. The PC-robot communication was implemented through the User Datagram Protocol (UDP), and the control is implemented using ROS.

We computed the displacement speed using the Kinovea software. A marker was painted on the robot to facilitate tracking, and average speed computation. We also calculate the MCoT, using (20), where E is the energy consumed calculated by summing the mechanical work of all motors over the run, $m = 12$ kg is the mass of the robot, $g = 9.81$ m/s^{-2} is the gravitational acceleration on earth, and d is the distance traveled for each run. Only the positive work is accounted for, and the negative work is not subtracted because it is not recovered.

$$\mathrm{MCoT} = \frac{E}{mgd} \tag{20}$$

III. REAL-TIME EXPERIMENTAL RESULTS

A. Controlled Laboratory Experiments

Fig. 9 shows a time-lapse of the controller versions over 120 s, and the relative speed and the MCoT are reported in Table III. The second column of Table III represents the robot speed (in body length/min), and the third describes the dimensionless MCoT. The numbers displayed are median$_{\pm \text{std_}error}$.

Each experiment was repeated four times. As the results of the four runs were very close to each other (max standard deviation of 5% for speed, and 4% for MCoT for our proposed controller versions), this number appeared sufficient to demonstrate our results.

In Table III, the metrics reported for the commercial baseline controller are based on the slowest speed that the controller would accept as input, i.e., 0.2 m/s. This speed was the only means of comparison. Any higher velocity led to immediate failure: the body moving forward while the legs remain stuck in the mud. Even with the chosen speed of 0.2 m/s, the robot fell in after a few seconds in every experiment (see Fig. 9, first row) and never went further than one body length before failure. Therefore, the results of the commercially available controller are based on very short, but consistent, samples.

Fig. 10 shows the motion of the COM at each step for controllers v_2 and v_3 and well illustrates the difference between the model-based COM positioning and NESM-based COM positioning. It can be seen in this figure that while the NESM-based controller always moves the COM by similar amounts for all steps, the model-based controller tends to have a more scattered motion pattern because of the differences in estimated suction forces at each step. In addition, the extent of movements of the model-based controller tends to be larger than that of the NESM-based controller (see discussions).

B. Demonstration Experiments

To demonstrate the robustness of our controller to varying mud conditions, we performed experiments in the laboratory setup using two muds of different water ratios, with $R_w = 0.30$ and 0.38. The controller managed to traverse these mud conditions without any modification. The speed and MCoT in these conditions can be observed in Table IV.

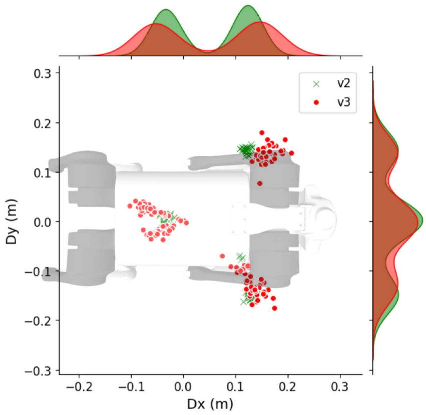

Fig. 10. Comparison of the movements of the COM for NESM-based COM positioning in v_2 (green crosses) and Model-based COM positioning in v_3 (red circles). The graph plots the points for all runs for each of the two versions. Each point represents the motion of the COM in reference to the COM before motion.

TABLE IV
MEDIAN SPEED (BODY LENGTH/MIN) AND MCOT (DIMENSIONLESS) FOR v_5 IN THREE DIFFERENT MUDS

Mud water content	Speed	MCoT
0.3	$1.64_{\pm 0.01}$	$3.09_{\pm 0.02}$
0.35	$1.72_{\pm 0.01}$	$2.27_{\pm 0.01}$
0.38	$1.85_{\pm 0.02}$	$2.03_{\pm 0.01}$

TABLE V
SPEED (BODY LENGTH/MIN) AND MCOT (DIMENSIONLESS) FOR OUR v_5 CONTROLLER IN DIVERSE DEMONSTRATION ENVIRONMENTS

Environment	Speed	MCoT
Dry soft sand	2.18	1.06
Moist hard sand	2.17	1.07
Sea	2.14	1.13
Wet sand	2.12	1.15
Grass/vegetation	2.09	1.24
Edge of pond	2.01	1.41
Edge of river: leaf litter and mud	1.91	1.69
Forest with water, branches, leafs	1.86	1.61

To showcase the practical applicability of our controller beyond controlled laboratory settings, we conducted trials where our robot traversed different natural environments, without making any modification to our controller (see Fig. 11). Each run (see Table V) lasted an average duration of 1 min 44 s. In addition, a demonstration video of the obtained experimental results and some shots of our tests in the natural environments is available at: https://youtu.be/TidYdtmdEr4. These experiments also demonstrate the generalizability of our controller, since no modification was made after lab experiments. Similar to lab conditions, the controller still detects the ground stiffness in all the environments, estimates the suction force, and positions its body in the right location to prevent falling. This includes also hard grounds or slightly soft grounds where the suction force is null or small.

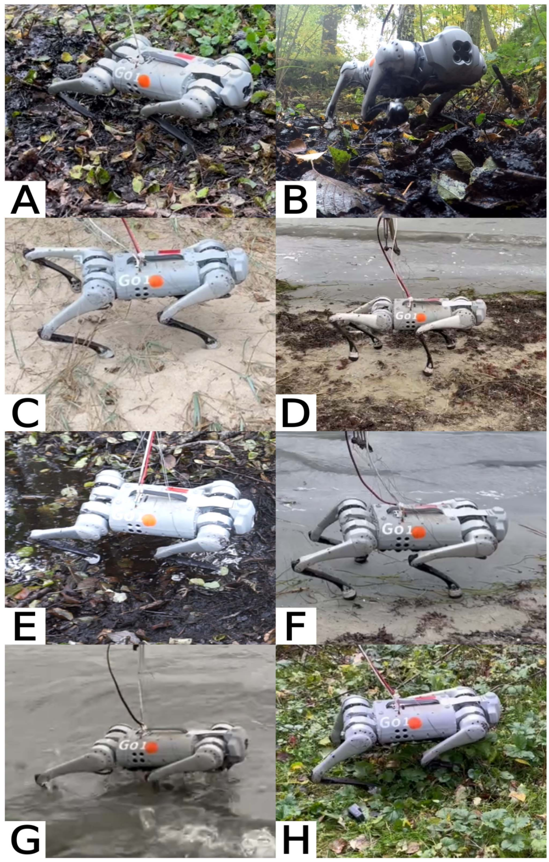

Fig. 11. Demonstration of our controller in different environments. A: Edge of a river with mud and leaf litter, B: Forest ground with leafs, branches and water, C: Dry sand, D: Moist sand on the beach, E: Edge of a pond, F: Wet sand, G: Inside the sea, H: Grass/vegetation.

IV. DISCUSSION

As shown in Table III, our controller consumes up to 4.42 times less energy than the commercially available one over the same distance. The co. controller's trotting gait, with high stride frequency and short stride length, suits elastically deformable ground where stored energy is partially recoverable and ground deformation is small. However, in mud, energy is irrecoverable, and force is required during both intrusion and extrusion phases. Our controller addresses this by using a creeping gait with large steps (53% of body length), minimizing time spent exerting force on mud. In addition, locomotion in mud requires a step height that minimizes the foot's time in the mud during the swing phase. In contrast, the co. controller keeps the legs submerged, increasing work and disrupting foot trajectory. Preliminary experiments showed that a longer swing duration reduced force on the foot and improved stability. Our initial controller thus favored a large swing phase, ensuring stability across all runs, but at the cost of slower speed (see Table III, Fig. 9). To increase the robot's speed while maintaining stability during insertion and extrusion, we added a foot-mud contact observer. This allowed an 8× increase in swing speed when the leg was in the air, doubling walking speed (2.37×). Swing speed during extrusion was limited by our own defined safety margin. Adding a GRF-based estimator improved contact detection accuracy but had minimal impact on speed, as the RMSE-based observer already detected most out-of-mud phases correctly. While the NESM ensures static stability, it does not account for force during lift-off. To solve this, our model-based COM positioning incorporates both leg configuration and estimated suction forces. The more scattered COM motions of v_3 compared to v_2 (see Fig. 10) indicate varying stiffness calculations at each step. In addition, the controller positioned the COM further from the swinging leg in most cases, thus increasing safety. The added safety allowed for faster leg extraction from the mud, enabling v_3 to reach 1.63× the speed of v_2. Further refinements in swing trajectory definition and force-based speed monitoring increased speed by 1.17× and 1.35×, respectively, resulting in an overall 6.37× higher speed over v_0. Tests in different muds and demonstrations in natural environments demonstrated the robustness and generalizability of our controller. Both robustness and generalizability are enhanced by model-based COM positioning, which adapts to each leg's sinkage and mud stiffness, reducing sensitivity to ground variations and enabling operation in diverse environments. Force-based leg's speed monitoring further improves these qualities. Maintaining high leg speed while preventing excessive suction force minimizes the risk of tumbling even on unpredictable terrain. While these controller enhancements improve adaptability to various substrates, performance remains constrained by hardware limitations. Thus, another research direction for improving mobility on deformable ground and increasing generalizability and robustness is foot design, as explored in [10].

The MCoT of our controller is over three times lower than that of the co. controller, indicating higher efficiency in mud. However, this comparison suffers limitations, as the dynamics-based trotting gait controller is designed for fast locomotion on hard surfaces, not resistive terrain. Our controller's MCoT is of similar magnitude to previous reports of legged locomotion in resistive terrains [14], [26], and as expected, is an order of magnitude higher than that of legged robots moving on hard grounds [27], [28], [29], [30]. It is consistent with the common-sense observation that walking in mud is considerably more difficult. We have not found any studies in biomechanics that allow for a comparison of our results with the energetic cost of locomotion in cohesive terrain, and this study may be the first to quantify it.

V. Conclusion

Soft, yielding terrains like sand, mud, and forest ground are common in nature, making it essential for quadruped robots to traverse them. However, most commercial robots use a trotting gait, which is robust and fast but poorly suited for muddy terrains. In this research, we designed and demonstrated a controller that allows quadruped robots to traverse muddy terrains. Our control architecture encompasses a creeping gait with a large stride length, force control for gravity compensation, swing speed monitoring, and positioning of the COM using the estimated suction force on the legs based on the model we developed. Using our controller, the robot was able to traverse a muddy field without any failure and did so with a much lower energetic cost than the commercial trotting gait controller developed for hard grounds. Although our controller also successfully enables traversing hard grounds, a quadruped robot would most benefit from using it as a dedicated gait to traverse soft deformable terrains, in complement to a trotting gait for rapidly traversing hard grounds.

The trotting gait is popular in quadruped robotics for its simplicity, stability, and energy efficiency. However, as we demonstrated, it is ill-suited for yielding, cohesive muddy grounds. The damping of mud at high speeds, the suction force exerted at withdrawal, and its anisotropy make the behavior at each step uncertain. Hence, unequal resistance in diagonal feet can cause imbalance and lead to the robot toppling over. Also, the dissipative nature of mud results in energy dissipation during each step, impeding energy recuperation. This means that to walk in mud efficiently, the number of steps shall be limited. It also means that momentum cannot be conserved, limiting the benefits of dynamic gaits.

Most recent advances in controllers for quadruped robots involve RL. A RL approach could be beneficial for navigating mud, a demanding and potentially damaging environment: high joint efforts raise motor temperatures, moisture can cause corrosion or short circuits, and dried mud dust harms mechanical and electrical systems. However, mud has a complex behavior that is spatially and temporally variant, and no simulator to our knowledge enables it to be simulated to train a RL controller. Instead, we opted for a model-based analytical approach to overcome the absence of a suitable simulator, thus leading to the development of a model for legged systems navigating muddy terrains. While Terramechanics traditionally focuses on traction perspectives for wheeled and tracked systems in natural environments, our model represents an initial step towards extending this framework to address the locomotion challenges faced by legged systems.

To the best of our knowledge, this is the first successful attempt to make a quadruped robot walk (or wade) in deep mud. The current controller could be further improved by using a more active posture during leg motion, for example by computing the required COM position thanks to the model, and once the peak force is reached, move the COM in anticipation of the next step, resulting in a faster and more natural gait. In addition, using force control during the intrusion phase of the swing trajectory could enhance stability and adapt to sharp variations of the environment's stiffness, for example, during transitions between two environments. Although this approach was attempted by the authors, a real-time limitation on the firmware side of the robot platform did not allow for bypassing the low-level PD + FF controller of the joints. Future work could explore incorporating our model into more advanced controllers, or even explore the possibility of advanced model-free controllers for wading in deep mud.

References

[1] L. Bruzzone and G. Quaglia, "Locomotion systems for ground mobile robots in unstructured environments," *Mech. Sci.*, vol. 3, no. 2, pp. 49–62, 2012.

[2] S. Godon, M. Kruusmaa, and A. Ristolainen, "Maneuvering on non-newtonian fluidic terrain: A survey of animal and bio-inspired robot locomotion techniques on soft yielding grounds," *Front. Robot. AI*, vol. 10, 2023, Art. no. 1113881.

[3] F. Angelini et al., "Robotic monitoring of habitats: The natural intelligence approach," *IEEE Access*, vol. 11, pp. 72575–72591, 2023.

[4] P. Arm et al., "Scientific exploration of challenging planetary analog environments with a team of legged robots," *Sci. Robot.*, vol. 8, no. 80, 2023, Art. no. eade9548.

[5] S. Choi et al., "Learning quadrupedal locomotion on deformable terrain," *Sci. Robot.*, vol. 8, no. 74, 2023, Art. no. eade2256.

[6] S. Fahmi, M. Focchi, A. Radulescu, G. Fink, V. Barasuol, and C. Semini, "STANCE: Locomotion adaptation over soft terrain," *IEEE Trans. Robot.*, vol. 36, no. 2, pp. 443–457, Apr. 2020.

[7] Y. Zhao, F. Gao, Q. Sun, and Y. Yin, "Terrain classification and adaptive locomotion for a hexapod robot Qingzhui," *Front. Mech. Eng.*, vol. 16, no. 2, pp. 271–284, 2021.

[8] C. Yao et al., "STAF: Interaction-based design and evaluation of sensorized terrain-adaptive foot for legged robot traversing on soft slopes," *IEEE/ASME Trans. Mechatron.*, vol. 29, no. 6, pp. 4039–4050, Dec. 2024.

[9] A. Ranjan, F. Angelini, T. Nanayakkara, and M. Garabini, "Design guidelines for bioinspired adaptive foot for stable interaction with the environment," *IEEE/ASME Trans. Mechatron.*, vol. 29, no. 2, pp. 843–855, Apr. 2024.

[10] S. Godon, A. Ristolainen, and M. Kruusmaa, "Robotic feet modeled after ungulates improve locomotion on soft wet grounds," *Bioinspiration Biomimetics*, vol. 19, no. 6, 2024, Art. no. 066009.

[11] S. Godon, A. Ristolainen, and M. Kruusmaa, "An insight on mud behavior upon stepping," *IEEE Robot. Automat. Lett.*, vol. 7, no. 4, pp. 11039–11046, Oct. 2022.

[12] X. Liang et al., "The amphihex: A novel amphibious robot with transformable leg-flipper composite propulsion mechanism," in *Proc. 2012 IEEE/RSJ Int. Conf. Intell. Robots Syst.*, IEEE, 2012, pp. 3667–3672.

[13] S. Liu, B. Huang, and F. Qian, "Adaptation of flipper-mud interactions enables effective terrestrial locomotion on muddy substrates," *IEEE Robot. Automat. Lett.*, vol. 8, no. 12, pp. 7978–7985, Dec. 2023.

[14] S. Gart, R. Alicea, W. Gao, J. Pusey, J. V. Nicholson, and J. E. Clark, "Legged locomotion in resistive terrains," *Bioinspiration biomimetics*, vol. 16, no. 2, 2021, Art. no. 025001.

[15] J. Lee, J. Hwangbo, L. Wellhausen, V. Koltun, and M. Hutter, "Learning quadrupedal locomotion over challenging terrain," *Sci. Robot.*, vol. 5, no. 47, 2020, Art. no. eabc5986.

[16] N. Kashiri et al., "An overview on principles for energy efficient robot locomotion," *Front. Robot. AI*, vol. 5, 2018, Art. no. 129.

[17] S. Hirose, H. Tsukagoshi, and K. Yoneda, "Normalized energy stability margin and its contour of walking vehicles on rough terrain," in *Proc. 2001 ICRA. IEEE Int. Conf. Robot. Automat.*, IEEE, 2001, vol. 1, pp. 181–186.

[18] Y. Ozkan Aydin et al., "Geometric mechanics applied to tetrapod locomotion on granular media," in *Biomimetic Biohybrid Systems: 6th Int. Conf., Living Machines 2017*, Stanford, CA, USA: Springer, 2017, pp. 595–603.

[19] C. Prados, M. Hernando, E. Gambao, and A. Brunete, "Romerin: Organismo robótico escalador basado en patas modulares con ventosas activas," *Revista Iberoamericana de Automática e Informática Ind.*, vol. 20, no. 2, pp. 175–186, 2023.

[20] M. Hernando, A. Brunete, and E. Gambao, "Romerin: A modular climber robot for infrastructure inspection," *IFAC-PapersOnLine*, vol. 52, no. 15, pp. 424–429, 2019.

[21] C. Prados, M. Hernando, E. Gambao, and A. Brunete, "MoCLORA—An architecture for legged-and-climbing modular bio-inspired robotic organism," *Biomimetics*, vol. 8, no. 1, 2022, Art. no. 11.

[22] J. Carpentier et al., "The pinocchio C++ library: A fast and flexible implementation of rigid body dynamics algorithms and their analytical derivatives," in *Proc. 2019 IEEE/SICE Int. Symp. System Integration*, IEEE, 2019, pp. 614–619.

[23] R. Featherstone, *Rigid Body Dynamics Algorithms*. Berlin, Germany: Springer, 2014.

[24] C. Prados, M. Hernando, E. Gambao, and A. Brunete, "Torque-based control of a bio-inspired modular climbing robot," *Machines*, vol. 11, no. 7, 2023, Art. no. 757.

[25] P. Gonzalez de Santos, E. Garcia, and J. Estremera, "Stability in walking robots," in *Quadrupedal Locomotion: An Introduction to the Control of Four-legged Robots*. Berlin, Germany: Springer, 2006, pp. 33–56.

[26] C. Li, A. M. Hoover, P. Birkmeyer, P. B. Umbanhowar, R. S. Fearing, and D. I. Goldman, "Systematic study of the performance of small robots on controlled laboratory substrates," in *Processing of SPIE, Microand Nanotechnology Sensors, Systems, and ApplicationsII*, vol. 7679, pp. 291–303, Bellingham, WA, USA: Society of Photo-Optical Instrumentation Engineers (SPIE), 2010.

[27] S. Seok et al., "Design principles for energy-efficient legged locomotion and implementation on the MIT cheetah robot," *IEEE/ASME Trans. Mechatron.*, vol. 20, no. 3, pp. 1117–1129, Jun. 2015.

[28] K. Sreenath, H.-W. Park, I. Poulakakis, and J. W. Grizzle, "A compliant hybrid zero dynamics controller for stable, efficient and fast bipedal walking on mabel," *Int. J. Robot. Res.*, vol. 30, no. 9, pp. 1170–1193, 2011.

[29] Z. Chen, Q. Xi, C. Qi, X. Chen, Y. Gao, and F. Gao, "Fault-tolerant gait design for quadruped robots with two locked legs using the G_f set theory," *Mechanism Mach. Theory*, vol. 195, 2024, Art. no. 105592.

[30] H. Kolvenbach, D. Bellicoso, F. Jenelten, L. Wellhausen, and M. Hutter, "Efficient gait selection for quadrupedal robots on the Moon and Mars," in *Proc. 14th Int. Symp. Artif. Intell., Robot. Automat. Space (i-SAIRAS 2018), ESA Conf. Bur.*, 2018.

Simon Godon received the B.Sc. degree followed by his Arts et Metiers General Engineering degree (M.Eng) from Arts et Metiers ParisTech, France, in 2019, and subsequently completed the M.Sc. degree in robotics with the University of Bristol, Bristol, United Kingdom. He is currently working toward the Ph.D. degree in robotics with Tallinn University of Technology (TalTech), Estonia.

His research focuses on legged robotics and locomotion in complex, yielding environments.

Carlos Prados received the Degree in Industrial Electronic and Automation Engineering from the Universidad de Valladolid (UVa), Valladolid, Spain, in 2018, the Master Degree in automation and robotics from the Universidad Politécnica de Madrid (UPM), Madrid, Spain, in 2020.

He belonged during two years to the Engineering Department of the European Organization for Nuclear Research (CERN), Geneva, Switzerland, as a Robotic Engineer. From January 2021 to September 2023, he was a Ph.D. student in modular, legged, and climbing robotic systems at UPM. Since October 2023, he works in ARX Robotics as Robotic Software Tech Lead.

Ahmed Chemori (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees both in automatic control from the Grenoble Institute of Technology, Grenoble, France, in 2001 and 2005, respectively.

He has been a Postdoctoral Fellow with the Automatic Control Laboratory, Grenoble, France, in 2006. He is currently a tenured Research Scientist in automatic control and robotics with the Montpellier Laboratory of Informatics, Robotics, and Microelectronics. His research interests include nonlinear, adaptive, and predictive control and their applications in robotics.

Asko Ristolainen received the B.Sc. and M.Sc. degrees in mechatronics and the Ph.D. degree in information and communication technology from the Tallinn University of Technology, Tallinn, Estonia, in 2008, 2010, and 2015, respectively.

He is currently a Senior Researcher with the Centre for Biorobotics, School of Information Technologies, Tallinn University of Technology. His research interests include tactile and flow sensor design in robotics and remote environmental sensing.

Maarja Kruusmaa received the Ph.D. degree in robotics from Chalmers University of Technology, Gothenburg, Sweden, in 2002.

Since 2008, she has been a Professor with Tallinn University of Technology (TalTech) as a PI of Centre for Biororobitcs, a research group focusing on bio-inspired robotics, underwater robotics and novel underwater sensing technologies. From 2017 to 2022, she was a Visiting Professor with NTNU AMOS (Centre for Excellence of Autonomous Marine Operations and Systems). Her research interests include novel locomotion mechanisms for underwater environments and on flowable media and novel methods for underwater flow sensing.

Appendix 4

IV

S. Godon, A. Ristolainen, and M. Kruusmaa. "Robotic feet modeled after ungulates improve locomotion on soft wet grounds". *Bioinspiration & Biomimetics*, 19(6):066009, 2024

Bioinspiration & Biomimetics

PAPER • OPEN ACCESS

Robotic feet modeled after ungulates improve locomotion on soft wet grounds

To cite this article: S Godon *et al* 2024 *Bioinspir. Biomim.* **19** 066009

IOP Publishing Bioinspir. Biomim. 19 (2024) 066009 https://doi.org/10.1088/1748-3190/ad839c

Bioinspiration & Biomimetics

CrossMark

OPEN ACCESS

RECEIVED
6 July 2024

REVISED
16 September 2024

ACCEPTED FOR PUBLICATION
4 October 2024

PUBLISHED
4 November 2024

PAPER

Robotic feet modeled after ungulates improve locomotion on soft wet grounds

S Godon* , A Ristolainen and M Kruusmaa

Centre for Biorobotics, School of IT, Department of Computer systems, Tallinn University of Technology (Taltech), Tallinn, Estonia

* Author to whom any correspondence should be addressed.

E-mail: simon.godon@taltech.ee

Keywords: animal leg, foot, bioinspiration, mud, soft yielding ground, quadruped robot

Abstract

Locomotion on soft yielding grounds is more complicated and energetically demanding than on hard ground. Wet soft ground (such as mud or snow) is a particularly difficult substance because it dissipates energy when stepping and resists extrusion of the foot. Sinkage in mud forces walkers to make higher steps, thus, to spend more energy. Yet wet yielding terrains are part of the habitat of numerous even-toed ungulates (large mammals with split hooves). We hypothesized that split hooves provide an advantage on wet grounds and investigated the behavior of moose legs on a test rig. We found that split hooves of a moose reduce suction force at extrusion but could not find conclusive evidence that the hoof reduces sinkage. We then continued by designing artificial feet equipped with split-hoof-inspired protuberances and testing them under different conditions. These bio-inspired feet demonstrate an anisotropic behavior enabling reduction of sinkage depth up to 46.3%, suction force by 47.6%, and energy cost of stepping on mud by up to 70.4%. Finally, we mounted these artificial feet on a Go1 quadruped robot moving in mud and observed 38.7% reduction of the mechanical cost of transport and 55.0% increase of speed. Those results help us understand the physics of mud locomotion of animals and design better robots moving on wet terrains. We did not find any disadvantages of the split-hooves-inspired design on hard ground, which suggests that redesigning the feet of quadruped robots improves their overall versatility and efficiency on natural terrains.

1. Introduction

Legged robots present an interesting blend of agility, versatility, and endurance, making them suitable for tasks in natural environments [1–3]. Among those environments, soft yielding grounds, deforming under the robot's weight, are particularly challenging to access [4]. Locomotion on yielding grounds is researched heavily in terramechanics [5]. This research field, however, which addresses locomotion on natural yielding grounds from a traction perspective, focuses on the shearing forces of wheeled or tracked vehicles. Compared to locomotion using wheels or tracks, legged locomotion on yielding grounds is mainly challenged by leg sinkage, leg extrusion force, and stability [4, 6–8].

In the past 20 years, some research started to address the physics of interactions between moving robots and deformable grounds, with an emphasis on granular media [9–17]. With the recent advances in quadruped robotics, works addressing quadruped locomotion on soft ground started to appear, with focus on control [18–24], leg or foot design [25–30], both [31, 32], or ground properties estimation [22, 30].

However, little work has addressed locomotion on mud or other soft wet grounds (e.g. wet snow). These grounds are different from dry granular media because they have a behavior that depends on the rate of stress and the direction of stress, they deform under load but do not recover: they are called viscoplastic. The few works in this domain address the characterization and modeling of mud behavior under vertical loads [6, 7] or robot models to address different characteristics of the mud behavior such as the effects of mud water content on flipper-driven locomotion, leg compliance, or rotation speed and shape of elliptic rotating legs [33–35]. Even fewer addressed

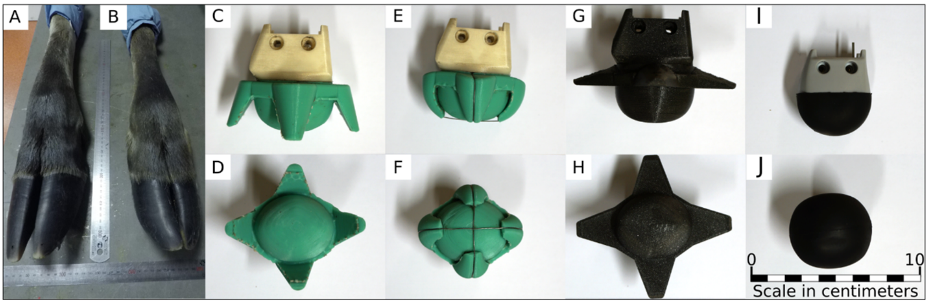

Figure 1. The moose legs and the four different synthetic feet tested. (A) Moose front leg, (B) Moose hind leg. (C), (D) The proposed bio-inspired anisotropic foot. (E), (F) The proposed bio-inspired foot with fastened digits. (G), (H) A foot with rigid extended digits. (I), (J) The commercial Go1 foot. Figures (C)–(J) are at the same scale, displayed in (J).

quadruped locomotion in shallow mud [18, 36], and only our own previous work addressed quadruped locomotion in deep mud [8].

Yet, muddy fields are ubiquitous. Sea shores, lake banks and riverbanks, snow, wetland, marshes or wet forests, are examples of lands that are inaccessible to legged robots. In our previous research [8], we demonstrated a quadruped controller for wading in muddy fields and showed that using a static walking gait and estimating extrusion forces based on sensor signals reduced energy consumption and increased speed.

However, the physics of interaction with soft wet grounds is complex and controller design is limited by the hardware of the robot. This work is inspired by the observation that many large ungulates, living also in wet terrains have split hooves in the front of their feet and two back digits a few centimeters above the ground at the back of their feet (even-toed ungulates). There does not seem to be biology research investigating ungulate locomotion on wet ground besides a work studying cow step length and speed in excrata [37]. Some robot research suggest that the split hooves provide stability and added traction in accidented terrains [26, 38]. However, we hypothesize that they also enable to improve locomotion performance on yielding terrains, such as mud or sand because their anisotropic motion makes them expand at intrusion into the ground and contract at extrusion. This should lead to reduced sinkage and suction force when pulling out the leg, both leading to reduced energy consumption of walking. Total energy spent is an indicator of the cost of traversing, and thereby the endurance.

Therefore, our hypothesis that split hooves improve motion on yielding terrains can be decomposed into three hypotheses: (I) split hooves enable to reduce sinkage in muddy terrains, (II) split hooves enable to reduce suction force in muddy terrains, (III) split hooves enable to save energy for moving in muddy terrains.

To answer our research questions, we first conducted rig experiments using moose feet (figures 1(A) and (B)), an even-toed ungulate living in wet areas and snow, and then designed a synthetic foot (figures 1(C) and (D)) inspired by the split hooves' characteristics, which we compared to three reduced versions of the foot (figures 1(E)–(J)). Finally, we mounted our bio-inspired feet on a Go1 quadruped robot traversing a muddy track.

2. Materials and methods

2.1. Preliminary rig experiments with moose feet

The moose legs were obtained from a local hunting association, the legs were dissected and held in cold but above freezing temperature for 48 h while the experimental rig was prepared. The experiments lasted approximately 5 h. We performed two types of experiments for each leg: digits free and digits fastened. To fasten the digits, we used zip ties and steel wire to bind the digits together. The amount of water in the mud was dictated by the setup: the mud had to be soft enough to enable all four toes to be submerged, but also hard enough so the maximum force could be reached within the range of motion of our actuator, i.e. 30 cm. We could therefore test only one water content, i.e. $R_w = 0.34$. The ratio of water to solid matter in the mud R_w was computed according to the following formula, where M_w is the mass of water, and M_{ds} the mass of dry soil:

$$R_w = \frac{M_w}{M_{ds}}.$$

The experimental setup can be observed in figure 2(A). On the top of a rigid frame, is mounted a 30 cm range linear actuator (Moteck LD3-24-40-E6-300), to which the feet were attached. The linear actuator provides position feedback at 150 Hz. On the bottom part of the rigid frame, a Force/Torque sensor (ATI Axia80-M20) records force at a rate of 150 Hz.

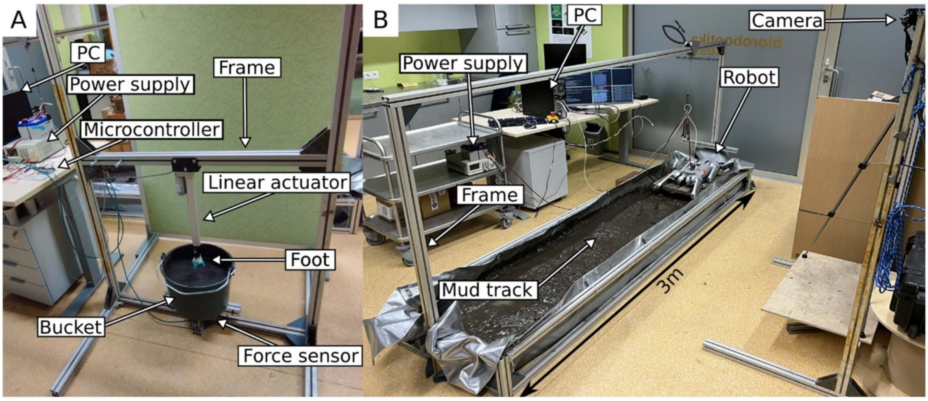

Figure 2. The two experimental setups used in this research. (A): Linear test rig. It consists of a frame on which are mounted a linear actuator on the upper part, and a force sensor on the lower part. On the linear actuator are mounted the different feet to test. On top of the force sensor is positioned a bucket of soil. The low-level control of the motor is performed on a microcontroller, and the power comes from an external power supply. High-level commands and recording of force and position are done from an external computer using ROS. (B) A track filled with mud on which a Go1 quadruped robot walks. The robot is secured by a trolley freely following the robot and attached to it with steel cables. The track contains a 3 m × 0.8 m × 0.12 m volume of mud. High-level control of the robot and data recording is done through an external computer using ROS. Power comes from an external battery connected to a power supply to enable longer runtime and to insert an emergency stop in the power circuit. A camera records the scene to measure the robot's position.

For each experiment, a 300 N target force was given, and the rig went down until the target force was reached, at a controlled constant speed of 5.5 mm s^{-1} (which was the maximum speed reachable by the actuator).

The low-level control of the motor was implemented using a microcontroller, and high-level commands and data recording were implemented using the robot operating system (ROS). The power was provided to the motor by an external power supply unit.

The tests were conducted for the two different digit configurations described above, for two different legs, and repeated ten times, resulting in 2 × 2 × 10 experiments.

For processing the data, we filtered both the position and force curves, and offset them so the contact range would start when the recorded force was above a 1 N threshold. We then computed the work W using the following equation, where z_i is the depth from the mud surface, F_i is force, and n_f is the final timestep:

$$W = \sum_{n=1}^{n_f} F_n \left(z_n - z_{n-1}\right).$$

Further, we calculated the components of the total work: the positive downward work of pushing the foot down until the target force was reached, the negative work representing the recoverable elastic energy when the foot is lifted, and the positive upward work, representing the energy spent to withdraw the leg from the substrate.

2.2. Design of bio-inspired feet and rig experiments

Taking inspiration from the ungulates' digits, we designed a silicone (Elite double 22 from Zhermack) foot consisting of the same shape as the original Go1 ball foot (see figures 1(I) and (J)) and added deformable digits on its periphery (figures 1(C) and (D)). The material was chosen because of its ease of use and because of the promising results obtained using this material in our previous research [6]. The shape of the digits results from mimicking the conic structure of the digits. The width of the digits, and thereby the radial stiffness was determined in an iterative process involving finite element method (FEM) analysis and rapid prototyping followed by manual testing of the feet in mud with varying properties while making sure that they provide significant resistance to sinkage. Figure 3 shows the FEM model of the final version of the foot when subjected to a 60 N upward force, to simulate the intrusion phase of the foot into mud (A), and when subjected to a 30 N downward force (half of the maximum sinking force [6]), to simulate the extrusion phase of the foot (B). The FEM was conducted in ®Solidworks using a hyperelastic model, with the data from the tensile tests performed in [39] for the material properties. The model was constrained with a fixed support on the top surface, where the leg is fixed. For the intrusion phase, force was defined as a uniform pressure on all down-facing surfaces. For the extrusion phase, force was split evenly between a negative pressure on the down-facing surfaces, representing suction force, and a positive pressure on the up-facing surfaces, representing the weight of mud on top of the foot. The proposed final design of the

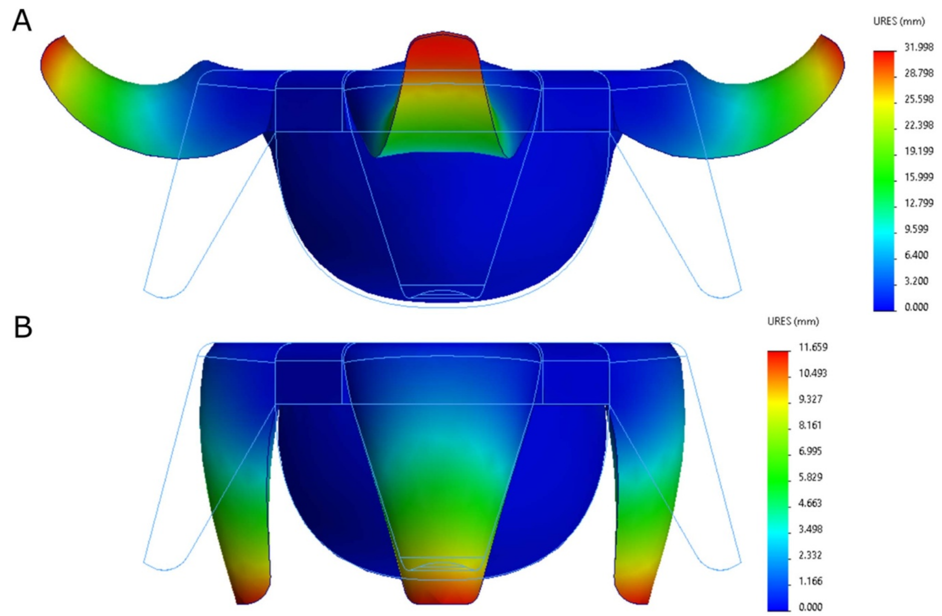

Figure 3. Finite element method of the proposed foot. (A): Resultant displacement (mm) of the foot when subject to a vertical upward force of 60 N, simulating the intrusion phase of the foot into mud. The red parts show the maximum displacement (32 mm), and the blue part the minimum (0 mm). The simulation shows that when subjected to a 60 N upward force, the digits fully extend passively. The light blue lines represent the shape of the undeformed foot. (B) Resultant displacement (mm) of the foot when subjected to a 30 N downward force, simulating the extrusion phase of the foot. The red parts show the maximum displacement (11.7 mm) and the blue regions show the minimum displacement (0 mm). The simulation shows that when subjected to a 30 N downward force, the foot digits retract passively. The light blue lines represent the shape of the undeformed foot.

foot enables it to passively, fully extend, and retract its digits to increase sinkage resistance and reduce suction force, respectively. A fabric mesh was cast inside the lower part of the foot to resist tearing, and a rigid kernel was placed at the center of the mold to provide a strong anchor point for the screw during the assembly with the leg.

The experimental setup for synthetic legs and moose legs was the same, see figure 2(A). For artificial feet experiments, the force and position were recorded in the same way as in the animal's feet experiments. However, thanks to the smaller dimensions of our bio-inspired feet, we could test different water contents of the mud without being limited by the dimensions of the experimental setup.

The water contents tested are 0.21, 0.25 and 0.27, which are three values selected in the region where the behavior of mud varies significantly depending on the water content. Below 0.2, the behavior of mud remains relatively constant, while after 0.27, the mud has a very low stiffness and would not support the load within the range of the target force [6]. The target force for the artificial feet was selected so it would be later comparable with the experiments with the Go1 robot. We experimentally established that with the controller used for the Go1 experiments, the maximum force on a single foot was 60 N, or half of the robot's weight. Therefore, for the rig experiments on the four different feet, we set a target force command of 60 N.

The experiments were conducted with specimens on figures 1(C)–(J). with each specimen, the experiment was performed 10 times under each mud consistency (this accounts for 4 × 10 × 3 experiments altogether). Data processing was identical to what was described for the moose feet experiments.

2.3. Experiments on a quadruped robot

The robot experiments with GO1 were conducted with a controller developed and tested in our previous research [8]. The controller was specially developed for walking in deep mud, and it was established in [8] that the commercially available foot of GO1 does not allow walking in deep mud (the robot gets stuck and falls).

The controller developed in [8] is based on a tripod static gait, which places the body in a stable position based on the estimated ground properties, measured and modeled during the intrusion phase of the leg. In this controller design, the inputs—leg sequence, step length and height, swing duration, clearance, and stance width—are kept constant throughout the experiment. The controller is designed to minimize excessive suction forces by slowing leg movement while it is in mud and shifting the robot's center of mass further from the leg when high suction forces are anticipated, thus preventing the robot from toppling. These two features, combined with the bio-inspired artificial feet's reduced sinkage, account for the differences in speed and mechanical cost of transport (MCoT) observed in the results section. The controller remains the same across all three sets of experiments, with varying results arising from differences in sinkage depth and suction force between the two sets of feet or ground stiffness. For more details on the controller, we refer interested readers to [8].

The setup of the robot experiment is shown in figure 2(B). The robot was walking on a 12 cm deep muddy track and secured by a freely rolling trolley suspended above the robot (for safety and for the convenience of using an external power source). High-level commands and data recording were performed using ROS software on an external computer for simplicity. The experiments were also video recorded to track the distance covered by the robot. The videos were post-processed using the ®Kinovea software. The MCoT of the robot was computed during post-processing by summing up the mechanical output of all motors for the entire experiments. The contribution of each motor was calculated with the following formula:

$$W_i = \sum_{n=0}^{n_f} \tau_i(n)\,\omega_i(n)$$

where n represents the timestep, n_f the last timestep of the experiment, τ_i the estimated torque of the motor i, and ω_i the estimated rotational velocity of the motor i. ω_i and τ_i are directly available from motor feedback. Only the positive work is computed, the negative work is not subtracted from the result because negative work is not practically recovered.

The MCoT was then computed using the following formula:

$$\mathrm{MCoT} = \frac{E}{\mathrm{mgd}}.$$

Where E is the total mechanical energy spent, computed by summing the individual works from all motors W_i, $m = 12$ kg is the mass of the robot, $g = 9.81$ m s^{-2} is gravitational acceleration, and d is the distance covered by the robot, measured from video recording using the ®Kinovea software.

The soil had a water content of 0.25 which is the same water content as for the rig experiment. That allowed us to later establish that the energy saving for the robot and isolated foot experiments were consistent with each other.

Three different experiments were performed:

- Using the original Go1 robot feet in mud, which served as a baseline
- Using the original Go1 feet on hard ground, to compute the MCoT in the absence of mud and therefore compare the contribution of our feet to the mud-related part of the MCoT.
- Using our bio-inspired anisotropic feet

3. Results

3.1. Moose leg experimental results

The first experiments were performed on moose legs, one front leg (figure 1(A)), and one hind leg (figure 1(B)) in two conditions: the digits fastened to the foot and the digits allowed to move freely. The results of the experiments performed on moose feet can be observed in figure 4. Figure 4(A) shows the four phases of work for each condition and for each leg. Figure 4(B) shows the depth reached during the intrusion phase for the four test conditions. Figure 4(C) presents the maximum suction force reached while pulling the leg out of the mud after the step for a hind leg and a front leg. The results are consistent for both the hind and front legs of the moose with respectively 8.4% (p-value < 0.01) and 4.3% (p-value < 0.01) increase in suction force when the digits are fastened. However, the sinkage is not statistically (for the hind leg) or in absolute value different for both legs (26.9 cm vs 26.8 cm for the front leg, p-value < 0.01, and 25.8 cm vs 25.9 cm for the hind leg, p-value > 0.8). The work spent in mud deformation is also similar for both front and hind legs (18.03 J vs 17.86 J for the front leg, p-value > 0.7, and 13.93 J vs 14.14 J for the hind leg, p-value > 0.4).

3.2. Proposed bio-inspired anisotropic foot

The proposed anisotropic foot design can be observed in figures 1(C) and (D). To make experiments comparable, it is designed based on the original foot of the Go1 robot (figures 1(I) and (J)) and similar to other commonly available quadruped commercial robots. Our proposed design is achieved by adding passive appendices expected to serve the functionality of ungulate toes (figures 1(A) and (B)). The passive silicone appendices expand and retract as force is applied during intrusion and extrusion. The manufacturing is simple, and it resists tearing thanks to an embedded fabric mesh. A rigid fastener is used to fasten the foot to the robot with screws. Additionally, we proposed two variations for comparative experiments: a bio-inspired foot with fastened digits (figures 1(E) and (F)) and rigid extended digits (figures 1(G) and (H)).

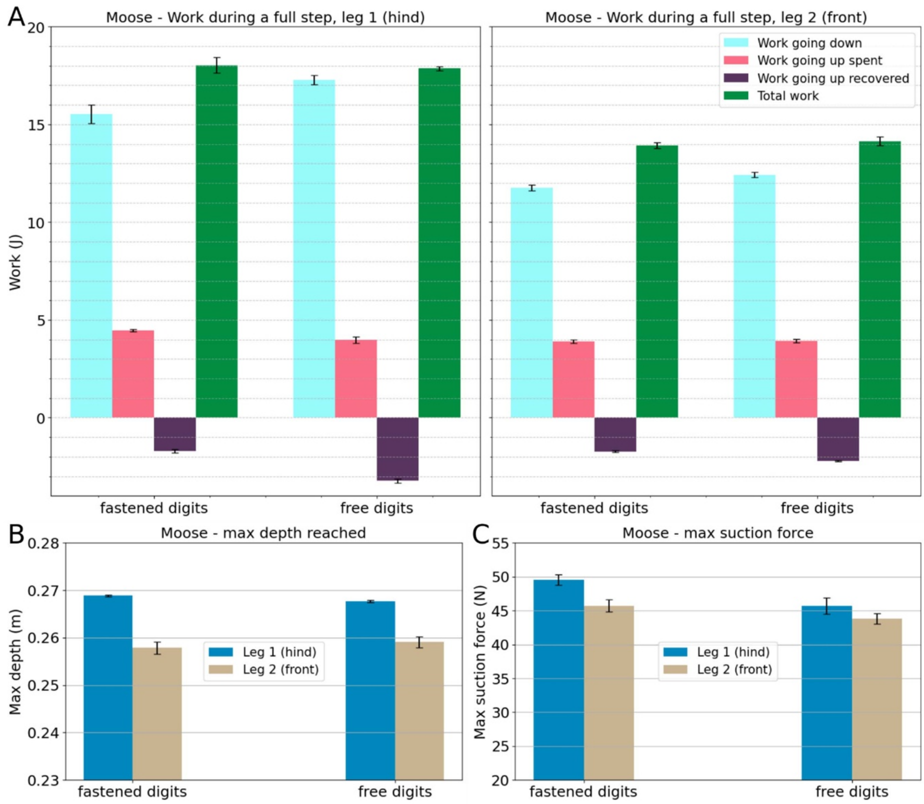

Figure 4. Experimental results for the moose feet experiments. This figure illustrates the three metrics tested for both the front and hind legs, with fastened or free digits. It demonstrates the similar behavior of the front and hind legs for all the parameters tested and indicates a difference between fastened and free digits in the suction force. (A) Work during the different stages of the step (B) Maximum depth reached during intrusion of the leg (C) Maximum suction force during pullout of the leg. Each of the bars represents the median of a series of 10 samples, and the error bars represent their standard error.

3.3. 1D test results in soft ground

Figure 5 presents the results obtained in the rig experiments using the synthetic feet with three different water contents. Figure 5(A) shows that compared to the original Go1 foot, the proposed foot enables lowering the energy spent for ground deformation, by 19.1% (p-value < 0.01), 70.4% (p-value < 0.01), and 40.3% (p-value < 0.01) respectively for the low, medium and high water contents. The rigid extended foot demonstrates an even higher energy saving of 82.4% (p-value < 0.01) on the medium water content condition, mainly gained from the intrusion phase, because the foot sinks less (figure 5(B)) due to its already fully extended digits, while it takes a few millimeters for the bio-inspired foot to expand them. Sinkage depth is also reduced in low, medium and higher water content conditions, with a 18.4% (p-value < 0.01), 46.3% (p-value < 0.01) and 37.4% (p-value < 0.01) sinkage depth reduction, respectively. In the very wet condition, the anisotropic design of the bio-inspired foot demonstrates its ability to reduce the suction force (figure 5(C)). It reduces it by 82.1% (p-value < 0.03), 47.6% (p-value < 0.01) and 21.0% (p-value < 0.01) compared to the original Go1 foot in the least, medium and wettest conditions, respectively. The rigid extended foot here demonstrates that simply increasing the foot surface, without anisotropic feature is impeding locomotion, with an increase of 71.1% (p-value < 0.01) in the suction force in the wettest condition compared to the bio-inspired anisotropic foot.

Figure 6 shows typical curves observed in the wettest condition. This condition was chosen because it is the one that best demonstrates the contributions of all the features present in the different feet. Figure 6(A) shows the force vs depth curves for the four different tested feet. The graph reads in the clockwise direction, i.e. the force and sinkage both increase up to the target force, then the depth starts to decrease (foot withdrawing). The withdrawing causes the force to decrease (elasticity) and then to quickly become negative due to the suction force, until the suction

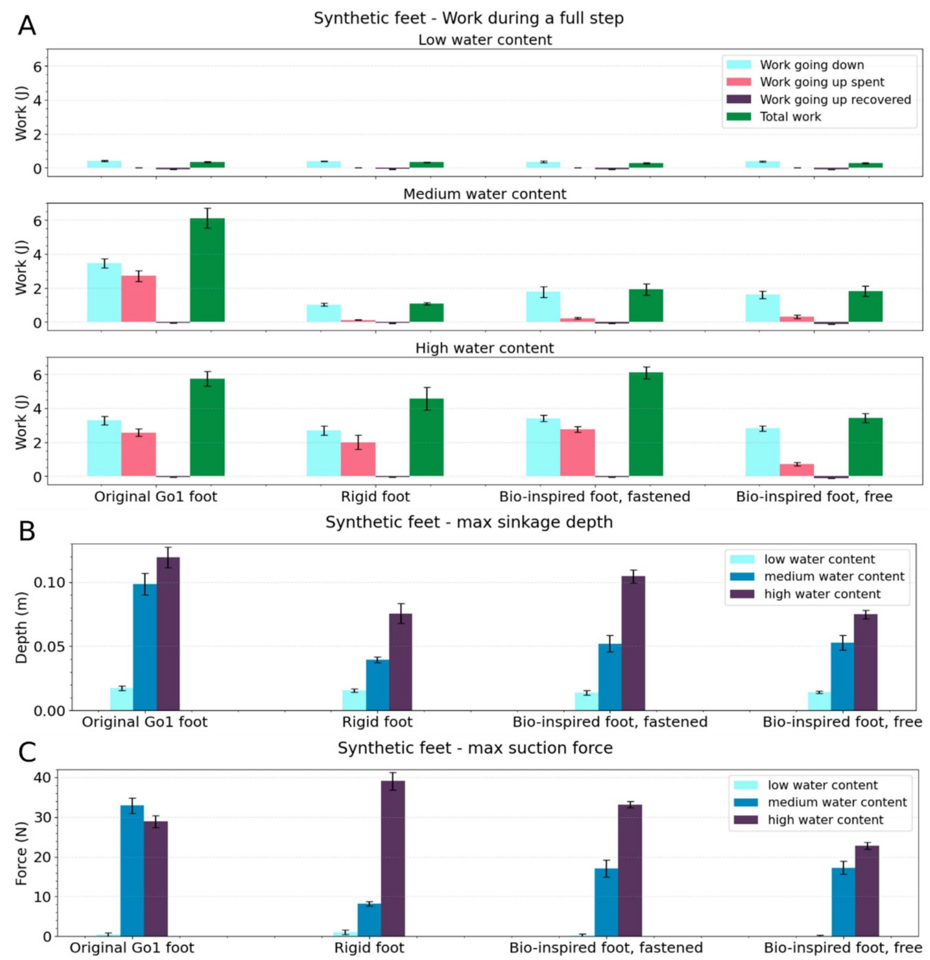

Figure 5. Experimental results of the linear rig tests performed using the four synthetic feet on muds with three different water contents. This graph illustrates how each foot's behavior varies with the water content, and for each water content, the three metrics we compare per foot. (A) Work during an entire step, including the positive work exerted when pushing down, the positive work from withdrawing the foot from the mud, and the negative work from elastic energy stored in the foot. Each graph summarizes results from a different water content. (B) The maximum depth reached by all the synthetic feet given the input force command. (C) The maximum suction force during the withdrawal phase of the step, after the target force was reached. Each of the bars represents the median of a series of 10 samples, and the error bars represent their standard error.

is released, and the force returns to zero. The area covered by the loop represents the work exerted by the foot on the mud. Figure 6(B) shows the force vs time curve. This curve allows to compare the speed at which the different feet reach the target force or release the suction.

Figure 7 shows timeshots of the robot traversing the track using the original Go1 feet, the bio-inspired anisotropic feet, and as a comparison, on hard ground using the original Go1 feet.

Figure 8 shows the performances of the quadruped robot on the track in the three test conditions. On the left (figure 8(A)), the MCoT is depicted. The MCoT using the original Go1 feet is 2.42, which is slightly higher than the 2.12 measured in our previous research [8], where the experiments were performed with $R_w = 0.35$, i.e. a thinner and less sticky mud. Compared to using the original Go1 feet, the bio-inspired feet lead to a 38.7% (p-value < 0.01) energy saving. If we deduct the base cost of transport from this, i.e. the cost of transport on hard ground (0.736), we end up with a contribution of mud to the MCoT of 1.680 with the original Go1 feet, and 0.749 with the bio-inspired feet. Therefore, for the component of MCoT which is due to mud, the bio-inspired feet help to save 55.6% of the energy which is coherent with the 40.2%–70.3% observed in the 1D rig experiments. Figure 8(B) shows that the speed of the

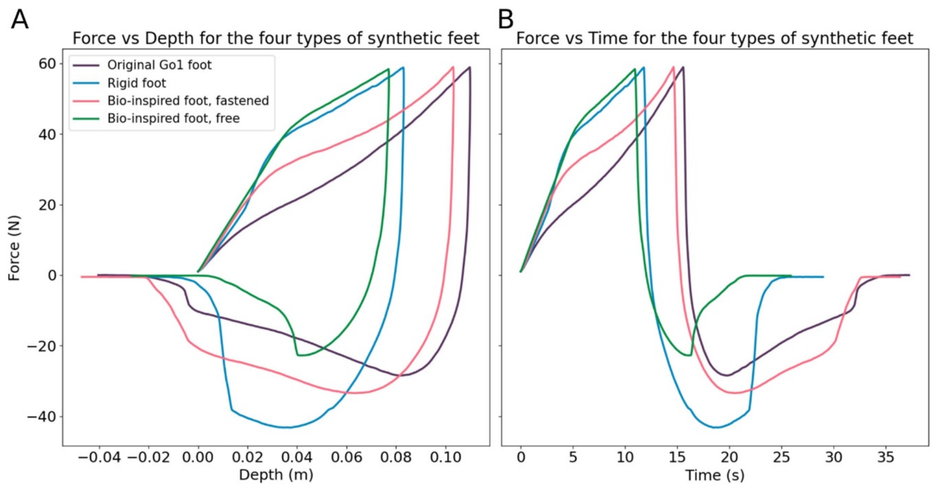

Figure 6. Example curves for the force vs depth relationship (A) and force vs time relationship (B). The examples here are taken from the wettest of the three conditions tested, which is the one best demonstrating all the contributions of the different features of the feet. The curves demonstrate how the three feet have the same effect on mud at the beginning, how some feet reach the force target faster and shallower, and the differences in suction force and their timing, for all the different feet.

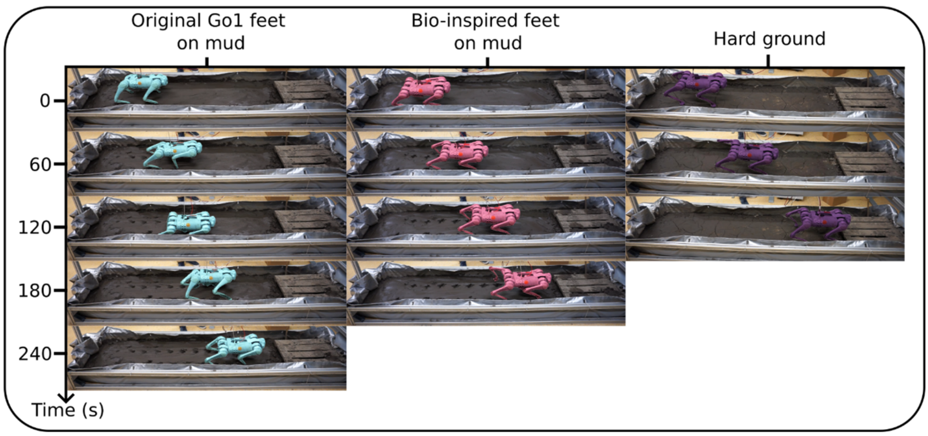

Figure 7. Illustration of the experiments performed with the quadruped Go1. Timeshots of the quadruped walking in the mud using the original Go1 feet or the bio-inspired anisotropic feet and walking on hard ground for comparison. The timeshots demonstrate the different progression speeds of the robot in all three conditions tested. The robot was segmented using segment-anything.com.

robot also is increased using the bio-inspired feet. The speed using the original Go1 feet is 0.83 body length per minute (bl/min), which is similar to our previous research [8], where it was at 0.85 bl min^{-1}. Compared to using the original Go1 feet, the bio-inspired feet enable the robot to progress 55.0% (p-value < 0.01) faster. Figure 8(C) illustrates the footprints left by the quadruped robot after traversing the track, with the original Go1 feet on mud (left), with the bio-inspired anisotropic feet on mud (center), and on hard ground (right).

4. Discussion

Our hypotheses were that split hooves inspired by ungulates have an advantage on wet terrains because they (I) reduce sinkage, (II) reduce suction force, and thereby altogether (III) save energy of locomotion. The summary of the hypotheses results is presented in table 1.

The experiments with the moose feet firmly confirmed the second hypothesis (increase of the suction force at extrusion by 8.4% (p-value < 0.01) and 4.3%

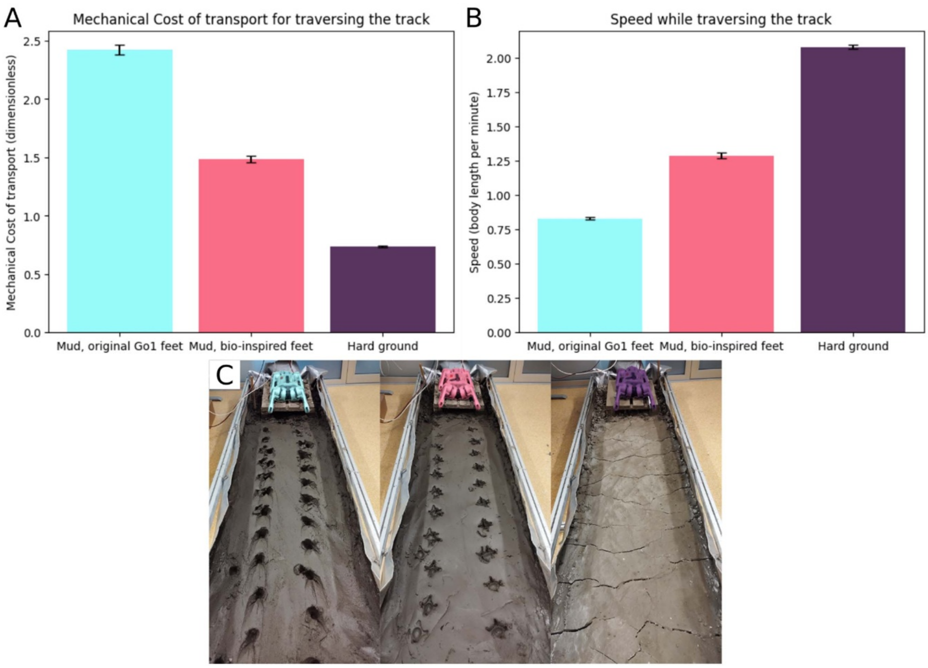

Figure 8. Experimental results with the quadruped robot. The graph shows the difference in Mechanical Cost of Transport (MCoT), speed, and the tracks left by the robot for all three conditions tested. (A) The MCoT of the quadruped while traversing the track filled with mud, while wearing the original Go1 feet, the bio-inspired anisotropic feet, and as a comparison, the same gait on hard ground. (B) The corresponding speed of the quadruped for each experiment. (C) The corresponding tracks left by the robot with original feet on mud (left), with the bio-inspired anisotropic feet on mud (center), and on hard ground (right). The robot was segmented using segment-anything.com. The results reported here represent the median and standard error of a series of 5 runs per condition.

Table 1. Summary of the hypotheses and conclusions from experiments.

	Reduced sinkage (Hypothesis I)	Reduced suction (Hypothesis II)	Saved energy (Hypothesis III)
Moose feet	Inconclusive	Confirmed	Inconclusive
Synthetic feet	Confirmed	Confirmed	Confirmed
Robot	N/A	N/A	Confirmed

(p-value < 0.01) with fastened digits). It also confirms that the effect of suction force is passive as it exists also with the dead animal's feet. Both rear and front feet have the suction force reduction effect. Due to the limitations of the experimental setup, the results were however confirmed only for the water content of 0.34, we therefore cannot confirm that the effect exists or is significant for various mixtures of mud.

The results for the reduced sinkage and energy saving for a moose leg were inconclusive (neither confirmed nor rejected). It could be because the expected effect does not exist, the effect is not passive and cannot be observed with a dead animal or the effect could not be measured because of the restrictions of the experimental setup. The maximum force applied during the experiments was 300 N while the animal weighed about 400 kg, so 1333 N per leg on a tripod gait. The effect may become apparent at larger forces. It is also possible that reduced sinkage is not totally passive because the animal may actively expand the digits during intrusion (our further experiments with synthetic feet indirectly confirm this explanation as the digits of synthetic feet extend passively). Also, our rig allowed only 1D motion whereas the animal might change the orientation of the feet while stepping. Finally, it is possible that sinkage reduction does not play a significant role in ungulate locomotion, or the mechanics are more complicated than what we can observe with passive animal experiments.

For the synthetic ungulate foot inspired design, all three hypotheses were confirmed: the design allowed reducing sinkage, reducing suction force and reducing the overall energy consumption. The rig experiments with synthetic feet were performed on three types of muds with varying water content and the effects were observable in all cases. On mud with low water content, which hardly deforms, the bio-inspired anisotropic foot behaved similarly to the original Go1 foot. Even though percentage-wise the improvements seem huge (reduction of 19.1%, 18.4%, and 82.1% of the energetic cost, sinkage depth, and maximum suction force respectively), the energy, suction force, and work in the almost hard ground are low in absolute values, so the new design of the foot has only marginal benefits with respect to the conventional robot foot design. The real advantage of the ungulate-inspired design becomes apparent with a wet ground where the results were very significant, by all the three metrics we measured (40.3–70.4% of energy saved, 37.4%–46.3% sinkage depth reduction, and 21.0%–47.6% of suction force reduction).

Comparative experiments with variations of the synthetic feet can be used to explain the effects of the design. The rigid extended foot performed even better in the medium water content condition because of its constantly larger surface area, but its static shape does not allow an easy suction force release. Mud on the upper surface of the extended digits also weighs it down. The foot with the fastened digits has the same advantage of reduced suction as the anisotropic foot and the rigid foot in the wettest condition but it sinks deeper. All these behaviors can be visualized on the force vs time and force vs sinkage curves presented in figure 5. There, the original Go1 foot and the foot with fastened digits behave in an equivalent way, as expected. The bio-inspired anisotropic foot and the rigid extended foot, on the other hand, behave also in a similar way to each other during the intrusion phase, but the benefit of the digits' retraction can be well observed when the suction force is quickly released by the bio-inspired anisotropic foot. On the contrary, the rigid foot is impeded by a resistive suction force up to the mud surface, in the same way as the original Go1 foot.

These results complement our previous research [6], where we demonstrated that simply adjusting foot stiffness could increase the force generated by 33% in mud. Our earlier work also highlighted the necessity for an anisotropic design to mitigate suction forces, a challenge we addressed with our bio-inspired anisotropic foot design.

While there appear to be no other studies specifically focused on foot design for locomotion in deep mud, we can draw parallels from research on dry granular materials. For instance [27], found that segmented foot designs reduced sinkage depth by 5% of the leg length in dry sand and pebbles. Similarly [29], also observed that bird-inspired biomechanical feet diminished sinkage in loose sand [25] and [31] reported that larger foot surface areas decreased sinkage depth in various granular materials, noting that in cases of deep sinkage, strong foothold prevents slippage. [30] further indicated that compared to spherical feet, cylindrical feet sink approximately 44% less in dry sand under a static load of 50 N.

Overall, these findings suggest that using larger feet, altering the shape of the feet, or using deformable feet with segments, or made from soft materials, can reduce sinkage in different flowable materials. However, a larger foot, while beneficial in reducing pressure and sinkage, may not be ideal for wet, cohesive materials like mud due to the suction forces that hinder foot liftoff, as demonstrated in [6], and in the current paper. This highlights the necessity of using a deformable foot for locomotion in mud, as was demonstrated in this research.

Finally, the experiments performed on the Go1 quadruped robot confirmed our hypothesis of energy reduction. During locomotion, the MCoT is not only due to the base cost of locomotion, which we measured by performing tests on hard ground, but is also due to the resistive behavior of mud. By comparing the MCoT of the robot through the mud track using both the original Go1 feet, and the bio-inspired anisotropic feet, we established that the latter enabled saving more than half of the energy lost in mud. The reduced sinkage and suction force not only make locomotion easier but also faster, with a significant increase of the locomotion speed of the quadruped using the bio-inspired anisotropic feet, with the same controller. The differences observed in the various settings are only due to the sinkage of the feet and the reduced suction force, which in turn impact the time and energy the robot spends inserting and extruding its feet from the mud and ensuring the robot's stability; the robot speed is not controlled, but instead the increased speed and reduced MCoT emerge from easier locomotion enabled by the feet design.

Overall, our research shows that the bio-inspired anisotropic foot presents several advantages for locomotion on mud. Its passively expanding and retracting digits enable to reduce sinkage, suction force and energetic cost of moving in mud. Also, we cannot think of any use case when these feet would impede locomotion. On hard ground, the passive digits would not touch the ground so they would not disturb foot placement, and at the same time they contribute to energy reduction when the robot is on soft ground. We believe that the advantage exists also on dry yielding grounds such as dry sand or dry snow: reduced sinkage would be reasonable to expect in all yielding grounds whereas the suction force might occur only in case of wet mixtures. Our work also did not address controller design: all robot experiments were performed with a controller for a static gait developed in our previous paper [8]. It is possible that an improved controller design would enhance the effects of wet ground locomotion further or the robot could use different controllers for different substances (e.g. changing water content).

It is also worth noting that besides energy saving the novel foot design also increases the fault-tolerance of the robot (and possibly the survival of an animal). Since it sinks in less and needs less force to get the foot loose, it is less likely to stay stuck.

Finally, it is speculated that split hooves also add stability on uneven terrains so it might play the same effect on robots and could complement the research on the design of more stable feet [13, 27, 32] for soft or uneven grounds. Future work thus can address ungulate locomotion and robot locomotion in versatile yielding and uneven terrains to understand the complicated interaction between mechanical feet design in multiphase environments.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.12673097 [40].

Acknowledgment

No animals were killed for the purpose of this study. The legs of the moose were obtained from Nõo Hunting Association, operating under the Estonian Wildlife Management Laws, during the hunting season.

Funding

This work was supported by the European Union's Horizon 2020 research and innovation programme ROBOMINERS under Grant 820971 (G S, K M, R A).

Conflict of interest

Authors declare that they have no competing interests.

Author contributions

Conceptualization: G S, K M, R A. Experimentations: G S. Investigation: G S, K M, R A. Visualization: G S. Funding acquisition: K M. Project administration: K M, R A. Supervision: K M, R A. Writing—original draft: G S, K M Writing—review & editing: G S, K M, R A.

ORCID iDs

S Godon https://orcid.org/0000-0003-1928-2696
A Ristolainen https://orcid.org/0000-0003-3029-9667
M Kruusmaa https://orcid.org/0000-0001-5738-5421

References

[1] Bellicoso C D, Bjelonic M, Wellhausen L, Holtmann K, Günther F, Tranzatto M, Fankhauser P and Hutter M 2018 Advances in real-world applications for legged robots *J. Field Robot.* **35** 1311–26
[2] Mattamala M *et al* 2024 Autonomous forest inventory with legged robots: system design and field deployment (arXiv:2404.14157)
[3] Fan Y, Pei Z, Wang C, Li M, Tang Z and Liu Q 2024 A review of quadruped robots: structure, control, and autonomous motion *Adv. Intell. Syst.* **6** 2300783
[4] Godon S, Kruusmaa M and Ristolainen A 2023 Maneuvering on non-Newtonian fluidic terrain: a survey of animal and bio-inspired robot locomotion techniques on soft yielding grounds *Front. Robot.* AI **10** 1113881
[5] Wong J Y 1989 *Terramechanics and Off-road Vehicles* (Elsevier)
[6] Godon S, Ristolainen A and Kruusmaa M 2022 An insight on mud behavior upon stepping *IEEE Robot. Autom. Lett.* **7** 11039–46
[7] Chen X, Yi J and Shan J 2024 A reduced-order mud reaction force model for robotic foot-mud interactions *2024 IEEE Int. Conf. on Advanced Intelligent Mechatronics (AIM)* (IEEE)
[8] Godon S *et al* 2024 Walking in mud: modelling, control and experiments of quadruped locomotion (https://doi.org/10.36227/techrxiv.172047167.78902329/v1)
[9] Qian F, Zhang T, Korff W, Umbanhowar P B, Full R J and Goldman D I 2015 Principles of appendage design in robots and animals determining terradynamic performance on flowable ground *Bioinspir. Biomim.* **10** 056014
[10] Hosoi A E and Goldman D I 2015 Beneath our feet: strategies for locomotion in granular media *Annu. Rev. Fluid Mech.* **47** 431–53
[11] Zhang T and Goldman D I 2014 The effectiveness of resistive force theory in granular locomotion *Phys. Fluids* **26** 101308
[12] Li C, Zhang T and Goldman D I 2013 A terradynamics of legged locomotion on granular media *Science* **339** 1408–12
[13] Chopra S, Tolley M T and Gravish N 2020 Granular jamming feet enable improved foot-ground interactions for robot mobility on deformable ground *IEEE Robot. Autom. Lett.* **5** 3975–81
[14] Bagheri H, Jayanetti V, Burch H R, Brenner C E, Bethke B R and Marvi H 2023 Mechanics of bipedal and quadrupedal locomotion on dry and wet granular media *J. Field Robot.* **40** 161–72
[15] Slonaker J, Motley D C, Zhang Q, Townsend S, Senatore C, Iagnemma K and Kamrin K 2017 General scaling relations for locomotion in granular media *Phys. Rev.* E **95** 052901
[16] Gkliva R, Remmas W, Godon S, Rebane J, Ochs K, Kruusmaa M and Ristolainen A 2024 A multi-terrain robot prototype with archimedean screw actuators: design, realisation, modelling, and control *IEEE Access* **12** 95820–30
[17] Zhang J, Chen X, Shen W, Song J and Zheng Y 2024 A toe-inspired rigid-flexible coupling wheel design method for improving the terrain adaptability of a sewer robot *Bioinspir. Biomim.* **19** 046003
[18] Lee J, Hwangbo J, Wellhausen L, Koltun V and Hutter M 2020 Learning quadrupedal locomotion over challenging terrain *Sci. Robot.* **5** eabc5986
[19] He J and Gao F 2020 Mechanism, actuation, perception, and control of highly dynamic multilegged robots: a review *Chin. J. Mech. Eng.* **33** 1–30
[20] Lu G, Chen T, Rong X, Zhang G, Bi J, Cao J, Jiang H and Li Y 2023 Whole-body motion planning and control of a quadruped robot for challenging terrain *J. Field Robot.* **40** 1657–77
[21] Choi S, Ji G, Park J, Kim H, Mun J, Lee J H and Hwangbo J 2023 Learning quadrupedal locomotion on deformable terrain *Sci. Robot.* **8** eade2256

[22] Wang C, Zhang R, Dong W, Li T, Jiang L, Xu W, Xu P, Zhou Y and Zou M 2024 Trafficability anticipation for quadruped robot in field operation *J. Field Robot.* **41** 851–66
[23] Su Y, Yang H, Ding L, Xu C, Xu P, Gao H, Niu L, Li W and Liu G 2023 A unified foot–terrain interaction model for legged robots contacting with diverse terrains *IEEE/ASME Trans. Mechatronics* **29** 2661–72
[24] Han Y, Lu Z, Liu G, Zong H, Zhong F, Zhou S and Chen Z 2023 Contact detection with multi-information fusion for quadruped robot locomotion under unstructured terrain *Front. Mech. Eng.* **18** 44
[25] Yao C, Shi G, Xu P, Lyu S, Qiang Z, Zhu Z, Ding L and Jia Z 2024 STAF: interaction-based design and evaluation of sensorized terrain-adaptive foot for legged robot traversing on soft slopes *IEEE/ASME Trans. Mechatronics* (https://doi.org/10.1109/TMECH.2024.3350183)
[26] Ranjan A, Angelini F, Nanayakkara T and Garabini M 2023 Design guidelines for bioinspired adaptive foot for stable interaction with the environment *IEEE/ASME Trans. Mechatronics* **29** 843–55
[27] Chatterjee A *et al* 2023 Multi-segmented adaptive feet for versatile legged locomotion in natural terrain *2023 IEEE Int. Conf. on Robotics and Automation (ICRA)* (IEEE)
[28] Catalano M G, Pollayil M J, Grioli G, Valsecchi G, Kolvenbach H, Hutter M, Bicchi A and Garabini M 2021 Adaptive feet for quadrupedal walkers *IEEE Trans. Robot.* **38** 302–16
[29] Zhang R, Pang H, Wan H, Han D, Li G and Wen L 2020 Design and analysis of the bionic mechanical foot with high trafficability on sand *Appl. Bionics Biomech.* **2020** 3489142
[30] Yang H, Zhang C, Ding L, Wei Q, Gao H, Liu G, Ge L and Deng Z 2024 Comparative study of terramechanics properties of spherical and cylindrical feet for planetary legged robots on deformable terrain *J. Terramech.* **113** 100968
[31] Kolvenbach H *et al* 2021 Traversing steep and granular martian analog slopes with a dynamic quadrupedal robot (arXiv:2106.01974)
[32] Chen G, Qiao L, Zhou Z, Lei X, Zou M, Richter L and Ji A 2024 Biomimetic lizard robot for adapting to Martian surface terrain *Bioinspir. Biomim.* **19** 036005
[33] Liu S, Huang B and Qian F 2023 Adaptation of flipper-mud interactions enables effective terrestrial locomotion on muddy substrates *IEEE Robot. Autom. Lett.* **8** 7978–85
[34] Zhong B, Zhang S, Xu M, Zhou Y, Fang T and Li W 2018 On a CPG-based hexapod robot: amphiHex-II with variable stiffness legs *IEEE/ASME Trans. Mechatronics* **23** 542–51
[35] Ren X *et al* 2013 An experimental study on the locomotion performance of elliptic-curve leg in muddy terrain *2013 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics* (IEEE)
[36] Raibert M, Blankespoor K, Nelson G and Playter R 2008 Bigdog, the rough-terrain quadruped robot *IFAC Proc. Vol.* **41** 10822–5
[37] Phillips C J C and Morris I D 2000 The locomotion of dairy cows on concrete floors that are dry, wet, or covered with a slurry of excreta *J. Dairy Sci.* **83** 1767–72
[38] Abad S-A, Sornkarn N and Nanayakkara T 2016 The role of morphological computation of the goat hoof in slip reduction *2016 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)* (IEEE)
[39] Gkliva R and Kruusmaa M 2022 Soft fluidic actuator for locomotion in multi-phase environments *IEEE Robot. Autom. Lett.* **7** 10462–9
[40] Godon S, Ristolainen A and Kruusmaa M 2024 Dataset for the article: robotic feet modeled after ungulates improve locomotion on soft wet grounds *Zenodo* (https://doi.org/10.5281/zenodo.12673097)

Curriculum Vitae

Simon Pierre Godon

ORCID	0000-0003-1928-2696
E-mail	simon.godon@taltech.ee

Fields of research

ETIS RESEARCH FIELD: 4. Natural Sciences and Engineering; 4.13. Mechanical Engineering, Automation Technology and Manufacturing Technology; CERCS RESEARCH FIELD: T125 Automation, robotics, control engineering ; SPECIFICATION: Locomotion in robotics

ETIS RESEARCH FIELD: 4. Natural Sciences and Engineering; 4.6. Computer Sciences; CERCS RESEARCH FIELD: T121 Signal processing

ETIS RESEARCH FIELD: 4. Natural Sciences and Engineering; 4.7. Telecommunications; CERCS RESEARCH FIELD: T181 Remote sensing

Institutions and positions

01.09.2024–...	Tallinn University of Technology, School of Information Technologies, Department of Computer Systems, Junior Research Fellow (1,00)
01.02.2020–31.08.2024	Tallinn University of Technology, School of Information Technologies, Department of Computer Systems, Junior Research Fellow (0,75)
10.10.2019–31.01.2020	Tallinn University of Technology, School of Information Technologies, Department of Computer Systems, Engineer (1,00)

Academic degrees

Simon Pierre Godon, Phd student, (sup) Maarja Kruusmaa; Asko Ristolainen, Robotic locomotion in low-yield environments, Tallinn University of Technology School of Information Technologies, Department of Computer Systems.

Education

28.08.2016–19.09.2019	MSc Robotics - University of Bristol and MEng Mechanics/electronics - Arts et Metiers ParisTech

Completed projects

- MNVA22037 "Adapting to the rapidly changing Arctic Implications of changing hydrodynamic conditions on the coastal-marine environments in Svalbard: A joint study of Tallinn University of Technology and The University Center in Svalbard" (20.05.2022−11.07.2024); Principal Investigator: Maarja Kruusmaa; Tallinn University of Technology, School of Information Technologies, Department of Computer Systems (coordinator), Tallinn University of Technology, School of Science, Department of Marine Systems (partner), Tallinn University of Technology, School of Science, Department of Geology (partner); Financier: Ministry of Foreign Affairs; Financing: 300 000 EUR.
- VFP19025 "Resilient Bio-inspired Modular Robotic Miners" (1.06.2019−31.05.2023); Principal Investigator: Maarja Kruusmaa; Tallinn University of Technology, School of Information Technologies, Department of Computer Systems (partner); Financier: European Commission; Financing: 633 750 EUR.
- PRG1243 "Multiscale Natural Flow Sensing for Coasts and Rivers" (01.01.2021−31.12.2021); Principal Investigator: Jeffrey Andrew Tuhtan; Tallinn University of Technology, School of Information Technologies, Department of Computer Systems (coordinator); Financier: Estonian Research Council; Financing: 257 125 EUR.

Teaching

Robotics guidance and software
6 ECTS
Role: Develop lecture material and assignment material, give lectures, set up the online course environment, assist and grade students

Publications

2025

Godon, Simon; Prados, Carlos; Chemori, Ahmed; Ristolainen, Asko; Kruusmaa, Maarja (2025). Walking in Mud: Modeling, Control, and Experiments of Quadruped Locomotion. IEEE/ASME Transactions on Mechatronics, 1−12. DOI: 10.1109/TMECH.2025.3560588.

2024

Godon, S.; Ristolainen, A.; Kruusmaa, M. (2024). Robotic feet modeled after ungulates improve locomotion on soft wet grounds. Bioinspiration & Biomimetics, 19 (6), #066009. DOI: 10.1088/1748-3190/ad839c.

R. Gkliva; W. Remmas; S. Godon; J. Rebane; K. Ochs; M. Kruusmaa; A. Ristolainen; (2024). A Multi-Terrain Robot Prototype With Archimedean Screw Actuators: Design, Realization, Modeling, and Control. IEEE Access, 12, 95820−95830. DOI: 10.1109/ACCESS.2024.3426105.

2023

Godon, Simon; Kruusmaa, Maarja; Ristolainen, Asko (2023). Maneuvering on non-Newtonian fluidic terrain: a survey of animal and bio-inspired robot locomotion techniques on soft yielding grounds. Frontiers in Robotics and AI, 10, 1113881. DOI: 10.3389/frobt.2023.1113881.

Burlet, Christian; Stasi, Giorgia; Godon, Simon; Gkliva, Roza; Piho, Laura; Ristolainen, Asko (2023). ROBOMINERS resilient reflectance/fluorescence spectrometers. <i>EGU General Assembly 2023: EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023.</i>Copernicus GmbH, EGU--12056. DOI: 10.5194/egusphere-egu23-12056.

2022

Godon, S.; Ristolainen, A.; Kruusmaa, M. (2022). An Insight on Mud Behavior Upon Stepping. IEEE Robotics and Automation Letters, 7 (4), 11039−11046. DOI: 10.1109/LRA.2022.3194667.

Industrial property

Invention: Robotic Foot Design for Enhanced Locomotion on Soft and Wet Grounds; Owners: Tallinna Tehnikaülikool, Tallinna Tehnikaülikool, Infotehnoloogia teaduskond, Arvutisüsteemide instituut; Authors: Simon Pierre Godon, Maarja Kruusmaa, Asko Ristolainen; Priority number: P202400026; Priority date: 03.11.2024.

Elulookirjeldus

Simon Pierre Godon

ORCID	0000-0003-1928-2696
E-post	simon.godon@taltech.ee

Teadustöö põhisuunad

ETIS VALDKOND: 4. Loodusteadused ja tehnika; 4.13. Mehhanotehnika, automaatika, tööstustehnoloogia; CERCS VALDKOND: T125 Automatiseerimine, robootika, juhtimistehnika

ETIS VALDKOND: 4. Loodusteadused ja tehnika; 4.6. Arvutiteadused; CERCS VALDKOND: T121 Signaalitöötlus

ETIS VALDKOND: 4. Loodusteadused ja tehnika; 4.7. Info- ja kommunikatsioonitehnoloogia; CERCS VALDKOND: T181 Kaugseire

Töökohad ja ametid

01.09.2024–...	Tallinna Tehnikaülikool, Infotehnoloogia teaduskond, Arvutisüsteemide instituut, Doktorant-nooremteadur (1,00)
01.02.2020–31.08.2024	Tallinna Tehnikaülikool, Infotehnoloogia teaduskond, Arvutisüsteemide instituut, doktorant-nooremteadur (0,75)
10.10.2019–31.01.2020	Tallinna Tehnikaülikool, Infotehnoloogia teaduskond, Arvutisüsteemide instituut, Biorobootika keskuse insener (1,00)

Teaduskraadid

Simon Pierre Godon, doktorant, (juh) Maarja Kruusmaa; Asko Ristolainen, Robotic locomotion in low-yield environments, Tallinna Tehnikaülikool, Infotehnoloogia teaduskond, Arvutisüsteemide instituut.

Haridustee

28.08.2016–19.09.2019	MSc Robotics - University of Bristol and MEng Mechanics/electronics - Arts et Metiers ParisTech

Lõppenud projektid

- MNVA22037 "Kiiresti muutuvate hüdrodünaamiliste keskkonnatingimustega kohanemine Teravmägede rannikumeres: Teravmägede Ülikoolikeskuse ja Tehnikaülikooli ühisprojekt" (20.05.2022−11.07.2024); Vastutav täitja: Maarja Kruusmaa; Tallinna Tehnikaülikool, Infotehnoloogia teaduskond, Arvutisüsteemide instituut (koordinaator), Tallinna Tehnikaülikool, Loodusteaduskond, Meresüsteemide instituut (partner), Tallinna Tehnikaülikool, Loodusteaduskond, Geoloogia instituut (partner); Finantseerija: Välisministeerium; Eraldatud summa: 300 000 EUR.
- VFP19025 "Kohanemisvõimelised kaevandusrobotid" (1.06.2019−31.05.2023); Vastutav täitja: Maarja Kruusmaa; Tallinna Tehnikaülikool, Infotehnoloogia teaduskond, Arvutisüsteemide instituut (partner); Finantseerija: Euroopa Komisjon; Eraldatud summa: 633 750 EUR.
- PRG1243 "Mitmemastaabiline looduslike veevoolude mõõtmine rannikualadele ja jõgedele" (01.01.2021−31.12.2021); Vastutav täitja: Jeffrey Andrew Tuhtan; Tallinna Tehnikaülikool, Infotehnoloogia teaduskond, Arvutisüsteemide instituut (koordinaator); Finantseerija: Sihtasutus Eesti Teadusagentuur; Eraldatud summa: 257 125 EUR.

Õppetöö

Robotics guidance and software
6 ECTS
Role: Develop lecture material and assignment material, give lectures, set up the online course environment, assist and grade students

Publikatsioonid

2025

Godon, Simon; Prados, Carlos; Chemori, Ahmed; Ristolainen, Asko; Kruusmaa, Maarja (2025). Walking in Mud: Modeling, Control, and Experiments of Quadruped Locomotion. IEEE/ASME Transactions on Mechatronics, 1−12. DOI: 10.1109/TMECH.2025.3560588.

2024

Godon, S.; Ristolainen, A.; Kruusmaa, M. (2024). Robotic feet modeled after ungulates improve locomotion on soft wet grounds. Bioinspiration & Biomimetics, 19 (6), #066009. DOI: 10.1088/1748-3190/ad839c.

R. Gkliva; W. Remmas; S. Godon; J. Rebane; K. Ochs; M. Kruusmaa; A. Ristolainen; (2024). A Multi-Terrain Robot Prototype With Archimedean Screw Actuators: Design, Realization, Modeling, and Control. IEEE Access, 12, 95820−95830. DOI: 10.1109/ACCESS.2024.3426105.

2023

Godon, Simon; Kruusmaa, Maarja; Ristolainen, Asko (2023). Maneuvering on non-Newtonian fluidic terrain: a survey of animal and bio-inspired robot locomotion techniques on soft yielding grounds. Frontiers in Robotics and AI, 10, 1113881. DOI: 10.3389/frobt.2023.1113881.

Burlet, Christian; Stasi, Giorgia; Godon, Simon; Gkliva, Roza; Piho, Laura; Ristolainen, Asko (2023). ROBOMINERS resilient reflectance/fluorescence spectometers. <i>EGU General Assembly 2023: EGU General Assembly 2023, Vienna, Austria, 24-28 Apr 2023. </i> Copernicus GmbH, EGU--12056. DOI: 10.5194/egusphere-egu23-12056.

2022

Godon, S.; Ristolainen, A.; Kruusmaa, M. (2022). An Insight on Mud Behavior Upon Stepping. IEEE Robotics and Automation Letters, 7 (4), 11039−11046. DOI: 10.1109/LRA.2022.3194667.

Tööstusomand

Patentne leiutis: Robotijala disain paremaks liikumiseks pehmel ja märjal pinnasel; Omanikud: Tallinna Tehnikaülikool, Tallinna Tehnikaülikool, Infotehnoloogia teaduskond, Arvutisüsteemide instituut; Autorid: Simon Pierre Godon, Maarja Kruusmaa, Asko Ristolainen; Prioriteedi number: P202400026; Prioriteedi kuupäev: 03.11.2024.

ISSN 2585-6901 (PDF)
ISBN 978-9916-80-332-5 (PDF)