THESIS ON INFORMATION AND SYSTEM ENGINEERING C34

A task-oriented design of a biologically inspired underwater robot

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Declaration: I hereby declare that this doctoral thesis, submitted for the doctoral degree at Tallinn University of Technology, is my original investigation and achievement and has not been submitted for any other degree or examination.

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Abstract

This thesis explores a methodology of a task-oriented biologically inspired robot design process. Robotics is a quickly emerging discipline and engineers working in this field are using many different methodologies. The design process is often divided between different domains where mechanics, electronics and software are developed independently, not in the same iteration loop. The problem is also how to handle biologically inspired design, as it is unfamiliar to engineers and it is hard to estimate time and resources needed.

After describing various methodologies used in the past and at present, we propose a lightweight agile design methodology which is adapted from Extreme Programming method in software engineering and modified for the purpose of biologically inspired mechatronics design. This methodology is good at handling unknown factors and changing requirements.

We applied this methodology to design a biologically inspired underwater robot. Our robot uses fin propulsion and it resembles fish. We know that fish are much more efficient swimmers than man-made machines, and our goal was to make a robot that has better manoeuvrability and lower energy consumption than currently available robots. Our approach was to learn as much as possible from good swimmers in biology and adapt their naturally evolved properties to the robot. Such kind of a robot is not an exact copy of any fish, but combines several useful properties from many biological species to fulfil the requirements of our task oriented design.

Our research also validates this design methodology by developing a series of prototypes and performing a series of tests as well as by Computational Fluid Dynamics computer simulations with 3D models of the robot compared to 3D models of the other fish and geometrical objects.

The design choices are task-specific and environment-specific. We prove by practical experiments and computer simulations that these design choices are adequate and the robot is able to perform the initially specified tasks. This also proves that the proposed design methodology is usable for this type of applications and tasks.

Kokkuvõte

Doktoritöö raames vaatleme metoodikat, mida tuleks kasutada bioloogiast inspireeritud robotite projekteerimisel ja valmistamisel.

Robootika on kiirelt arenev teadusharu, milles tegutsevad insenerid on saanud oma erialase ettevalmistuse kas mehhaanika, elektroonika, programmeerimise või automaatika alal ja seetõttu kasutatakse ülesannete lahendamisel ka nendel erialadel levinud parimaid inseneripraktikaid. Selle juures on aga probleemiks, et mehhaanikas kasutatavad disainimeetodid on halvasti kasutatavad robotite tarkvara disainil ja tarkvara disaini meetodid ei sobi jällegi mehhaanika disainiks. Nii kasutataksegi robotite disainil segamini mitmeid erinevaid metoodikaid ja kogu projekteerimine jagatakse mehaanika, elektroonika ja tarkvara osaks, selle asemel, et vaadelda neid kolme komponenti üheskoos.

Omaette probleemiks on ka bioloogiast inspireeritud disaini aspektid, kuna bioloogia on halvasti formaliseeritav ja inseneridel pole reeglina varasemat sellealast kogemust. Tänasel päeval on enamus bioloogiast inspireeritud roboteid tehtud selleks, et kontrollida mõne bioloogia hüpoteesi paikapidavust, või siis täidavad nad meelelahutuslikke funktsioone. Juhul kui ka bioloogiast inspireeritud lahendused muidu kasutust leiavad, on nad tihtipeale ühekordse iseloomuga, sobitatud ainult ühe konkreetse probleemi lahendamisele ja seetõttu pole nende kohta ka standardiseerituid komponente ega kataloogiandmeid. See teeb selliste projektide realiseerimise aja ja keerukuse prognoosimise raskeks, kuna planeerimise ja projekteerimise algandmed on ebatäpsed.

Käesolevas töös vaatleme seni kasutusel olevaid disainimetoodikaid ja pakume välja tarkvaraarendusest tuntud Ekstreemprogrammeerimise metoodika robootikale kohandatud varianti.

Ekstreemprogrammeerimise meetod on välja arendatud just nimelt ajas muutuvate ja halvasti formaliseeritud disainiprobleemide lahendamiseks, samas on seal aga puudu mehhaanika disaini jaoks hädavajalikud osad nagu modelleerimine ja simuleerimine. Kui lisada juurde need puuduvad metoodika osad ja soovitused, mida bioloogiast inspiratsiooni saamiseks silmas peab pidama, siis saame metoodika, mis sobib robootika arenduseks paremini kui teised senised meetodid.

Olen selle töö käigus ka seda meetodit ise praktiliselt katsetanud, rakendades seda bioloogiast inpsireeritud allveeroboti väljatöötamiseks. Antud robot kasutab edasiliikumiseks sõukruvide asemel uimi. Me teame, et kalad on efektiivsemad ujujad kui mehhaanilised seadmed ja oma töös olen võtnud erinevatelt kaladelt minu ülesande seisukohast kasulikke omadusi. Selliselt kokkupandud seade meenutab küll kalu, kuid pole ometigi koopia ühestki reaalselt eksisteerivast kalaliigist, kuna ka tema tööülesanne on teine kui kaladel.

Tehtud valikute õigsust kontrollin läbi mitmetel katsetel saadud mõõtmistulemuste ja arvutis läbi viidud modelleerimise ja simuleerimise tulemuste.

Läbiviidud eksperimendid annavad aluse väita, et robot on suuteline täitma temale algselt seatud ülesanded ja samuti näitab see, et väljapakutud disainimetodika on sobilik sellelaadiliste ülesannete jaoks.

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I am also grateful to Enterprise Estonia that has financed a market research project to evaluate the potential of the developed bio-inspired underwater robot.

Many experiments would have not been possible without the help of my valuable assistant Deivid Pugal who contributed a lot to preparing the first prototype.

Finally I would like to thank my family and friends for their understanding, patience and support and help, especially when I needed assistance in conducting practical experiments.

Contents

Chapter 1

Introduction

The focus of this thesis is on development of a new kind of method for designing a biologically inspired underwater robot that has properties of various biological swimmers and has therefore several advantages over traditional underwater robots. We address issues of task-specific and environment-specific design and discuss advantages and disadvantages of our design decisions. We also explain our design methodology and experimental results. The need for a new kind of a design method arouse from a practical necessity. Robotics is a relatively new engineering discipline and so far most of the development is done in universities or in big companies. While university projects often do not have practical industrial output, they can experiment with different designs and they also do not care about a systematic design methodology. On the other hand, big companies have often more resources and can use existing industrial design methods, but they do not experiment much. In our case we had a small university team and SME (small or medium-size enterprise), a practical problem to solve and a result to deliver. First we looked for classical design methods, but quickly discovered that they are not applicable for various reasons. We then adapted the agile development methodology that is well known in software engineering. In next chapters we describe and discuss all aspects of our proposed methodology.

1.1. The problem

Our original goal was to design a vehicle for environmental monitoring in The Baltic Sea. The purpose of that robot was monitoring of underwater vegetation and benthic morphology. This task arose from practical needs of environmental biologists; the researchers needed a practical, flexible and multipurpose monitoring robot. The problem appears to be non-standard in the sense that environmental biologists had not found any suitable commercial robot for their purpose. All available models had some disadvantages that made them unsuitable. They needed a robot for two different types of tasks. One task was to quickly cover large seabed areas and videotape the vegetation coverage. Comparing the amount of seaweed over several years tells much about environmental conditions in the current area. The second task was to take samples and to explore points of interest more closely.

The problem of biologists was that those robots that can be towed behind the boat to cover quickly large areas cannot be stopped or used for detailed observation because of the lack of thrusters and those robots that are maneuvreable cannot be towed because of their bad hydrodynamic shaping. Even when used for manoeuvring across the seabed the water jets from propellers rise mud and sediments and decrease visibility.

This all means they needed a robot built according to their own specification. The robot was supposed to be not just any kind of a robot but had several restrictions. It was supposed to be light and easy to operate; the main requirement was silent and non-turbulent bottom following ability with quick manoeuvrability and hovering mode if needed. The robot was also supposed be deployable from an inflatable boat.

The next set of problems that arose was connected with task- and environment specific design decisions. After evaluating the existing technological possibilities and available technologies, we reached the conclusion that the best solution would be to replicate several fish and their behaviours, that means we decided to do biologically inspired design. This again raises the question of a design methodology. There is no systematic biologically inspired design methodology available.

Yet another problem was that we did not have any experience in the field of underwater robotics, so we did not have any idea how long this design process would take and how many resources we need. Both of these issues are connected to handling uncertainties of the design process. In addition, this work was partly performed by a small size enterprise. Though it was partially supported by universities and several foundation we still had very little resources available compared to big research centres with dedicated equipment. This proposed additional restrictions to the design choices.

The systematic design methods used in mechanical engineering and mechatronics were not applicable for this problem domain. These methods use much planning and computer aided methodologies for designing mechanical parts. Our problem was that the suitable solution would be a biologically inspired design, but these solutions were not well described by expert knowledge used in simulation and design software, the details were not available from the product catalogues, also there was little use of CAD/CAM tools using well adapted industrial design methods. We still decided to go on with our project and started also developing a methodology for our own purpose. We adapted the Agile software development procedure, known in software engineering, and broadened it to cover issues of mechatronics.

1.2. Outline of the thesis

Previously, we described the motivation of our work and the problem scope. In the next chapter we give an overview of existing solutions and state-of-the-art in the field. The remaining sections describe our approach and discuss the results.

Chapter 2 gives an overview of underwater robotics in the world, Chapter 3 describes the basic aspects of fish biology and the terminology used to describe their propulsion mechanisms. In Chapter 4 we discuss the biomimetic design as an alternative to the traditional mechatronics design.

We also describe state-of-the-art in biomimetic underwater robotics. Later in this chapter we address the biomimetic design principles and define these properties that are important for our biologically inspired robot. This chapter also describes the new design methodology that is suitable for biologically inspired robot design.

In Chapter 5 we describe the prototypes of the developed robot and describe the preformed tests. We start with the first experimental model, analyse its performance, then describe the second improved prototype and finally describe the third experimental model.

In Chapter 6 we also give a short overview of a performed market survey and envision the potential of our developed robot.

Chapter 7 provides the evaluation of the methods discussed in the earlier chapters, gives the results obtained so far and discusses the future research directions.

1.3. Contribution of the thesis

The first contribution of this thesis is a light-weight biologically inspired task oriented agile design methodology for robotics. This methodology is good in handling not very well defined design processes where developers do not have all the necessary competence and resources or the design object can not be fully specified in the beginning.

The second contribution is an innovative design of a task-oriented biologically inspired underwater robot. The robot is not just a replica of any existing fish, but design inspiration comes from several different fish and each of them contributes their specifically well adapted properties to the robot. The resulting robot combines therefore only the useful properties of fish that are needed for performing the specified tasks. To our best knowledge, this is the first hybrid and task-specific bio-inspired underwater robot developed so far.

The third contribution is a comparative study of wake turbulence characteristics of different fish and the biomimetic robot. This study can be expanded when needed and offers insight to the theoretical limits of performance of underwater robots.

Chapter 2

Underwater robots

In this chapter we give a short description of different types of underwater robots in the world. We also describe shortly their usage and availability.

We can divide underwater robots into subclasses according to different principles. One way is to classify according to their usage, another way is to classify according to the degree of autonomy.

If we classify according to the degree of autonomy, then we have three main categories. The first group is Remotely Operated Vehicles (ROV) that are built for inspection of different underwater objects like pipelines, cables, etc. These devices have short range that is limited to the tether length. Some examples are in Fig. 1 and 7. According to Marine Technology Society ROV Committee data from 1990 only 27 companies offered cheap ROVs with a price less than 100 000 USD comprising 35 models altogether of which only 500 vehicles were produced [1]. According to ROV information portal ROV Exchange, 18 manufacturers offer currently 70 different models of ROV-s.

Fig 1. Perry Tritech Triton XL ROV

Fig 2. Maridan AUV

Fig 3. Kongsberg Hugin AUV

The second group are tow-able robots (UTV – Underwater Towed Vehicle) that are towed with a constant speed and are able to cover large areas very quickly. These robots have some limited intelligence that allows them to automatically maintain the preprogrammed depth. UTVs are mostly used for environmental monitoring purposes. There are approximately 10 producers of these vehicles. One example of this kind of robots is Acrobat UTV in Fig. 4 from Seasience Inc.

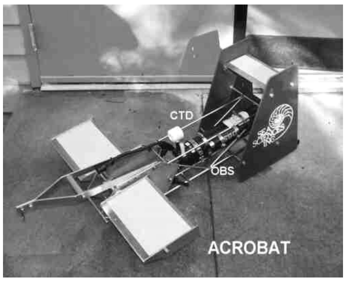


Fig. 4. Seasciences Inc UTV Acrobat

Fig. 5. Hydroid Inc. REMUS 100

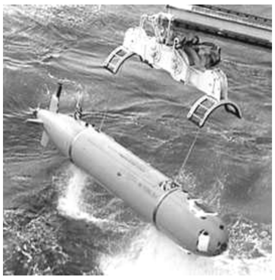


Fig. 6. Autosub AUV.

The third group is fully autonomous (AUV – Autonomous Underwater Vehicles) robots. These robots swim according to the pre-programmed path or explore an area on their own following some guidance or search algorithm. These robots must use some procedures to cope with unexpected situations. While ROVs and UTVs are teleoperated and have a cable for communication with the operator, AUVs are using acoustic communication or radio communication when on surface. Acoustic communication is unfortunately not very reliable and in addition the used frequencies are very long, which means that the possible speed of data communication is very slow. That means these robots must be able to survive mostly without human intervention.

A good example here is Autosub AUV, shown in Fig. 6, from National Oceanography Center, University of Southampton [2]. This robot has been in use since 1996 for scientific surveys. The total number of missions completed is 271 and the total number of mission hours is 750. The total distance traveled is 3 596 km, the deepest mission has been 1 003 m, and the longest mission has been 262 km and 50 hrs. The longest autonomous, unescorted operation has been 1812 km [2]. The robot has been extensively used under Antarctic and Arctic ice shields. In 2005 it explored 25 km during 27 hours under the Fimbulisen Glacier in Antarctica [60].

Another good example is MARIDAN AUV shown in Fig. 2, which is designed to be flexible, and is suitable for a wide range of underwater missions covering both civilian and military requirements [3]. On a completely autonomous mission the vehicle performs a pre-programmed survey, but the vehicle can be observed by an operator over an acoustic link from the support ship within a distance of 2 kilometers. This robot is designed to be used for offshore oil and gas field surveys, mineral field surveys, telecommunication cable surveys, offshore pipeline pre-lay surveys and post-lay inspections, military surveys, wind mill park construction surveys, search & recovery and for oceanographic surveys.

Yet another good example is SeaGlider in Fig. 9 from University of Washington [4]. This craft is designed to cross oceans and during the voyages it collects environmental data and relays them through a satellite link. The novelty of this robot is in its ability to change its buoyancy and use it for horizontal propulsion.

Kongsberg HUGIN , shown in Fig. 3 is also a noticeable example of successful AUVs [5]. In 1995 the project was started as cooperation between Statoil, Norwegian Defense Research Establishment (FFI), Norsk Undervannsintervensjon (NUI) and KONGSBERG. Its intended civilian usage covers high-resolution high-speed seabed mapping and imaging, ocean exploration and monitoring, marine geological survey, inspection of underwater engineering structures and pipelines, search operations and its military usage covers mine countermeasures - MCM, rapid environmental assessment - REA / Battlespace access, anti-submarine warfare - ASW, intelligence, surveillance and reconnaissance.

We must mention also Hydroid Inc. REMUS AUV, shown in Fig.5 [6]. This AUV is used successfully for environmental monitoring and for hydrographic surveys.

Another type of classification can be made according to the usage of robots. These two main subclasses are: working and monitoring class.

Working ROV-s are big and heavy, weighting several tons and are able to repair and build mechanical constructions like pipelines, oil pumps etc. under water. The monitoring class can be divided into three more subclasses: ordinary, mini and micro class. Here the division is done according to the size of robots. Both the working and monitoring class has ROVs, UTVs and AUVs.

Fig. 7. Videoray Pro III ROV

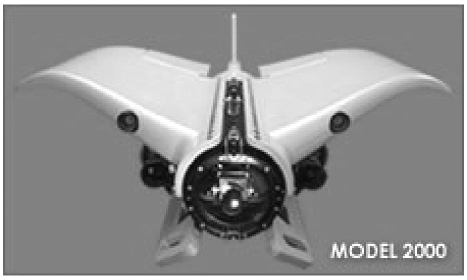


Fig. 8 Novaray 2000 ROV/ UTV

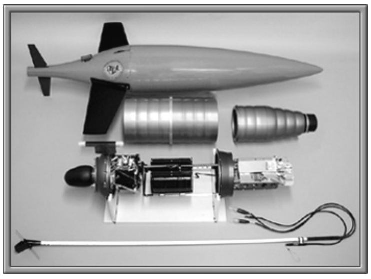


Fig. 9. SeaGlider

Sometimes ROV-UTV-AUV hybrids are made. They are more complicated, but more versatile. One example of ROV-UTV hybrids is Novaray 2000 shown in Fig. 8 from Nova Ray Inc [7]. This vehicle is small, light and suitable for environmental monitoring purposes. The main disadvantage of this robot is the usage of thrusters for maneuvering. In our conditions the propellers raise instantly the volatile mud from the seabed and visibility becomes zero, so the video recording becomes impossible. A much better solution would be the usage of buoyancy control mechanism and locomotion principles that fish use. That would not disturb the sea bed and would permit video recording. This robot was a solution, closest to our needs, but the unsuitable buoyancy control was the reason why we started to build our own robot.

Chapter 3

In the previous chapter we gave an overview of underwater robots and mentioned the problem that robots with propellers create strong water jets and turbulence. As we described briefly in Chapter 1, the main design requirement of our robot was having as low turbulence as possible. The second requirement was the ability to follow the bottom profile and a good maneuverability. If we look how nature has solved the problem of underwater locomotion, then we see that fish create very little turbulence and almost do not raise mud from seabed when swimming. This suggests us that biologically inspired design might be better for the task we have. In this chapter we give a short overview of fish propulsion and introduce the terminology used to describe fish swimming. This brief introduction facilitates later our discussion on biologically inspired design.

Principles of fish swimming

Fish use their body and fins for locomotion. However, not all fish use the same body parts to create thrust and these body parts are not used in the same way. It varies a lot depending on their environment and their living conditions.

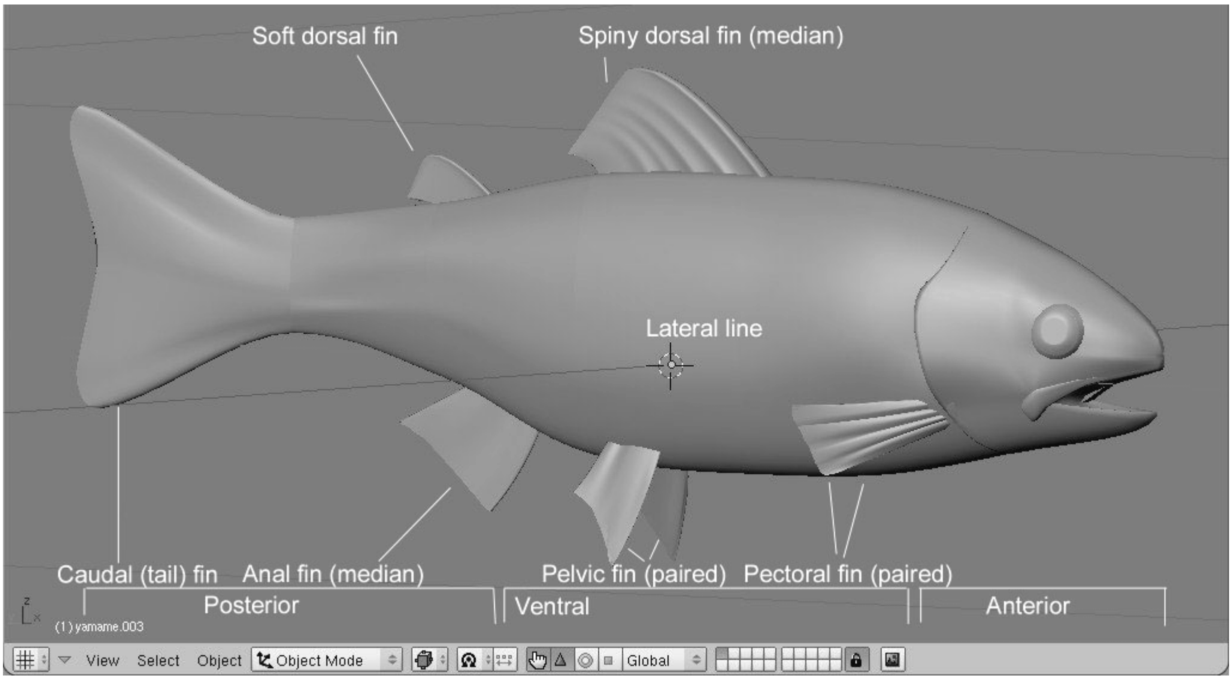


Fig. 10. Fish terminology (salmon)

Fish produce thrust using a variety of different mechanisms and using different fins (see Fig. 10). The physics and physiology of fish swimming are summarized in works of Blake [8] and Webb [9] and the most recent comprehensive review in this field is published by Videler [10]. We still give a short overview here and refer also to “A Quick Course in Ichthyology” [120].

Muscles provide power for swimming and constitute up to 80% of the fish itself. The muscles are arranged in multiple directions and allowing fish to move in any direction (Fig. 13). Some fish use undulatory body movement. That means a sinusoidal wave passes down from the head to the tail and creates pressure differences between two sides. This Bernoulli force lift and rowing movement of the tail pushes the body along its longitudinal axis. These forces are shown in Fig. 11. The fish body has three different forms of drag. These types are described in Fig. 12. The pressure and vortex drag can be minimized by changing body shape and skin drag is reduced by slime excrete. In Fig. 10 and Fig. 14 the names of the fins are given. We give here a short overview of their purposes:

- Caudal fin - provides thrust, and controls the direction of the fish

- Pectoral fins - act as rudders and hydroplanes to control yaw and pitch. Also used for braking by causing drag.
- Pelvic fins - mostly for controlling pitch
- Dorsal and anal fins - controlling roll

The caudal fin gives the most of the propulsive force. In Fig. 14 the different types and the usage of the caudal fin are described.

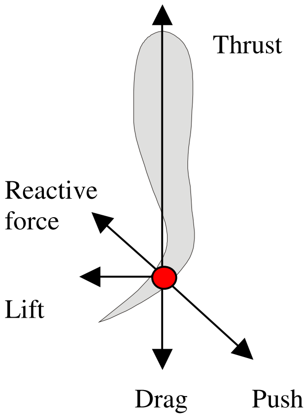


Fig. 11. Forces acting on a fish

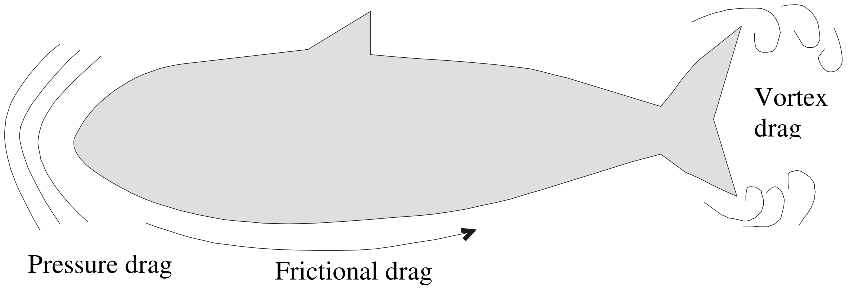


Fig. 12. Drag forces

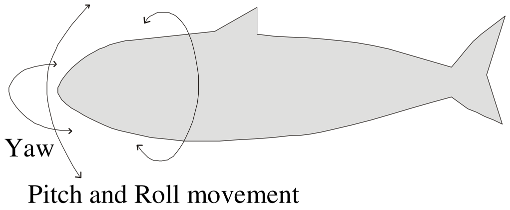


Fig. 13. Fish movements

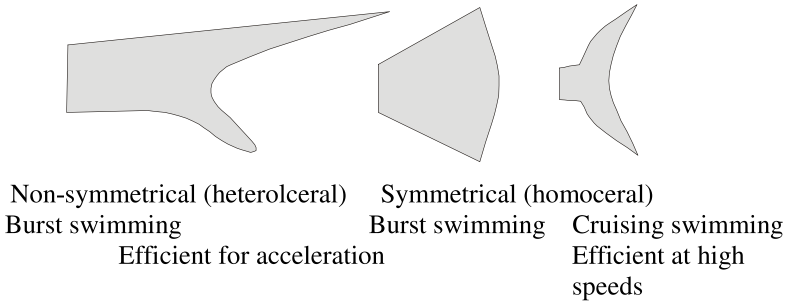
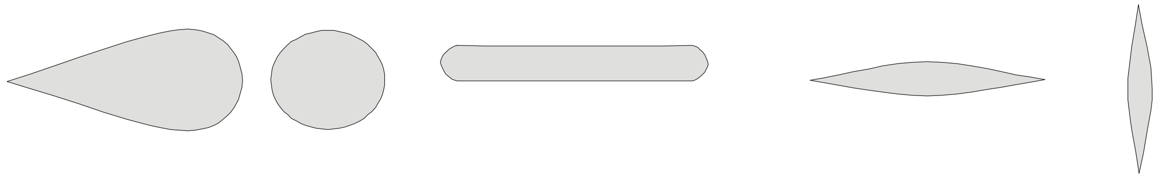


Fig. 14. Types of caudal fin



Fusiform body – side and front view

Attenuated body

Depressed body (flattened dorso ventrally)

Compressed body (flattened side to side)

Fig. 15. Body types

Fish can also have different body forms. A short description of them is given in Fig. 15. A Fusiform body is adapted for cruising at high speed, the attenuated shape allows to maneuver, the depressed shape is good for quick acceleration and bottom following and compressed shape gives a great agility, good maneuverability and enables quick accelerations.

Next we describe fin propulsion according to the usage of fins. The classification of swimming modes of fish described here comes from Lindsey [11] and D.J. Randall [12]. First we give the swimming type and secondly we give the swimming mode.

I. The first type is movements of the body and/or the caudal fin (called also as BCF type, see Fig. 11). This mode accounts for the primary propulsive forces in 85% of the fish families [8, 10, 13]. Fish undulate their bodies to create a near sinusoidal wave of bending which increases in amplitude from head to tail. This production of thrust along the body creates vortices in the fluid, which grows in magnitude until it is shed into the wake behind the fish [14,15].

   BCF swimming modes are:

   - Anguilliform;
     Undulating mode, propulsion by a muscle wave in the body of the animal which progresses from the head to the tail like for eel and lamprey. The side-to-side amplitude of the wave is relatively large along the whole body, and it increases toward the tail. A good example is eels that travel to the Sargasso Sea for spawning.
   - Subcarangiform;
     Less musculature used than in Anguilliform locomotion. Between 1/2 and 2/3 of body muscle mass is used to generate undulating waves down the body. A typical swimming mode for many common freshwater fish like trout and salmon. Both fishes cover large distances to swim to their spawn rivers.
   - Carangiform;
     They are oscillating a tail fin and a tail peduncle like salmon, trout, tuna and swordfish
   - Thunniform;
     Thrust is generated with a lift-based method, allows for the greatest long-term speed. This mode is inefficient for slow swimming, turning manoeuvres and rapid acceleration. Used by sharks and, tunas.
   - Ostraciiform;
     Oscillating mode, motion is slow back and forth movement of a tail fin but without moving the body like boxfish. This mode is considered to be an inefficient swimming method. These fish live in reefs where speed of swimming is not important. For defence they compensate the slow speed with a very powerful toxin.

The second major subgroup is median and/or paired fin propulsion (also called as MPF propulsion) which use undulation or oscillation of median or pectoral fins. This type accounts for the primary propulsive forces in 15% of the fish families [10,13]. This group has two subgroups, divided by the usage of undulatory or oscillatory motion:

II. Undulation of median or pectoral fins

   - Amiiform;
     The bowfin utilize this style of undulations passing along the dorsal fin while the body axis is in many cases held straight when swimming. Locomotion waves may pass in the direction along the dorsal fin, and may show widely varying amplitude, particularly during turning or braking. Amiiform swimmers have not changed their form from Jurassic age 200 millions years ago.
   - Gymnotiform;
     This type of swimmers lack pelvic fins and dorsal fins. The anal fin is extremely long; this fin is undulated to allow the fish to move both forward and backward. The caudal fin is absent or, in the apteronotids, greatly reduced. These fish have a rigid body and do not have the enhanced friction drag that results from body undulations significantly increasing the swimming drag compared to that of the rigid body. Examples are: neotropical electric fish, South American electric fish, or American knifefish.
   - Balistiform;
     They undulate simultaneously both dorsal and anal fins, like triggerfish.

- Rajiform;
  Rays and knifefish use a swimming mode in which long fins extending along most of the body length undulate to cause propulsion. They are good bottom followers.
- Diodontiform;
  Propulsion is achieved by passing undulations down the broad pectoral fins. Up to two full wavelengths may be visible along the fins, while undulations are often combined with oscillatory movements of the fin as a whole. An example is pufferfish.

III. Oscillations of median or pectoral fins:

- Tetraodontiform;
  The body of these fish is inflexible, and undulation during movement is limited to the caudal fin. Because of this, they are slow and rely on their pectoral and caudal fins for propulsion. However, movement is usually quite precise; dorsal and anal fins aid in manoeuvring and stabilizing. In most species, all fins are simple, small, and rounded. Examples are boxfish, pufferfish and filefish.
- Labriform;
  Pectoral fins are used to push water, similar to a rowing effect. An example is labridae, a tropical coral reef fish.

In Fig. 16 we give also a short diagram to show how the swimming modes described above are the result of adaptation in different conditions.

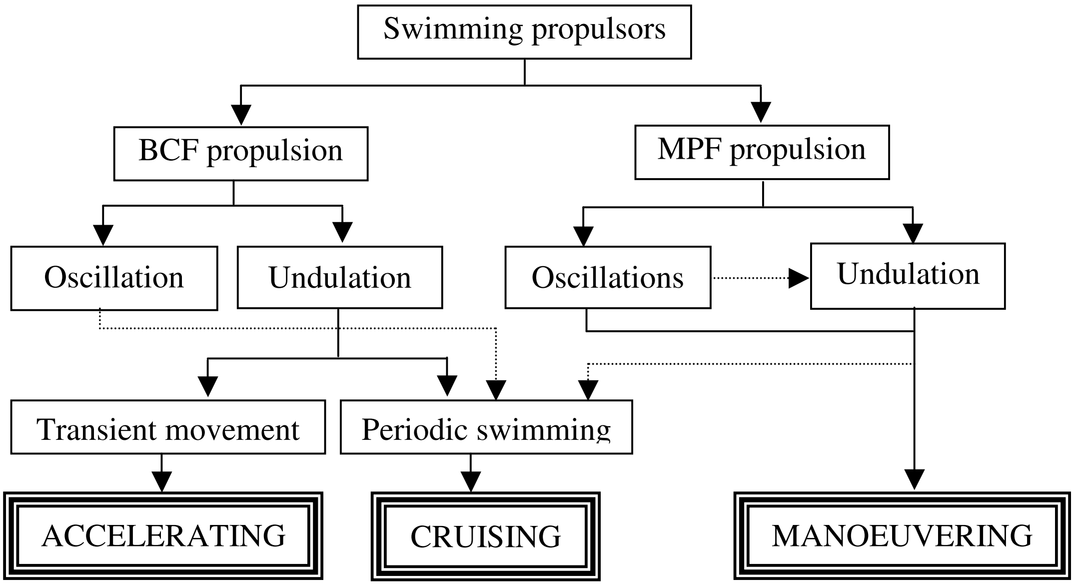


Fig. 16. Diagram showing the relation between propulsions modes and swimming functions. (Adapted from [13])

As we see, different fish have adapted themselves for living in their environment and feeding habits. This suggests us that in order to be effective and successful in our robot design we have to define our robots "living" conditions and then choose the corresponding propulsion mechanism.

Chapter 4

Biomimetic design – what it is and why to use it

This chapter explains the principles of biomimetic and biologically inspired design. The term biomimetic design is understood as a design that uses biology for inspiration. The history of biologically inspired engineering spans for thousands of years back into the history. The earliest known example was probably 3,000 years ago when ancient Chinese attempted to create artificial spider silk in order to produce cheaper cloth. They never succeeded, but many generations of inventors have still gathered inspiration from biology and invented many other things.

Currently many research organizations in the world have turned towards Nature to get new innovative ideas. Some of the centres are: The Biomimetic Network for Industrial Sustainability [16], Centre for Biomimetics at the University of Reading [17], The Centre for Biomimetic and Natural Technologies, University of Bath [18], Biomimicry Guild in USA [19], Biomimetics New Zealand Inc. [20], BIKON-The Biomimetics Network in Germany [21], Biologically-inspired Product Development Centre in University of Maryland, USA [22], The Key Laboratory for Terrain-Machine Bionics Engineering, Ministry of Education, China [23]. Also the journal "Bioinspiration & Biomimetics" [24] and Journal of Bionics Engineering - Jinlin University China [25] are founded for publishing related scientific work and textbooks are written about the subject [26].

Evolution has had time to develop creatures that are perfectly adapted to their living environment. If we look at fish, then these creatures are the one of the oldest living examples among us. Some of them are good in manoeuvring and others are very fast swimmers, some of them are good in hiding and others are efficient predators. The common property to all of them is that they are very energy efficient, if we compare them to a man made technology [27,28,29]. So we may say that fish are all some how specialised to be successful in their underwater living environment. If we design an underwater robot and decide to use fin propulsion, then we do a biomimetic design, because we use fins, and are using an idea borrowed from biology.

If we decide to learn from Nature's long experience, then we propose next steps to follow:

- Define task and environment conditions for application
- Find which properties and features of robot are the most with respect to our new design.
- Analyze habits and properties of biological creatures that live in similar a environment.
- Compare man made technologies and those found in nature and select some most contributing properties of the robot that should be implement using biomimetic methods. We can of course replicate the whole creatures as nature has created them, but it is rarely entirely possible and not needed

These biologically inspired design issues might be different and could be for example:

- Control related design choices like usage of central pattern generator for controlling actuators [49,50,51,52].
- Construction related problems like body shape [53].
- Mechanical design related locomotion principles like usage of undulation or oscillation for movement [54,55] or usage of legs instead of wheels [119].
- Usage of solar or other environmental or biological energy sources [62,63,64,65,66].
- Usage of genetics algorithms for learning and adaptation. [67,68,69].
- Communication related problems using for example ultrasonic or electroreception, tactile signals or body shapes and colors for transmitting meanings. [70,71,72,73,74,75,76,77].
- Sensory input related design issues like using neural networks for classifying input signals or using flexible skins that sense environment signals.[78,79,80,81,82,83].
- Usage of artificial muscles instead of electric motors [55].

From these subject areas we should identify the most important factors that have the biggest impact to our task and context oriented design. Then we have to compare the available industrial technologies to the biological solution and decide which way to go. If we decide that biological creatures have advantages in some areas, then we have to find a ways to reproduce the desired effects. All the all other design decisions should follow from these most important factors and design decisions. Biomimetic design cannot be well described by formal rules. The replication process of desired features is full of surprises and new solutions to overcome some technical challenges. This process requires rapid reactions and redesigns and is therefore hard to handle by well-known design methodologies. In the next chapter we look state-of-the-art in biomimetic underwater robotics

4.1. Biomimetic robots

In this chapter we give an overview of biomimetic underwater robots built so far. There are not many of them, so we can shortly describe most of them. We classify them here according to their purpose of development.

The first kind of projects are done to study some certain aspects of fish locomotion [39,40] or are trying to verify some biological hypothesis [41,45,48]. For example the Katolab in Japan has studied the fin motion of Black Bass to understand how the various fins are controlled for advancing, backing, hovering and turning [39]. Ken McIsaac from The University of Western Ontario has focusing on eel-like swimming robots and developed mathematical model for anguilliform locomotion [40]. Dr. Ehsan Honary from Intelligent Autonomous Systems (Engineering) Laboratory from University of West of England has created underwater robot capable of altering its density by heating oil. This robot replicates principles used by sperm whales [41].

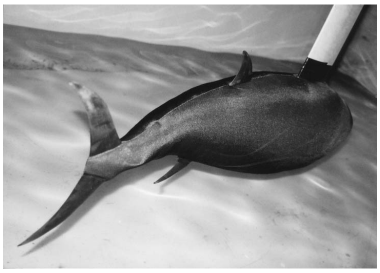


Fig. 17. MIT Robo Tuna


Fig. 18. Experimental model of PF-550, built for study up-down motion mechanism

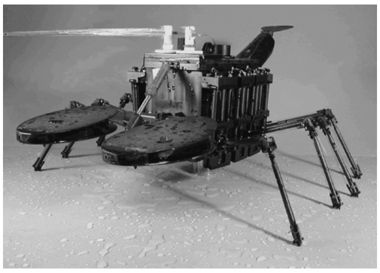


Fig. 19. RoboLobster


Fig, 20. Lamprey-Based Undulatory Robot

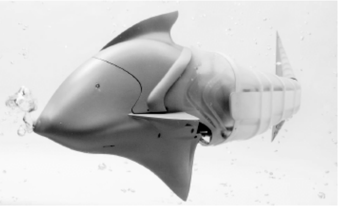


Fig. 21. Aircuda


Fig. 22. Aqua ray

Another good example is Northeastern University Marine Science Center Biomimetic Underwater Robot Program, which has been successful in replicating lobster (Fig. 19) and lamprey (Fig. 20). They started their program at 1992 and continue their studies at present. This is one of the most long lasting studies today [31].

Dr. Koichi Hirata with his co-workers do noticeable work in Japan National Maritime Research Institute. Their research work started in 1999 at the Ship Research Institute, part of the Japan Ministry of Transportation in Tokyo Japan. Their study has focused mostly on fish such as pike or tuna that are fast and efficient swimmers. They have built various different models and have tested them for speed, efficiency, manoeuvrability etc. One example of their work is in Fig 18 [32].

The second kind of projects use fish like robots to study problems of biomimetic technologies in robotics [42]. The best-known robotics fish is perhaps the MIT "robotuna" project [30] (Fig. 17), which began about 1993 with the overall goal of developing a better propulsion system for autonomous underwater vehicles, or AUVs. The team leader was Michael S. Triantafyllou, a professor in the Department of Ocean Engineering. One of the main outcomes of this work was confirmation to the Gray's paradox that the drag of the swimming fish RoboTuna appears to be less than the drag on the straight RoboTuna. A good example is also Prof. Huosheng Hu's and his PhD student Jindong Liu's work from University of Essex, United Kingdom who have also built a Robotic Fish. The main purpose of these robots has been modelling and optimisation of robotic fish behaviours. These robots were also shown to the public in London Aquarium (Fig 24) [34]. The third good example is also a robotic fish that was made in Seattle Robotics Society in 2002. This robot was probably one of the first fully autonomous robot fish. It was also equipped with a sonar. This robot is shown in Fig. 23 [33]. The fourth example here comes from China where the project of underwater bionic robotic fish (Fig. 25) was co-developed in 2004 by the Institute of Robotics in Beijing University of Aeronautics and Astronautics (BUAA) and the Automation Research Institute under Chinese Academy of Sciences [35]. The fifth good example here is FESTO pneumatics based robots Aircuda (Fig. 21) and Aqua ray (Fig. 22) [61]. They were built for pneumatics component manufacturer FESTO to study how their components can be used for replicating fish.

The third kind of projects replicate real fish for entertainment purposes. The good example is from Japan where the now-extinct “coelacanth” has been given a new life in the form of a 12 kg, 70cm long fish robot. Developed as the No. 1 robot of “Mitsubishi Animatronics” (Fig. 26) and exhibited at the science museum “Aquatom”, the robot moves freely and swims like a real fish. The “body” is covered with a soft silicon-resin material, driven by a built-in battery, and designed for computer control via wireless communications. Ryomei Engineering (a subsidiary of Mitsubishi Heavy Industries), in cooperation with two other Hiroshima-area engineering companies, has developed a robot resembling a koi carp (Fig 27). The robot was demonstrated at a pond on the grounds of Hiroshima Machinery Works. The robot is modelled after Nishiki koi carp. This robot was also equipped with an underwater camera.

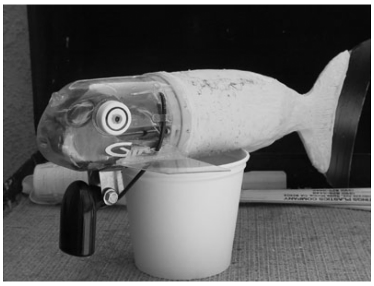


Fig. 23. Seattle Robotics Society fish robot


Fig. 24. Robot fish in public show in London Aquarium on the 10th. Aug. 2005


Fig. 25. Institute of Robotics in Beijing University of Aeronautics and Astronautics robot fish

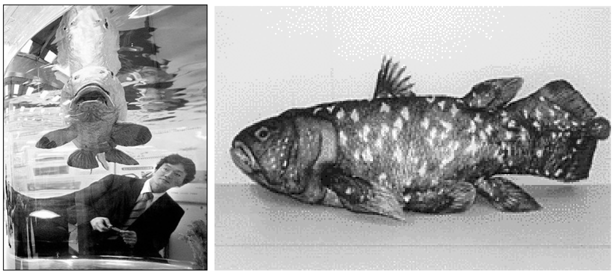


Fig. 26. Mitsubishi animatronics robots


Fig. 27. Koi carp

The fourth kind of biomimetic robots are built by some private companies that have tried to use biomimetic principles in their commercial products. Nekton Research LLC has built an experimental robot Transphibian (Fig. 28) and PilotFish (Fig. 29) with fins. PilotFish is reported to be extremly good in maneuvering, it can stop immediately when needed. They also claim that the thrust of Transphibian has increased and energy consumption is lowered compared to their other propeller driven underwater robots [36].

Another good example is Hobie Cat Company, which has adopted fin propulsion to pedalled kayaks shown in Fig. 30 [37]. They got their inspiration from penguin swimming principles. Their work is based on MIT Proteus experimental vessel made in 1997 by James T. Czarnowski et al.[38].

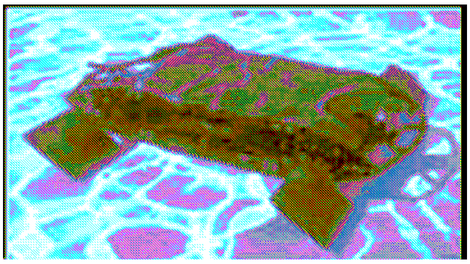


Fig. 28. Nekton Research LLC Transphibian

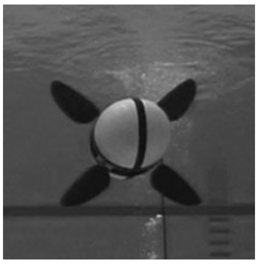


Fig. 29. PilotFish

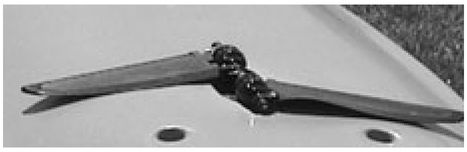


Fig. 30. Hobie Cat fin propulsion unit

Our robot does not fit into these three first categories described above because we do not study fish biology or locomotion principles and our robot is also not for entertainment. By its motivation of development, it is similar to the Nekton Research or Hobie Cat Company's approach. The difference however is that our robot has got influences from several different fish.

Although there are thorough overview studies of fish locomotion [13,44,56,57,58,59] and control methods [43,46,47], there is no systematic study that demonstrates how the specific design choices are related to environmental condition and task requirements. In present day very few attempts have been made to design task-oriented and context-oriented biomimetic underwater robots. Example here is the Nekton Research Transphibian that is inspired by Sea Turtle, robot is very good in maneuvering and is used for finding and destroying mines. There is also no consistent methodology available to follow if we want to do such kind of design. This is the reason why we started developing our own methodology.

Our initial task was to design an underwater robot that can monitor the seabed, take water samples, measure temperature and salinity of the water. The robot should be manoeuvrable if travelling between rocks and should be fast when covering vast flat areas. If we decide to do a biomimetic design, then we should first look for suitable examples from Nature. Which fish have adopted their body and behaviour during the evolution for this kind of tasks?

We cannot find any fish that does exactly the same that we need, no fish takes for example water samples, and no fish uses wires to communicate with humans, no fish has never developed batteries for storing energy. But maybe we should copy the specific properties useful for us from different fish, what are close enough to our goals and create something that has some useful properties from many different fish?

The next important step that we look at, is the overall biomimetic design methodology. In the next chapter we try to formulate questions related to biologically inspired design and propose a methodology for this kind of a design.

4.2. Design methodologies

The previous chapter was describing biomimetics-related problems. We still need an overall good design strategy to follow in order to efficiently solve these problems.

In order to be able to propose any new methodology we should first ask from ourselves: is there any existing methodology available what can be applied to our problem? In robotics we do not have much discussion about how to exactly design robots. Only very few works have been dedicated to this problem. The term "design" can be understood very broadly. Some of the works explore only mechanical aspects of the problem [87], others are concentrating to the software design only [85], solving control problems [86,88,91], mechanical and software design issues [89,90], task oriented design [92,93], and few of them try to see all aspects of the design process [84,94,95].

We mostly apply our own ideas or use something adapted from other fields of engineering. Designs methods in mechanical engineering, for example, are derived from methods used in construction engineering, and have evolved for several hundreds of years. A traditional view to the research and development activities in engineering separates design methods used in research and development in two parts [96]:

- **Research** –uses unstructured design methods, is difficult to plan and is therefore unpredictable.
- **Product Development** –uses structured methods, is planned and should be therefore predictable.

Courses also teach that the generic product development process should follow the rules shown in Fig. 31:

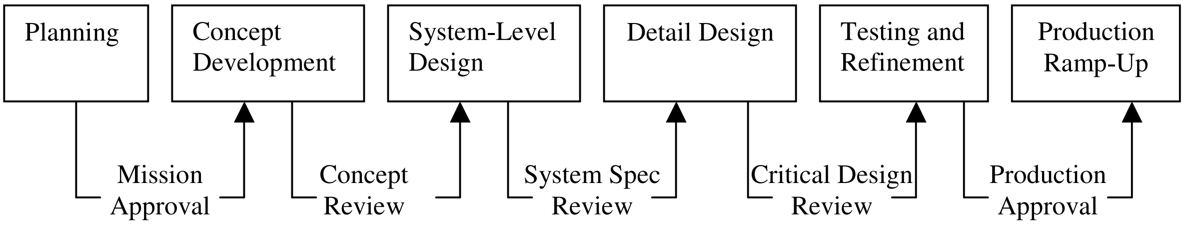


Fig. 31. The Generic Product Development Process

The concept development step in this methodology could be done using the common best engineering practices, which means we draw functional block diagrams to describe and draw tables to systematically organize the ideas. This table, which is sometimes called the FRDPARRC (Functional Requirements, Design Parameters, Analysis, References, Risks and Counter Measures) table could contain the following [97]:

- **Functional Requirements (Events)**-are described by words
  A list of independent functions that the design has to accomplish. Series (1,2,3…) and Parallel (4a, 4b..) Functional Requirements (Events) can be listed to create the Function Structure.
- **Design Parameters (Ideas)** – described by words & drawings
  Ideally independent means to accomplish each Functional Requirement. A Functional Requirement can have several potential Design Parameters. The “best one” must be selected.
- **Analysis Experiments** – described by words, Equations, Spreadsheets
  Economic (financial or maximizing score etc), time & motion, power, stress, etc.Feasibility of each Design Parameter must be also proven.
- **References** – described by historical documents, internet sources, etc.
  Anything that can help to develop the idea including personal contacts, articles, patents, web sites.
- **Risk** – described by words, drawings, and analysis
  Risks are described as High, Medium or Low and risk of development assessment for each Design Parameter is given here.
- **Counter-measures** – described by words, drawings, analysis
  Ideas or plan to mitigate each risk, including the use of off-the-shelf known solutions are described here.

After finishing the FRDPARRC Table we can follow the overall Design Process rules what are designed to develop an idea in steps from coarse to fine. The Design Process rules according to [98] are (quotation):

– First Step: Evaluate the resources that are available.
– Second Step: Carefully study the problem and make sure you have a clear understanding of what needs to be done and what are the constraints (rules, limits). Steps 1 & 2 are often interchangeable.
– Third Step: Start by creating possible strategies using words, analysis, and simple diagrams
  - Imagine possible data flows, and energy flows from start to finish or from finish to start.
  - Continually ask “Who?” “What?”, “Why?”, “Where”, “How?”
  - Simple exploratory analysis and experiments can be most enlightening.
  - Whatever you think of, others will too, so think about how to defeat that about which you think.

– Fourth Step: Create concepts to implement the best strategies, using words, analysis, and sketches
  - Use same methods as for strategies, but now start to sketch ideas
  - Often simple experiments or analysis are done to investigate effectiveness or feasibility
  - Select and detail the best concept…

– Fifth Step: Develop modules, using words, analysis, sketches, and solid models.
– Sixth step: Develop components, using words, detailed analysis, sketches, and solid models.
– Seventh Step: Detailed engineering & manufacturing review.
– Eighth Step: Detailed drawings.

– Ninth Step: Build, test, modify…
– Tenth Step: Fully document process and create service manuals…

This is indeed a very general common sense methodology and is usable in various engineering disciplines. Mechanical engineering often uses Computer-aided engineering (CAE) methods which uses software to help engineers in areas like stress analysis on components and assemblies, thermal and fluid flow analysis with computational fluid dynamics (CFD), kinematics, mechanical event simulation (MES). It also includes analysis tools for process simulation for operations such as casting, molding, and die press forming and optimization of the product or process. In this process they draw their plans with Computer-aided design (CAD) software and later use Computer-aided manufacturing (CAM) software that controls mills and lathes.

Using these tools is done according to Waterfall model in which development is seen as flowing steadily downwards (like a waterfall) through the phases of requirements analysis, design, implementation, testing (validation), integration, and maintenance.

Later the concept Integrated Computer-Aided Manufacturing (ICAM) method was introduced, which was an initiative managed by the United States Air Force and started from 1976 [99]. The idea of this method was to shift the focus of manufacturing from a series of sequential operations to parallel processing. ICAM also started to look other not directly technical parameters that influence the design. This method later becomes IDEF, the standard for modeling and analysis in management and business improvement efforts.

The family of ICAM Definition Languages, short IDEF, was finished in the 1980s [100]. These "definition languages" have become standard modeling techniques. They cover a range of uses from function modeling to information, simulation, object-oriented analysis and design and knowledge acquisition. This standard has now 16 subjects, where first six are more or less completed and in active use and others are still in a research phase. These subjects are among the others:

1. IDEF0 - Function Modeling. - Designed to model the decisions, actions, and activities of an organization or a system. Help to organize the analysis of a system and to promote good communication between the analyst and the customer
2. IDEF1 - Information Modeling. Is generally used to 1) identify what information is currently managed in the organization, 2) determine which of the problems identified during the needs analysis are caused by lack of management of appropriate information, and 3) specify what information will be managed in the TO-BE implementation.
3. IDEF1X - Data Modeling. Is a method for designing relational databases, is not well-suited for non-relational system implementations
4. IDEF2 - Simulation Model Design – is based on experience with continuous, discrete, and network simulation language design
5. IDEF3 - Process Description Capture. - Provides a mechanism for collecting and documenting processes. There are two IDEF3 description modes, process flow and object state transition network.
6. IDEF4 - Object-Oriented Design. IDEF4 views object-oriented design as part of a larger system development framework, rather than an object-oriented analysis and design method that is ambiguous.
7. IDEF5 - Ontology Description Capture.- Ontological analysis is accomplished by examining the vocabulary that is used to discuss the characteristic objects and processes that compose the domain, developing rigorous definitions of the basic terms in that vocabulary, and characterizing the logical connections among those terms. The product of this analysis, an ontology, is a domain vocabulary complete with a set of precise definitions, or axioms.
8. IDEF6 - Design Rationale Capture – searches the answer to the question – “Why is this design the way it is?”

Traditional industrial robotics has been area of heavy industry and engineering, where big companies have their own design departments and where they have recourses to implement long-lasting projects using traditional mechanical engineering methods. These robots have also been very expensive and design costs have been high.

But robots are also part of mechatronics; they have something from mechanical engineering, electronics engineering and software engineering [101]. The term Mechatronics was first used by Mr. Tetsuro Mori, who was a senior engineer of the Japanese company Yaskawa, in 1969. It emerged as the serious discipline only in the 1990s. Engineers in mechatronics have got their education in one of the fields of mechanics, electronics, computer or software engineering. In USA engineers can be accredited with one of the three main engineering societies: ASME, ASCE or IEEE. In United Kingdom the continuing dispute between IEE and IMechE, the electrical and mechanical engineering institutions is ongoing. This reflects the complexity of the field. Engineers with different backgrounds working in robotics industry do not understand each other well. They follow their own best practices from their own field.

One of the main problems in mechatronics is that mechanical design is made using mechanical engineering design methods and software design is done using software design methods. Few attempts have been made to publish universal design methods for mechatronics. Recently Bond Graph theory is invented for merging different mechatronics aspects of Mechanical, Electrical, Hydraulic, Thermal and Control Systems [106,107]. But this approach does not cover the software side.

Another example that we look here is called Real Time Mechatronics Design Process for Research and Education [102]. The short schematic of this design process is given in Fig. 32.

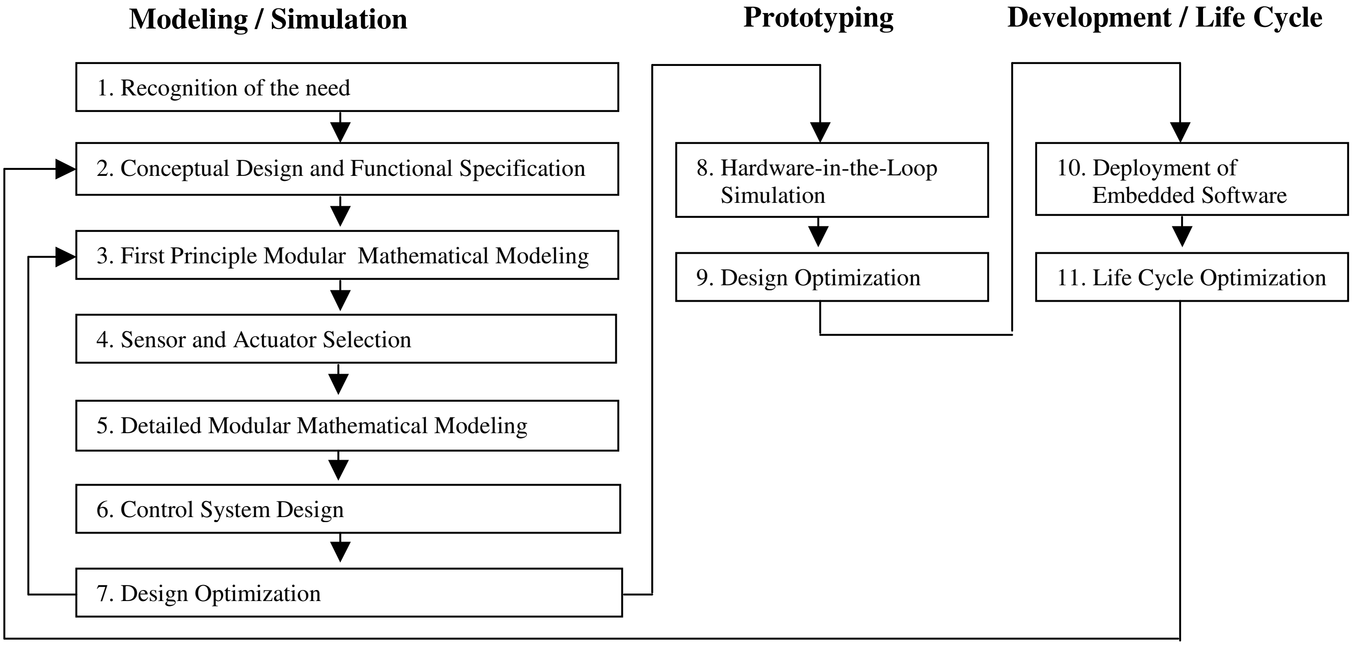


Fig. 32. Proposed Mechatronics Design Process

This design process includes software and electronics engineering in the same loop with mechanical engineering, but does not include the possibility of change of the design requirements in the design process. The other problem with that methodology is that mechanical design has a priority over control system and software. If we put mechanical design issues first, then we may not get the optimal solution. Maybe the most contributing design feature is control software or a novel electronics circuit? If that is true, then all other design decisions must follow these design choices, not the mechanical design. The mechanical engineering is of course important, but biologically inspired design may require equal treatment of all aspects.

Several studies show us that robotics industry in present day follows much the same trend as computer industry and has now achieved the same positions were computer industry was in the 70s [108,109,110,111]. The whole industry is in the long growth cycle (Fig. 33, Fig. 34).

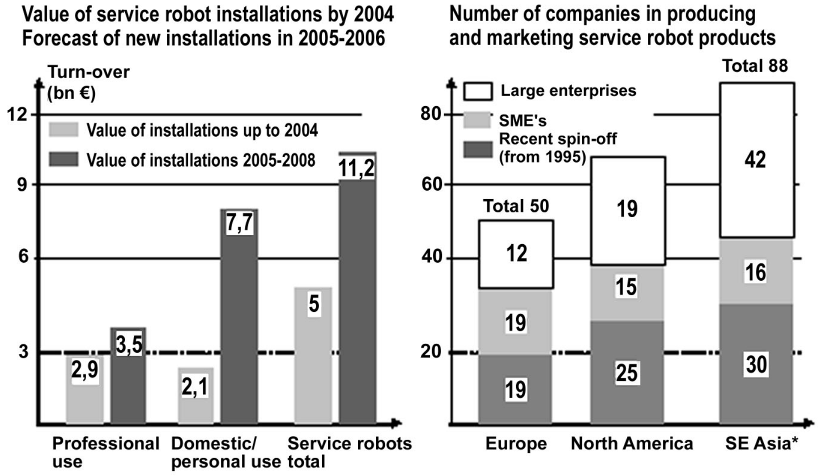


Fig. 33. Trends in Robotics by
IFR International Federation of Robotics

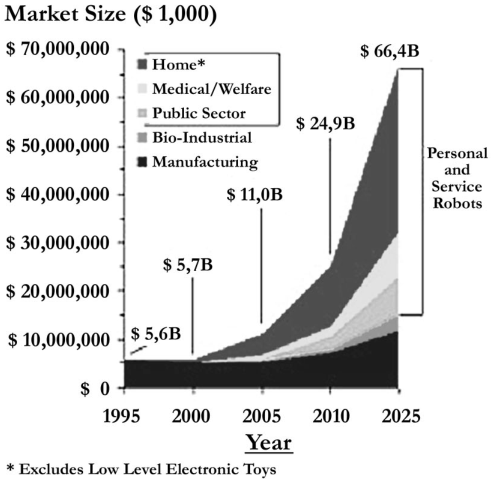


Fig. 34. Worldwide Robotics
Market Growth, Japan Robotics Association

That means many small and medium size companies (SME) are coming to the market with their own products and they have limited resources to spend for research and development. These SMEs are actively searching new areas to expand this technology but they also lack experience and resources to develop their products in traditional ways. They do not necessarily have an access to expert systems that can automate the mechanical engineering design processes; they also cannot allow any failed projects. Often the deadlines are driving the development cycle. This all means that they need a different design methodology. As we mentioned in the introduction, the current work was also motivated by the need of a better design approach and the author of this thesis is himself working in an SME partially financing the project.

If somebody decides to do a biomimetic design, then the situation is even worse; we cannot find any biomimetic actuators or any other biomimetic design solution in the databanks of expert systems in use. We usually even do not know exactly how to implement them and that means we can only approximately estimate the cost and time of the project. But what to do if we see that biomimetic approach is more promising than traditional? What is a good design methodology for us to follow?

The same kind of question has been asked countless times by small software developing companies: how to design and implement a computer program and estimate resources needed if we do not have any experience with this particular technology or subject? How to finish a project that cannot be entirely described and when its goals are changing during the design and implementation process? The traditional design methods are good, but are producing unusable systems and outdated designs in case of sudden change of design requirements.

Software engineers are having some progress in defining such methodologies and next we give a short overview of them.

The very first attempts to define software engineering methods were made in 1968 when the term “software engineering” was used in the title of a NATO conference held in Germany. Later, in 1972, IEEE Computer Society published its “Transactions on Software Engineering”. In 1976 a committee was established within IEEE Computer Society for developing software engineering standards. Since then this subject has been evolving and in 1990 IEEE started planning for an international standard, which defines a required body of knowledge and recommended practices. As the result, “Guide to the Software Engineering; Body of Knowledge” was published [103].

This document gives recommendations for software design, construction, testing, and maintenance and gives an overview of the tools and methods.

Software engineers use so-called “traditional methods” witch involve heavy planning, predicting and careful implementation of plans (Divide-and-Conquer, Stepwise Refinement, Top-Down vs. Bottom-Up Strategies, Data Abstraction and information hiding, Function-Oriented (Structured) Design, Object-Oriented Design, Data-Structure-Centered Design, Component-Based Design (CBD)) and so-called “Agile methods” that adapt and learn when task is not well defined, or traditional methods can not be applied [104, 105]. They are also called “lightweight methods” because they try to minimize the amount of bureaucracy, focusing on productivity by relying on team discipline and capability rather than rigorous processes and strict plans. Table I gives an overview of recommendations for traditional methods, and for agile methods.

Table I. Design methodologies in software engineering

Factor	Traditional Methodologies	Agile Methodologies
Scope or requirements	Issues are well known Problem domain is well understood Subject will not change during the project	Uncertain requirements Problem scope is unknown Subject can change
Resources, such as money, infrastructure, people, technologies	Approved and available Has been done before Budget is sufficient and certain People familiar with tasks and tools	Not fully approved or available Need proof of concept Money is tight Uncertain budget New skills needed
Time	Clearly determined Clear milestones	Not well defined/open Unclear milestones
Risks	Well understood Minor impact	New technologies Unknown risks Major impact

These “Agile Methods” have several subclasses, all focusing on different aspects of managing complexity of unknown factors. Some of them are: Rational Unified Process (RUP), Extreme Programming (XP), Agile Unified Process (AUP), Scrum, Open Unified Process (OpenUP), and Team Software Process (TSP) [112]. We describe here shortly the major agile methodologies [113].

- **Rational Unified Process (RUP):** the Rational Software Corporation, a division of IBM since 2002, created this method. RUP is not a single concrete prescriptive process, but rather an adaptable process framework, intended to be tailored by the development organizations and software project teams that will select the elements of the process that are appropriate for their needs. RUP is based on a set of six key principles for business-driven development:
    1. Adapt the process.
    2. Balance stakeholder priorities.
    3. Collaborate across teams.
    4. Demonstrate value iteratively.
    5. Elevate the level of abstraction.
    6. Focus continuously on quality.

  The RUP lifecycle is an implementation of the spiral model. Assembling the content elements into semi-ordered sequences has created it and RUP lifecycle organizes the tasks into phases and iterations. A project has four phases: Inception phase, Elaboration phase, Construction phase and Transition phase. It has also a set of building blocks, or content elements, describing what is to be produced, the necessary skills required and the step-by-step explanation describing how specific development goals are achieved. The main building blocks, or content elements, are the following: Roles (who) – A Role defines a set of related skills, competencies, and responsibilities, Work Products (what) – A Work Product represents something resulting from a task, including all the documents and models produced while working through the process. Tasks (how) – A Task describes a unit of work assigned to a Role that provides a meaningful result.

  Project planning in RUP occurs at two levels. There is a coarse-grained or Phase plan, which describes the entire project and a series of fine-grained or Iteration plans which describe the iterations. RUP is suitable for implementing in large organizations.
- **XP (Extreme Programming):** XP builds an evolutionary design process that relies on refactoring a simple base system with each iteration. All design is centered around the current iteration with no design done for anticipated future needs. The result is a design process that is disciplined, yet startling, combining discipline with adaptivity in a way that arguably makes it the best developed of all the adaptive methodologies. It is suitable for small up to 10 person teams, providing solutions that should fit in a rapidly changing or uncertain environment. XP depends heavily on testability of the developed solution.
- **Crystals:** Crystals share a human orientation with XP, but this people-centeredness is done in a different way. It explores a least disciplined methodology that could still succeed, consciously trading off productivity for ease of execution. It also puts a lot of weight in the end of iteration reviews, thus

encouraging the process to be self-improving. Its assertion is that iterative development is there to find problems early, and then to enable people to correct them. It places more emphasis on people monitoring their process and tuning it as they develop.

- **ASD (Adaptive Software Development):** At the heart of ASD are three non-linear, overlapping phases: speculation, collaboration, and learning. It views planning as a paradox in an adaptive environment, since outcomes are naturally unpredictable. In traditional planning, deviations from plans are mistakes that should be corrected. In an adaptive environment, however, deviations guide us towards the correct solution.
- **Scrum:** Scrum focuses on the fact that defined and repeatable processes only work when tackling defined and repeatable problems with defined and repeatable people in defined and repeatable environments. Scrum divides a project into iterations (which they call sprints) of 30 days. Before you begin a sprint you define the functionality required for that sprint and then leave the team to deliver it. The point is to stabilize the requirements during the sprint. However management does not disengage during the sprint. Every day the team holds a short (fifteen minute) meeting, called a scrum, where the team runs through what it will do in the next day.
- **FDD (Feature Driven Development):** FDD like other adaptive methodologies focuses on short iterations that deliver tangible functionality. In FDD's case the iterations are two weeks long. FDD has five processes. The first three are done at the beginning of the project: Develop an Overall Model, Build a Features List, and Plan by Feature. The last two are done within each iteration: Design by Feature and Build by Feature. Each process is broken down into tasks and is given verification criteria.

The common part of them is that all these agile methods are iterative, incremental and evolutionary by nature. The agile development can be described by a sentence: "we know, we don't know everything what is needed, but we can live with that and still come up with the solution". So what is exactly this agile development method? We look at it more closely using Extreme Programming methodology as an example.

One of the best known agile development practices is Extreme Programming or XP, which is a lightweight discipline of software development based on principles of simplicity, communication, feedback, and courage [114].

Biomimetic design shares some features with agile software design methods because both of them are trying to handle badly defined and rapidly changing design requirements. Both of them try to address problems that require new skills and are generally new fields for developers.

In the following we look how to apply Extreme Programming software engineering principles to mechatronics and biomimetic design. We choose XP because it is the oldest and the most explored practice in use and it is also suited for small development teams.

XP is designed for use with small teams who need to develop software quickly in an environment of rapidly changing requirements and there are twelve key practices in XP [114]. We give them here and we analyze how these principles can be applied to the biomimetic robot design process:

1. **The Planning Process** or the Planning Game.
   The XP planning process allows the XP "customer" to define the business value of desired features, and uses cost estimates provided by the programmers, to choose what needs to be done and what needs to be deferred.

   If applied to robotics, the idea of having the end user and all designers constantly in the design loop can certainly lower the risks.
2. **Small Releases**.
   XP teams put a simple system into production early, and update it frequently in a very short cycle.
   This idea of having as fast as possible feedback can also lower the risks in robotics.
3. **Metaphor**.
   XP teams use a common "system of names" and a common system description that guides development and communication.

   In robotics as in other engineering fields, misunderstandings between customer and developer often occur because of not having a common terminology.
4. **Simple Design.**
   A program built with XP should be the simplest program that meets the current requirements. There is not

much building "for the future". Instead, the focus is on providing business value. Of course it is necessary to ensure that you have a good design, and in XP this is brought about through "refactoring", discussed below.

In all engineering disciplines a principle of doing things “as simple as possible, but as complicated as needed”would help to increase the reliability and lower the costs.

5. **Testing.**
XP teams focus on validation of software at all times. Programmers develop software by writing tests first, then writing software that fulfills the requirements reflected in the tests. Customers provide acceptance tests that enable them to be certain that the features they need are provided.
In mechanical engineering the testing of all individual parts is not a new idea, but acceptance tests with the customers are not always practiced.
6. **Refactoring**.
XP teams improve the design of the system throughout the entire development. Keeping the software clean does this: without duplication, with high communication, simple, yet complete.
Refactoring in robots design should be understood as constant work to improve existing and tested designs, not developing new solutions from scratch.
7. **Pair Programming.**
XP programmers write all production code in pairs, two programmers working together at one machine. Pair programming has been shown by many experiments to produce better software at similar or lower cost than programmers working alone.
In robot design the pair programming should be seen as teamwork during the design process.
8. **Collective Ownership.**
All the code belongs to all the programmers. This lets the team go at full speed, because when something needs changing, it can be changed without delay.
In biomimetic robot design process this should be understood as shared knowledge of every aspect of the design between developers. This makes easier to communicate the ideas and helps to find weaknesses.
9. **Continuous Integration.**
XP teams integrate and build the software system multiple times per day. This keeps all the programmers on the same page, and enables very rapid progress. Perhaps surprisingly, integrating more frequently tends to eliminate integration problems that plague teams who integrate less often.
This practice should be understood as constant and early fitting of new ideas to the existing design. The design process itself should be teamwork. It should make easier to introduce the new features.
10. **40-hour Week.**
Tired programmers make more mistakes. XP teams do not work excessive overtime, keeping themselves fresh, healthy, and effective.
This practice is oriented towards the design team, and should keep them fresh. Many other ways also exist to stimulate creative thinking.
11. **On-site Customer.**
An XP project is steered by a dedicated individual who is empowered to determine requirements, set priorities, and answer questions as the programmers have them. The effect of being there is that communication improves, with less hard-copy documentation - often one of the most expensive parts of a software project.
Having a customer as a design team member helps certainly to keep up the necessary communication between the supplier and customer.
12. **Coding Standard.**
For a team to work effectively in pairs, and to share ownership of all the code, all the programmers need to write the code in the same way, with rules that make sure the code communicates clearly.
In context of robotic design this would mean that all aspects of design is well documented and shared between the members of the team.

As we see, the one type of rules are for managing the project team, while the second type of rules are for managing the problem and the third type of the rules are for managing the product. So what are these key ideas that we can adapt from this methodology? They all are of course needed and important, but in our view the most crucial are the rules minimizing risks and uncertainties. We propose that these rules are:

- **The Planning Process**
- **Small Releases**
- **Simple Design**
- **Testing**
- **Refactoring**
- **Continuous Integration**
- **On-site Customer**

As we showed before, the agile methods are iterative processes. How should an iteration step in Extreme Programming look like? [115]. In Fig. 35 we describe the typical iteration step in XP.

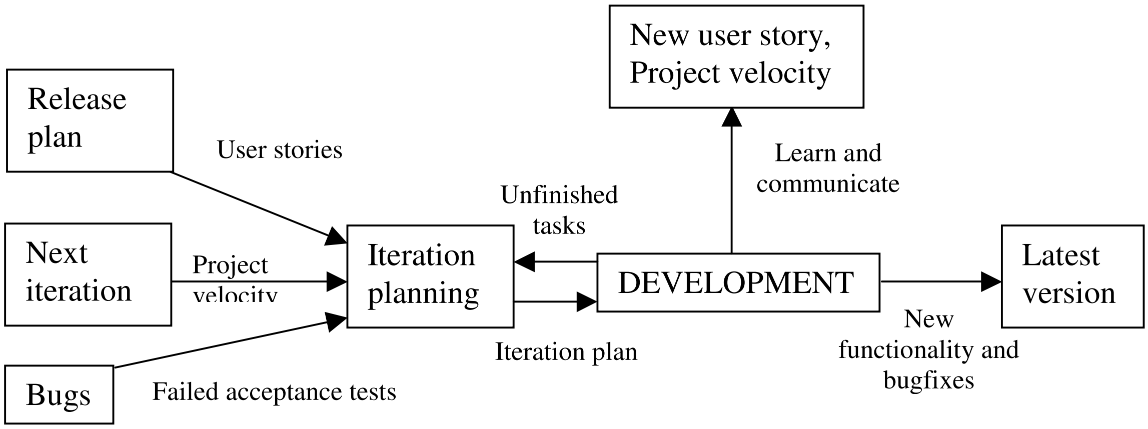


Fig. 35. Iteration steps in Extreme Programming.

In the very beginning of the design process, the user stories and use cases from different users are collected and recorded. The use cases are descriptions of different scenarios and tasks that are needed to be performed and are needed to define the properties of the future product. The user stories are needed to create acceptance tests and estimate the project velocity. They should only provide enough detail to make a reasonably low risk estimate of how long the story will take to implement. When the time comes to implement the story, developers will go to the customer and receive a detailed description of the requirements face to face. Then the designers create the release plan and divide it into simple and logical iteration steps. After each of these steps is completed, the acceptance and bug tests must show if it is possible to start the new iteration step. These short iteration steps should ensure, that the design team will not let in any bugs unnoticed and will not make any costly mistakes in their design.

But are these Extreme Programming principles enough for our biorobotics design purpose? Maybe we should add some additional steps? In our view we should learn also from general engineering methodologies and we propose here to modify this iteration process by some additional steps.

In software design the future program is not very often modeled by mathematical methods to prove its correctness (in software the term modeling often means compiling of data descriptions, or use cases into the descriptive model, using the modeling language UML) or simulated to find out its possible performance characteristics. Software developers do not consider these processes to be important and customers also do not know anything about it, so they do not require them from developers. In mechanical engineering, every detail cannot always be tested fully, because of other details are not implemented yet, and modeling and simulation can at least partially replace the missing details in the tests. We can argue of course that modeling and simulation are not always possible, especially if we do biomimetic design, where we do not have enough experience and statistical data, but we should do it at least partially every time we have a chance, because modeling is an important part of test-driven development.

Another problem may rise from the fact that SMEs and small development teams may not have enough competence available for doing simulation and modelling, or the deadlines do not leave time for modeling.

The third obstacle for doing simulations comes from the fact that biomimetic design problems can be badly specified in the beginning. We may for example find that fins are more energy effecient then propellers, but if we still do not know how to implement the fins and what materials to use, then we are unable to specify the initial task for modeling.

In this case we must do prototypes first. When we have test data available and still have problems achieving our goal, then it is much easier to start with modeling and simulation, because modeling can be an important early indicator of failure or success. This course of actions depends from situation and every developer should find its own order of design steps. One important rule of agile modeling is that every design team must create their own guidelines that fit to their problem domain.

The second aspect that is done differently in software development and mechanical engineering is maintenance of the product. This task is often overlooked in all engineering disciplines and in all design methodologies. For software, the makers and maintainers are almost always the same and maintenance methods and tools are same as developing methods and tools. In mobile robotics, maintenance is often done in field conditions by the end user, and serviceability must be considered during the design process. The easiness of serviceability will always not come out from user stories either, because service contractors sometimes do service and they are not interviewed. So this design parameter is solely designer's responsibility to foresee. In conclusion we want to add three additional key practices to our proposed agile task-oriented design process:

1. **The robots key parameters should be modeled.**
2. **The robots key parameters should be simulated.**
3. **The robot must be tested for serviceability and ease of repair and maintenance.**

These practices should be also included into the iteration steps. The tests for serviceability should be a part of acceptance tests. In our view, modeling and simulation should be done in parallel with the development. Fig. 36 describes our proposed changes in this design.

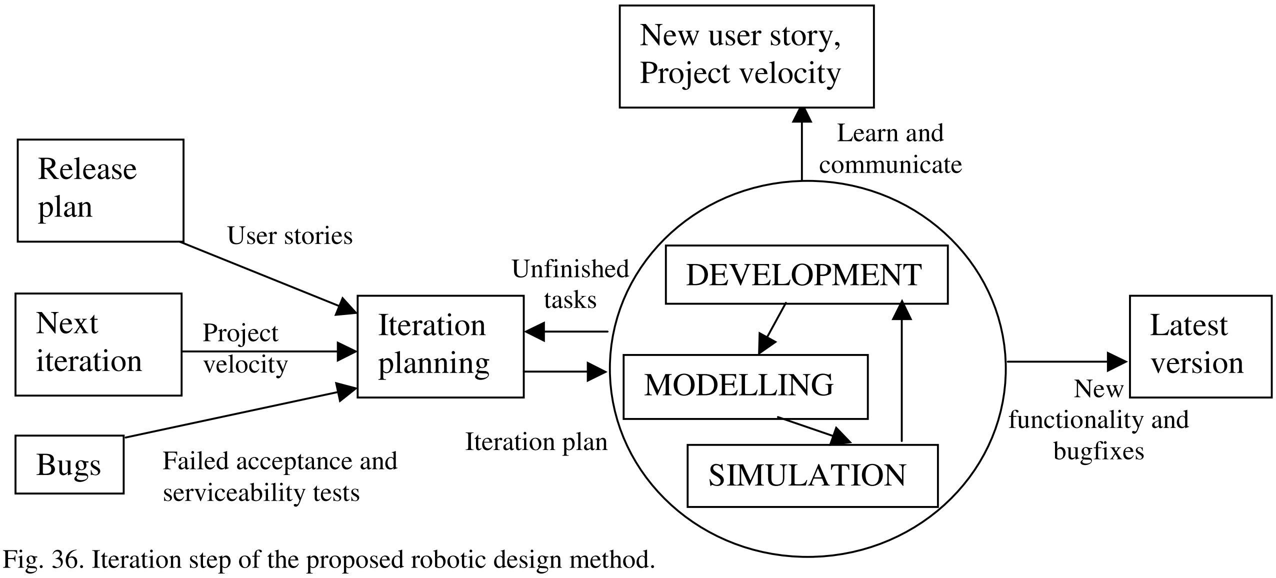


Fig. 36. Iteration step of the proposed robotic design method.

So far, we have looked at mechanical engineering and software engineering. We have found that Extreme Programming methods have a potential to handle badly formulated situations and we have proposed adding modeling and simulation requirements to this methodology. In order to do successful biomimetic design with this methodology we must add also guidelines for solving biomimetic problems. We integrate all these suggestions into a one general task and context oriented design methodology.

In mechanical design methods the first priority is given to the design of the hardware and the secondary objectives are electronics and software design. We think this approach is too limited and does not lead to the best solution. In biologically inspired design we must search for the best solution considering the task- and context limitations. If we find out that the best solution can be achieved by using a certain software method, then we must design our hardware to match the requirements of the algorithms. If we find that a certain mechanical property contributes most to the overall design, then we must design software according to these requirements. A successful robot has mechanical, electronics and software aspects all balanced and weighted according to their contribution to the overall result. Favoring mechanical aspect over other aspect will easily lead to overly complicated software and not optimal electronics.

In the next chapter we summarize the proposed methodology of a biomimetic robot proposed by us.

4.3. A task oriented agile design process

As all Agile development methods are collectively owned and free information exchange is considered to be crucial for the success, it is very important that all team members participate in all steps as much as possible, as this ensures that information reaches the same way to every team member. The following steps must be done jointly:

1. **Formulate the problem.**
   Identify application areas, application environments, task descriptions and end-user requirements where the technologies will most likely be used. You need to do it in every iteration step, in order to be sure that the task has not changed.
2. **Collect user stories.**
   Find decision makers, users, maintainers, and experts in the field. Collect their experiences with similar equipment and technologies. You need to be in contact with your users continuously, because their working environment or task requirements can change and they forget to tell you about it.
3. **Find the financial limits, evaluate resources.**
   Estimate the cost of building; analyze the cost of maintenance and operating cost. Find the all-possible uses of the technology and the design. Remember that other users than your customer might also have use for your design. If this is the case that the user base could be larger, your cost might be lower.
4. **Formulate task oriented limits.**
   Try to foresee other uses and future requirements of your customer. Do the additional interviews with the users and ask directional questions to find yes or no answers. Remember that your vocabulary is different than users vocabulary, and they give different meanings to the technical terms than you. Remember that small changes in the task descriptions can lead to the big differences in the project's complexity.
5. **Analyze the currently available technologies and biological solutions, find the best ones.**
   Evaluate solutions that cover mechanical, electronic, software and control design. Analyze why the biological solution is effective, analyze industry practices. Choose the best one.
6. **Weight the contribution of mechanical, electronics and software components, and find which properties contribute most to the overall solution.**
   Remember that overall design is a balanced and weighted sum of different details. Find the detail that contributes the most to the overall solution; prepare to test its feasibility first. The detail can be software, electronics or mechanics. If the test fails, then everything must be redesigned and started from the beginning.
7. **Create strategies for implementations for mechanical, electronics and software details.**
   Find the details you can buy and identify those you need to manufacture yourself. Estimate when the details are supplied or manufactured.
8. **Create documentation**
   Draw the charts, do drawings, calculate the parameters, do functional plans for details. This documentation becomes later a part of user documentation.
9. **Create release plan.**
   Write down the overall plan, specify steps and milestones, divide your work into smallest steps you can. Try do find steps that can be done in parallel. Assign resources to this release plan. It is important to understand that financial resources, manpower, equipment and knowledge must cover all steps.

10. **Set the deadline for iteration step.**
    Do not plan your steps to be long. A good step length is a week or two.
11. **Reuse the existing design if possible.**
    Existing design is tested and although it is maybe not the best, it allows testing other components. If project is fully tested and completed, then is right time to improve details, not before. ”Make it work, make it right, make it fast”.
12. **Do the modeling, simulation and build the concept.**
    Create the mathematical model of the most important aspects of your design. If you are not able to handle the problems complexity do a simplified model of most crucial parts.

    Simulate the model with computer simulation methods; find the theoretical limits of your design. If the problem is too complex to be simulated accurately, do a simplified simulation, so you can later compare something with measurement data.

    Build a model of most crucial details first, and then broaden the design until you have a sufficiently good test model.
13. **Test the performance, measure it.**
    Measurement data is the basis for evaluating your iterations steps and future design decisions.
14. **Test for bugs.**
    Test how your design fits the functional test model. If the bug is found, create a test for it.
15. **Test for serviceability.**
    Assemble and disassemble the details, try to achieve design where disassembling does not break the construction and where you have the least amount of dependencies in disassembling.
16. **Test for acceptability.**
    Compare your design with user expectations, show your design to the users, and listen to their comments.
17. **Estimate the velocity of the project.**
    Document your steps, measure how long they take and how you have spent resources for this iteration step. This gives you an idea how good your release plan estimates are.
18. **Start the next iteration**

To draw a conclusion we summarize here features, advantages and benefits of using a proposed methodology

Features, Advantages and Benefits of proposed methodology

1. Is a hybrid design for mechanics, electronics and software.
2. Does not prefer mechanical design to the other design parts.
3. Is task and context specific.
4. Allows doing biomimetic design.
5. Handles the changing design requirements.
6. Design is done hand-in-hand with the customer that ensures customer satisfaction and mutual understanding.

Disadvantages of proposed methodology

1. The main problem with that methodology is that the end product might be something completely different from what it was specified in the beginning. It is common to all Agile methods that the changes during the design process are seen as positive features and not as initial planning process mistakes. This design methodology is a process and does not guarantee staying within the initial budget and timeframe, but in case these things happen it produces a better result than traditional waterfall design methods.
2. Suits for small teams.

We believe that using this improved and adapted Extreme Programming methodology, we are better prepared to handle the uncertainties a biomimetic robot design. In the next chapter we look more closely at the task and context oriented design procedure of a biomimetic underwater robot.

4.4. A task oriented design of a biomimetic underwater robot

In earlier chapters we discussed the state-of-the-art in underwater robotics and biomimetic design. We also proposed a methodology to design a biomimetic vehicle. In this chapter we describe briefly how we implemented several design iterations using this methodology.

4.4.1. The problem

Our initial task was given by environmental scientists who needed a robot that could help them to monitor underwater vegetation and correlate videos with other measurement data. The existing commercial solutions were all unable to satisfy the requirement for a silent and non-turbulent bottom following with the ability to stop and hover over a spot.

ROVs are remotely operated, but cannot be reliably towed because their shape is not hydrodynamically optimised and their propellers create a lot of drag when they are stopped. Another negative aspect of ROVs is that they create strong water jets that raise bottom sediments.

UTVs are towable vehicles, but they are not able to stop and hover over a spot when needed. Their manoeuvrability is also poor, they can mostly keep depth, but are unable to do horizontal manoeuvres because the lack of engines. Also, they cannot collect water samples because they have a positive buoyancy and they can submerge only when they are towed with a certain speed.

AUVs are usually built for covering large distances where human operator interference is not possible and their ability to manoeuvre is not good. This is partially caused by their current purpose – the ocean is big and the chance to hit something beneath the surface is very slim. Also AUVs that are able to communicate with a human operator are too heavy and clumsy to be operated by one person from an inflatable boat.

4.4.2. User stories

We decided also to find out if we can find other possible uses of this robot and did some additional interviews with rescue workers, marine archaeologists and navy divers. The main requirements of all these parties appeared to be the same – they all needed a robot that is able to move silently, without creating turbulence. We found that task and context oriented factors for all these user groups were similar. During these interviews we proposed them several design ideas and asked for feedback, but most of our ideas were quickly turned down. We may say that these consultations proved later to be very valuable and prevented us from building prototypes that would have not met the user requirements.

4.4.3. Financial limits and resources

One main requirement was to build a relatively cheap robot, with the price not over 10 000 EUR, because extensive experience of the experts tells them that equipment will be frequently lost, broken or stolen anyway.

4.4.4. Task oriented limits

The requirements determining our vehicle design can be divided into two large categories. The first category consists of environmental factors that are unique to The Baltic Sea. The second category is the human and task specific factors. In the following subsections we describe both of the categories closer.

Environmental factors:

The Baltic Sea is in many senses different from subtropical and tropical seas or exposed seas like The Nordic Sea. The factors influencing our choices for the vehicle's design are the following:

1) **Depth**: The Baltic Sea is relatively shallow and therefore the underwater vehicles do not have to operate under high pressure.
2) **Turbidity**: water is very turbid due to floating detritus and therefore visibility is very low.

3) **Extension of vegetation**: due to low visibility, the euphotic zone (the zone of penetration of light into the water column) is rather narrow and therefore the vegetation is limited to the costal regions in the depth down to approximately 20m. The regions of interest for environmental monitoring are usually near the coastline in the depth from 1m to 6m.
4) **Properties of the seabed**: most of the seabed in the depth of interest is covered with mud or small particles of zoo- and phytoplankton that has settled down and is extremely volatile.
5) **Human inhabitancy**: The Baltic Sea is under a severe antrophic pressure. Costal regions that are especially interesting for monitoring are full of harbours, beaches, fishing nets, dense surface traffic, etc.

Human- and task specific factors:
This research is strongly demand-driven and therefore we pay lot of attention to satisfying the requirements of the users, which are in the first place environmental scientists. The human and task specific factors that influence our vehicle design are the following:

1) **Main functions**: the main function of the device is to facilitate environmental monitoring. For that the robot must record a video of a seabed. The highest priority is to facilitate monitoring of underwater vegetation.
2) **Additional functions**: if possible, the device should also permit measuring other environmental parameters, like temperature, pressure, salinity and make it possible to correlate these parameters with hydro biological data. The robot must be able to collect water samples. It could also be used for other type of benthic surveys and diving under ice in winter.
3) **Operational requirements**: the device should be portable, preferably operated by one person only from an inflatable boat; it should support storing, processing and mapping of environmental data.

   The robot must work in two different modes. One mode is towing behind the boat to cover large areas quickly. At the same time it should maintain a constant height from the seabed to videotape it from a rather close distance. Another mode is a semiautonomous mode where operator can guide the robot to the point of interest.

   The robot must be able to stop and hover over s point of interest when needed. This situation appears when the operator notices something interesting during the scanning and stops the boat. This ability allows switching from the towing mode to the remotely operated mode.

   The robot must be able to keep its distance from the seabed then towed with a high speed behind the boat. The robot must not create turbulence when moving. This restriction comes from the fact that places that are needed to explore are often covered with very volatile sediments and slightest disturbance can raise small particles from the seabed and then the visibility will drop to zero.

   The robot must be energy efficient, because it has its batteries on board and extra weight will influence its ability to swim autonomously

   The robot must be able to perform quick horizontal and vertical manoeuvres when required. This situation arises when the robot encounters rocks on a flat seabed.

4.4.5. Available technologies

We had to choose between a biologically inspired design and a conventional design. As the main requirements were bottom profile following, good maneuverability, non-turbulent motion and ability to hover and non of the commercial robots were able to satisfy all these requirements, we searched inspiration from the biological world.

Conventional design means usage of propeller thrusters and biologically inspired design leads us to fish propulsion mechanism – the undulating fin movements. Usage of propellers means that for horizontal and vertical movement we must have different motors and when moving vertically, the horizontal thrusters are not in use and are “a dead weight”. The second problem with the thrusters is that when towed, the motors are switched off and they are creating a lot of drag. At the same time towing means what the additional wing-fins are needed, and there is no use of them while maneuvering using the thrusters.

For this reasons we decided to implement the biologically inspired solution as fins can be used for both steering and propelling the robot and this allows us to reduce the weight of the robot, having not the dead weight on board. We chose biologically inspired design because it allows us to achieve the non turbulent movement and promises to be more energy effective [116].

We also quickly found that none of the existing fish do behave exactly like we needed. The fast swimmers were not good in maneuvering and good maneuvering means slow forward speed. So we decided to fuse different properties from different fish into one robot. Other design considerations were the following:

- We decided to make our robot initially not longer than 1,5 m and not heavier than 20 kg. These parameters should allow one person to operate the robot single-handedly.
- We had a requirement to have two modes: a towing mode and an autonomous mode. The towing mode requires the usage of steering blades for controlling the depth (Fig. 37). The autonomous mode can be achieved by different propulsion methods. Fins can be used both for steering and propelling, they also do not create water jets, so the only good design decision was to use fins for propelling our robot. To use both fins and propellers would mean unnecessary extra weight and propellers would cause additional drag while not in use.
- We had a requirement to allow the robot to stop on spot. To achieve this we had two options: to use active thrusters or to adjust buoyancy. We chose to adjust buoyancy, because it also allows us to save electrical energy and does not create water jets.
- Changing the buoyancy can be done in several ways. We chose to use compressed air filled buoyancy tanks. Another way might be to change volume mechanically or to use materials that change their volume by temperature change. We think that implementing compressed air based design is more reliable than a pure mechanical volume changing design and is more energy efficient than a temperature controlled volume design. The robot is also going to be used by organizations that have access to diving equipment and refilling the standard scuba divers rescue balloon on board the robot is not a problem for them. Another benefit is that we can more easily collect sediments that change the robots buoyancy and the center of mass. To change the center of mass we decided to use several buoyancy tanks. This allows also changing the equipment on board of the robot, because we can compensate the possible differences in their mass.
- We can also use buoyancy control mechanism for propelling the vehicle horizontally if needed. This is easily done if we change buoyancy selectively. By increasing lift a little in the nose we point the nose slightly upward and the robot starts to rise, but as its body acts as a wing, the robot will not surface vertically but at some angle. If we later decrease the lift a little in the nose, then we point the robot down and again the robot starts to glide. By doing so we can move horizontally.
- The released air from the buoyancy tanks makes the robot's body surface more slippery and decreases the drag of the body. This is also supported by biological evidence as fish use slime for the same purpose.
- We had a requirement to be able to maneuver horizontally and vertically. We chose already to use fins for steering and propelling our robot. To minimize the number of fins we choose to use one tail fin that can be used both for steering left and right and propelling the robot and two side fins for changing the depth and for propelling. This design leads us to a flat body with an ellipse-like cross section. This flat body acts also as a steering surface and helps to keep a constant depth while towed, because the tow cable and tow force vector are at 30 or 40 degree angle from the robots horizontal axes.
- The ellipsoid like cross section of the robot makes it hard to turn quickly around the vertical axis. One solution is to add steering surfaces to the top and to the bottom of the robot, but another solution is to turn the robot by 90 degrees, so that it becomes from horizontally compressed to vertically compressed. This can easily be done, if we change robot's buoyancy and move the center of mass to the left or to the right. These modes are shown in Fig. 38.

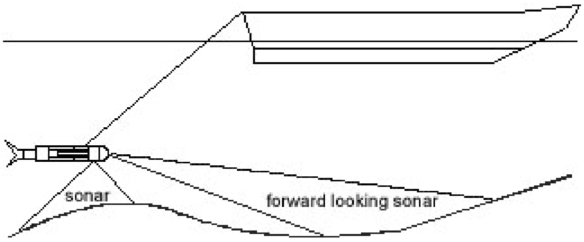


Fig. 37. Robot's usage in a towing mode.

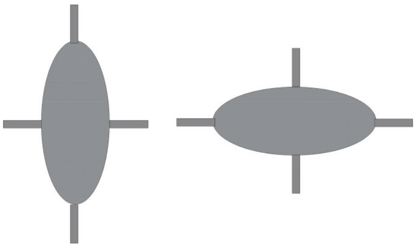


Fig. 38. Orientation of the vehicle: vertically compressed (to the left) and horizontally compressed (to the right).

- Having the ability to change the body orientation has other advantages as well. Sometimes we can encounter strong underwater currents. Some of them are horizontal, but some can be vertical. An ability to change orientation makes it easier to withstand them, because we can reduce our drag in the desired direction. It makes it also simpler to swim if the thick underwater vegetation is present or when we work between big rocks or boulders. Turning the body from horizontally compressed mode to the vertically compressed mode allows also changing depth much quicker.

  The usage of two orientation modes is supported by biological evidence. Dorsoventrally compressed fish (like rays and stakes) are ground-dwelling fish. Their body shape is adapted to bottom following. A laterally compressed body shape (like of sunfish, bluegill and angelfish) is good for leisurely swimming and hiding or for predators who need stability for attack and manoeuvrability.
- Important part of our design was also the question how to implement the robot's body. One option was to do a hard shell, another option was to implement a flexible shell and the third option was an intermediate design using scale leaves covered body type. All three types are also represented in the natural world and all of them have their advantages and disadvantages. The hard shell is the easiest to implement, but allows only very limited oscillatory movement based on Ostraciiform or Thunniform propulsion, described in Chapter 3, by caudal (tail) fin. The fully flexible body would allow us to implement any type of propulsion, but because of technological reasons we decided not to implement it. Instead we found many advantages in using scales for covering the body. This solution is easier to manufacture, allows constructing flexible body, would permit using undulatory movement based Carangiform or Subcarangiform propulsion for the caudal fin and the most interesting property of it is having different drag coefficients and skin surface resistance from the nose to the tail and from the tail to the nose.
- For technological and cost reasons, we decided to put all electronics and motors into watertight compartments and to use the outer shell only for hydrodynamic shaping. That means that the outer body shell is not watertight and water will be between the shell and the watertight compartments. The usage of scales would allow water easily to escape from inside of the body when the robot is taken out of water.

The chosen design allows our robot to behave like fast swimming fish, such as tuna or shark, when the robot is in a horizontally compressed mode and the caudal fin is in use. It has also good bottom following properties as rays have. When the robot uses the side fins, it will act like Labriform fish Labridae who is good in maneuvering between coral reefs.

When the robot turns into the vertically compressed mode, and uses side fins, it behaves as Tetraodontiform fish like oxfish, pufferfish or filefish who are good in station keeping and maneuvering. When the robot is using its caudal fin; it will act like dolphin, who is a very fast and efficient swimmer.

By replicating different fish properties, our biologically inspired fish like robot is not an exact copy of any real fish but incorporates only those properties that are needed for our task. This makes it unique compared to other bio-inspired underwater robots.

4.4.6. Contribution of mechanical, electronic and software components

The most critical details in this design are the buoyancy control and the fin propulsion, the next important part is the control software and the electronics comes as third. That means, we must do our design so that it helps to implement the most important details first and with a greater certainty.

4.4.7. Strategies for implementations

In order to keep the hardware cost as low as possible, we chose to manufacture only these components what were not available at all. Those components were fin propulsion related mechanical parts. All other components are commercially available.

The main components of the robot are: 3 x 24V DC motors for actuating fins, 3 x 360 degree potentiometers for feedback control, a low-light adapted waterproof security camera with lighting, a small echo sounder and a side-scan sonar, an ARM9 processor-based single-board computer for signal processing and control logic, an MSP430-based microprocessor for analog-digital conversion for controlling DC motors and sensors, a 3D accelerometer, a

3D magnetometer, a 3D inclinometer for navigational feedback and 20 D size batteries for storing energy.

While building a ground robot, the designer has usually several alternative options where to place all these components, but the designer of an underwater robot must keep in mind the requirements to balance the robot so that the center of mass stays in the right place in order to achieve stability. As batteries are the heaviest component, we should place them first. We also chose to implement a robot that can swim in a horizontally compressed or a vertically compressed mode, so we also do not specify the top and bottom surface of our robot. This reduces the options for the placement of the components even more. The camera, the sonar and the echo sounder must look forward in order to be useful, and so their purpose dictates their location. The position sensors should be in a place where they give smallest measurements errors and the buoyancy tanks must be placed so that they can effectively change the orientation of the robot. The last main constraint is the requirement to make the robot to have zero buoyancy which means that the density of the robot must be equal to the density of water. In this situation the robot does not sink immediately, when placed in water, and is able to dive when we decrease its buoyancy using the buoyancy control system. To achieve zero buoyancy we must carefully adjust the volume and weight of the robot.

During the first design iteration we decided to test the buoyancy control and in the next iteration steps the fin propulsion as the two most critical design factors.

4.4.8. Documentation

For documenting our work we set up a web site and used wiki based collaboration software. This provides us with an efficient communication as some members of the design team were from another city.

4.4.9. The release plan

We did also a release plan for our design iteration steps, it is given in Table II.

Table II. Release plan for implementation

Iteration step	Task to solve during iteration
1	Implement the robot with a hard body, test the buoyancy control, implement simple control software.
2	Improve the design, test the caudal fin propulsion, measure its performance, improve control software.
3	Improve the design, integrate the buoyancy control and the caudal fin propulsion, improve control software.
4	Improve the design, model the drag of the robot, reduce the drag of the robot with scale leaves capable of undulatory movements, improve control software.
5	Improve the design, improve control software, test maneuverability, implement the Central Pattern Generator based control, improve human-robot interface.
6	Test for durability, do the final acceptance tests.

4.4.10. Deadlines for steps

In agile development the good step length is considered to be a week or two weeks. In our design process we managed to keep only some design steps so short. Those steps that included field testing and modeling were in practice much longer and lasted even up to 6 months. The delays in testing were mainly caused by failures of mechanical end electronic components, while delays in modeling and simulation were caused by computational complexities of the problem and the lack of the previously obtained similar data to verifying the simulation results to be sure we did modeling correctly.

4.4.11. Reuse of the existing design

The agile software design methodology has an important concept of refractoring. The purpose of it is that old designs are usually more tested. Knowing when the design works and when it does not is more valuable for the whole project than just implementing new design models and then finding out that they are also not working as planned. Agile development helps to manage the design time and to keep it under control. From this viewpoint the gradual improvement of an old and already known solution is better. In our development cycle we could not always keep the old one. The outer shell of the first robot, fin propulsion motors, the air tank, and an ARM-based Linux computer as well as 3D sensors were all gradually replaced because of their malfunctioning. The MSP computer, the camera and the sonars are still holding and will be used as long as possible.

4.4.12. Modeling, simulation and concept building with testing

For the sake of readability we describe the steps “Modeling, simulation and concept building” and the next steps “Test for performance”, “Test for bugs”, “Test for serviceability”, “Test for acceptability” all in one chapter as it is hard to separate these iteration steps. These steps are also described in our papers (see I, II, III, IV and V). As the design process itself is cyclic and returns back to the same points over and over, it is not convenient to describe the results in the same manner. All previous steps were repeated during each cycle. The biggest changes, however, always happened during the modeling, simulation and concept building step. Therefore we describe these steps more accurately.

4.4.12.1. The first prototype

The first prototype is described in papers “Buoyancy Control of a Semiautonomous Underwater Vehicle for Environmental Monitoring in Baltic Sea” (see I) and “Design of a Semiautonomous Biomimetic Underwater Vehicle for Environmental Monitoring” (see II).

The first principal test model covers the release plan steps 1 and 2. The main purpose of the first test model was to validate the concept of orientation changing and to collect test data to implement the fin propulsion in next models. The first model also served as the testbed for the control system. In these tests we did not place echo sounder and sonar into the robot as testing these were not the purpose of this prototype.

In Fig. 39 and Fig. 40 we see the overall design concept of the first prototype. In Fig. 41 and Fig. 42 the tests are shown.

The main purpose of the first test run was to test the orientation change. As we did not have any idea in the beginning about how our design will work and how exactly we must implement it, we decided that we cannot do any modeling before the first proof-of-concept prototype is built. We hoped to collect some test data for further processing and we implemented all essential parts of the robot. As the performance of the robot is affected by its mass, we added all components although we did not use them during the experiments. For example we did not use the OMAP computer, as we managed to program the MSP computer for testing.

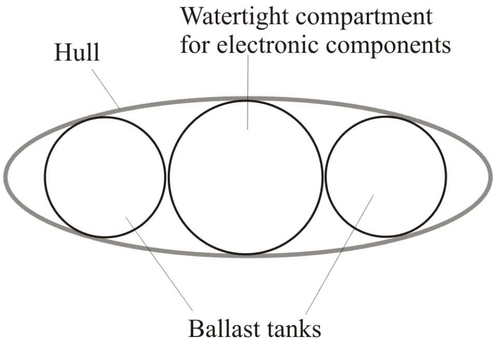


Fig. 39. The design concept of the orientation changing buoyancy control.

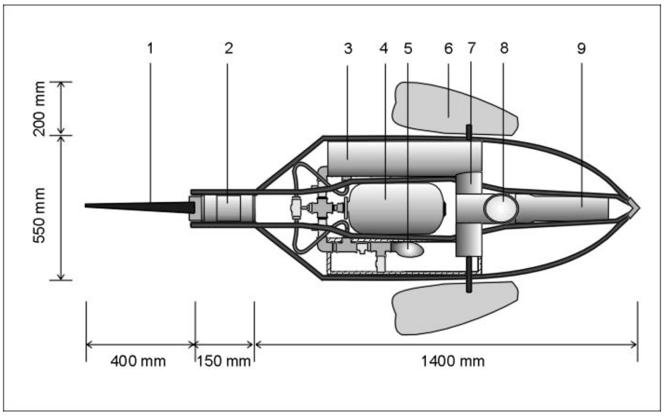


Fig. 40. Internal layout of the vehicle (1-fin, 2-stepper, 3-PVC tube, 4-compressed air tank, 5-rubber tank, 6-fin, 7-stepper, 8-camera, 9-batteries and electronics).

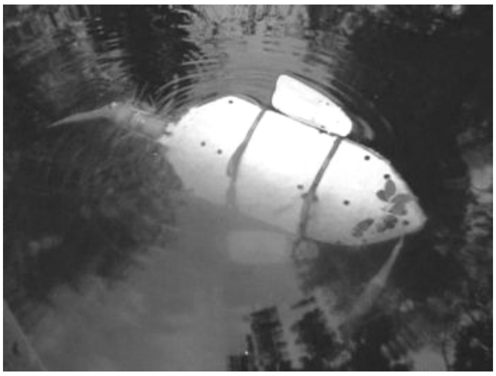


Fig 41. Pond test. Robot surfaces in a vertical mode using only one side balloon.

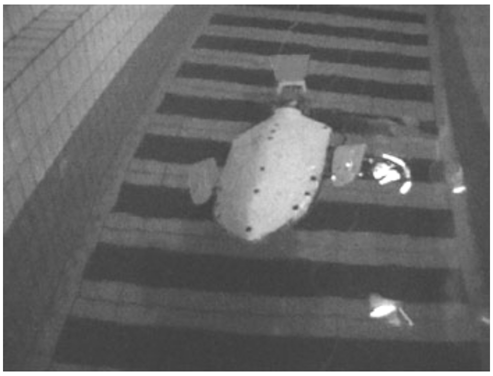


Fig. 42. Pool tests for caudal fin propulsion

The experiments showed that the buoyancy control system, where we can change buoyancy to 1 kg positive or negative, is powerful enough to change quickly robot's orientation in water. However for achieving better stability and balance we decided to add the third buoyancy tank in the tail section during the next iteration step. This would allow the robot to "stand up" on the tail or the nose and would add one more degree of freedom.

The second release plan step was to test the tail fin propulsion and measure the drag. For drag measurements we towed the robot through water and measured the drag force. The results of these experiments are shown in Table III and are discussed in more detail more in "Design of a Semiautonomous Biomimetic Underwater Vehicle for Environmental Monitoring" (see II).

For fin propulsion measurements we set up the experiment so that we could change the frequency of the caudal fin. Unfortunately the used DC motor with the gearbox did not allow us to change the amplitude. We also experimented with the orientation of the fin. During the experiments we found that we had underestimated the required power to propel the robot and must change the tail propulsion and side fin units during the next iteration steps. After changing the tail motor we performed several experiments at varying frequencies. The results are described in Table IV and Table V and are also discussed in detail in "Design of a Semiautonomous Biomimetic Underwater Vehicle for Environmental Monitoring" (see II).

Table III. Drag test results and corresponding drag coefficients

speed v (m/s)	Measured Drag force F (N)	Drag coefficient 2
0.27	5	0.292
0.34	10	0.368
0.37	12	0.373

Table IV. Robot's performance with 20 kg body weight

	Time (s)	Speed (m/s)	Voltage(V)	Tail Position	Tail movement
1	373	0,017	12	Vertical	Continuous
2	541	0,012	12	vertical	Continuous
3	193	0,033	12	vertical	Continuous
4	341	0,019	12	vertical	Continuous
5	150	0,043	12	vertical	Continuous
6	105	0,061	17	vertical	Continuous
7	96	0,067	17	horizontal	Continuous

Table V. Robot performance with 21.5 kg weight during the second test

	Time (s)	Speed (m/s)	Voltage (V)	Tail position	Tail movement
1	95	0,07	12	vertical	Continuous
2	155	0,04	12	vertical	Cyclic
3	60	0,11	17	vertical	Continuous
4	91	0,07	17	vertical	Cyclic
5	140	0,05	12	horizontal	Continuous
6	180	0,04	12	horizontal	Cyclic
7	73	0,09	17	horizontal	Continuous
8	90	0,07	17	horizontal	Cyclic
9	70	0,09	17	horizontal	Cyclic
10	90	0,07	17	horizontal	Cyclic
11	76	0,08	17	horizontal	Cyclic

We also measured the robots ability to submerge using its side fins when the robot was towed with an approximate speed of 0,1 m/sec. The measured submerging speed was 0,025 m/sec.

We found that having a strong tail motor does not automatically guarantee the greater speed of the robot, as according to the Newton's Third Law the robots body starts to oscillate because of the tail movement and if the caudal fin movement is repeated with the same frequency for a long time, then this parasitic oscillation reduces speed. However we also found that this effect makes it possible to reverse direction of robot´s motion. The experiments showed also that a non regular tail movement can reduce or eliminate the parasitic body oscillation. The observation that a linear tail movement causes a non-linear motion (first accelerating and then decelerating) of the robot and a non-linear tail fin movement (two tail beats-stop-two tail beats-stop) causes the linear motion of the robot (accelerating first, then maintaining the constant speed), is subject that should be studied more thoroughly as this phenomenon does not exist for propeller driven robots. For them the greater speed means also the faster propeller rotation and the propeller cannot be stopped for a while to increase speed as it will immediately cause additional drag. This observation also gives us the possibility to save energy while maintaining a constant speed.

The tests with the first robot prototype gave us enough confidence and design feedback information to continue with the second test model and with the next release plan steps.

4.4.12.2. The second prototype

The second prototype is described in the paper “Biomimetic Fish-like Underwater Robot for Shallow Water Applications” (see III). This prototype was built using the experiences gathered during the experiments with the first prototype and covers release plan step nr 3. Fig. 43 and Fig 44 describe the second version of the robot.

After a careful analysis of the first model we found several ways to make this version of a robot smaller and lighter. This was also a reason not to refactor the original body, but to build a new one. When the first model was tested we encountered a problem of body oscillation, when the caudal tail fin was used for propulsion. This parasitic movement was reducing the forward speed of the robot. While the body of the robot was very streamline and did not create any noticeable turbulence, it was also very hard to perform maneuvers and change the direction of the movement. To solve these problems we decided to redesign the body shape to give it a keel to the bottom and to the top of the robot. We also added the third buoyancy balloon to the tail section to improve the orientation changing abilities. One of the design features of the second prototype was a 360 degrees rotatory sensor head that allows adjusting sensors better before the mission.

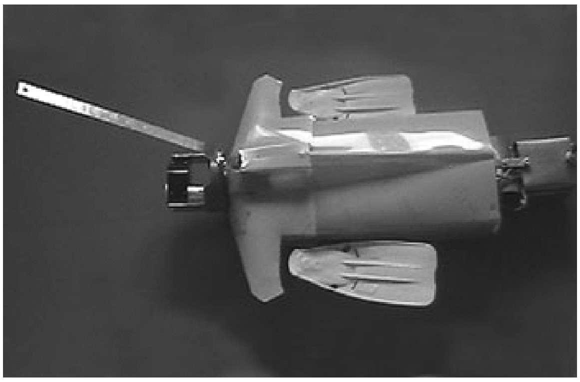


Fig 43. Second prototype

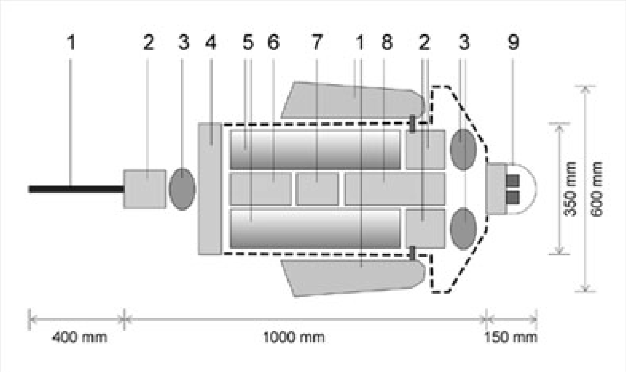


Fig.44. Internal layout (1 – fins; 2 – motors; 3 – buoyancy control; 4 – air supply; 5 – batteries; 6 – gyro and inertial sensor; 7 – OMAP; 8 – control electronics; 9 – camera and sonar head)

To compare the second prototype with the first prototype, we performed the same tests, what were performed with the first prototype. The drag measurements are shown in Table VI and are discussed in detail in “Biomimetic Fish-like Underwater Robot for Shallow Water Applications” (see III). With the second prototype we achieved a greater average swimming speed (see table VII) and larger submerging and surfacing angles (see table VIII).

The tests showed us that although the drag coefficient of the robot (see table VI) was worse than the drag coefficient of the first model, the robot still achieves a greater speed (see table VII). This can be explained by the reduced weight (16 kg, instead of 21 kg) and the reduced body oscillation. During the experiments we also added median fins, to further decrease the body oscillation, but quickly discovered that they are going to break when the robot is on dry land for maintenance and transport.

Table VI. Drag Coefficients

Drag coefficient of the first prototype	Drag coefficient of the second prototype
0.37	1.09

Table VII. Average Swimming speed

first prototype (20 kg)	first prototype (21.5 kg)	second prototype (16 kg)
0.02 m/s	0.08 m/s	0.12 m/s

Table VIII. Submerging and surfacing angles

first prototype	second prototype
15 degrees	45 degrees

We also conducted tests to measure the robot's ability to move using tail fin propulsion. The speed of the first and the second model are shown in Table VII. The speed of the first model increased significantly when we increased the mass by 1.5 kg, as this reduced the body oscillation. While the tail fin of the first model was too weak in the beginning, the tail motor of the second prototype appeared to be too powerful, as it again caused the body oscillation. As we already noticed, the body oscillation has large influence to the speed. Redesigning the tail fin so, that tail oscillation does not influence the whole body is key for achieving greater speed and efficiency. In current design it can be achieved by reducing tail fin area or increasing the robots overall mass. Another and better solution would be adding an additional joint with the damper springs. This solution would absorb the oscillation energy and would also allow implementing undulatory movement of the tail.

We also measured robot's vertical maneuvering ability, the 15 degree angle of attack of previous model was not sufficient for avoiding large obstacles. Our tests with the second model showed that the robot is able to move up or down under 45 degree angle in the towing mode. This suggests that the robot can avoid boulders and rocks that it may encounter.

This test model also features better control software and electronics. We also found that Texas Instruments OMAP ARM platform used in the first prototype was not suitable for advanced control as its design and implementation quality is bad and we lost 3 boards because static electricity was destroying its flash memory content. Another electronics related design change was related to the MSP430 computer. We were forced to add an external 8MHz quartz clock, otherwise its internal clock drifted too much and we lost serial connection to this computer.

When performing the experiments we noticed that with too strong strokes of the tail fin the water would flow backwards across the body of the robot. This gave us the idea to implement the outer shell as scale leafs, so the surface has different friction in different directions. This property should further improve robot's speed.

4.4.12.3. The third prototype

The third prototype is described in a paper “Computational Fluid Dynamics Simulations of a Biomimetic Underwater Robot” (see IV) and a technical report “CFD Simulations and the Real World Measurements of the Drag of a Biologically Inspired Underwater Robot” (see V).

The third model was built according to the release plan step 4 to solve two main problems we encountered. The first problem was the body oscillation problem and the second objective was to reduce drag that has increased after changing the body shape.


Fig. 45. The third prototype with redesigned fins and an additional joint.

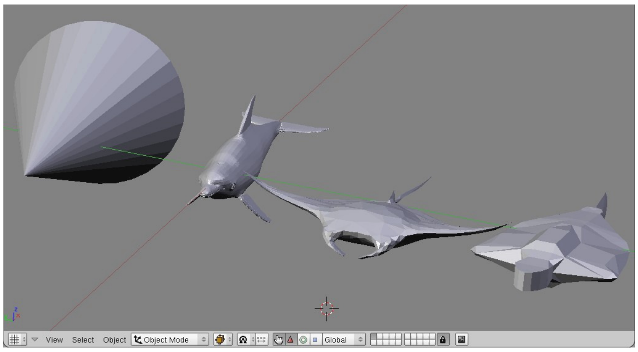


Fig. 46. The test objects

The body shape was redesigned (Fig. 45) taking into account the test results with the previous model, tested and while it satisfied us functionally we asked ourselves a question – can we make it more efficient? We already had found that the robot has sufficient vertical maneuvering ability, and we did not have to redesign the basic principles of the robot. For further drag reduction we needed to know where are the theoretical limits of the drag. To find it out, we made a 3D CAD model and used it for computational fluid dynamics simulation. We measured the turbulence of our robot’s model (Fig. 54, 56, 58) and compared it with the models of known good swimmers (Fig. 46) like Manta Ray (Fig. 53, 55, 57) and Dolphin (Fig. 48, 50, 52). We also simulated a cone as a very turbulent object for reference (Fig. 47, 49, 51).

These results are described in Table IX. We measured the simulated pressure in front of and behind the bodies and also recorded water speed and direction behind those bodies. From this data we calculated circulation which indicates how streamlined the bodies are. These results showed that our robot’s model behaves comparably well with the models of the fish.

Table IX. Numerical values of Circulations

Model	Circulation
Cone	–5,358
Dolphin	–1,439
Robot	–0,886
Manta ray	–0,810

The simulation results also indicated that robots body creates lift, as pressure behind the robot drops fast and becomes lower then pressure behind the robot (see Fig. 56).

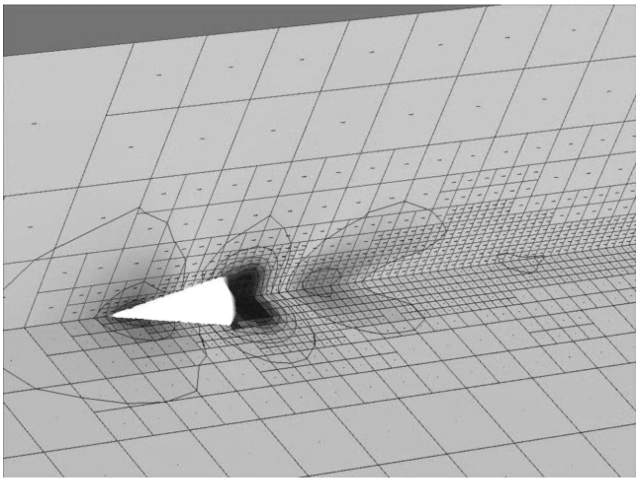


Fig. 47. The 4D simulation of the cone.

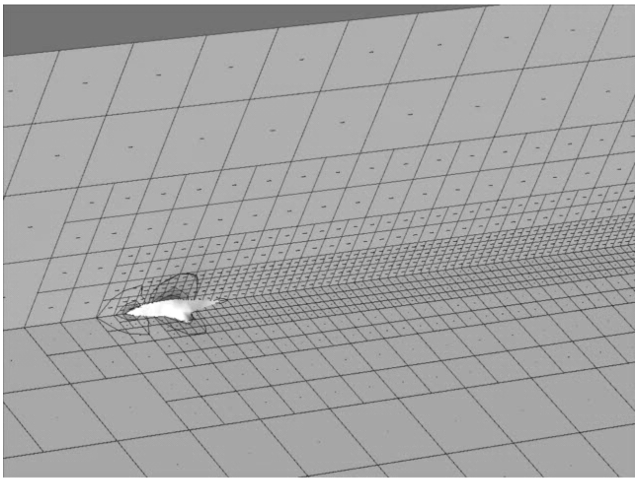


Fig. 48. 3D simulation of a dolphin

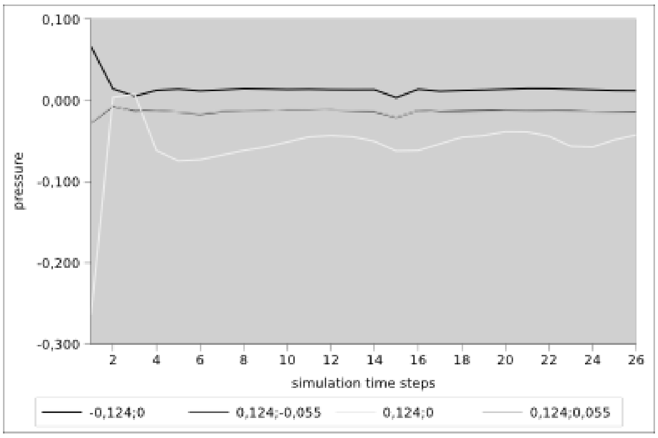


Fig. 49. The pressure measurements of the cone.

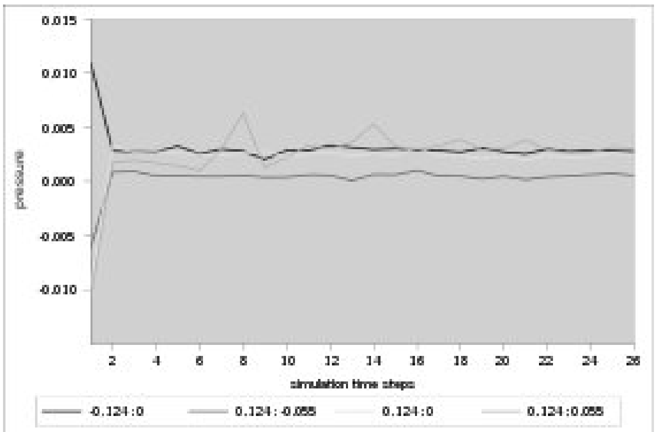


Fig. 50. Dolphin pressure changes

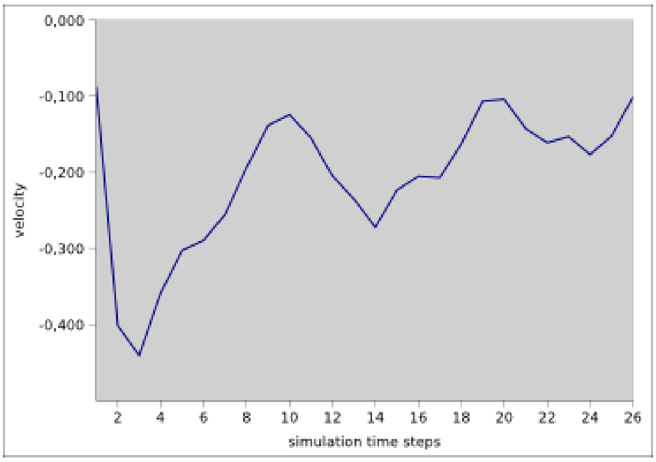


Fig. 51. The velocity changes around the cone

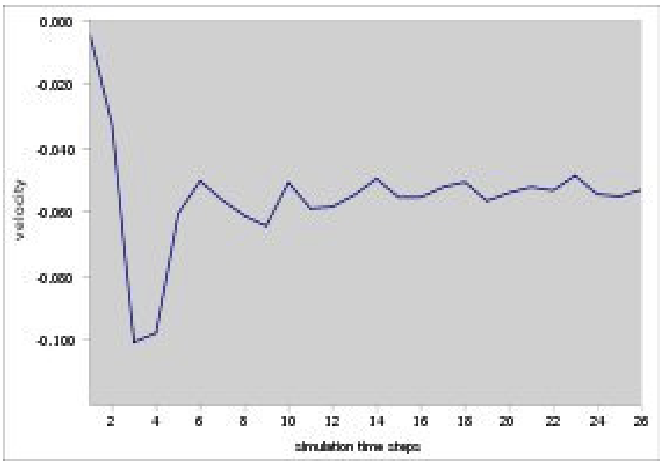


Fig. 52. Dolphin circulation

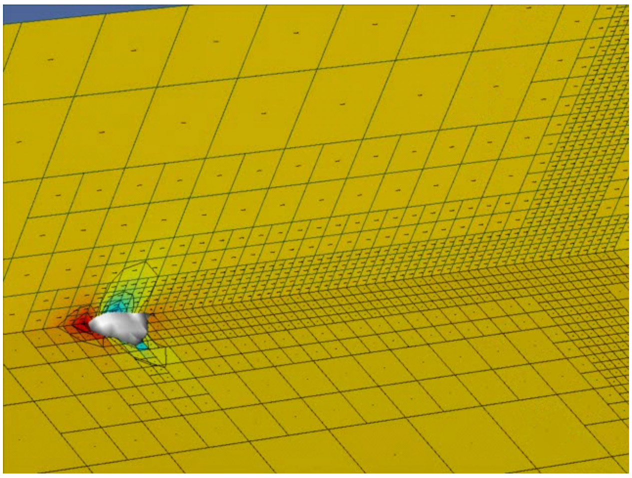


Fig. 53. 3D simulation of a manta ray

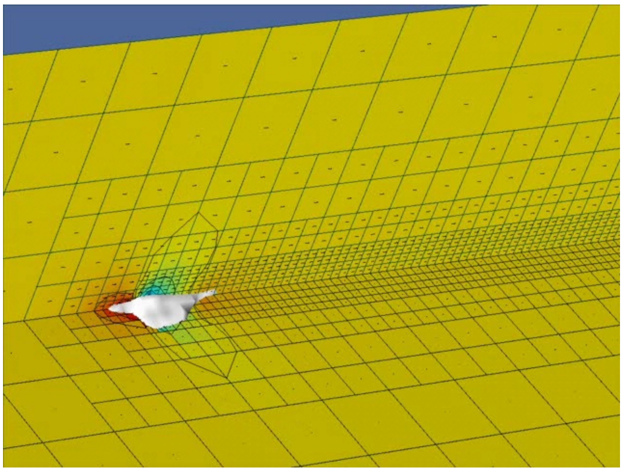


Fig. 54. 3D simulation of the robot

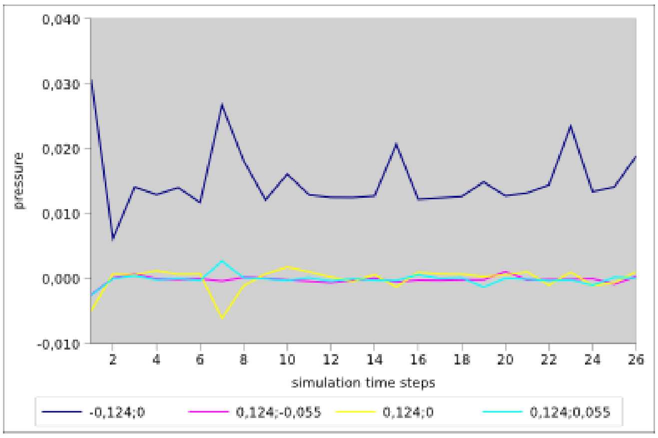


Fig. 55. Manta ray pressure changes

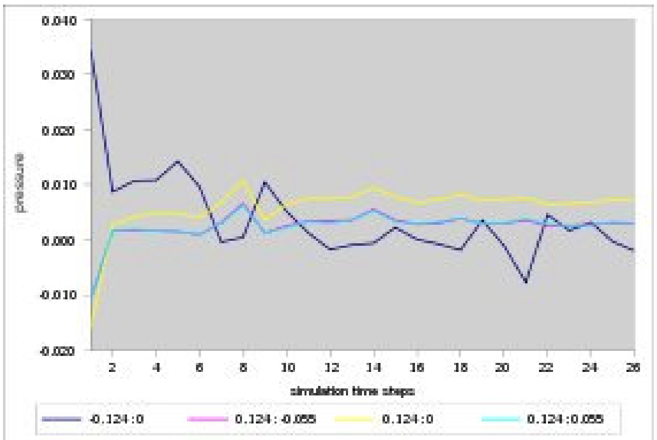


Fig. 56. Robot pressure changes

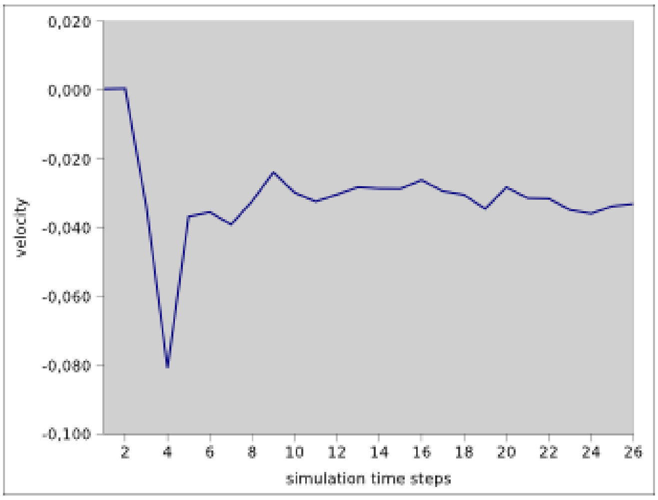


Fig. 57. Manta ray circulation

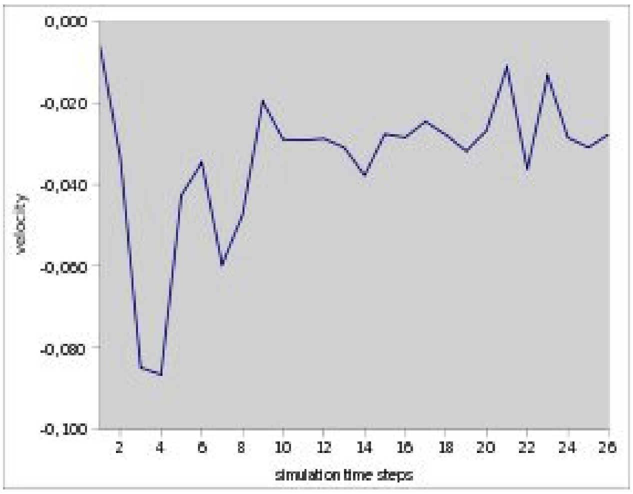


Fig. 58. Robot circulation

The second simulation was done to find robots drag limits for this body shape. We also measured the drag experimentally and later used the same towing speeds to compute the ideal pressure values around the robot's body (Fig. 59). From these pressure values we calculated the theoretical drag. This experiment is also described in the technical report (see IV).

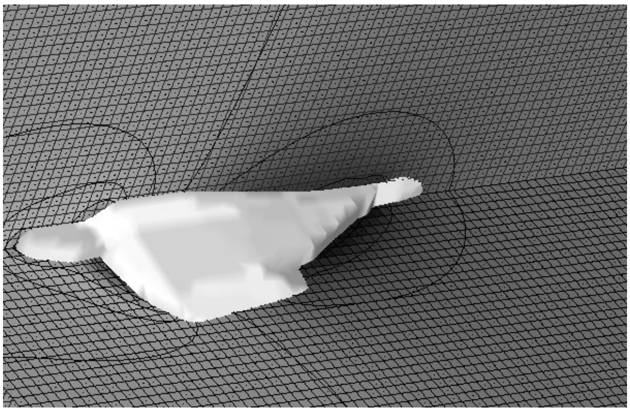


Fig. 59. The robots model and the pressure field around the object.

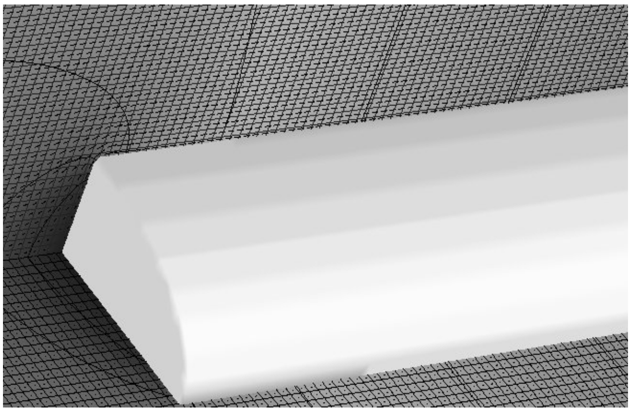


Fig. 60. The ellipsoid model and the pressure field around the object.

The results show us that the theoretical limit for the drag coefficient is still 10 times better than we have achieved so far (see the table X and Fig. 61). The differences can be explained by the roughness of robot surface and by some non-smooth corners and joints of the actual body. This simulation also did not take the frictional drag into account as we did not know the frictional drag of materials used in robot. Experimental drag measurements however showed that the third model has much lower drag coefficient than the second model (see table XI).

Table X. Numerical values of pressure field

nr	Speed m/s	Pmeasured (Pa)	P1sim (Pa)	P2sim (Pa)	Robots measured Re
1	0,17	26,41	5,98	0,73	2,16E+05
2	0,19	28,95	7,47	0,91	2,36E+05
3	0,22	28,68	10,02	1,22	2,72E+05
4	0,26	29,07	14,00	1,71	3,29E+05
5	0,29	34,10	17,40	2,13	3,68E+05
6	0,33	34,62	22,55	2,75	4,17E+05
7	0,36	39,01	26,83	3,28	4,46E+05
8	0,38	42,36	29,90	3,65	4,81E+05
9	0,42	46,18	36,52	4,46	5,21E+05
10	0,45	48,00	41,93	5,12	5,68E+05
11	0,50	66,11	51,76	6,30	6,25E+05
12	0,56	77,68	64,93	14,25	6,94E+05
13	0,63	87,71	82,18	25,44	7,81E+05

Pmeasured – Measured pressure of the robot (Pa)
P1sim – Simulated pressure of the ellipsoid (Pa)
P2sim – Simulated pressure of the robot (Pa)

Table XI. Drag Coefficients

Drag coefficient of the first prototype	Drag coefficient of the second prototype	Drag coefficient of the third prototype
0.37	1.09	0,53

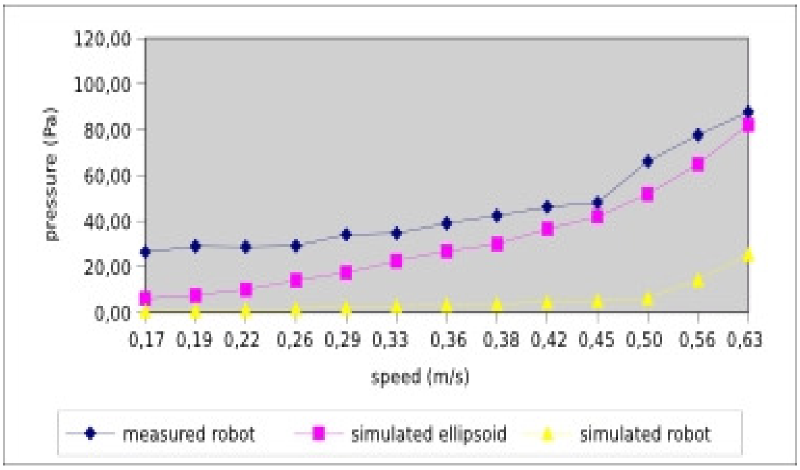


Fig. 61. simulation and measurements results compared.

The tests also showed that for the current bodyshape the speed 0,5 m/sec is a theoretical limit where the laminar flow around the body becomes turbulent as its Reynolds number changes from 5,68E+05 to 6,25E+05. The measurements show that the actual critical speed is lower 0,45 m/sec. The difference can be explained by measurement errors and surface roughness.

This also indicates that the theoretical drag can not be10 times better as Table X suggest, but is already in the close range, as pressure values show transition from laminar to turbulent flow close to the theoretical values.

To solve the second, body oscillation problem, we decided to add one more joint to the tail section at 1/3 body length from the tail. This joint allows us to implement carangiform style swimming. We also redesigned the caudal fin and made it from a flat surface to the drop-shaped cross-section. However, we did not add the additional motor to power the central joint. This motor would increase the weight of the robot and would give an additional load to the batteries. Instead of the motor we designed the joint with springs, so the inevitable oscillation energy will be collected by springs and will be released a moment later back to the environment. This design feature forces also to correct the caudal fin movement patterns, which is now needed to be synchronized with the spring actuated joint movement. This joint now allows us to perform undulatory movement with the tail fin.

In order to allow the tail section to move, the last 1/3 of the body was covered with scale leaf like plastic sheets. This design gives directional surface drag to the robot and should decrease vortex drag as it recollects its energy. During the redesign process we also managed to further decrease the length of the robot by 10 cm.

We also redesigned the side fins and made their cross section also to be drop-shaped. This would reduce the turbulence the flat surfaces are creating.

Chapter 5

Conclusions and future work

The current thesis explores ways to design a new type of a biologically inspired underwater robot. We analyzed environmental, task, and economical restrictions that influence the design decisions. We proposed an overall design methodology to overcome these restrictions and showed how step-by-step approach, which includes planning, analyzing, prototyping, and modeling, gives us the desired result.

Our initial task was to build an underwater robot that could be used for environmental monitoring. The robot must be light, operable by one person from an inflatable boat. The robot is going to be used in two different modes. One mode is a bottom the following mode, where the robot is towed behind the boat. In this mode the robot must videotape the seabed. The important factor here is the non-turbulent motion and an agile maneuvering to avoiding rocks and boulders along the path.

The second mode was the maneuvering mode, where the operator guides the robot to the point of interest. In this mode the non-turbulent movement is also important. The second objective is an ability to hover over spot without disturbing the seabed.

We conclude that the initial requirements are fulfilled. The robot's weight is 16 kg, its length is 1.5 m. These parameters allow the usage of the robot from an inflatable boat by one person.

The bottom following mode is also accomplished. As described in Chapter 4.4.12.2, our robot has achieved the required agility to avoid rocks and boulders. We experimentally measured the surfacing ability while towing the robot with a standard towing speed of approximately 1.8 km/h, and found that the robot can change its vertical direction by more than 45 degrees angle. If we consider that the average visibility under water in The Baltic Sea is 5 – 6 m, then even if the sonar is not finding the obstacle, the operator can rely on the video feed and safely raise the robot over the boulders that are 5-6 m above the seabed.

The maneuvering mode is also accomplished. We have proven by tests that we can change robot's buoyancy so that it changes robot´s orientation in any direction. This also means that we have achieved the ability to stop on the spot without creating turbulence that could cause the disturbance on the seabed. During the tests where we measured robot´s self-propelling ability, we achieved the speed 0.1 m/s that is sufficient for slow maneuvering.

In conclusion we can say that the robot can technically be used in the planned role. However, more tests are still required to achieve the theoretically predicted performance. According to our release plan we still need to complete steps 5 and 6, but the crucial part for the success still comes from the market. Our preliminary market research shows that there is a need for hundreds of robots like this.

5.1. Lessons learned

After finishing many successful design iterations we may say that agile software development rules are applicable to the robot design process with some corrections. The short and conclusive wisdoms of the proposed task oriented biomimetic design cycle are (here is a simplified version, the detailed version is in chapter 4.2.1):

I. Have an end user involved early in your design process
II. Specify the task and the environment restrictions
III. Find the biologically suitable examples.
IV. Analyze the examples' working principles.
V. Implement the found principles in the best way.
VI. Make it as simple as possible and as complicated as needed
VII. Test your model in an early stage of the design as soon as possible.
VIII. Analyze the test results with using the computer models.
IX. Continue the work with an improved test model.

These rules have been proved experimentally to work well. The robot can maneuver horizontally and vertically, it can also regulate its buoyancy so that it can hover over a spot, or can change its body orientation, which helps enormously in maneuvering as the robot can change its depth using compressed air and using the fins.

The robot can be operated by one person from an inflatable boat, can also videotape the seabed and creates very little turbulence when moving. This suggests that we have achieved the desired mechanical performance. We still have to improve its software, this is the main issue of the next iteration step.

We also proposed the new task oriented design methodology. Our success suggests that the methodology is useful and allows avoiding costly mistakes caused by inexperienced developers. The continuous tests, simulations and constant consultations with the end users have so far helped to achieve the result where initial specifications are fulfilled, by the developers who did not have any previous experience in this field.

However while following our initial design methodology, we still could not foresee everything in our design process. The tests teach us that as important as the functional design is also the maintainability and transportability of the robot. These two considerations are just as important as all other design considerations. While we might think logically that an underwater robot operates only in water environment; it is just simply not true. Our robot spends most of its time on land waiting for maintenance or upgrade or is traveling to the test site. That means that the robot must survive the beating of a rough road in a car and must be easily serviceable in the place of operation. We learned also, that the first test model was too long to be transported without problems in an ordinary car. To solve this problem, we were forced to assemble it on the test site. When we first started do sketch our design methodology, we did not think of it as one of the main criteria, but after finishing many release plan iterations we think of it as of a very important consideration.

During the tests with the second model we almost completely redesigned electronics, as the first design was unreliable and did not work well when inductive noise from dc motors disturbed and static electricity destroyed the microelectronics. The second model teaches us also that too much modularity is also not good. While it may seem to be good to have many interchangeable modules, it creates to many cables and cable connectors that take too much valuable space and are prone to cause equipment malfunctioning. We may conclude this lesson with the words “make it as simple as possible and as complicated as needed”.

Many robot builders overlook the importance of the simulation models, and consider them as unnecessary and imprecise. Our experience shows us that modeling and simulation can give necessary inspiration and feedback for improving the design and finding the weak spots that have got overlooked although the simulations are not covering all aspects of the design. In our work modeling helps us to redesign the body shape and gives us the knowledge that practically we have achieved a drag coefficient close to the theoretical values and further improvements must be made elsewhere.

While still not being in the end of our own design cycle, we can already say that the experimental step-by-step validation process by building consequent experimental models proves to be a valuable tool for achieving the result and avoiding costly mistakes. The principle “test the robot early – test the robot often – model it” which is derived from agile software development principle “release your software early – release it often” is good and helps to save resources.

5.2. Future work

In the immediate future we complete the release plan step 5 and begin with the step 6. The step 5 includes introduction of Central Pattern Generator (CPG) driven control for fin actuators and better human-robot communication possibilities. That means also integrating additional sensors to the overall control.

This type of control was chosen because it is supported by strong biological evidence, several researches show that that this type of control is used by animals for performing cyclic movements [49,50,51,52]. Because we initially chose to implement the fin propulsion, the usage of CPG for controlling the fin movement is the most plausible solution.

The implementation of CPG however means programming. Here we again will benefit from our agile methodology, as we derived it from Extreme Programming (XP) software methodology. The XP methodology requires the test driven software development. As we proposed earlier we extend it here to cover also hardware testing in the same loop, as hardware performance is really the true measure of successful software.

The release plan step 6 means intensive tests to cover all possible usage scenarios in order to pass customers acceptance tests. Through these tests we expect to improve robots performance to the level that allows using it in everyday work.

Chapter 6

Perspectives

We mentioned above that this project started because there was a need to help to meet the objectives set by EU Water Framework Directive (WFD) [121]. In this chapter we look briefly the implications of this document to our robot and perspectives that this directive is opening.

In 2000, the European Parliament has adopted a text that put in place a coherent framework for protecting and improving water quality and resources across EU. It fixes compulsory rules for member states. The WFD requires ambitious improvements in water quality and introduces new powers to control emissions of dangerous substances to water. Table XII shows the timetable of this project.

Table XII. Timetable for implementation [117]

Year	Issue
2000	Directive entered into force
2003	Transposition in national legislation Identification of River Basin Districts and Authorities
2004	Characterization of river basin: pressures, impacts and economic analysis
2006	Establishment of monitoring network Start public consultation (at the latest)
2008	Present draft river basin management plan
2009	Finalize river basin management plan including progamme of measures
2010	Introduce pricing policies
2012	Make operational programmes of measures
2015	Meet environmental objectives
2021	First management cycle ends
2027	Second management cycle ends, final deadline for meeting objectives

In early stages of this project we did a short investigation about the possible demands for monitoring equipment. In 2005 we widened this research and Institute of Technology Tartu University ordered a preliminary market research to find out potential usage and demand for this kind of robots. We can bring out here some unpublished data of this report. Table XIII summarises the current situation in monitoring activities around the The Baltic Sea and Table XIV describes the situation after meeting the objectives of this Directive.

These tables are compiled using publicly available sources and interviews with Dr. Georg Martin from Estonian Marine Institute. Dr. Martin is responsible for monitoring activities in Estonia and has good knowledge about situation in other Baltic Sea countries. These projections are only estimates, based on needed monitoring activities per kilometer of shoreline.

We also expected that one diver does 200 hours of work per year and cost of one hour in Estonia, Latvia, Lithuania, Poland and Russia is 1000 EEK and for Finland, Sweden, Denmark and Germany is 4000 EEK.

Currently only Denmark is able to fully perform all required activities. We used their data to estimate the needs of other countries. Russia is the only Baltic Sea country who is not a member of EU, but we expected them to follow the practices of other countries.

Table XIII. Sea monitoring capabilities in Baltic Sea region in 2005.

Country	Shoreline length (official)	Shoreline length (shortened)	Divers	Hours (year bases)	Cost (EEK year)
Estonia	3 700	600	1	200	200 000
Finland	1 126	1182	5	1 000	4 000 000
Sweden	3 475	2600	10	2 000	8 000 000
Denmark	7 313	2074	35	7 000	28 000 000
Germany	2 389	1084	5	1 000	4 000 000
Latvia	531	480	1	200	200 000
Lithuania	99	170	1	200	200 000
Poland	491	550	1	200	200 000
Russia	280	821	1	200	200 000
SUM	19 404	9561	60	12 000	45 000 000

Table XIV. Sea monitoring requirements after implementing the EU Water Framework Directive.

Country	Shoreline length (official)	Shoreline length (shortened)	Divers	Hours (year bases)	Cost (EEK year)	Cost (EEK year, calculated by shortened shoreline)
Estonia	3 700	600	3	700	700 000	1 980 000
Finland	1 126	1082	10	2 000	8 000 000	14 282 400
Sweden	3 475	2600	17	3 400	13 600 000	34 320 000
Denmark	7 313	2074	35	7 000	28 000 000	27 376 800
Germany	2 389	1084	12	2 400	9 600 000	14 308 800
Latvia	531	480	2	400	400 000	1 584 000
Lithuania	99	170	2	400	400 000	297 000
Poland	491	550	2	400	400 000	1 584 000
Russia	280	821	2	400	400 000	874 500
SUM	19 404	9561	85	17 100	61 500 000	96 607 500

The whole market size of underwater equipment in the world was approx. 1.2 billion EUR at 2005. In year 2010 the market is expected to grow up to 1.4 billion EUR [118]. This market consists of ROVs, AUVs and also of their instruments and navigation systems. Big ROVs are more expensive, we estimate that only 11% of all market is for small robots. That means approx. 132 million EUR.

As interviews with environmental biologist around The Baltic Sea revealed, they wish to use one robot for every 2 divers. That makes 42 robots for the whole Baltic Sea region. It is also expected that one robot can save up to 1/3 of expenses needed for monitoring, that makes 20 – 32 million EEK per year.

The shoreline of all European countries is approx. 95 000 kilometers (the longest shoreline belongs to Norway with 25 000 kilometers, Great Britain has 13,500 kilometers and Greece has 12,500 kilometers), from that The Baltic Sea shoreline is approx. 19 000 kilometers. That makes us believe that the market in other European countries is 4 times larger than our domestic Baltic Sea market.

If we compare EU with USA, we see that shoreline of inland water bodies is 2 times larger than in Europe and shoreline of open water is 1,5 times smaller.

That makes us believe that a large market exists for new type of monitoring robots. This market can even be several times larger if the robot is going to be used in other roles such as for demining, search and rescue, etc.

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Curriculum Vitae

1. Personal Data

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3. Education

Educational Institution	Graduation Time	Speciality / grade
Tallinn University of Technology	2007	Information Technology / Ph.D.
Tallinn University of Technology	1991	Information Technology / Graduate Engineer

4. Language Skills (basic, intermediate or high level)

Language	Level
Estonian	Mother Tongue
English	High Level
Russian	Intermediate
Finish	Intermediate

5. Special Courses

Course Date and time	Educational institution or organization
July 2005	Euron / Geoplex Summer School on Modelling and Control of Complex Dynamical Systems; University of Bologna Residential Centre of Bertinoro, FC, Italy
2004 autumn and 2005 spring	Halmstad University, Sweden, Prof. Josef Biguni machine vision course “Image analysis I” ja “Image analysis II”
1997-2002 MBA programme	Tallinn University of Technology

6. Professional employment

Period	Institution	Position
1998 -	Private consultant	
1994 - 1998	Osborne Computer Eesti AS	Sales Manager
1991 - 1994	Aetec AS (Profit Software Eesti AS now)	Senior Software Engineer
1988 - 1990	Institute of Cybernetics, Estonian Academy of Science	Engineer

7. Scientific Work

M. Listak, D. Pugal, M. Kruusmaa, “Biomimetic fish-like underwater robot for shallow water applications”, Proc. of the 13th International Conference on Advanced Robotics (ICAR 2007), August 21-24, 2007, Jeju, Korea

Madis Listak, Deivid Pugal, Maarja Kruusmaa “Computational Fluid Dynamics Simulations of a Biomimetic Underwater Robot” Proc. of the 13th International Conference on Advanced Robotics (ICAR 2007), August 21-24, 2007, Jeju, Korea

Madis Listak, Deivid Pugal, Maarja Kruusmaa, ”Computational Fluid Dynamics Simulations of a Biomimetic Underwater Robot”, 8th International Workshop on Research and Education in Mechatronics, Tallinn, 2007

Madis Listak, Georg Martin, David Pugal, Alvo Aabloo, Maarja Kruusmaa, "Task-oriented Design of an Underwater Vechicle for Environmental Monitoring in the Baltic Sea" Proc of the IWUR2005 International Workshop on Underwater Robotics for Sustainable Management of Marine Ecosystems and Environmental Monitoring 9-11 nov. 2005 Genoa Italy

Madis Listak, Georg Martin, David Pugal, Alvo Aabloo, Maarja Kruusmaa, "Design of a Semiautonomous Biomimetic Underwater Vehicle for Environmental Monitoring, " Proc of the 2005 IEEE Int. Symposium on Computational Intellgence in Robotics and Automation (CIRA 2005), June 27-30, 2005, Espoo, Finland

Madis Listak, Maarja Kruusmaa, "Buoyancy Control of a Semiautonomous Underwater Vehicle for Environmental Monitoring in Baltic Sea ", Proc. of the Int. IEEE Conf. Mechatronics and Robotics 2004 (MechRob'04), Vol. 2, pp. 252 - 257, 13. - 15. Sept. 2004, Aachen.

Mart Anton, Andres Punning, Alvo Aabloo, Madis Listak, Maarja Kruusmaa, "Towards a Biomimetic EAP Robot", in Proc. of TAROS 2004, "Towards Autonomous Systems", University of Essex, 6.-8. Sept. 2004.

Madis Listak, Georg Martin, Maarja Kruusmaa, "Light Control Method for Automatic Benthic Algae Recognition"; The XVIIIth International Seaweed Symposium Bergen, Norway, June 20-25, 2004

Madis Listak, Georg Martin, Maarja Kruusmaa, "Using image analysis for calculating the overall coverage of underwater vegetation in Baltic Sea region"; IASTED conference on "Visualization, Imaging and Image Processing" (VIIP 2003), Benalmadena, Spain 2003

Madis Listak, Georg Martin, Maarja Kruusmaa, "Automatic image detection system - a tool for monitoring underwater macrovegetation"; Baltic Sea Science Congress 2003 Helsinki, August 24th - 28th, 2003

8. Thesis Accomplished and Defended	Graduate Engineer Thesis, 1991
9. Research Interest	Robotics, Machine vision
10. Other Research Projects	-

Signature Date

Elulookirjeldus

1. Isikuandmed

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3. Hariduskäik

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Tallinna Tehnikaülikool	2007	doktorantuur
Tallinna Tehnikaülikool	1991	insener

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Inglise	Kõrgtase
Vene	Hea
Soome	Hea

5. Täiendusõpe

Õppimise aeg	Õppeasutuse või muu organisatsiooni nimetus
Juuli 2005	Euron / Geoplex Summer School on Modelling and Control of Complex Dynamical Systems; University of Bologna Residential Centre of Bertinoro, FC, Italy
2004 sügis ja 2005 kevad	EITSA stipendiumiga Halmstadi Ülikoolis prof. Josef Biguni masinnägemise kursused “Image analysis I” ja “Image analysis II”
1997-2002 MBA programm	Tallinna Tehnikaülikool

6. Teenistuskäik

Töötamise aeg	Ülikooli, teadusasutuse või muu organisatsiooni nimetus	Ametikoht
1998 -	Vabakutseline ettevõtja, konsultant	
1994 - 1998	Osborne Computer Eesti AS	müügijuht
1991 - 1994	Aetec AS (praegune Profit Software Eesti AS)	vanem tarkvarainsener
1988 - 1990	Eesti Teaduste Akadeemia Küberneetika Instituut	insener

7. Teadustegevus

M. Listak, D. Pugal, M. Kruusmaa, “Biomimetic fish-like underwater robot for shallow water applications”, Proc. of the 13th International Conference on Advanced Robotics (ICAR 2007), August 21-24, 2007, Jeju, Korea

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Madis Listak, Georg Martin, David Pugal, Alvo Aabloo, Maarja Kruusmaa, "Task-oriented Design of an Underwater Vechicle for Environmental Monitoring in the Baltic Sea" Proc of the IWUR2005 International Workshop on Underwater Robotics for Sustainable Management of Marine Ecosystems and Environmental Monitoring 9-11 nov. 2005 Genoa Italy

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Mart Anton, Andres Punning, Alvo Aabloo, Madis Listak, Maarja Kruusmaa, "Towards a Biomimetic EAP Robot", in Proc. of TAROS 2004, "Towards Autonomous Systems", University of Essex, 6.-8. Sept. 2004.

Madis Listak, Georg Martin, Maarja Kruusmaa, "Light Control Method for Automatic Benthic Algae Recognition"; The XVIIIth International Seaweed Symposium Bergen, Norway, June 20-25, 2004

Madis Listak, Georg Martin, Maarja Kruusmaa, "Using image analysis for calculating the overall coverage of underwater vegetation in Baltic Sea region"; IASTED conference on "Visualization, Imaging and Image Processing" (VIIP 2003), Benalmadena, Spain 2003

Madis Listak, Georg Martin, Maarja Kruusmaa, "Automatic image detection system - a tool for monitoring underwater macrovegetation"; Baltic Sea Science Congress 2003 Helsinki, August 24th - 28th, 2003

8. Kaitstud lõputööd

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9. Teadustöö põhisuunad

robootika, masinnägemine

10. Teised uurimisprojektid

-

Allkiri Kuupäev

List of publications

This Thesis is a summary based on the following papers, which are referred to in this text by their Roman numerals:

I. Madis Listak, Maarja Kruusmaa, "Buoyancy Control of a Semiautonomous Underwater Vehicle for Environmental Monitoring in Baltic Sea", Proc. of the Int. IEEE Conf. Mechatronics and Robotics 2004 (MechRob'04), Vol. 2, pp. 252 - 257, 13. - 15. Sept. 2004, Aachen.
II. Madis Listak, Georg Martin, David Pugal, Alvo Aabloo, Maarja Kruusmaa, "Design of a Semiautonomous Biomimetic Underwater Vehicle for Environmental Monitoring," Proc, of the 2005 IEEE Int. Symposium on Computational Intelligence in Robotics and Automation (CIRA 2005), June 27-30, 2005, Espoo, Finland
III. M. Listak, D. Pugal, M. Kruusmaa, "Biomimetic fish-like underwater robot for shallow water applications", Proc. of the 13th International Conference on Advanced Robotics (ICAR 2007), August 21-24, 2007, Jeju, Korea
IV. Madis Listak, Deivid Pugal, Maarja Kruusmaa; "Computational Fluid Dynamics Simulations of a Biomimetic Underwater Robot", Proc. of the 13th International Conference on Advanced Robotics (ICAR 2007), August 21-24, 2007, Jeju, Korea
V. Madis Listak, Deivid Pugal, Maarja Kruusmaa; "CFD Simulations and Real World Measurements of Drag of Biologically Inspired Underwater Robot", Technical report

Other publications, relevant to my work but not included in this Thesis

VI. Madis Listak, Deivid Pugal, Maarja Kruusmaa**,** **"**Computational Fluid Dynamics Simulations of a Biomimetic Underwater Robot**",** 8th International Workshop on Research and Education in Mechatronics**,** Tallinn, 2007
VII. Madis Listak, Georg Martin, David Pugal, Alvo Aabloo, Maarja Kruusmaa, "Task-oriented Design of an Underwater Vechicle for Environmental Monitoring in the Baltic Sea" Proc of the IWUR2005 International Workshop on Underwater Robotics for Sustainable Management of Marine Ecosystems and Environmental Monitoring, Genoa Italy, 9-11 nov. 2005
VIII. Mart Anton, Andres Punning, Alvo Aabloo, Madis Listak, Maarja Kruusmaa, "Towards a Biomimetic EAP Robot", in Proc. of TAROS 2004, "Towards Autonomous Systems", University of Essex, 6.-8. Sept. 2004
IX. Madis Listak, Georg Martin, Maarja Kruusmaa, "Light Control Method for Automatic Benthic Algae Recognition"; The XVIIIth International Seaweed Symposium Bergen, Norway, June 20-25, 2004
X. Madis Listak, Georg Martin, Maarja Kruusmaa, "Using image analysis for calculating the overall coverage of underwater vegetation in Baltic Sea region"; IASTED conference on "Visualization, Imaging and Image Processing"(VIIP 2003), Benalmadena, Spain 2003
XI. Madis Listak, Georg Martin, Maarja Kruusmaa, "Automatic image detection system - a tool for monitoring underwater macrovegetation"; Baltic Sea Science Congress 2003 Helsinki, August 24th - 28th, 2003

Publications

Appendix A

Buoyancy Control of a Semiautonomous Underwater Vehicle for Environmental Monitoring in Baltic Sea

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Abstract – **This paper describes a preliminary prototype of a semiautonomous underwater vehicle. The vehicle is designed for environmental inspection in Baltic Sea region. The environmental characteristics and the purpose of the vehicle set several restrictions to the vehicle's design. The concept represented here aims at meeting these restrictions. The paper focuses on describing a novel buoyancy control mechanism based on two controllable lateral ballast tanks. The buoyancy control permits using the vehicle in two modes - horizontally compressed and vertically compressed. These modes are used in different environmental conditions and for different monitoring tasks.**

I. INTRODUCTION

Our goal is to design a vehicle for environmental monitoring in Baltic Sea that is in the first place meant for monitoring of underwater vegetation and benthic morphology.

Baltic Sea is one of the most severely polluted seas in the world. The extent and distribution of underwater vegetation gives a lot of information about pollution, climatic conditions, ice conditions etc., therefore vegetation is monitored regularly. At present underwater monitoring is done by divers, which is laborious, expensive and dangerous.

We have designed a prototype of a vehicle that is equipped with an underwater camera and is meant to replace the human diver. In addition to hydrobiological surveys the vehicle can also be used to record other environmental parameters like water temperature, pH-level, salt content, etc. Since the device is equipped with an underwater camera it can also be used for underwater inspection e.g. at rescue operations, construction work, etc. in shallow waters.

The paper at hand describes the preliminary prototype of the vehicle and focuses on a novel buoyancy control mechanism. The buoyancy control permits using the vehicle at different orientations, either horizontally or vertically compressed, depending on the environmental conditions and task specification.

This paper is organized as follows. In the rest of the introductory part we describe the task requirements. Next, we describe our buoyancy control mechanism. Sections 3,4 and 5 describe the mechanical, pneumatic and control system of the prototype respectively. We end this paper with concluding remarks and an outline for the future work.

A. Task description

The requirements determining our vehicle design can be divided into two large categories. The first category consists of environmental factors that are unique to the Baltic Sea. The second category is the human and task specific factors. In the following subsections we describe both of the categories closer.

B. Environmental factors

Baltic Sea is different in several senses from subtropical and tropical seas or exposed seas like Nordic Sea. The factors influencing our choices for the vehicle's design are the following:

1) Depth: Baltic Sea is relatively shallow and therefore the underwater vehicles do not have to operate under high pressure.

2) Turbidity: water is very turbid due to floating detritus and therefore visibility is very low.

3) Extension of vegetation: due to low visibility, the euphotic zone (the zone of penetration of light into the water column) is rather narrow and therefore the vegetation is limited to the costal regions in the depth down to approximately 20m. The regions of interest for environmental monitoring are usually near the coastline in the depth from 1m to 6m.

4) Properties of the seabed: most of the seabed in the depth of interest is covered with mud or small particles of zoo- and phytoplankton that has settled down and is extremely volatile.

5) Human inhabitancy: Baltic Sea is under a severe anthrophic pressure. Costal regions that are especially interesting for monitoring are full of harbours, beaches, fishing nets, dense surface traffic, etc.

C. Human- and task specific factors

This research is strongly demand-driven and therefore we pay lot of attention to satisfying the requirements of the users, which are in the first place environmental scientists. The human and task specific factors that influence our vehicle design are the following:

1) Main functions: the main function of the device is to facilitate environmental monitoring. The highest priority is to facilitate monitoring of underwater vegetation.

2) Additional functions: if possible, the device should also permit measuring other environmental parameters, like temperature, pressure, salt content and make it possible to correlate these parameters with hydrobiological data. It could also be used for other type of benthic surveys and diving under ice in winter.

3) Operational requirements: the device should be portable, preferably operated by one person only; it should support storing, processing and mapping of environmental data.

4) Cost requirements: since the vehicles can occasionally be lost, their cost has to be kept as low as possible.

II. DESIGN CONCEPT

Categorization provided in [1] divides underwater vehicles according to their purpose in three categories. The first category is commercial vehicles used mainly by offshore oil and gas industry for exploitation and exploration of oil and gas fields. These vehicles are usually heavy, they tolerate high pressure that makes them applicable in deep ocean surveys and they are very expensive. Military vehicles are basically used for reconnaissance, intelligence gathering and demining, they often operate in a fleet, are fully autonomous and expensive.

The third category is low cost academic research tools, like for example [2]. The vehicle described in this paper certainly falls into the last category. Its main function is to support scientific benthic surveys. Also its cost has to be kept low to afford using several vehicles along the costal line and to decrease the risk of loosing some of them in fishing nets or on underwater rocks.

According to the restrictions specified above we describe the main features of the design.

A. Semiautonomous and remotely operated modes

Underwater navigation and mapping is still a field of intensive research. Despite of several emerging solution, the methods of underwater navigation are still under development [3]. In addition, a fully autonomous vehicle must carry its own batteries. The batteries have to be charged often and they increase the weight of the vehicle. A fully autonomous vehicle can be lost more certainly (environmental researchers report every year loss of theft of a great deal their equipment). Considering these disadvantages we propose a semiautonomous vehicle that can be operated in two different modes:

1) Towing mode: in this mode the vehicle is towed behind a boat or a ship. With the help of bow sonar it adjusts its height from the bottom. The power supply and localization unit are on the surface as well as the data storage for the gathered data. The towing mode permits covering large distances at speed. At present, benthic surveys are often done by towing a diver behind a boat. According to preliminary calculations, replacing the diver with a vehicle like this will be approximately 10 times more efficient.

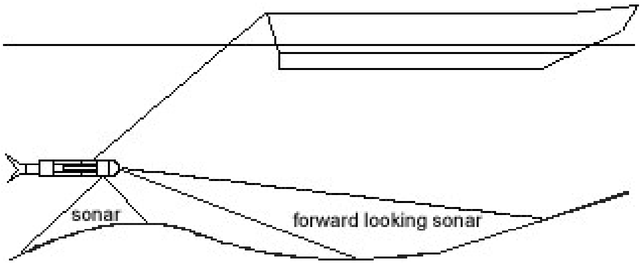

Fig. 1. Using the vehicle in a towing mode.

2) Remote control mode: the operator can manually drive the vehicle. This mode requires more control surfaces for greater manoeuvrability. This mode can be used for closer inspection of underwater sites or diving under ice.

B. Fin-like control surfaces

Underwater vehicles almost exclusively use thrusters for locomotion. This is an effective means of propulsion but as a side-effect it generates high turbulence. The bottom of Baltic Sea is to a great extent covered with very lightweight detritus, specially the regions of the greatest interest for environmental monitoring. Tests with underwater vehicles show that at the moment the thrusters are switched on, visibility becomes practically zero and it takes a long time before the extremely volatile detritus settles down again. We therefore have decided to use elevators instead of the thrusters in a tow mode to control the depth of the vehicle and additional rudders for yaw stability.

In the future, we aim at using the caudal-fin like propulsion in the remotely controlled mode and pectoral-fin like motion for stability and manoeuvrability [4][5], but this is still a topic for future research.

C. Orientation of the vehicle

The novel aspect of this vehicle is a flattened streamlined body that can be used at different orientations, either horizontally or vertically compressed.

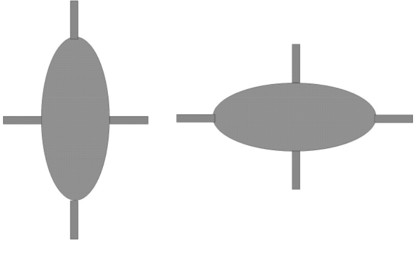

Fig. 2. Orientation of the vehicle: vertically compressed (to the left) and horizontally compressed (to the right).

The two orientations are used in different conditions.

1) Horizontally compressed. This orientation will be mostly used at towing mode. The advantage of the horizontally compressed shape is that the whole body of the vehicle operates as an elevator and works against lift forces. Horizontally flattened body can also used to submerge to the seabed for a closer inspection. Since its cross section is smaller than of the vertically compressed body, it is easier to stabilize the vehicle in lateral currents.

1) Vertically compressed. This orientation will be mostly used in a remote controlled mode and in a towing mode at low speeds in very shallow waters with opulent vegetation. Costal regions interesting for hydrobiologists and other environmental scientists are often shallow bays fully covered with underwater vegetation. Some algae can grow up to 1m – 1.5m and reach up to the water surface. A vehicle with a vertically compressed body is much less likely to get stuck in the dense vegetation or between underwater rocks. A laterally compressed vehicle is able to heave and submerge faster at low speeds and has better manoeuvrability. When a caudal fin is added, it can be used to propel the body forward in a remotely operated mode.

The usage of two orientation modes is supported by biological evidence. Dorsoventrally compressed fishes (like rays and stakes) are ground-dwelling fishes. Their body shape is adapted to bottom following. Laterally compressed body shape (like of sunfish, bluegill and angelfish) is good for leisurely swimming and hiding or for predators who need stability for attack and manoeuvrability.

III. BUOYANCY CONTROL

Underwater vehicles use buoyancy control mainly to submerge and surface or compensate for a changing weight For example, [6] uses a variable buoyancy control to compensate the weight of the payload fetched from the bottom. While buoyancy is traditionally controlled by compressed air and water, alternative methods have also been reported. For example, buoyancy control of [7] is inspired by sperm whales and uses oil temperature regulation for decent and ascent.

The novel aspect of this research is that it uses buoyancy regulation not only to compensate its negative buoyancy and for depth control but also to change the orientation of the vehicle.

The general idea is to use two ballast tanks at both sides of a compressed streamlined body (Fig. 3). In the horizontally compressed mode both tanks are used to regulate buoyancy. In the vertically compressed mode, only the upper tank is filled with the air and is used to control vehicles buoyancy.

Vechicle has 0 buoyancy then its density is equal to the sea-water density. The density of vechicle depends on its mass and volume. Vechicles buoancy is designed to be negative. To have 0 buoancy the ruber balloons must filled with 0,5 litres of air. The overall weight of the vechicle is 15 kg. Balloon can hold 64 litres of air and both ruber air expansion chambers can contain up to 1,5 liters of air.That means that total lift force can be 2,5 kg and for changing orientation we have 1 kg directional lift force available.

IV. MECHANICAL STRUCTURE

The layout of the interior of the vehicle is represented in Fig. 4. Since our aim is to keep the cost of the vehicle low, the prototype is built from off-the shelf components that are easily replaceable.

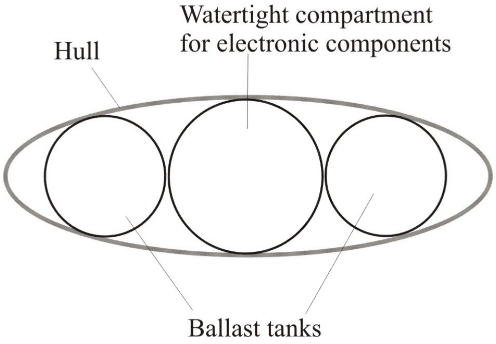

Fig. 3. The design concept of the orientation changing buoyancy control.

The streamlined hull of the vehicle houses the pneumatic system, servos and stepper motors to control the control surfaces, electronic circuits, batteries and sensors. The supporting rod of the vehicle is used to fix these components. The hull is floodable and made of fibreglass. Openings in the hull are for cameras, forward and bottom-looking sonar, lights, and to attach the rudders to the body of the vehicle.

Variable ballast tanks are placed at both sides of the vehicle and made of PVC tubes. Trimming weights can be added or removed from the bow and stern ends of these tubes to compensate changes in buoyancy when modules are changed or payload is added.

The compressed air balloon is fixed between the supporting rods between the ballast tanks at the centre of the vehicle.

The PVC tube in the bow part of the vehicle is a watertight compartment sealed with a silicon sealant and fixed between the supporting skeleton. This compartment houses control electronics and batteries for emergency cases. When the off-board power supply is disconnected or communication with the surface control unit is lost, the vehicle will surface.

The watertight PVC tube housing in stern of the vehicle is for a stepper-motor powering the caudal fin.

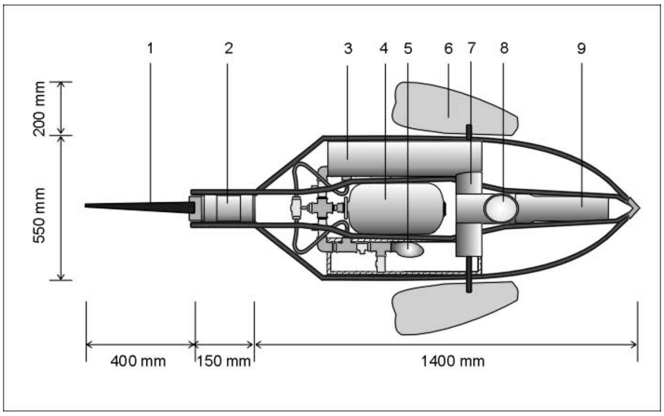

Fig. 4. Internal layout of the vehicle
(1-fin, 2-stepper, 3-PVC tube, 4-compressed air tank, 5-rubber tank, 6-fin, 7-stepper, 8-camera, 9-batteries and electronics)

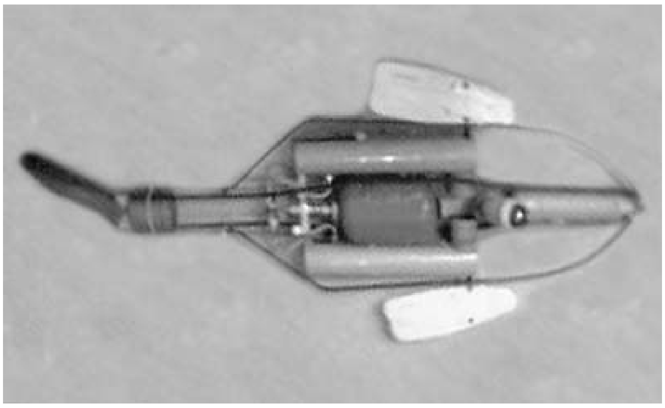

Fig. 5. Partially completed prototype of the vehicle without the floodable outer shell.

The void between the PVC tubes and the compressed air balloon coincides with the opening in the hull and is meant for a down-looking camera and sonar. There is a symmetrical opening on the upper part of the hull that permits adding an additional camera. When the vehicle is operated in a vertically compressed configuration, aquatic environment can be inspected at both sides of the vehicle. The void in the bow in front of the watertight compartment is prepared to host the bow sonar.

The empty regions at both side of the watertight compartment are prepared for containers of water samples and sensors that analyse them (like salinometer, microscope, PH- sensor, etc.). It is planned that these sensors are interchangeable and are used depending on the environmental conditions and the mission.

As it was explained in introduction, water in Baltic Sea is quite turbid and therefore visibility is low. Two halogen lamps in front of the elevators are used to increase visibility or to cancel out reflections when the vehicle operates in very shallow water in a direct sunlight. The reason of having two sources of light on the sides of the vehicle is that there is usually lots of floating plankton and parts of underwater macrovegetation. Since camera is attached in the middle of the vehicle, the scene is illuminated from the sides and reflection is not as intensive as in case of a single source of light. In addition to the halogen lights, to arrays of LEDs are used for spectral analysis of vegetation.

Fig. 6. LED light source with housing

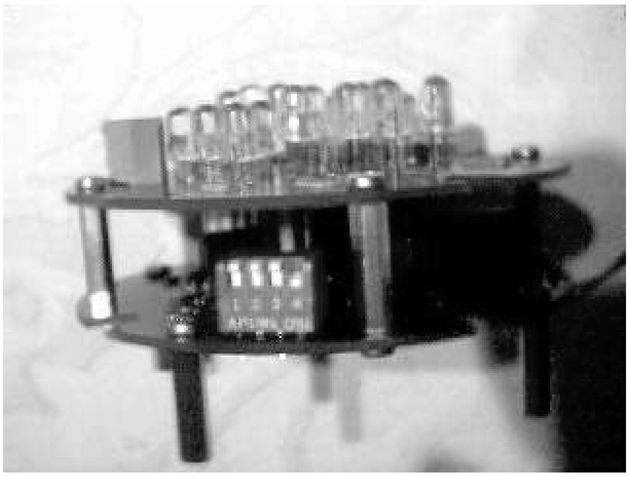

Fig. 7. LED lights and control electronics

V. PNEUMATIC SYSTEM OVERVIEW

Buoyancy of the vehicle is controlled by regulating the volume ratio of water and air in ballast tanks. The tanks have outlets at both ends so that water can flow in or out. In the middle of the tank, there is an air expansion chamber made from rubber. When the chamber is filled with air, water will drain from the tank and the buoyancy of the vehicle increases.

Both ends of the ballast tanks have also a place for trimming weights that can be used to compensate for the change of weight of the vehicle or adjust the centre of gravity when modules are changed or added.

The compressed air balloon supplies air at a pressure of approximately 8 at. This air is used to inflate the air expansion chambers in the ballast tanks. The compressed air balloon is connected to the chambers with air inlet hoses. A Y-branch divides the inlet path to two branches. There are two pairs of valves at both branches. The first pair of valves is outlet valves that can be controlled independently. This permits inflating or deflating only one of the air expansion chambers at time when the vehicle is operating in a laterally compressed configuration. The second pair of valves is the check valves that prevent water from intruding into the pneumatic system.

The air outlet hoses are attached between the air expansion chambers and openings at the frontal part of the vehicle. Like inlet paths, the outlet paths have check and outlet valves.

Both branches are connected together with additional Y-branches, a hose and an outlet valve near the frontal end of the pressured air balloon. This valve is opened when the vehicle is operating in a horizontally compressed configuration. This guarantees an equal pressure in both air expansion chambers and therefore improves pitch stability and controllability of the vehicle.

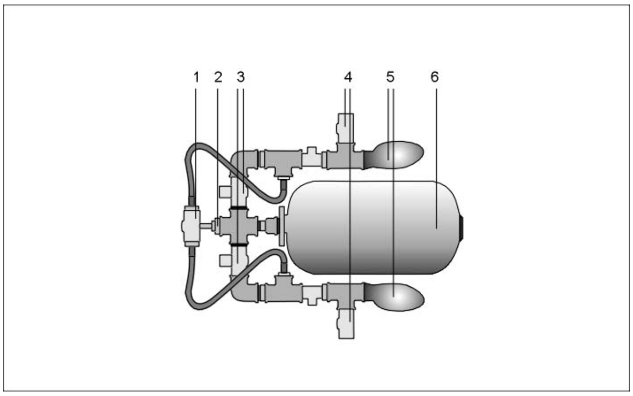

Fig. 8. Pneumatics
(1-pressure equalizing valve, 2-air inlet, 3-input valves, 4-output valves, 5- rubber tanks, 6-compressed air tank)

VI. CONTROL

The block diagram of the vehicle's electronics is provided in Fig. 9.

The control of the vehicle is hierarchical. The surface control unit is a laptop computer connected to the GPS receiver and accessible for a human operator via a graphical user interface. The surface unit receives and stores sensor data that can be later analysed by environmental scientist. It also receives acknowledgement and state signals from the underwater unit and sends down high level commands.

The surface and underwater control units are connected via an Ethernet link. The underwater control system is in turn hierarchical, consisting of a Strong ARM 400 MHz processor on the highest level, TI MSP processor on the middle layer and PIC processors on the lowest layer.

The X-Scale architecture based Intel Strong ARM processor is responsible for communication with the surface unit, for passing up camera data, for processing the received high level commands, high level planning and controlling the next control level.

It is connected to external data storage and colour camera via an USB link and to the compass and inclinometer via RS232.

Connection to the lower level MSP processor is also established through RS232 serial interface.

Texas Instrument's MSP430 microcontroller is an ultra-low power 16-bit RISC mixed-signal processor. It receives high level commands from Strong ARM, decomposes the tasks and passes commands down to the next level microprocessors responsible for executing the commands. It also reports back to the Strong ARM processor about the success or failure of the commands.

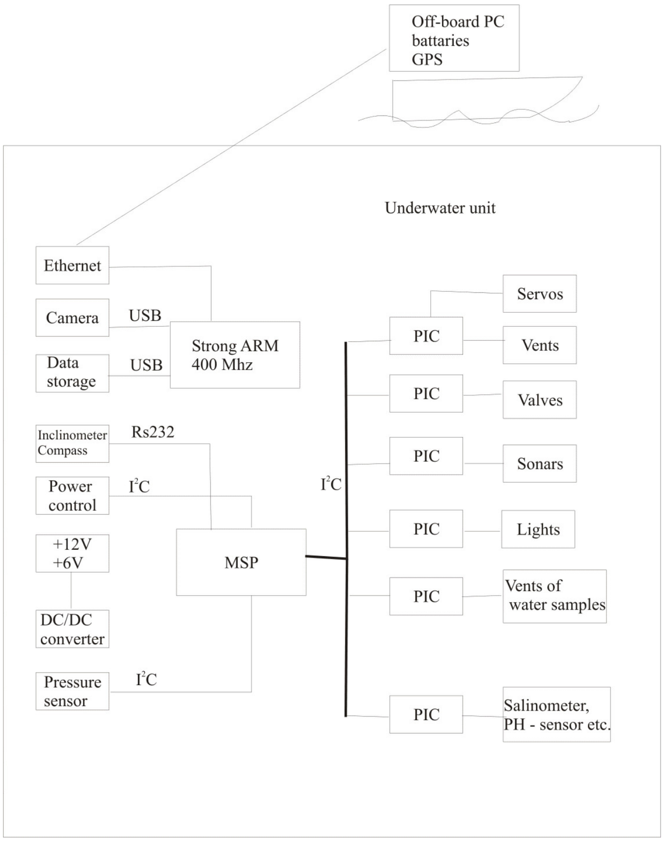

Fig. 9. Block diagram of electronics and control.

The lowest level of control consists of an array of Microchips' PIC18F1320 16-bit 40 MHz processors. These processors are responsible for steering the actuators and receiving sensor data. They are connected to the MSP processor via I^2C interface.

The first PIC processor is responsible for driving the motors of the rudders and vents. The next processor drives the valves of the pneumatic system. The third processor receives data from the bottom and front-looking sonar, analysis the data and passes it forward to the MSP processor.

The fourth PIC processor is used to establish proper lightning conditions. Our preliminary experiments have shown that spectral analysis would facilitate recognition and categorization of underwater macrovegetation. First, it could help a human expert to distinguish between plants and uncovered seabed in case of low visibility. Second, we aim at developing an image processing method that automatically recognizes vegetation from a video tape. We have therefore built an array of LEDs with different wavelengths. The PIC processor under consideration is thus responsible for steering the arrays of LEDs and switching the halogen lamps in and out when spectral analysis is performed.

The next PIC processor steers the vents of the containers of water samples.

Additional processors can be added to process data from additional sensors.

VII. CONCLUSIONS AND FUTURE WORK

This paper describes the preliminary prototype of an underwater vehicle. The vehicle is built for environmental inspection in shallow waters of Baltic Sea. The design concept is based on the environmental restrictions, human factors and cost requirements.

The novel aspect of the vehicle's design is the buoyancy control that permits using the vehicle in two orientations, horizontally and vertically compressed. The orientation can be changed by controlling ballast tanks at both sides of the vehicle.

At present, the construction of the vehicle is mostly complete but underwater test are not yet done. The next phase of this study is therefore a careful testing of the system and all subsystems of the vehicle both is pool environment and in a natural environment where currents and surging is present, and the bottom is uneven.

This semiautonomous vehicle is designed to be used is two modes, a towing mode behind a boat and in a remotely operated mode. The towing mode permits covering long distances at high speed compared to the human diver and therefore considerably increases the efficiency of environmental inspection. We also anticipate that the towing mode is easier to implement that the remotely operated mode since the vehicle has less degrees of freedom and needs fewer control surfaces.

We therefore first aim at building a working prototype that can be used in towing mode by environmental scientist. This involves in fist hand implementation of depth control of the vehicle with help of rudders and front and bottom looking sonar at the same time maintaining yaw and roll stability. At present, the preliminary control model is ready but not tested yet.

The remotely operated mode in a laterally compressed orientation is a more complex task and definitely implies thorough investigation of control models and vehicles kinematics and dynamics.

Parallel to the vehicle's design we also work at image recognition algorithms for classification of underwater vegetation.

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Appendix B

Design of a Semiautonomous Biomimetic Underwater Vehicle for Environmental Monitoring.

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Abstract – **This paper describes a preliminary prototype of a fishlike biomimetic underwater robot. The goal is to develop a semiautonomous vehicle for environmental monitoring in shallow waters. We describe the vehicle and discuss the environmental factors that have influenced the design. Experimental results illustrate the performance of the prototype.**

I. INTRODUCTION

Biomimetic underwater vehicle design has attracted the attention of researchers for several reasons. Fish and other aquatic animals are efficient swimmers. They have remarkable manoeuvrability, trajectory following capability and they efficiently stabilize themselves in currents and surges. They also leave a less noticeable wake than conventional underwater vehicles equipped with thrusters. Artificial aquatic creatures also help us to understand how their biological counterparts are functioning.

Biomimetic underwater devices reported so far include a robotic tuna fish [1, 2], buoyancy control inspired by the sperm whale [3], control of a fish by means of caudal fin [4] or pectoral fins [5]. In [6] an exhibition system is proposed for enhancing event spaces that includes an animatronics system for modern-day fish, coelacanths, and Cambrian world creatures, able to swim under their own electric power. Most of the biomimetic underwater vehicles mimic carangiform swimming (propulsion through the water with oscillating movements of the tail and the rear part of the body) [7]. Other types of swimming are also implemented for example anguilliform (eel-like) locomotion [8] and locomotion with the help of elongated pectoral fins [9, 10].

Most of this research is carried out mainly for scientific purposes with the motivation of investigating and implementing mechanics and kinematics of swimming and of developing new control algorithms for fish-like locomotion.

Unlike the above cited studies, the design of the robot described in this paper is motivated by the task requirements. The main goal of development of this device is environmental monitoring in shallow waters of the costal regions in Baltic Sea and in inland surface water bodies. The biomimetic design of the vehicle is the most suitable one for the task requirements. The main objective of this study is not to implement any certain type of mechanical design, swimming mode or control method but to build a device for practical use to environmental scientists. It is first and foremost meant for doing the laborious, expensive and dangerous work that is at present done by divers.

This paper describes task requirements and the design of the prototype. We also represent some experimental results from this early stage of the prototype development and some characteristics of its performance. We finish this paper with conclusions and remarks about future work directions.

A. Design considerations

The Baltic Sea is a closed and shallow sea. The depth of The Baltic Sea reaches 80m but the regions most interesting for environmental inspection usually lie near the coastline at the depths reaching 20m. On the eastern and southern coast of the sea, shallow bays are often only a few meters deep.

Most of the research and product development of underwater vehicles is directed towards use in much deeper water [11]. Commercial vehicles are used mainly by offshore oil and gas industry for exploitation and exploration of oil and gas fields or for scientific deep ocean surveys. Also military vehicles used for reconnaissance, intelligence gathering and demining, are capable of operating in much deeper water.

These vehicles are usually heavy, tolerate high pressure and are very expensive. Vehicles for shallow water on the contrary do not have to be especially strong and powerful which makes their construction and use easier and cheaper.

At the same time vehicles operating in very shallow water and surf zone face different kinds of design problems [12]. Their weight and size has to be kept small, they require good manoeuvrability, which is especially difficult to achieve in surges. An important part of environmental inspection is the regular monitoring of macro vegetation and therefore the most difficult regions are the most interesting for environmental scientists. In shallow bays some algae can grow up to 1m – 1.5m and reach the water surface. A vehicle operating in such an environment has to be able to move in dense vegetation.

Since the coasts of The Baltic Sea are densely inhabited, fishing nets, harbours, surface transportation and beaches make the environmental conditions even more complicated.

In contrast to tropical or subtropical seas and the deep ocean, water in The Baltic Sea is very turbid. During summer, when water contains lots of zoo and phytoplankton, visibility is often only few meters or even less in surf zones.

The seabed of The Baltic Sea is to a great extent covered with mud or extremely volatile detritus, mainly particles of zoo and phytoplankton that have settled down.

Conventional underwater vehicles almost without exceptions propel themselves through the water with the help of thrusters [13]. The advantages of thrusters are that they are powerful, efficient, able to move the vehicle with at speed and are commercially available. Also there exist advanced methods to control underwater vehicles with thrusters [14].

The disadvantage of thrusters is that they create strong turbulence. This feature makes it difficult to design a vehicle with thrusters that meet the requirements of the task description. On the one hand visibility is very low. Therefore a vehicle that is used for benthic surveys, like monitoring underwater vegetation or bottom morphology, has to be close to the seabed. On the other hand, if the vehicle creates turbulence close to the seabed, visibility becomes practically zero and monitoring of the bottom is not possible.

Current AUVs and ROVs are also mostly operated from ships and often weight hundreds of kilos or tons. This is impossible in Baltic Sea, no ship can enter the zones of interest to biologists. Therefore our device must be light enough to operate from an inflatable boat.

II. DESIGN CONCEPT

1. Semiautonomous and remotely operated modes

Since different types of mission require different performance, the vehicle is designed to be used in two modes.

1) Towing mode. In this mode the vehicle is towed behind a boat. This mode is used for repetitive surveys of the seabed. The main challenge is to keep a constant distance from bottom and not to collide with the boulders and rocks that are common in the sea.

2) Remote control mode. In this mode the robot must hold itself over certain points of interest. That means manoeuvring backward and forward and also stabilizing in currents. This mode can be used for close inspection, taking water samples or diving under ice.

2. Horizontally and vertically compressed modes

The shell of the robot has a flattened ellipsoid shape. Depending on the task of the robot, the vehicle can be used in two different orientations (Fig. 1).

1) Horizontally compressed. This orientation will be mostly used at towing mode. The advantage of the horizontally compressed shape is that the whole body of the vehicle operates as an elevator and works against lift forces. Horizontally flattened body can also used to submerge to the seabed for a closer inspection. Since its cross section is smaller than of the vertically compressed body, it is easier to stabilize the vehicle in lateral currents.

1) Vertically compressed. This orientation will be mostly used in a remote controlled mode and in a towing mode at low speeds in very shallow waters with opulent vegetation. A laterally compressed vehicle is able to surface and submerge faster and has better manoeuvrability in the horizontal plane.

The streamlined hull of the vehicle houses the pneumatic system, servos and stepper motors to actuate the control surfaces, electronic circuits, batteries and sensors. These components are fixed inside a vertical framework encased in a floodable fibreglass hull. There are openings in the hull for cameras, forward and bottom-looking sonar, lights, and for attaching the rudders to the body of the vehicle.

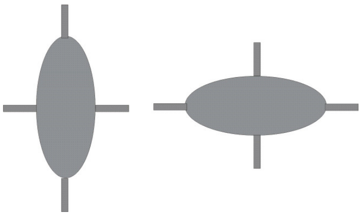

Fig. 1. Orientation of the vehicle: vertically compressed (to the left) and horizontally compressed (to the right).

III. MECHANICAL STRUCTURE

The layout of the interior of the vehicle is represented in Fig. 2. Since our aim is to keep the cost of the vehicle low, the prototype is built from off-the shelf components that are easily replaceable.

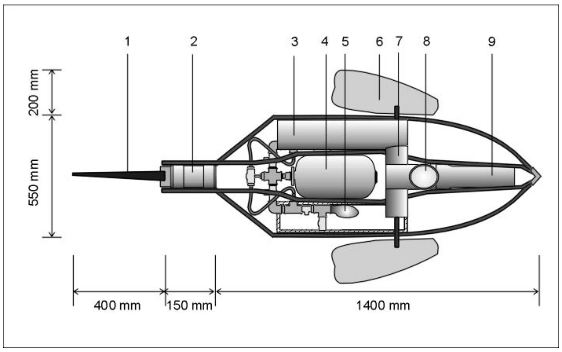

Fig. 2. Internal layout of the vehicle
(1-fin, 2-stepper, 3-PVC tube, 4-compressed air tank, 5-rubber tank, 6-fin, 7-stepper, 8-camera, 9-batteries and electronics)

Variable ballast tanks made of PVC tubes are placed at both sides of the vehicle. Trimming weights can be added or removed from the bow and stern ends of these tubes to compensate changes in buoyancy when modules are changed or payload is added.

The compressed air balloon is fixed between the framework and the ballast tanks at the centre of the vehicle.

The PVC tube in the bow part of the vehicle is a watertight compartment sealed with a silicon sealant and fixed within the supporting skeleton. This compartment houses control electronics and batteries for emergency cases. When the off-board power supply is disconnected or communication with the surface control unit is lost, the vehicle will surface.

IV. PNEUMATIC SYSTEM OVERVIEW

Regulating the ratio of water to air in the ballast tanks controls buoyancy of the vehicle. The tanks have outlets at both ends so that water can flow in or out (Fig. 3). In the middle of the tank, there is an air expansion chamber made from rubber. When the chamber is filled with air, water will drain from the tank and the buoyancy of the vehicle increases.

Both ends of the ballast tanks also have a place for trimming weights that can be used to compensate for the change of weight of the vehicle or adjust the centre of gravity when modules are changed or added.

The compressed air balloon supplies air at a pressure of approximately 8 at. This air is used to inflate the air expansion chambers in the ballast tanks. The compressed air balloon is connected to the chambers with air inlet hoses. A Y-branch divides the inlet path to two branches. There is a pair of valves at each branch. The first valve is an outlet valve, controlled independently on each side. This permits inflating or deflating only one of the air expansion chambers at time when the vehicle is operating in a laterally compressed configuration. The second pair of valves are the check valves that prevent water from entering the pneumatic system.

The air outlet hoses are attached between the air expansion chambers and openings at the front of the vehicle. As the inlet paths, the outlet paths have check and outlet valves.

Both branches are connected together with additional Y-branches, a hose and an outlet valve near the front end of the pressured air balloon. This valve is opened when the vehicle is operating in a horizontally compressed configuration. This guarantees an equal pressure in both air expansion chambers and therefore improves pitch stability and controllability of the vehicle.

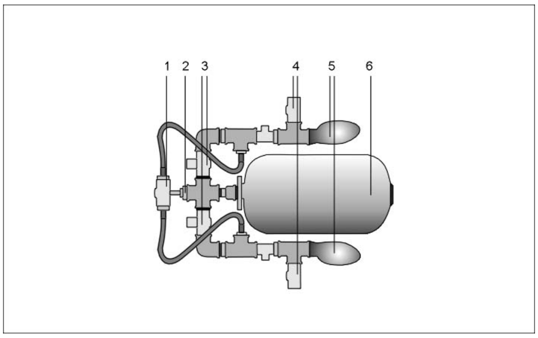

Fig. 3. Pneumatics
(1-pressure equalizing valve, 2-air inlet, 3-input valves, 4-output valves, 5-rubber tanks, 6-compressed air tank)

V. CONTROL SYSTEM

Our robot has a three-layered control system as shown in Fig. 4. The upper layer is Texas Instrument's OMAP5912 Strong-ARM based microcomputer, which communicates with the offboard PC and is responsible for determining the dive plan for the next layer. It also records and pre-processes video input.

The second layer is an ultra-low power 16-bit RISC mixed-signal processor Texas Instrument MSP430. It receives the dive plan from the upper layer Strong-Arm OMAP5912 via a serial port. The main task of this control layer is to follow the dive plan by controlling the actuators, and to collect inputs from sensors. Sensor input and performance of actuators is also recorded for later processing.

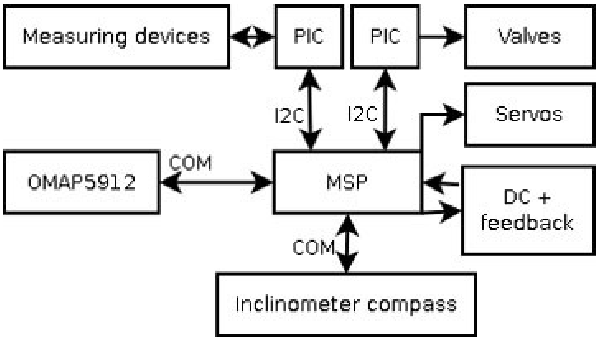

Fig. 4. Conceptual control system

The third layer consists of an array of PIC processors that control the actuators and sensors. Some actuators have built-in PIC microprocessors while others (like valves) have external PIC processors. Communication between MSP430 and PIC processors is done via I2C protocol.

Active control of robot is done by the MSP430, which is responsible for interpreting the dive plan, forwarding commands to lower level PIC controlled devices and communicating the results back to the upper layer OMAP5912. Since the MSP430 has many PWM outputs, it also directly drives the 2 servomotors and reads the tail position from the angle decoder connected to the DC motor of the tail.

The communication protocol is described in Fig. 5. Communication between the OMAP5912 and MSP430 layer is implemented by a command language easily understandable by humans. Communication between the MSP430 and PIC processors is implemented by binary transmission.

The human operator can program mission in a flexible way writing a program such as: “turn left”, “go forward”, “give a temperature reading”, etc

The MSP430 converts these high level commands into a binary form for PIC processors, waits until the commands are executed and sends back the acknowledgement to the MSP430. This permits saves MSP430 processing time for other tasks like video signal recording and transmitting information back to the boat.

The OMAP5912 processor of the upper control layer can send 3 types of commands to the second layer MSP430: “insert sequence item”, “start/stop sequence” and “device control”. Syntax of the command is “*device identifier=command*”. Each command is mirrored from the MSP back to the OMAP5912 to ensure the proper reception of the command.

Received commands are collected on the stack of the internal memory of the MSP430 and are executed sequentially.

It is possible to start or stop processing the sequence of commands by sending a start/stop sequence instruction. It is also possible to control an individual device (e.g. a fin) by sending a single device control command.

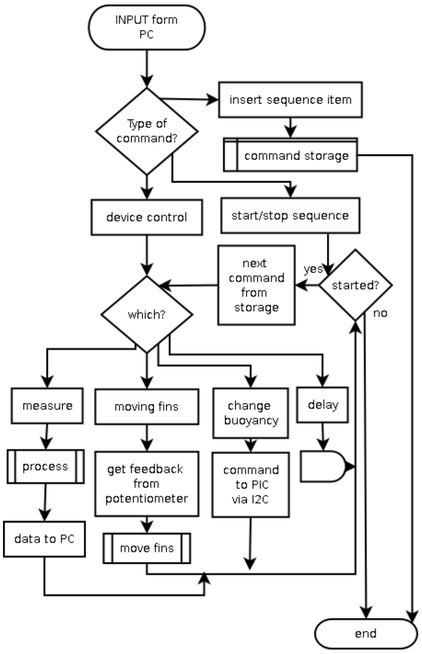

Fig. 5. Communication flow.

VI. EXPERIMENTAL SETUP

Preliminary experiments were conducted to test the functionality of the prototype of the robot and the feasibility of the design.

The first experiment was conducted outdoors in a pond to test the buoyancy control of the robot (Fig. 6) .The second set of experiments was conducted in an indoor pool to evaluate the performance of the actuators (Fig. 7).

The goal of the pool tests was to measure the drag force of the robot's body and performance of the tail fin used as a steering device in the towing mode or a propulsion device in the autonomous mode

These experiments were done in a pool of size 6,5m x 2,5m. Water in the pool was 0.9m deep. The floor of the pool has colour stripes of a width of 0.24m. We used this pattern of the stripes to calculate the speed of the robot from recorded videos.

To determine the drag force we towed the submerged robot with different speeds and measured the force at the same time.

To measure the performance of the tail, the robot was powered by an external power supply. This allowed us to experiment with different supply voltages. A specially designed electronic circuit allows us to vary the PWM signal. The amplitude of the tail fin did not change.

We experimented with two different tail fin configurations, horizontal and vertical with respect to the body of the robot, while the robot's body was always in the horizontal configuration. The robot had zero buoyancy, so it was fully under water but did not touch the bottom. We also experimented with two different body weights. In the first experiment the overall weight of the robot was 20 kg and in the second experiment we increased it to 21,5 kg.

For tail fin movement we used a DC motor with a gearbox and an angle decoder. The motor driving the fin actuator was operating in 12V mode or in 17V mode.

The oscillating frequency of the tail movement in 12 V mode is 0,26 Hz and in 17 V mode, 0,625 Hz. The amplitude of the tail movement is 0,8 m measured from the tip of the tail. The area of the tail is 0,0866 m^2. Power consumption in the 17 V mode was 34W and in the 12V mode 18W.

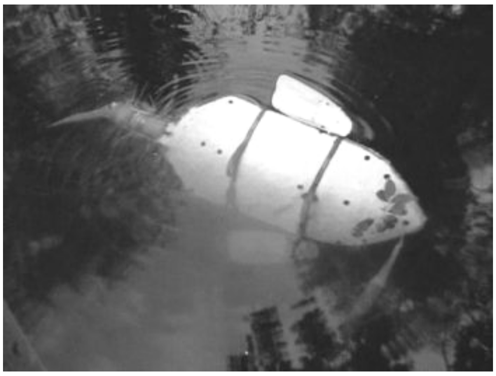

Fig. 6. Pond test. Robot surfaces in vertical mode using only one side balloon.

VII. TEST RESULTS

The goal of the pond experiment was to the test robot's ability to regulate buoyancy. The air tank was filled with air at 4 atm and 10 submerging tests were successfully done. The depth was 2 m. The robot submerged and surfaced both in horizontal and vertical modes as well as changing its orientation when the lower tank was inflated or deflated (Fig. 6).

The pool tests we conducted to measure the energy efficiency and speed of the self-propelled movement. We tried to find guidelines to develop optimal actuator movements, optimal points for attaching stabilizing fins, optimal body weight and optimal working regimes for the tail. The test results are in [15]. The drag force can be be found from equation (1):

$$F_D = C_D \cdot \frac{1}{2} \cdot \rho \cdot v^2 \cdot S\,, \qquad (1)$$

where C_D is the drag coefficient, ρ is the density of fluid, v is speed of the vehicle and S is the characteristic surface area of the robot. We measured drag force and the speed of the vehicle (see Table I). Drag coefficient C_D can be estimated from equation (2):

$$C_D = \frac{2 \cdot F_D}{\rho \cdot v^2 \cdot S} \qquad (2)$$

It depends on the chosen reference surface area S.

There are several different areas from which to choose when determining the reference area used in the drag equation. If we think of drag as being caused by friction between the water and the body, a logical choice would be the total surface area of the body. If we think of drag as being a resistance to flow, a more logical choice would be the front area of the body which is perpendicular to the flow direction.

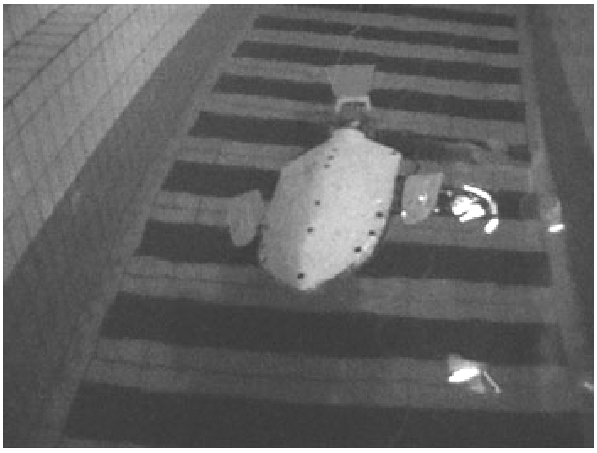

Fig 7. Pool test.

TABLE I.
Drag test results and corresponding drag coefficients

speed v (m/s)	Measured Drag force F (N)	Drag coefficient 1	Drag coefficient 2
0.27	5	0.031	0.292
0.34	10	0.039	0.368
0.37	12	0.039	0.373

If we model the vehicle as an elliptical cylinder with the length L=1.45m and axes a=0.3m and b=0.5m, the total reference surface area for the drag coefficient calculation is

$$S = 2\pi ab + \pi\left(2\cdot\left(a^2+b^2\right)\right)^{1/2}\cdot L = 4.44\left(m^2\right) \quad (3)$$

which is the total “wet surface” of the vehicle.

There is a slight difference between the drag coefficient of our vehicle compared with a cylindrical body of the similar ratio between the length and the diameter (L/D=4). The drag coefficient of the cylindrical body is 0.048 [16].

The actual drag coefficient of our vehicle is smaller. The conclusion is that our robot is more streamlined than a cylinder with similar parameters. Approximation to a cylinder with ratio L/D=7 and with parallel flow (C_D=0.033) could be used for modelling the robot.

We calculate drag coefficient 2 as cross section of elliptical cylinder with axes a=0.3m and b=0.5m. The total reference surface S would be

$$S = \pi ab = 0.47\left(m^2\right) \quad (4)$$

Compared to the ellipsoidal body in turbulent flow [17] the drag coefficient of our vehicle is about two to three times larger. The drag coefficient is about the same as of a cone with 30° angle.

The Reynolds number

$$\mathrm{Re} = \frac{Lv}{\nu} \quad (5)$$

where L is characteristic length of the body, v is swimming speed and ν is the dynamic viscosity of water, $\nu = 10^{-6}\frac{m^2}{s}$. The Reynolds number is $\mathrm{Re} \approx 5\cdot 10^5$ which could be interpreted as indicating turbulent flow.

We conducted two sets of experiments to measure the performance of the tail fin. The results of the first set of experiments are presented in Table II.

The test results diverge a lot because the robot’s body started to oscillate strongly. Oscillation decreases the speed and the robot even stopped at times. In tests 5-7 we disturbed the body oscillation using side fins.

TABLE II.
Robot performance with 20 kg body weight in the first test

	Time (s)	Speed (m/s)	Voltage (V)	Tail position	Tail movement
1	373	0,017	12	vertical	Continuous
2	541	0,012	12	vertical	Continuous
3	193	0,033	12	vertical	Continuous
4	341	0,019	12	vertical	Continuous
5	150	0,043	12	vertical	Continuous
6	105	0,061	17	vertical	Continuous
7	96	0,067	17	horizontal	Continuous

TABLE III
Robot performance with 21.5 kg weight in second test

	Time (s)	Speed (m/s)	Voltage (V)	Tail position	Tail movement
1	95	0,07	12	vertical	Continuous
2	155	0,04	12	vertical	Cyclic
3	60	0,11	17	vertical	Continuous
4	91	0,07	17	vertical	Cyclic
5	140	0,05	12	horizontal	Continuous
6	180	0,04	12	horizontal	Cyclic
7	73	0,09	17	horizontal	Continuous
8	90	0,07	17	horizontal	Cyclic
9	70	0,09	17	horizontal	Cyclic
10	90	0,07	17	horizontal	Cyclic
11	76	0,08	17	horizontal	Cyclic

In the second set of experiments represented in Table III we increased the robot’s body weight to 21,5 kg. This extra weight makes the robot more stable and oscillation of the body almost ceases. We also experimented with two different frequencies and tail movement modes. In the continuous mode the tail worked periodically all the time. In the cyclic mode the tail executed two cycles, then rested in the middle position for 5 sec.

It can be seen that the test results depend on the body weight. When the robot weights less, the oscillation of the body decreases speed. Strong oscillation was also caused by overly large amplitude of tail fin movement and must be reduced in further tests. Observations of fish suggest that optimal tail turning angle is 10-20 degrees.

The tests also show that the orientation of the tail fin does not influence the performance of the robot. The horizontally attached fin did not have much advantage over the vertically attached fin. We can use this property to adjust or rotate the tail fin so that it creates less turbulence and does not decrease visibility.

The third conclusion is that it is possible to adjust tail movement cycles so that the robot does not loose speed. This means that we can preserve energy, because stopping tail movement for a while disturbs the oscillation of the body and therefore increases efficiency. It is also possible to decelerate or even reverse the speed, if we can control tail movement and area.

We also measured the robots ability to submerge using its side fins when the robot was towed with an approximate speed of 0,1 m/sec. The measured submerging speed was 0,025 m/sec.

VIII. CONCLUSIONS AND FUTURE WORK

This paper describes the preliminary prototype of an underwater vehicle. The vehicle is built for environmental inspection in shallow waters of The Baltic Sea. The design concept is based on environmental restrictions, human factors and cost requirements.

At present we have tested our robot in a pool and in a pond. The test results show that the robot is functional but its efficiency can be increased. These preliminary test results can be used to redesign the robot. The goal for redesign is to achieve greater efficiency, speed and manoeuvrability. We are also developing a mathematical model that can predict our robot's performance. Different tail sizes and shapes will be tested to find the optimal type of tail. Field tests in the sea are scheduled for the coming ice-free season. In parallel we are developing control algorithms and computer vision software for automatic image processing to recognize different algaes from on-board video input. We are also developing a small expert system for classification of seaweeds based on visual appearance, seabed and depth information. The result of this work will provide knowledge about vegetation to environmental scientists.

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Appendix C

Biomimetic Fish-like Underwater Robot for Shallow Water Applications.

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Abstract **- This paper describes the prototype of a fishlike biomimetic underwater robot. The design considerations of the vehicle are task-specific. The vehicle is designed for visual inspection in shallow waters with low visibility and volatile sediments. In those conditions a vehicle with thrusters would cause too much turbulence. We propose a biologically inspired underwater vehicle that uses fins for propulsion and operates in towed, tethered remotely operated and autonomous modes.**

In this paper we describe the design of the vehicle and experiments in a towed mode. In the towed mode the vehicle is dragged after a boat at low speed while staying close to the bottom for visual inspection. We show that it can follow the ground profile at a speed suitable for visual inspection.

Index Terms – underwater robotics, biologically inspired robot fish, environmental monitoring.

I. INTRODUCTION

Fishes and other aquatic animals inspire many underwater robots. The reasons for that are their swimming efficiency, great maneuverability, trajectory following and station keeping capability.

Biomimetic underwater devices reported so far include a robotic tuna fish [1, 2], control of a fish by means of a caudal fin [4] or pectoral fins [5]. Most of biomimetic underwater vehicles mimic carangiform swimming (propulsion through the water with oscillating movements of the tail and the rear part of the body) [7][boxfish][flexible bodies]. Other types of swimming are also implemented, for example anguilliform (eel-like) locomotion [8][9,10] and locomotion with the help of elongated pectoral fins [11, 12].

The aim of this study is to design an underwater robot with a fish-like locomotion for practical environmental monitoring purposes. As such, the goal is not to mimic aquatic animals or to implement dynamics and kinematics of swimming as closely as possible but rather to make use of these features in practical applications.

As an application area we consider visual inspection of shallow water bodies with low visibility. Many inland water bodies fall into this category (lakes, rivers, ponds, bogs) as well as shallow and closed seas. For example The Baltic Sea is considered to be an exploitation area of such a device. It is very shallow and turbid. At the same time it is one of the most severely polluted seas in the world and according to EU directives is under regular environmental monitoring. At present visual transect surveys are done by divers.

The bottom of this kind of water bodies is usually covered with thick layer of mud or extremely volatile detritus (small particles of zoo- and phytoplankton). This poses a difficult problem. On the one hand the visibility is very low and one has to stay close to the bottom for visual inspection. On the other hand, locomotion in vicinity of the muddy bottom would decrease visibility. We therefore need a device, which creates as little turbulence as possible when moving.

Thrusters are efficient for fast locomotion, they are also commercially available and therefore inexpensive, but their operation creates a strong water stream. For the above-described application, in contrast, there is no need for fast locomotion but rather for good maneuverability and station keeping capability for close visual inspection. Locomotion of fins creates considerably less turbulence. Also it is possible to achieve good maneuverability by adding control surfaces.

The devices for visual inspection reported so far are too big and heavy for very shallow waters [13] and they almost exclusively used thrusters for locomotion [14]. We propose an alternative concept of an underwater robot. The design considerations of this device are based on task requirements. The vehicle should be able to operate in a very shallow water (1 m – 20 m) with a low visibility, create little turbulence, should be operated easily by only one person, be lightweight and inexpensive.

The goal is to build a vehicle that can be operated in 3 modes, towed mode, remotely operated mode and fully autonomous mode. At present we test the vehicle in the towed mode and this paper represents the first experimental results.

The rest of the paper is organized as follows. Section II presents the overview of the vehicle. In Section III we analyze the vehicle in a towing mode to find its capability to surface and submerge. Section IV represents the results of the field tests. The results show that the vehicle is able to follow the bottom profile when towed at low speed and is stable in still water.

II. VEHICLE OVERVIEW

This paper describes our second prototype vehicle (Fig. 1) that is designed considering the test results of the first prototype [ref to authors removed].

Fig 1. Second prototype without protective cover and with towing rod attached.

The main characteristics of the prototype are the following:

Weigh of the robot	16 kg
Length of the body	1,5 m
Width of the body	0,6 m
Electrical power	24 V

Our long-term goal is to design a vehicle capable of operating in three different modes with a varying degree of autonomy. In a towed mode the vehicle is dragged behind a boat at low speed and it should be able to follow the bottom profile at height sufficient for visual inspection. The tethered remotely controlled mode is to be used for a close visual inspection. The vehicle in an autonomous mode should be also capable of navigation and operates on an on-board power supply.

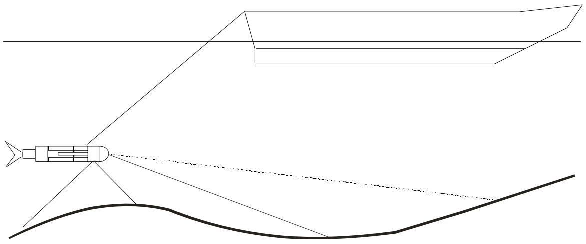

Fig 2. Operation in towing mode.

At present the vehicle is tested in a towed mode as shown in Fig 2. but is also capable of autonomous operation by propulsion of the caudal fin.

The towed mode is tested first for several reasons. First of all, in this mode the vehicle is presumably easiest to control. Second, our consultations with environmental scientists suggest that it satisfies the requirements of the target user group. The towed mode is best suited for visual transect surveys to replace the human diver. It permits covering long distances at speed suitable for visual inspection. As the problems of energy autonomy and underwater navigation do not have to be addressed in this mode we hope to demonstrate soon the usability of an operational prototype. Also, consultations with the potential users show even that a tethered mode is preferred to autonomous since environmental researchers suffer significant losses of their equipment because of bad weather conditions.

III. MECHANICAL STRUCTURE

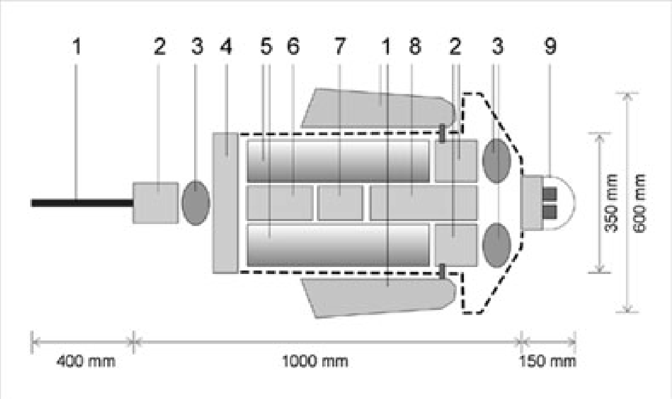

Fig. 3. Internal layout (1 – fins; 2 - motors; 3 - buoyancy control; 4 - air supply; 5 - batteries; 6 - gyro and inertial sensor; 7 – OMAP ; 8 – control electronics; 9 - camera and sonar head;)

The body of robot is made of an extruded polyester sheet attached to the aluminum and stainless steel frame. The overall schematic is described in figure 3. The robot has a compressed air supply of 200 bar for 76 l of air. This air is used for buoyancy control. The robot has three buoyancy control chambers – two of them are in the front and one in the back section. The airflow is regulated with 7 valves. Each buoyancy control chamber has an inlet valve and an outlet valve. One valve is equalizing pressure between two front chambers. The front chambers are used to change the orientation of the body from vertical to horizontal and back. Equalizing the pressure between these chambers helps to stabilize the body.

The robot is equipped with sonar and a color camera. These instruments are located in the front part and can be used in any orientation. For towing missions we have retractable towing rod what is connected to the front part so that it permits the vehicle to roll. The rod is in turn connected to a towing cable. Two battery packs supply 24 V for 3 dc motors driving fins through the reductors. The robot has one tail fin for steering and main propulsion and two side fins for additional propulsion and maintaining the depth. The fins are made of soft plastic to withstand impacts. The center of mass of the vehicle can be adjusted by changing the position of the batteries inside their shells. Electronics is located between the batteries to have better protection from environment and impacts. A gyro is located in the center of mass to reduce errors.

IV. ELECTRONICS AND CONTROL

The control system has 12 V backup power. The conceptual control system architecture is described in Fig. 4. The robot's mission control is performed by Texas Instruments 16-bit MSP430 microcontroller. This controller is responsible for controlling actuators and measuring devices. Its conceptual control loop is described in Fig. 5. The robot has also a StrongARM based OMAP which is used for recording the video stream from the color camera. It also reads data from Imagenex 852 echo sounder and is responsible for reprogramming the MSP 430 controller. Communication with the boat is also maintained through OMAP using an ethernet cable and TCP/IP protocol. For navigation we use 6 DOF inertial measurement device and 3 axes magnetometer from Rotomotion.

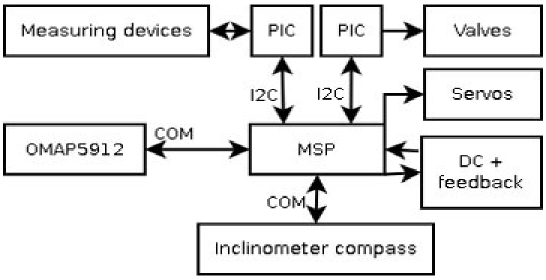

Fig. 4. Conceptual control system

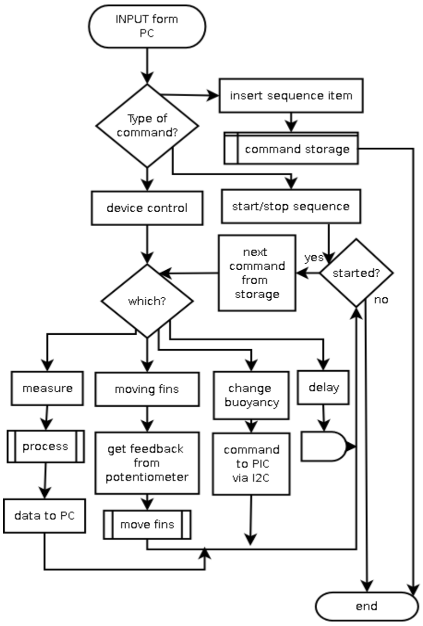

Fig. 5. Communication flow in MSP430 microcontroller

V. MODELING AND EXPERIMENTAL SETUP

For predicting robots performance and behavior we developed a theoretical model that describes submerging and surfacing. For that purpose we measured the drag coefficient of the body.

Experiments were made in a pond shown in Fig. 6. A 10m long track was marked to measure distance. In the first test we measured the speed of the robot and calculated the drag force according to Eq. 6.

Fig. 6. Measuring the drag force

A. *Measuring and modeling the drag force.*

We found drag force experimentally by dragging the robot with constant force and registering average speed of the robot. The drag coefficient

$$C_R = \frac{2 \cdot F_{dR}}{\rho \cdot v^2 \cdot S_R} \tag{1}$$

where S_R stands for cross section area of the robot and is approximately 0.088 m^2

TABLE I
DRAG FORCES, COEFFICIENTS AND MEASURED SPEEDS

Applied drag force (N)	Speed (m/s)	Drag coefficient
10	0.46	1.09
15	0.6	0.97
20	0.69	0.98

The results of the drag force measurements are represented in Table I and show that the average drag coefficient is 1.

Lift force generated by fins causes vertical movement of the robot. In Fig 7, F is the constant force applied to the robot through the towing rod, F_L is the lift force, F_{dF} is the drag force caused by fins and F_{dR} is the drag force caused by the body. As γ didn't change considerably during the experiments it is considered to have a constant value $\gamma = 30°$.

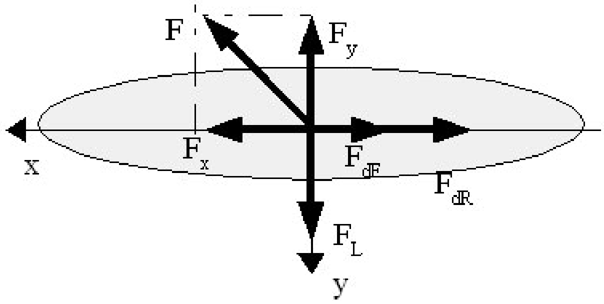

Fig. 7. Forces applied to the robot

According to [15] for a small angle of attack of a flat surface moving in continuous environment, the lift coefficient is approximately:

$$C_L = \frac{4 \cdot C_{Lmax} \cdot \alpha}{\pi} \tag{2}$$

and the drag coefficient is

$$C_D = \frac{4 \cdot C_{Dmax} \cdot \alpha \cdot \tan(\alpha)}{\pi} \tag{3}$$

where C_{Dmax} =1,2 and C_{Lmax} =1,38 for a flat surface. The angle of attack of a fin in our experiments is 30 deg. We can calculate lift and drag forces for a pair of fins of the robot.

$$F_L = \frac{4}{\pi} \cdot C_{Lmax} \cdot \alpha \cdot \rho \cdot S_{fin} \cdot v_x^2 \tag{4}$$

and

$$F_{dF} = \frac{4}{\pi} \cdot C_{Dmax} \cdot \alpha \cdot \tan(\alpha) \cdot \rho \cdot S_{fin} \cdot v_x^2 . \tag{5}$$

The drag force of the robot is

$$F_{dR} = \frac{1}{2} \cdot C_R \cdot \rho \cdot S_R \cdot v_x^2 \tag{6}$$

where C_R is the drag coefficient of a horizontally moving robot and S_R is the cross section area of the robot. Simply we get v_x as function on F_x

$$v_x(F_x) = \sqrt{\frac{F_x}{\frac{4 \cdot \rho}{\pi} \cdot C_{Dmax} \cdot \alpha \cdot \tan(\alpha) \cdot S_{fin} + \frac{1}{2} \cdot \rho \cdot C_R \cdot S_R}} \tag{7}$$

Thus the theoretical calculations show that the velocities corresponding to the applied forces {10 N, 15 N, 20 N} are {0.35 m/s, 0.43 m/s, 0.49 m/s}.

Test results of the drag force and speed measurements are represented in Table I. The results show that the theoretical calculations are very close to the experimental data.

B. Measuring and modeling the submerging speed.

If we consider the surface area of the robot flat we get drag force equation for vertical movement:

$$F_{dV} = \frac{4}{\pi} \cdot C_{Lmax} \cdot \alpha \cdot \rho \cdot S_{fin} \cdot v_x^2 - F \cdot \sin(\gamma) = \frac{1}{2} \cdot C_{Dmax} \cdot \rho \cdot S_{R2} \cdot v_y^2 \tag{8}$$

where S_{R2} is the surface area of the robot. If the difference between the lift force F_L and the vertical applied force F_y is balanced by F_{dV}, the vertical speed of the robot will be v_y . Theoretical values corresponding to applied forces {10 N, 15 N, 20 N} are {0.4 m/s, 0.49 m/s, 0.57 m/s}.

According to these theoretical calculations the submerging and surfacing capability satisfies the requirements of the application. For example, if the robot is towed behind a boat with the speed 1.8 km/h, which is a speed suitable for visual transect surveys, and it's drag force is about 20 N, then along the vertical distance 1 m the robot is able to submerge vertically 1.1 m and to surface 1.3 m, e.g. more than by 45 degrees angle.

The next series of experiments were conducted to measure the robot's submerging capability. In these experiments the buoyancy was set to neutral and side fins were set to submerging position under 30 degrees angle of attack. The robot was towed with a constant force and time and depth were recorded. The experimental results are represented in Table II.

TABLE II
SUBMERGING SPEEDS

Applied drag force (N)	Speed (m/s)
10	0.16
15	0.2
20	0.2

The submerging capability of the robot appeared not to be as good as it could be expected from the theoretical results. For the same example represented in Section VI (speed 1.8 km/h, drag force is about 20 N, horizontal distance 1 m) the robot submerges vertically 0.4 m while the theoretical calculations suggest the depth of 1.1 m.

Differences between theoretical values presented in the previous section and experimental values are probably due to the fact that body can act also as a fin. While dragging the body, even slight orientation change of the body can cause extra lift force. For instance flat body with the angle of attack equal 5 degrees and with surface area 0.35 m^2 moving with velocity 0.5 m/s can cause extra lift force approximately 10 N.

Thus the actual angle of submerging and surfacing is less that theoretically expected but is nevertheless sufficient for most of applications and can be improved by adjusting the center of mass of the robot so that the angle of the body will change and the additional lift force is decreased.

The tests also proved that the robot in a towed mode is sufficiently stable in still water. It maintained a constant yaw and pitch angle even without feedback correction. The test videos are available at web site [self-citation removed].

VI. CONCLUSION AND FUTURE WORK

This paper described a prototype of a fish-like underwater robot for shallow water applications. The biomimetic design of the vehicle makes it suitable for visual inspection of a bottom with volatile sediments and low visibility.

For fast visual inspection the vehicle is towed behind a boat while keeping a constant height from the bottom. This paper analyzed the robot's ability to follow the ground profile. The calculations show that the robot is able to submerge and surface fast enough even if the bottom is rather uneven. The calculations were confirmed by experimental data. The submerging speed gained form the experimental data was somewhat less than estimated by theoretical calculations but can be presumably increased by adjusting the center of mass and the yaw angle.

The experiments also reviled that in the towed mode the vehicle is sufficiently stable in still water. Our next step is to implement the feedback control of the robot by using forward and down looking sonar signals, inclinometers and gyro for feedback. The goal is to make the vehicle stable also in currents and waves and to follow the ground profile.

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Appendix D

Computational Fluid Dynamics Simulations of a Biomimetic Underwater Robot

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***Abstract*—This paper represents a comparative study of hydrodynamic properties of a biomimetic underwater robot. The hydrodynamic properties are modeled with methods of computational fluid dynamics. In particular, we measure wake turbulence created by natural and man-made objects, an ideal cone, a dolphin, manta ray and the biomimetic robot. Our research is aiming at creating a biomimetic robot operating in shallow turbid waters near the bottom with volatile sediments and therefore we are interested in minimizing the turbulent flow created by the robot. The results of the computational fluid dynamics simulations show that the turbidity in a steady flow created by the model of our biomimetic robot is within the same range with fish and considerably better than of a non-streamlined object. It also gives us further guidelines for improving the design of our biomimetic underwater robot.**

I. INTRODUCTION

This paper represents a computational fluid dynamic (CFD) model of a biomimetic underwater vehicle and investigates its properties compared to a CFD model of a non-streamline object and fish. The aim of this study is to get comparative data about hydrodynamic properties of those objects and guidelines to improve the design of the biomimetic underwater vehicle.

A hydrodynamic model of an underwater robot permits us to determine the properties of the vehicle and facilitates the development of the control algorithms. The shape of the body determines the viscous drag of the vehicle and to a great extent the controllability of the robot. On the other hand the available technology sets constraints to the mechanical design of the robot. The constraints are set by the physical properties of the components, like weight and shape, and therefore in practice it is not possible to build a vehicle with ideal hydrodynamic properties. The irregularities and asymmetries of the body can change the hydrodynamic properties, in some cases, by even improving them [8]. We therefore view the design of the underwater vehicle as cyclic process where the hydrodynamic properties of the prototype are investigated theoretically, which in turn give suggestions for further improvements of the robot.

Due to the rapid increase of computational efficiency, the practical 3D CFD modeling is becoming increasingly popular as an efficient tool of investigating the hydrodynamic properties of robots [1]. Similar studies of comparing natural objects with artificial objects or their components to investigate their hydrodynamic properties are also reported previously [6].

In this work we use free GPL software Gerris [2, 3]. This software has been, for example, used to study ship turbulence [4]. It is a new generation software that exploits semi-structured quadtree/octree mesh models to increase computational speed without the loss of precision by permitting computation of the components of the model with a different precision. In this paper, we use a time-adaptive mesh to discretize the solution dynamically. This allows us to study time-dependent 3D Euler incompressible turbulent flow.

Mostly CDF modeling is performed using Reynolds averaged Navier-Strokes equations (RANS) and averaging is carried out in space and time. This solution has limited information about turbulence characteristics, because effects of turbulence are time-averaged.

In our simulations the averaging is done only spatially (Large Eddy Simulations-LES) and computational domain is discretized using cubic finite volumes that are organized as a spatial octree. This allows dynamic adaptation of the spatial resolution to follow the evolving flow structures. For example, in the vicinity of the robot the resolution is finer and in less interesting regions, only large structures are computed.

II. THE ROBOT

Fig. 1. The robot

The robot is a fin actuated biomimetic robot presented in Fig. 1. It is actuated by a tail fin and two side fins, equipped with a color camera and sonars, compressed air supply and air chambers to change the buoyancy. It is designed to be used

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in a towed mode as well as in an autonomous mode. In the towed mode the side fins are used as horizontal rudders to change the altitude. In the autonomous mode the robot moves forward by the tail fin propulsion. The detailed description of the robot can be found in [11].

The design considerations of the vehicle are task-specific. The vehicle is designed for visual inspection in shallow waters with low visibility and volatile sediments. Shallow water coastal regions often fall into this category, also inland water bodies (rivers, lakes, ponds, bogs) that often have a muddy bottom and low visibility. In these conditions it is important that the vehicle used for visual inspection creates as little turbulence as possible since the turbulent flow would beat up the silt from the bottom and decrease visibility.

Therefore we are interested in designing a vehicle that creates possibly little turbulent flow. The first choice is therefore to use fin propulsion, apart from the classical choice of propelled locomotion.

Besides the means of propulsion the vorticity of the wake also depends on the hydrodynamic properties of the vehicle itself. Theoretically, we would like to design a vehicle with ideal hydrodynamic properties. Practically, we are constrained by the available technology, components, task specification, end user requirements, and cost factors. These CDF simulations permit us to evaluate the hydrodynamic properties of our vehicle and compare them to natural objects as well as to man-made non-streamlined objects. Furthermore, it gives us guidelines to improve our vehicle's design.

III. MODELS

We are interested in comparative assessments of the wake turbulence. For this purpose we model and measure the wake turbulence of the following objects: the biomimetic underwater robot described in the previous section, an ideal cone, a dolphin and a manta ray.

To get a realistic 3D model of the underwater vehicle, the vehicle represented in Fig. 1 is photographed in the up-, side- and front view. The colored photos are converted to black and white images and converted to stl (stereolitography) format compatible with Gerris. The stereolitography images are converted to gtl (GNU Triangulated Surface) format by dividing the body to polygons. The model is corrected by hand in order to assure that there are no holes and gaps between the polygons.

The model of the dolphin and manta ray are retrieved from [4]. The Blender models are converted to stereolitography format and corrected by creating a new mesh with a polymender tool to compensate inaccuracies caused by conversions. Then the files are converted to gts format. The cone is created with Blender and saved to stl format. The resulting Bender CAD models of the objects are depicted in Fig. 2.

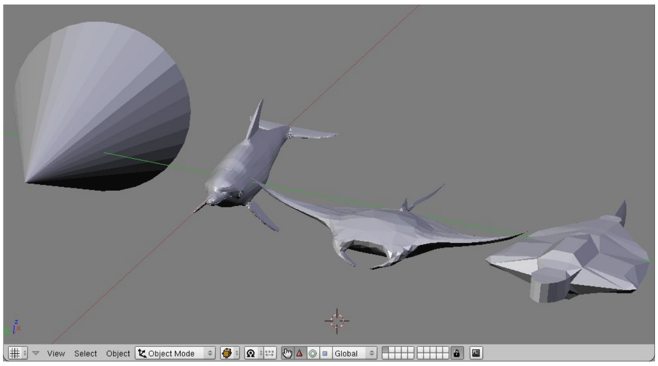

Fig. 2. The Blender models of the bodies.

As water flows around an object, the uniform velocity field gets disturbed. The disturbance of the flow basically depends on the shape of the object and parameters of the flowing liquid. By keeping the flow parameters equal and changing the shape of the object we can get comparative estimates about the hydrodynamic properties of them. In particular, we are interested in the velocity field formed behind the vehicle, in the wake, because the disturbances in this region are most likely to beat up some silt from the bottom. For that reason, some simulations of water flow have been done to determine the circulation of the velocity of water behind an object, caused by motion with a constant velocity. The velocity field is found with Gerris simulation software, as shown in Fig. 3. The output is a grid with velocity vectors known at each square of the grid. To find the circulation of velocity (further denoted also as a circulation), a contour behind the object is chosen in x-y plane, and the following integral is calculated:

$$\oint \vec{v} \cdot d\vec{l} \ , \tag{1}$$

The numeric result of the integral is a velocity circulation by the definition and it is related to local vorticities as follows:

$$\oint \vec{v} \cdot d\vec{l} = \int_S curl(\vec{v}) \cdot d\vec{s} \ , \tag{2}$$

where the term $curl(\vec{v})$ is a local vorticity and vector ds is a local infinitesimally small surface area with the direction of normal to the surface.

For comparability, all models are scaled down to the same length. . Table I describes the measures of the bodies.

The water velocity of the simulations is set to 0,5 m/s, water viscosity is set to 1, temperature is 20 degrees Celsius.

In addition, we also measure the velocity and pressure in the area right ahead and behind the body to find out if there are any changes and differences in these parameters.

TABLE I
MEASURES OF THE BODIES

	CONE	MANTA RAY	DOLPHIN	ROBOT
Max length	0,2	0,2	0,2	0,2
Max width	0,112	0,21	0,08	0,112
Max thickness	0,112	0,04	0,07	0,03

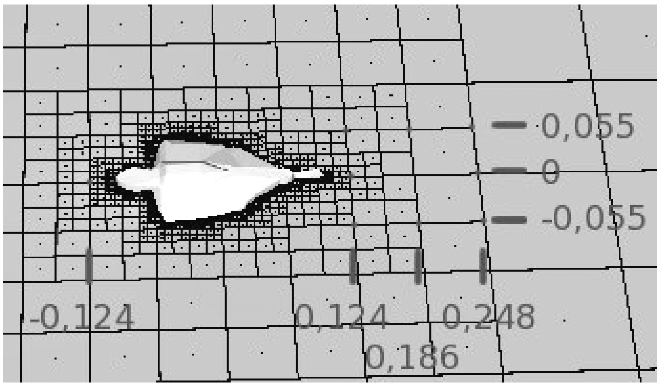

Fig. 3. The object, mesh of the velocity field and the coordinates of the points used for calculations.

The cone is chosen for modeling as an object creating large vorticities. It can be used as a reference to compare the characteristics of the robot to a non-streamlined body. The actual value of the circulation depends on the chosen contour in (1). We tried to choose as similar contours as possible for all the objects. Since the cone creates turbulences larger at the sides and behind of the object, and less turbulence straight behind, we have defined the circulation to be measured between the points shown in Fig. 3 (the rectangular area behind the object determined by the given coordinates).

As the biomimetic robot resembles a flatfish, the manta ray is chosen to be modeled as a species with a similar topology to the robot. Comparing those simulation results would give us n estimate how much can the hydrodynamic properties further improved and guidelines for doing it.

Other parameters we use for comparison are the pressure and the pressure difference in the front and behind of the object. For these measurements, we use only four points shown in Fig. 3, one in the front of the object and three points behind the object.

IV. RESULTS

This section represents the experimental results. The cone was chosen as an object with poor hydrodynamic properties. This object is used as a reference to compare the simulation data. Fig. 4 shows the 3D simulation of the cone. As mentioned above, for his object, the largest vortices are created quite far from the axis of symmetry.

Fig. 5 shows the pressure change of the cone in four points with the given coordinates. Fig. 6 shows the velocity circulation of the cone calculated over a rectangular trajectory behind the object defined by coordinates in Fig. 3

It can be seen that the circulation created by the cone varies heavily over time. This is the reason of the large variance of the velocity.

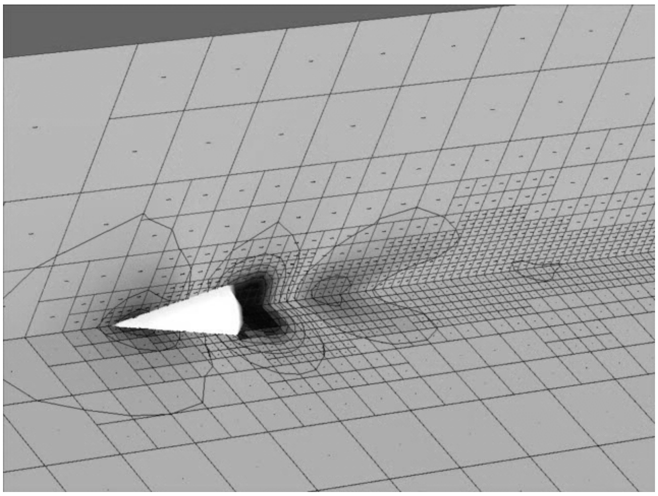

Fig. 4. The 4D simulation of the cone.

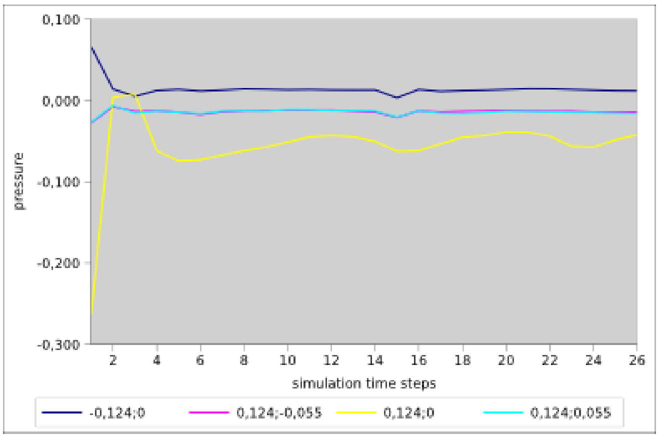

Fig. 5. The pressure measurements of the cone.

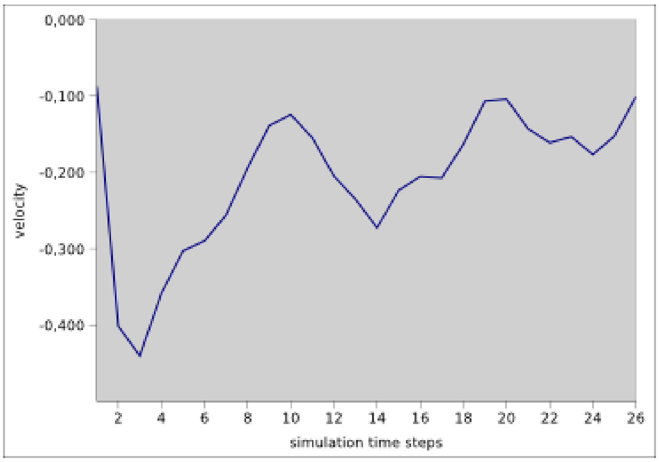

Fig. 6. The velocity changes around the cone

Figures 7-9 show the same simulation data for the model of a dolphin and Figures 10-12 for the manta ray.

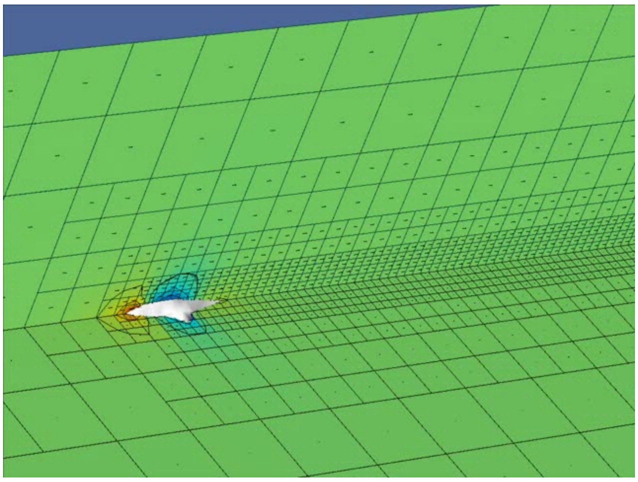

Fig. 7. 3D simulation of a dolphin

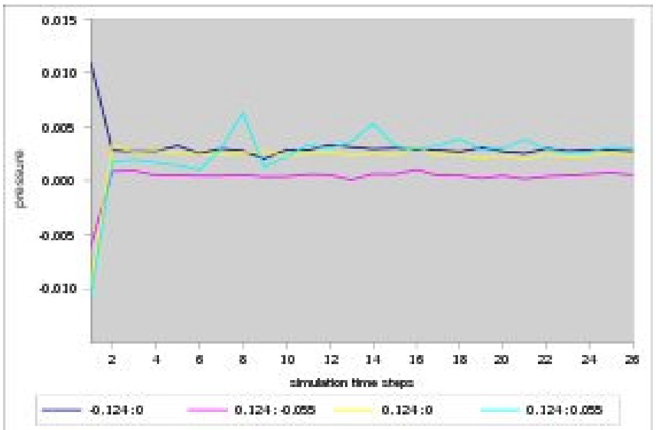

Fig. 8. Dolphin pressure changes

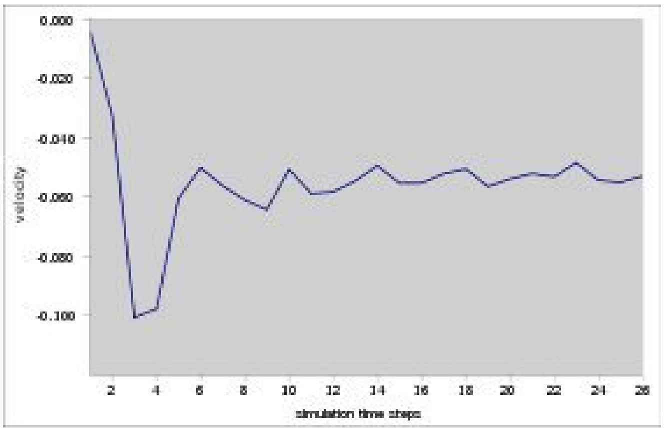

Fig. 9. Dolphin circulation

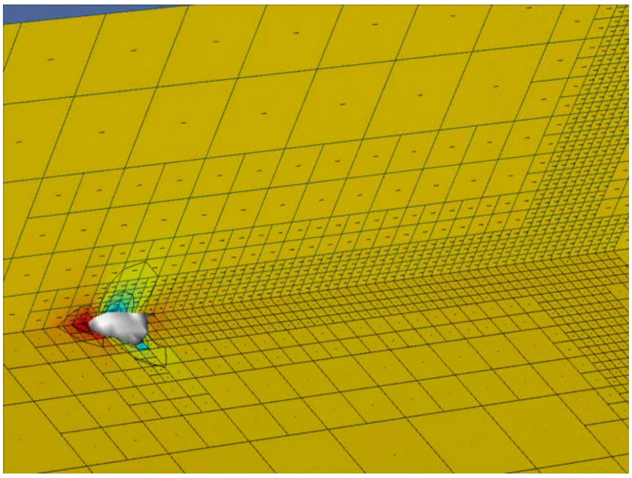

Fig. 10. 3D simulation of a manta ray

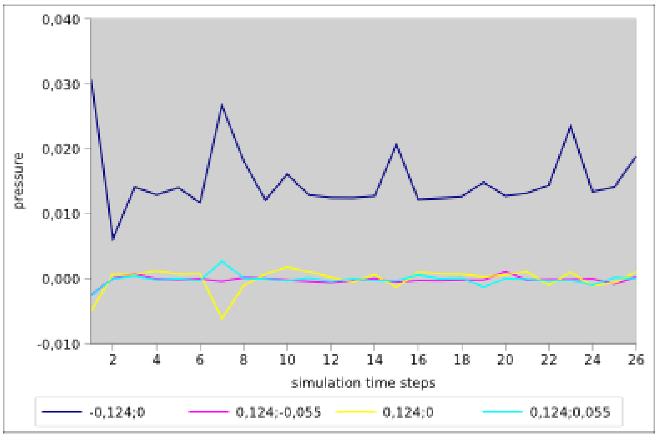

Fig. 11. Manta ray pressure changes

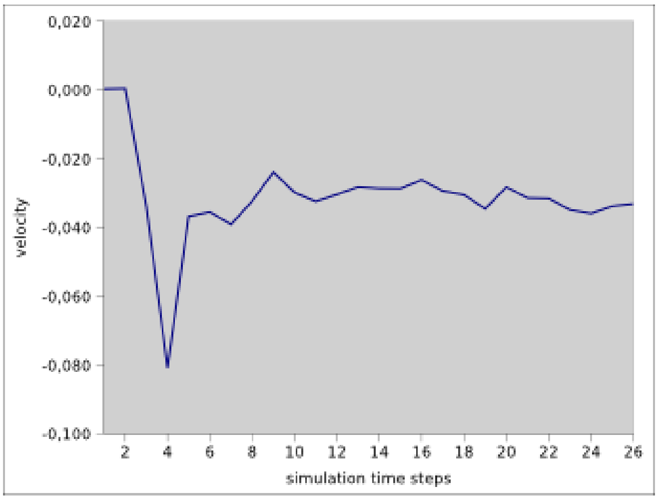

Fig. 12. Manta ray circulation

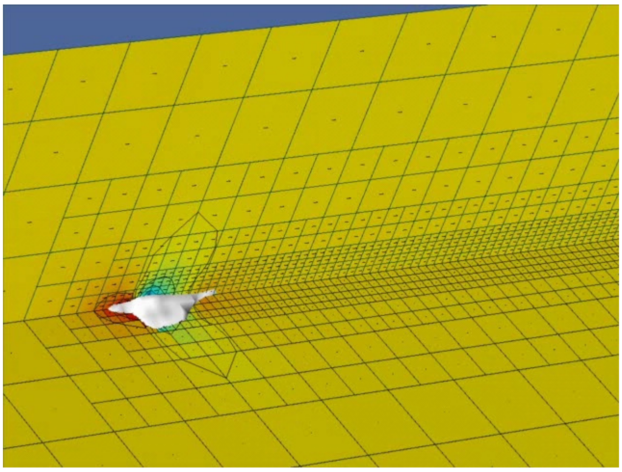

Fig. 13. 3D simulation of the robot

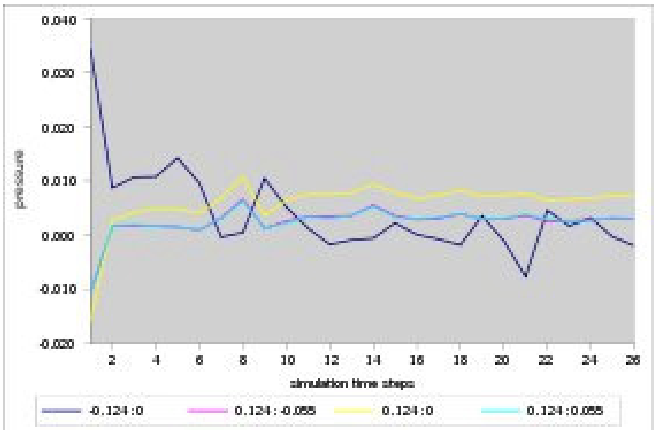

Fig. 14. Robot pressure changes

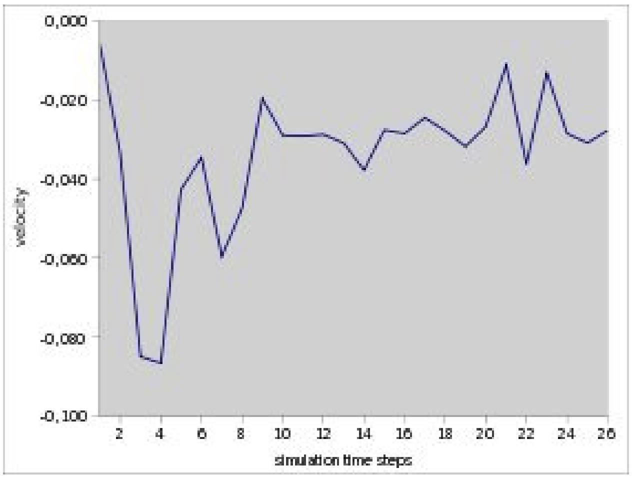

Fig. 15. Robot circulation

The same simulation data for the robot is represented in Fig. 13-15.

The difference with the previous objects is that the pressure in front of the robot and behind of the robot now differs, being slightly less in front of the robot. It has been investigated and demonstrated experimentally that fish are passively moving forward against its own drag, being able to extract additional energy from the environment [10]. As the experiments have also been conducted with dead fish, it suggests that the effect occurs not solely due to their motion patterns but also due to their body shape. The pressure difference (with the pressure being less in front of the robot) might indicate that due to the shape of the object, the Bernoulli force could act on the body, slightly increasing the drag. The force is created which induces a positive, upstream drag, thus making the swimming more efficient. Although, Bernoulli equation is applicable for ideal fluids and steady flow, we can still get some estimations of the force, because most of the flow of the water around the robot is quite steady. The dolphin and manta ray simulations, however, do not revile that such an effect is taking place. Apparently the shape of the dolphin, which is widest at the middle, does not create the asymmetry necessary for creating Bernoulli force.

Table II summarizes the numerical values of velocity circulations. It shows that the circulation of the robot is slightly lower than that of the dolphin and considerably lower than that of the cone (the sign here shows the direction of circulation and the absolute value shows the amount of circulation). At the same time, the manta ray is creating slightly less circulation than the robot.

TABLE II
NUMERICAL VALUES OF CIRCULATIONS

Model	Circulation
Cone	-5,358
Dolphin	-1,439
Robot	-0,886
Manta ray	-0,810

V. CONCLUSION

This paper presents comparative CFD simulations of an ideal cone, fish and a biomimetic robot. The velocity circulation of the water, caused by the robot, is less that of a dolphin and much less than of a non-streamline object chosen for a reference, although slightly larger than of a manta ray. The model of the robot is also shown to create Bernoulli force while the cone, the manta ray and the dolphin do not create such an effect.

The simulation results give us confidence that the underwater robot has acceptably good hydrodynamic properties. The manta ray is very close to the robot in terms of the topology of the body and their circulation values differ by less than 10%.

Manta ray has evolved from the bottom dwelling flat fish. It has apparently developed to create possibly little turbulence to hide and stay unnoticed near the bottom covered with silt. For example, it creates much less turbulence than the dolphin that is developed for swimming in mid-waters and near the surface.

The design of the robot can apparently be approved somewhat further by changing the configuration of the tail and the side fins closer to the manta ray. However, we conclude that the mechanical design of the robot is sufficiently good and comparable with fish that have evolved to create little turbulence. Further improvements of the mechanical design would be rather incremental.

However, the simulations results have to be treated with some criticism since the model of the robot, though created from the real object, is to some extent idealized. Our next immediate goal is to compare the simulation results to the experimental results of the real robot.

The impact of the Bernoulli force to the swimming efficiency needs to be investigated further before drawing conclusions about the significance of this effect. Although there is evidence suggesting that some fish seem to benefit from such a phenomenon, it was not found at simulations of neither the manta ray nor the dolphin. It is possible that its impact can be either beneficial of disadvantageous depending on the locomotion style of the fish.

This study shows that the hydrodynamic properties of the robot are good when we compare the circulation values around steady objects in a steady flow. However, the turbulence also depends on the locomotion style of the robot. Our further goal is to investigate various locomotion patterns, both in simulations and in pool tests. By comparing swimming styles of the fish and the robot, similar to this study we can choose actuation mechanisms and motion patterns most suitable to our task considerations.

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Appendix E

CFD Simulations and Real World Measurements of Drag of Biologically Inspired Underwater Robot

Madis Listak, Deivid Pugal, Maarja Kruusmaa

Abstract— **This paper discusses the differences between physical measurements of drag of underwater robot and computer simulation of drag of biomimetically inspired underwater robot. The hydrodynamic properties are modeled with methods of computational fluid dynamics. In particular, we simulate elliptical cylinder and the biomimetic robot and we compare simulation data with data gathered in real physical measurement of the robot. Our research is aiming to create a biomimetic underwater robot and therefore we are interested in minimizing the drag created by the robot. The results of the computational fluid dynamics simulations show that the ideal body of the robot has a low drag but its current implementation can be improved a lot. It also gives us further guidelines for improving the design of our biomimetic underwater robot.**

I. INTRODUCTION

This paper represents a study of computational fluid dynamic (CFD) model of a biomimetic underwater vehicle and investigates its properties compared to a 3D model of a non-streamline object and a real robot. The aim of this study is to get comparative data about hydrodynamic properties of those objects and guidelines to improve the design of the biomimetic underwater vehicle. This research is follow-up to the comparative study of fishes and our robot [1].

A hydrodynamic model of an underwater robot permits us to determine the properties of the vehicle and facilitates the development of the control algorithms. The shape of the body determines the viscous drag of the vehicle and to a great extent the controllability of the robot. On the other hand the available technology sets constraints to the mechanical design of the robot. The constraints are set by the physical properties of the components, like weight and shape, and therefore in practice it is not possible to build a vehicle with ideal hydrodynamic properties. The irregularities and asymmetries of the body can change the hydrodynamic properties, in some cases, by even improving them [8]. We therefore view the design of the underwater vehicle as cyclic process where the hydrodynamic properties of the prototype are investigated theoretically, which in turn give suggestions for further improvements of the robot.

Due to the rapid increase of computational efficiency, the practical 3D CFD modeling is becoming increasingly popular as an efficient tool of investigating the hydrodynamic properties of robots [2]. Similar studies of comparing natural objects with artificial objects or their components to investigate their hydrodynamic properties are also previously reported [7].

In this work we use free GPL software Gerris [3, 4, 5]. This software has been, for example, used to study ship turbulence [6]. It is a new generation software that exploits semi-structured quadtree/octree mesh models to increase computational speed without the loss of precision by permitting computation of the components of the model with a different precision. In this paper, we use a time-adaptive mesh to discretize the solution dynamically. This allows us to study time-dependent 3D Euler incompressible turbulent flow.

We use Gerris to compute pressures acting to the 3D model of the simulated object at given speeds. Knowing pressure and size of the objects we can compute its theoretical drag.

II. THE ROBOT

Fig. 1. The robot

The robot is a fin actuated biomimetic robot presented in Fig. 1. The robot is actuated by a tail fin and two side fins, equipped with a color camera and sonars, compressed air supply and air chambers to change the buoyancy. It is designed to be used in a towed mode as well as in an autonomous mode. In the towed mode the side fins are used as horizontal rudders to change the altitude. In the

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autonomous mode the robot moves forward by the tail fin propulsions. The detailed description of the robot can be found in [9].

The design considerations of the vehicle are task-specific. The vehicle is designed for visual inspection in shallow waters with low visibility and volatile sediments. Shallow water coastal regions often fall into this category, also inland water bodies (rivers, lakes, ponds, bogs) that often have a muddy bottom and low visibility. In these conditions it is important that the vehicle used for visual inspection creates as little turbulence as possible since the turbulent flow would beat up the silt from the bottom and decrease visibility. The robot should be able to move also with it own power.

Therefore we are interested in designing a vehicle that creates possibly little turbulent flow and for saving energy it should have as possible low drag. The first choice is therefore to use fin propulsion, apart from the classical choice of propelled locomotion, since it creates much less turbulence.

Besides the means of propulsion the vorticity of the wake also depends on the hydrodynamic properties of the vehicle itself. Theoretically, we would like to design a vehicle with ideal hydrodynamic properties. Practically, we are constrained by the available technology, components, task specification, end user requirements, and cost factors. These CDF simulations permit us to evaluate the hydrodynamic properties of our vehicle and compare them to natural objects as well as man-made non-streamlined objects. Furthermore, it gives us guidelines to improve our vehicle's design.

III. MODELS

We are interested in comparative assessments of the drag of body shape. We model and measure the drag of the following objects: the biomimetic underwater robot described in the previous section, an elliptical cylinder and we ccompare it to the measurement data of the real robot.

To get a realistic 3D model of the underwater vehicle, the vehicle represented in Fig. 1 is photographed in the up-, side- and front view. The colored photos are converted to black and white images and converted to stl (stereolitography format) compatible with Gerris. The stereolitography images are converted to gtl (GNU Triangulated Surface) format by dividing the body to polygons. The model is corrected by hand in order to assure that there are no holes and gaps between the polygons. The resulting Bender CAD model is depicted in Fig. 2.

The Blender models are converted to stereolitography format and corrected by creating a new mesh with a polymender tool to compensate inaccuracies caused by conversions. Then the files are converted to gts format. The ellipsoid is also created with Blender software and saved to stl stereolitography format.

The ellipsoid was chosen as an object with poor hydrodynamic properties. This object is used as a reference to compare the simulation data. Ellipsoids axes are as long as robots axes are.

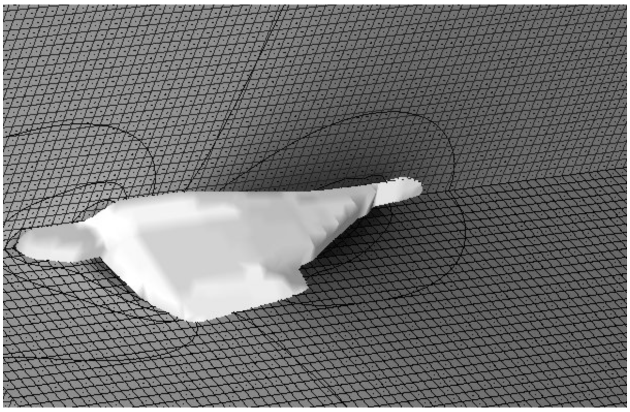

Fig. 2. The robots model and the pressure field around the object.

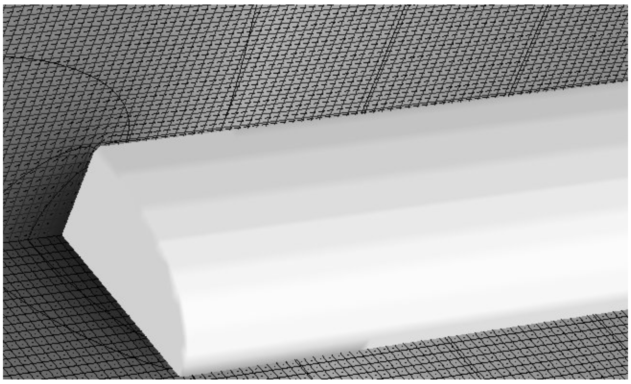

Fig. 3. The ellipsoid model and the pressure field around the object.

IV. EXPERIMENTAL SETUP

Series of tests with real robot were conducted in lake Harku. For this purpose the test track with length of 10 m was marked and robot was draged through the water with different speeds and resulting drag forces were recordid using the computer and Lutron FG-5000A-232 5 Kg force gauge that has RS232 data connection port. This load cell based device allows us to record several measurments in second and save them into the MS Access database. The speeds used were in range of 0,17-0,63 m/s. The same speeds were later used for simulations.

V. RESULTS

This section represents the experimental results. At all 23 good measurement were recorded. These series of data were then recalculated to be in mach with simulation data. The schematics of experiment is shown in Fig. 4.

The *Fm* is measured force and *Fs* id simulated force and also needed to be calculated in order to find robots drag force *Fd*.

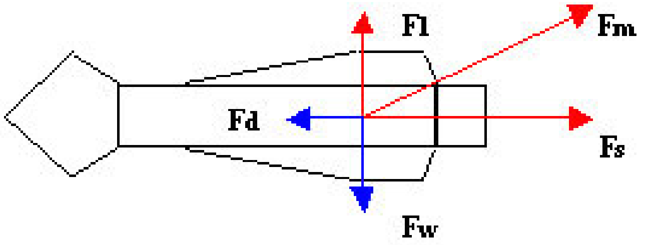

Fig. 4. The forces applied to the robot during experiment

There are three different types of drag. Parasitic drag, lift-induced drag and wave drag. Parasitic drag includes form drag, skin friction and interference drag. In our application the lift-induced drag is not relevant, because we don't have lifting body. Parasitic drag can be divided into the form drag, skin friction and interference drag. Form drag is caused by body shape, interference drag is caused by vortices created by the body and skin friction is influenced by material and smoothnes of it.

Because we have currently difficulties in measuring separately the influences of all three component of the parasitic drag we look them all together as parasitic drag.

For wavemaking drag, and parasitic drag the drag formula is:

$$F_d = C_D \cdot \frac{1}{2} \cdot \rho \cdot v^2 \cdot S \,, \qquad (1)$$

where F_d is drag force, C_D is drag coefitsient, ρ is water density, v is speed and S is cross section of the body.

Drag coefficient is not not a constant for either type of drag. Reynolds number and turbulent flow theory describe frictional drag. Froude number and wave theory describe wavemaking drag. Our robot moves under its own power mostly in underwater, so we do not calculate Froude number, because it is not relevant for this study. The Reynolds number is calculated as:

$$\mathrm{Re} = \frac{Lu}{\nu} \qquad (2)$$

where L [m] is the delegated length. In the stream-lined form, the body length is uses as L generally. (125 cm = 1,25m), ν [m^2/s] is kinematic viscosity of the water; (1.0~10-6m2/s) and u [m/s] is swimming speed.

During the experiments the force Fm was measured with load cell and force Fs was calculated as:

$$Fs = \frac{Fm \sin(45)}{\sin(90)} \qquad (3)$$

where angle between Fs and Fd is 90 degrees and angle between Fm and Fl is also 45 degrees. From the force Fs the pressure applied to the robot was calculated using the formula:

$$P = \frac{Fs}{S} \qquad (4)$$

where P is pressure in Pascals and S is a cross section of the robot. The cross section of the robot was calculated as ellipsoid with the same axis length. The S is 0,14 m^2.

These experimentally measured pressures were compared with simulated pressures. Table I contains both measured pressures and simulated pressures. It also contains Reynolds number *Re* for robot. From this table also the summary graph Fig. 5 was drawn.

TABLE I
NUMERICAL VALUES OF PRESSURE FIELD

nr	Speed m/s	Pmeasured (Pa)	P1sim (Pa)	P2sim (Pa)	Robots measured Re
1	0,17	26,41	5,98	0,73	2,16E+05
2	0,19	28,95	7,47	0,91	2,36E+05
3	0,22	28,68	10,02	1,22	2,72E+05
4	0,26	29,07	14,00	1,71	3,29E+05
5	0,29	34,10	17,40	2,13	3,68E+05
6	0,33	34,62	22,55	2,75	4,17E+05
7	0,36	39,01	26,83	3,28	4,46E+05
8	0,38	42,36	29,90	3,65	4,81E+05
9	0,42	46,18	36,52	4,46	5,21E+05
10	0,45	48,00	41,93	5,12	5,68E+05
11	0,50	66,11	51,76	6,30	6,25E+05
12	0,56	77,68	64,93	14,25	6,94E+05
13	0,63	87,71	82,18	25,44	7,81E+05

Pmeasured - Measured pressure of the robot (Pa)
P1sim - Simulated pressure of the ellipsoid (Pa)
P2sim - Simulated pressure of the robot (Pa)

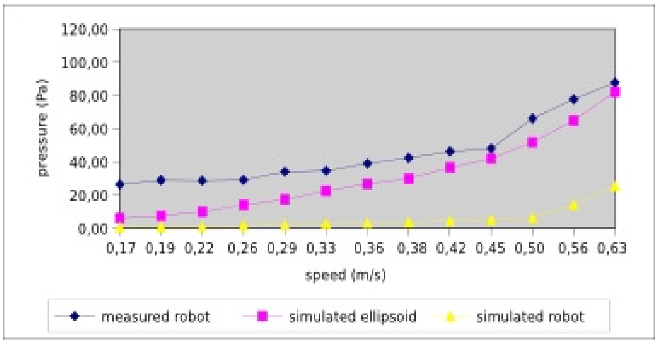

Fig. 5. simulation and measurements results compared.

From Table I and graph in Fig. 5 we can see, that ideal robot has much lower drag than real robot. Ideal robots *Re* changes abruptly in speed 0,50 m/s, in this speed the laminar flow will turn into the turbulent flow. Real robot has this turning point in lower speed of 0,45 m/s.

We also wanted to find power required to overcome the drag. This can be computed by formula:

$$P_d = F_s v \qquad (5)$$

where P_d is required power, F_s is drag force and v is speed

We also computed drag coefficient using formula (1) for speed 0,5 m/s using measurement and simulation data. The results of these calculations are given in Table II.

TABLE II

DRAG COEFFICIENT AND REQUIRED POWER

	Measured robot	Simulated robot
Drag coefficient Cd	0,53	0,05
Power P (W)	4,68	9,45

Real robot has some technologically rough surfaces, what explains why the turbulent flow starts earlier. It also has body material with real physical surface properties and this together with technological roughnesses explains, why the overall drag coefficient is higher than simulation results predict.

In speed 0,5 m/s the real robot creates turbulent flow and therefore also interference drag, while simulated robot has still laminar flow with much less interference drag.

Higher drag may also be explained with errors in measurement and with the fact that robot trajectory in the water was not always exactly the straight line and if robot was not facing directly into the horizontal direction then this creates additional drag.

VI. CONCLUSION

This paper presents comparative CFD simulations of ideal ellipsoid, 3D computer model of the biomimetic robot and a real biomimetic robot prototype. The ellipsoid was chosen because it is not streamline object, but close enough to the real robot and so it gives us reference object to compare with. The robots ideal computer model tells us, where the theoretical limits for drag reduction for this body shape are and test data tell how far we are from achieving perfect drag.

The simulation results give us also guidelines how to get close to the theoretical drag of the robot.

Our next goal is to improve robots coating and finishing to bring its drag as close as possible to the limits found by simulations.

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