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Design of control system of the experimental plant for pelvis movement imitation

Master's Thesis

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AUTHOR'S DECLARATION

I hereby declare that this thesis is the result of my independent work.

On the basis of materials not previously applied for an academic degree.

All materials used in the work of other authors are provided with corresponding references.

The work was completed .... guidance

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The author

....   signature

The work meets the requirements for a master's work.

 "......."....................201….a.

Supervisor

....   signature

Permit to defense

....   curriculum defense superior

"......."....................201… a.

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MASTER'S THESIS SHEET OF TASK'S

Year 2015 semester 2

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Curricula: MAHM02/13 - Mechatronics

Spetsiality: Mechatronics

Supervisor: Gennady Aryassov, Associated Professor;

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MASTER'S THESIS TOPIC:

(in English) Design of control system of the experimental plant for pelvis movement imitation

(in Estonian) Katsestendi juhtimissüsteemi projekteerimine vaagna liikumise imitatsiooniks

Thesis tasks to be completed and the timetable:

Nr	Description of tasks	Timetable
1.	**Decide on the goal of the thesis**	**25.01.2015**
2.	**Receive an experimental data from human using motion capture and inertial system**	**04.02.2015**
3.	**Create an experimental software for control the stand.**	**27.02.2015**
4.	**Analyze a movement of stand using machine vision and inertial systems.**	**31.03.2015**
5.	**Finish written part of the work**	**14.05.2015**

Solved engineering and economic problems: A comparison of optical and inertial system; processed data to control the plant; calculated parameters to control the plant; created software control of the stand; analyzed data movement of stand;

Additional comments and requirements: …………………………….......................

Language: English

Application is filed not later than 12.05.2015

Deadline for submitting the theses 22.05.2015

Student Anton Verchenko /signature/ ………...........   date 12.05.2015

Supervisor Gennady Aryassov /signature/ ……...........   date 12.05.2015

Referaat

Käesolev magistritöö on teostatud Tallinna Tehnikaülikoolis koostöös Peterburis paikneva ITMO ülikooliga kahepoolse koostöö programmi raames. Käesoleva töö eesmärgiks oli välja töötada madala hinnaklassiga, kuid efektiivse olemasoleva tugi-liikumissüsteemi seadme analoog, mida kasutatakse liikumispuuetega inimeste profülaktilistel või siis taastusravi eesmärgil. Minu ülesandeks antud töö käigus oli välja töötada antud seadme juhtimissüsteem. See sisaldas sisendandmete kogumist, juhtimissüsteemi välja töötamist ja seadme liikumise analüüsi.

Käesoleval ajal on liikumispuuetega (närvi ja lihaste häired) inimeste ravis kasutusel erinevad meetodid ja seadmed. Igas selles seadmes on kasutusel erinevad meetodid, sisendandmed ning liikumisanalüüs. Samuti kasutatakse neid seadmeid tervete inimeste liikumise analüüsiks. Käesoleva töö esimese peatükis antakse üldine ülevaade antud probleemist tervisekaitse seisukohast ning samuti kirjeldatakse teooriat, mida kasutatakse inimese puusaliigese liikumise uurimisel.

Sisendandmete kogumiseks kasutatakse erinevaid liikumise mõõdistamise meetodeid. Meetodid, mis põhinevad kiirendusanduritel või siis masinnägemisel on piisavalt paindlikud keeruliste liikumiste kirjeldamiseks alates kõndimisest kuni hüppamiseni. Selliste meetodite alusel kasutatavad väljundandmed sobivad inimese liikumise otseseks modelleerimiseks. Kuid eksisteerib ka teine lähenemine, kus analüüsitakse lihaste elektrilist aktiivsust EMG seadmete abil. Sellisel juhul on võimalik välja töötada mudeleid, mis lisaks liikumise kirjeldamisele võimaldavad ka kirjeldada jõudusid, mis tekivad lihastes liikumisel. Sellised mudelid on väärtuslikud eelkõige inimestele peale operatsiooni, kus on vajalik piirata suuri koormusi.

Kogutud andmete kvaliteet mõjutab mudeli täpsust ja seda nii matemaatiliselt kui ka reaalse seadme juures. Nõuded kogutud andmete kvaliteedile profülaktiliste seadmetele on küllaltki kõrged, kuna nendest sõltub ka ravimise kvaliteet. Käesoleva töö teises osas kirjeldatakse ja valitakse välja liikumise mõõdistamise süsteem. Võrreldakse optilist ja inertsiaalset süsteemi. Kirjeldatakse andmete kogumist ja etalonandmete töötlust.

Töö peamine eesmärk on seadme juhtimissüsteemi välja töötamine ning seda käsitletakse kolmandas peatükis.

Magistritöö viimane osa on seotud tugede ja põhiplaadi siirete andmete töötlemise ja analüüsiga. Teostatud on masinnägemise ja kiirendusandurite andmete analüüs. Kirjeldatud on töö saadud kiirendustega.

Töö käigus lahendati alljärgnevad ülesanded:

- Kogutud on etalonandmed inimesest;
- Realiseeritud liikumise etalonprofiil;
- Realiseeritud seadme juhtimine;
- Väljatöötatud kasutajasõbralik interface katsete läbi viimiseks;
- Analüüsitud tugede liikumine masinnägemise abil;
- Analüüsitud plaadi liikumine kiirendusandurite abil.

Abstract

This work was carried out based on Tallinn Technical University, through the dual master's program with the University ITMO. The aim of development was to create an inexpensive but effective analog of existing treatment systems for rehabilitation of people with disorders of the musculoskeletal system. My task was to develop a system to control the plant. This includes gathering the necessary input data, create of control system, and motion analysis setup.

At present time, for treatment and support of people with impaired gait (nerve and muscle disorders) used different methods and plants. They used their own input data, settings, and they own analysis of human motion. Such plants also may be used for analysis of movement of healthy people. Chapter one of work describes the general condition of a question of problems of musculoskeletal system and the theory of the movement of pelvic part of the human.

There are many methods for obtaining data from movements of human. Methods based on suits with accelerometers or motion capture system sufficiently flexible that allowing to estimate full range if movements, from a simple walk to squats and jumps. Such data are suitable for using in direct modeling of human gait. On the other hand, we have an opportunity of assessing movements by analyzing muscle activity, for example, using EMG. Methods based on EMG gives us a possibility for estimation of human gait, which allows to make a physical models, and use these data to improve postoperative recovery period.

Quality of data affects on accuracy of model, on mathematical and real models. Data requirements for plants used it therapeutics and treatments purposes are high, because quality of treatment depends from these data. The second Chapter of the work focuses on the selection of a motion capture system. A comparison of inertial and optical systems. Reference data collected from the human heel using the selected system.

Goal of this work is a design of control system for an experimental plant for human gait imitation, which can be used for an experiments and treatment in future. The third chapter describes the methods for control.

The last part of the diploma associated with the processing and analysis of the movements of the racks and the main plate. The analysis of data of machine sight and these accelerometers is made. Data processing of accelerometers and gyroscopes is described.

The following tasks were solved during this work:

– Collect an experimental data from human

- Create a motion diagram based on that data

- Programming of experimental plant

- Create a user-friendly interface

- Analysis of movement using machine vision and compare it with reference data

- Motion analysis of various points of plant using accelerometers

Реферат

Данная работа была выполнена на базе Таллиннского Технического Университета в рамках программы о двойной магистратуре с университетом ИТМО. Идея и разработка были предложены и проведены под руководством заведующего кафедры мехатроники университета ИТМО. Целью данной разработки является создание недорогого, но эффективного аналога существующих профилактических систем для лечения и восстановления людей с проблемами опорно-двигательного аппарата. Моей задачей, в ходе этой работы, являлась разработка системы управления этой установкой. Это включало в себя сбор входных данных, создание системы управления и анализ движения установки. На текущий момент установка находится в экспериментальном состоянии.

В настоящее время, для лечения и поддержки людей с нарушениями походки (нервные и мышечные нарушения) используются различные методы и установки. Каждая такая установка использует собственные методы, входные данные и собственный анализ движений. Также, подобные установки используются для анализа походки здоровых людей. Первая глава работы посвящена описанию общего состояния вопроса в сфере здравоохранения, а также описанию теории движения тазобедренной части человека.

Для сбора данных используется несколько типов систем захвата движения. Методы, основанные на акселерометрах или машинном зрении, достаточно гибкие для описания сложных движений, от походки до прыжков. Выходные данные этих систем подходят для прямого моделирования движения человека. Существует и иной подход, анализируя электрическую активность мышц, посредствам ЭМГ, возможно построение моделей, описывающих не только движение тела, но и силы, возникающие в мышцах. Подобные модели имеют ценность для людей в постоперационный период, когда следует соблюдать ограничения нагрузок.

Качество собранных данных влияет на точность модели, как математической, так и реальной. Требования к качеству данных для профилактических установок достаточно высоки, поскольку от этих данных будет зависеть и качество лечения. Во второй главе производится описание и выбор системы захвата движения. Сравниваются оптическая и инерциальная системы. Описываются сбор и обработка эталонных данных.

Целью работы является разработка системы управления установкой, чему посвящена третья глава дипломной работы.

Последняя часть работы связана с обработкой и анализом данных о перемещениях стоек и основной плиты. Проведен анализ данных машинного зрения и акселерометров. Описана работа с полученными ускорениями.

В ходе работы были решены следующие задачи:

- Собраны эталонные данные со стопы человека;
- Реализован эталонный профиль движения;
- Реализовано управление установкой;
- Разработан дружественный интерфейс для проведения экспериментов;
- Проанализировано движение стоек при помощи машинного зрения;
- Проанализировано движение платы при помощи акселерометров;

List of Abbreviations

MSS	Musculoskeletal system
WHO	World Health Organization
EMG	Electromyography
HSC	Hardware-software Interface
LED	Light-emitting diode
CPU	Central Processing Unit
HSL	Hero Script Language

Content

1. Theoretical information about hip movements

One of the main tasks of the experimental plant is definition of human movement patterns in the plane of pelvis, as well as simulation of random movements and fluctuations occurring in human joints. These movements are associated with elasticity of human joints and musculoskeletal system. Elastic springs are used to simulate such movement, located in the proposed locations of the real human joints, where connecting femur and pelvic bones.

1.1. Main state of question

Despite the wide steps of globalization and improvement of medicine in the world, disorders of the musculoskeletal system (MSS) are becoming widespread in the last decade. Statistics from World Healthcare Organization (WHO) suggest that MSS-diseases of spine, ligaments and muscles era common chronic diseases that affect more than 80% of the able-bodied population (30 – 50 years). This is due to high prevalence of sedentary lifestyles, lack of exercise and injuries sustained in falling accidents. Up to 90% of cases of spinal injuries are caused by traumas [1].

Urbanization increased the speed of spreading of diseases of MSS. Statistics from WHO, stated in the journal "Atlas of Health", suggests that in Russia dynamics of diseases MMS in last decade has grown by 30%. The number of people seeking treatment can be seen in the Table 1. This data should be considered with the amendment that large numbers do not mean greater percentage of diseases; these statistics show only people who considered having a treatment. In addition, since such diseases rarely cause death, it is very difficult to determine exact number of sick people. Russian specialists often associate it with the fact that people often ignore symptoms and do not seek help.

Number of discharged people with the diagnosis of dieses of locomotion system according to the "Atlas of Health" WHO, per 100 000 population [2]	
Austria	3 467
Germany	1 680
France	1 670
Russia	**976**
Spain	710
Israel	492

Table 1 WHO statistics

MSS diseases are difficult for treatment, and the main recommendation of WHO is the encouragement of lifestyle improvements, prevention of road traffic accidents, violence reduction and improvement of workspace to avoid mishaps.

However, diseases of MSS should be treated and locomotion system requires recovery. It is necessary to create conditions for life and recovery of people with locomotion disorders.

For successful treatment of MSS worldwide researchers and developers create special hardware and software, many of which are successfully applied in practice. The most modern and complex have many advantages that set them apart from other systems, such as feedback, taking into account the characteristics of every patient and automatic creation of advisory rehabilitation programs. Cost of such complexes slows down their spread in medical institutions even in economically developed and stable countries. Necessity of developing a low-cost analog system is increasing every year. It is not always needed to simulate and treat a complete human system. A human pelvis can be taken as the investigated and simulated part, since it is one of the most important elements of locomotion system. Pelvis connects the upper and lower parts of the body, and his movements are inextricably linked with the movement of rest locomotion system. Although in general the movement of pelvis can be represented as an inverse pendulum, there are difficulties in simulating the fluctuations associated with the presence of elastic elements in joints of femur and pelvis bones. Thus, to facilitate the construction of the mathematical movement of the pelvis we should begin with an estimation of pelvis plane movements.

1.2. Movements of human pelvis

Pelvic bone is the largest bone in the human body and the only bone that is different in men and women. Pelvis connects to the lower part of the spine, attaches the lower extremities and plays an important role in the support and storage of a number of vital organs. Body weight transfers through pelvis the spine to the pelvic girdle, next to the hips, knees, ankles through talus and calcaneus and at the end through the feet to the ground. Any anatomical abnormalities of the pelvis have a serious impact on the lower part of kinematic chain of musculoskeletal system.

Since kinematics of lower limbs depend on the movements of the pelvis, and movements of pelvis depend on the mobility of lower extremities, an idea was stated that imitation of pelvis movements for therapeutic purposes can help people with impaired MMS. One of the first researchers who used this principle was a Swiss scientist Gustav Zander. His training horse saddle was used for balancing the body and development of pelvis and back muscles and working on the principle of imitation of movement of the pelvis.

While walking pelvis oscillates under the influences of lower limbs. Oscillations occurs in two planes (Figure 1a) [3]. Curves on the figure represent movements of the center of gravity of pelvis. Blue curve is movement in horizontal plane, red – in sagittal plane. Sum of these projections create the movement in frontal plane similar to the movement of pendulum.

Steps may be described as follows:

- In horizontal plane, for each half step the pelvis is shifted in the direction of carrier foot for 2-2.5 cm, with an oscillatory motion with amplitude of 4-5 cm.
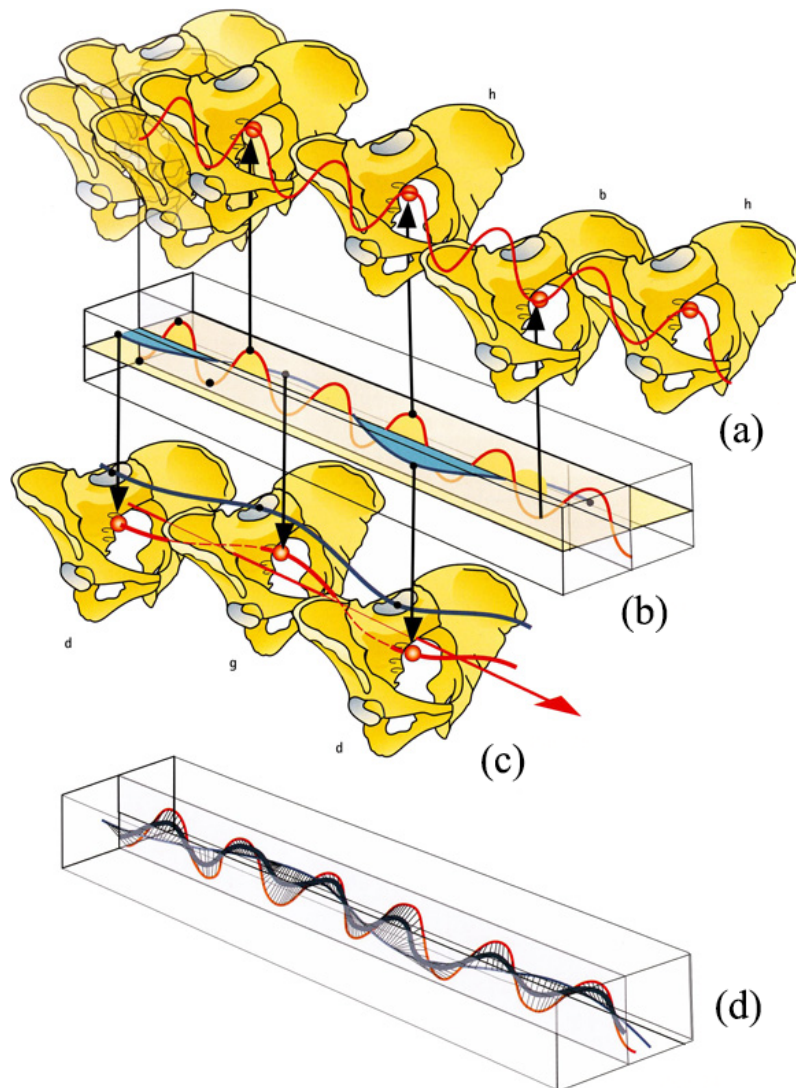

Figure 1 Movements of the pelvis in space. (a) – horizontal plane; (b) – horizontal and vertical plane; (c) – vertical plane; (d) – total representation of the center of gravity of the pelvis (thick blue line)

- Vertical plane – pelvis is in the maximum position in the transition of the carrier legs in the vertical position, the minimum in oscillatory phase. Thus, frequency of

movements in vertical plane is two times higher than in the horizontal plane. Therefore, each half step has their minimum and maximum in the vertical plane.

— Magnitude of oscillation in the vertical plane is approximately 5 cm.

Real curve of movements of the center of gravity (Figure 1d) is resulting curve of horizontal and vertical projection planes. It's projection on frontal plane will look like an inverse pendulum oscillations (Figure 2) [4].
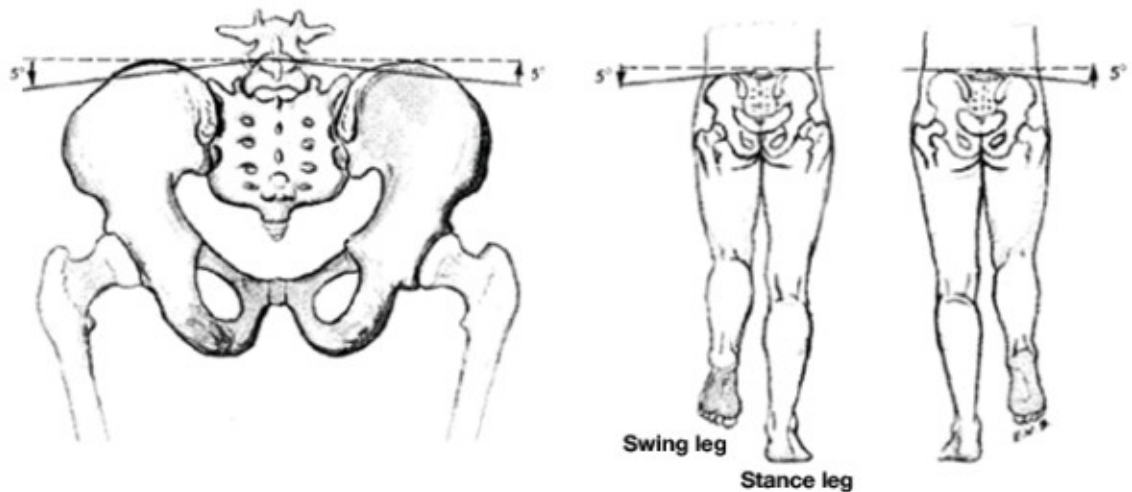

Figure 2 Rotations of the pelvis in frontal plane

When supported on one of the legs, the opposite side of pelvis is lowered. This swing is especially noticeable if you watch the slope of the line that connects two sacral fossa. As a result, the movement of pelvis causes bending of the lumbar spine in the same direction, which affects the slope of the dorsal and cervical spine. In the end, shoulder belt is rotated in a reverse side. Improper movement eventually can lead to distortion and diseases of vertebrate departments.
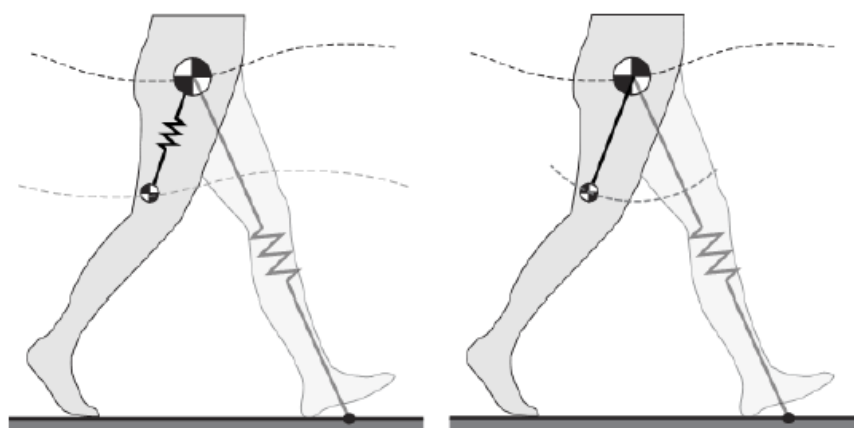

Figure 3 Lower part of body as a system of physical pendulums [5]

Except of movements in plane, the pelvis undergoes a rotation on the vertical and anteroposterior axes. However, during this work these rotations will not be considered.

Data movements from human foot will be used to simulate movements of the pelvis, because movements depend on gait cycle. In addition, collecting and setting the movement of the foot is easier than the movement of pelvis, because size of the foot does not significantly depend on physique parameters of patient [6]. In addition, the distance to the bone in the area of the foot is minimal due to the lack of large muscles or fat. The location of the sensors in the area of large muscle mass leads to the fact that in the process of obtaining data sensors move slightly in relation to skeletal system, thus making the results invalid.

2. Receiving data using motion capture

2.1. Motion capture systems

For analysis of human movements and further obtaining of movements profiles it is necessary to obtain data of the movement from various points on human body. There are several systems and methods of obtaining movement data. They can be divided into two broad categories: marker systems and markerless systems. The most widely used marker measurement methods use inertial sensors, optical systems and magnetic systems. Markerless technology [7] include machine vision and pattern recognition. The most well-known and cheap system of this type is Kinect. Also systems based on web cameras and special software can be used. Also it is possible to obtain data of human movements using mathematical models based on electromyography (EMG) [8]. However, these models are time consuming and require prolonged analysis and design.

In the sphere of research and analysis of biomechanics, the most important role is played by marker or token systems. They dominate in the field of gait analysis and data obtaining, as they have greater accuracy and flexibility of customization. In addition, such systems allow analyzing at not only macro level, but also micro; for example, studying the facial expressions and working with small muscles. Below are the examples of such systems.

Inertial system is an array of accelerometers, gyroscopes and magnetometers, which are installed at specific locations to provide the model of human movements. There are many systems differing in precision and price. Standard system consists of elastic costume with special sections for sensors. An example of such costume can be seen on Figure 4, left part is a human with elastic bandages that consist of an array of accelerometers; right part is a three-dimension representation of gait based on real-time data from accelerometers. Further, such data can be used for medical purposes, for example, to analyze the symmetry of gait [9] or create software for medical facilities

[10]. Large number of commercial optical systems makes it possible to choose the necessary one on the respective ratios of price/quality [11].
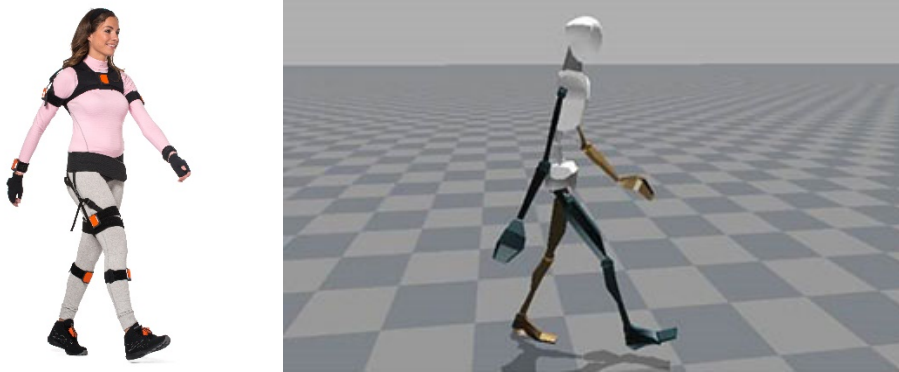

Figure 4 (a) Left – human in elastic costume with accelerometers; (б) right – 3D representation of accelerometers data

However, to achieve such results a big array of accelerometers is needed that is not always necessary. Nevertheless, in case of one or two sensors, only motion of sensors can be analyzed. Then it is necessary to process data of the position of point in space. Developers of inertial systems produce different sets of such sensors, including a sensor plus bandages for all body parts, as well as software for collecting and analyzing.

Passive optical system is a set of infrared cameras with infrared illumination (high-frequency strobe light), synchronized in time and located around some experimental sites. People dress up in a special costume, which has an array of passive markers that reflect a falling infrared light Passive optical system is a set of infrared cameras with infrared illumination (high-frequency strobe light), synchronized in time and located around some experimental sites. People dress up in a special costume, which has an array of passive markers that reflect a falling infrared light (Figure 5). Reflected lights enter the cameras, software compares data from relative cameras and creates a movement in axes. The result of processing is a three-dimensional model that reflects all movement of costume. Such systems are widely used in cinema and television. Main problem of passive optical system is a lack of marker identification, since confusion and mistakes of determining a movement of token can happen because of it. Such systems have been used for not only cinema and three-dimensional graphics, but for the development of feedback mechanisms in the rehabilitation complexes for people with impaired MMS, for example, in LokoMat [12].
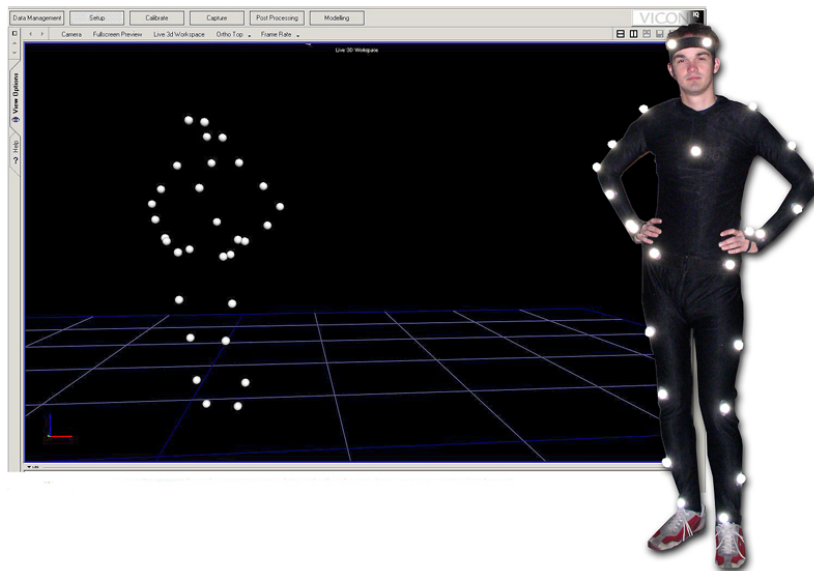
Figure 5 Costume with tokens and 3D representation of tokens in software

Problem of identification can be solved with active optical systems, in which markers are represented by LED and used radio synchronization with their own IDs.

The magnetic methods work similarly. Markers are magnets and magnetic receivers are cameras that determine the distortion of magnetic fields and determine the position of points in space. However, due to the sensitivity to the surrounding area and magnetic fields, such systems are not widespread.

There are also plural mechanical systems for data obtaining from humans. In that case, patient wears a special exoskeleton, which has angular sensors that determine the position of each joint. Main disadvantage of this method is the limited mobility of person, which makes the applicability of such systems severely limited.

In addition, data of movements can be obtained through the determination of muscles activity. Electromyography is the base of such methods – this is the electrical activity of muscles. Through tuning and optimization of model, muscles force and movements can be obtained from electrical activity. Then movements of skeleton are created from these data. This method is inconvenient to obtain data of movement of the complete musculoskeletal system of patient. Nevertheless, in medical purposes or for rehabilitation systems for limitation of loadings, this method is suitable. It should be noted that correlation between EMG activity and muscles activity is different among genders. [13].

2.2. Comparing inertial and optical systems

Comparing of inertial and passive optical systems was performed during the work. [14]. During the experiment there were conducted two dozen experiments with people of different gender and body composition. Comparison of systems was based on data movement of the human foot. Data were collected from foot; first accelerometer was mounted on the lifting of the foot, the second in the area of the Achilles tendon. Markers of optical system VICON were also placed there.

During the experiment each person performed similar tasks: walking in circle, walking diagonally straight and back, walking on the treadmill. Since sensors and markers were installed in the same places, it was possible to compare the results.

Experiment revealed the positive and negative aspects of each approach.

Inertial system:

- High mobility;
- High accuracy;
- No loss of sensors;
- Requires additional processing of data, especially if software have not possibility to receive a movement directly from acceleration and angular velocity [15].

Passive optical system:

- High accuracy;
- Displacement and velocity are output;
- Bulky;
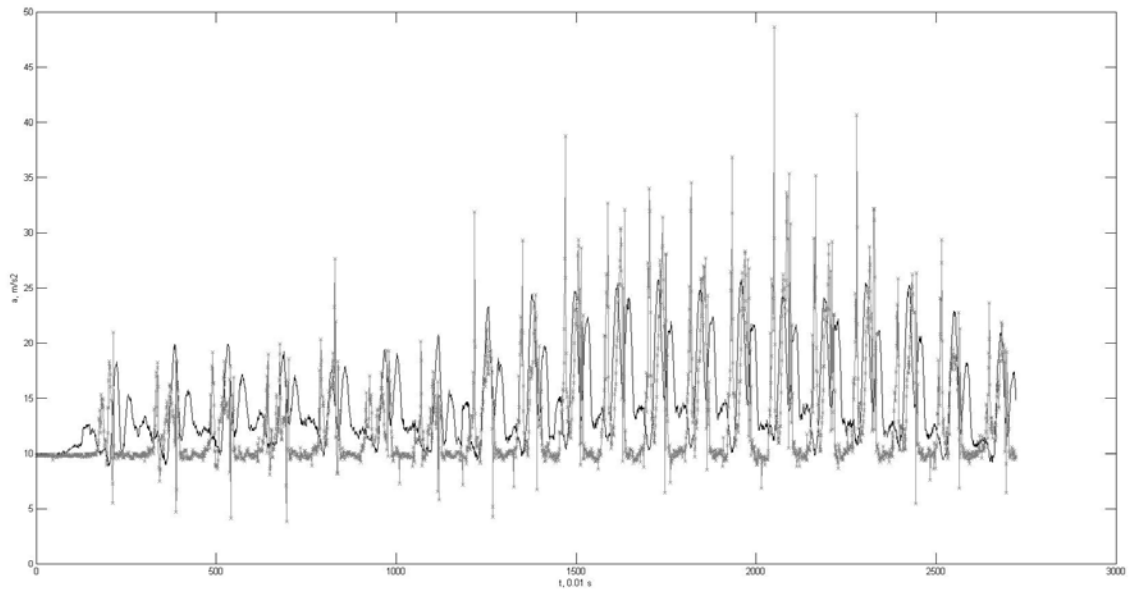- Requires additional processing in case of markers losses;

Figure 6 Comparison of accelerations obtained by optical system (black) and inertial system (gray)

It is difficult to determine the relative accuracy of systems, since the output results are fundamentally different. Optical systems give the displacement projected on axes but inertial system gives acceleration in space. Preliminary work on the data is required, as well as the availability of benchmark with which you can compare. Comparison of optical and acceleration systems is on Figure 6. Data from optical system was processed and presented as acceleration. On the figure the difference between graphs is continuous throughout the experiment. Cycles of step are the same, but accelerations have some inconsistencies with each other. Absence of reference acceleration data does not let to determine the exact error.

Comparison of technical characteristics of systems are on Table 2:

	Optical system Bonita 10 [16]	**Inertial wireless system XSENS** [17]
Precision	0.5 mm for every point	Static: <1 degree Dynamic: 2 degree
Frequency	250 Hz	Inner: 1800 Hz Transfer frequency: 1 sensor – 120 Hz 6 sensors – 75 Hz 12 sensors – 50 Hz

Transfer delay	2 ms	2 – 5 ms
Measurement distance	0.3 – 5 m	Up to 50 m
Output	Two-dimensional positions projected on the axes	Three-dimensional position (rotation matrix, quaternion) Three-dimensional acceleration Three-dimensional speed of rotation

Table 2 Comparison of characteristics of used systems

Dynamic accuracy of the inertial system is lower than static accuracy because in the experiment the sensors are mounted on elastic suit that move relative to the body, which limits the accuracy of the system. The estimation and visualization of the movements are a little faster than in optical system [18]. Also, the presence of additional and stronger noise in inertial sensors (compared to the optical system), post-processing and numerical integration increase error in data. Despite this, the data of the inertial system is similar to the data from the optical system, as confirmed by other studies [19].

Based on advantages and disadvantages, data from VICON optical system was taken for further work with experimental plant and simulation of pelvis movement, since it provides movement which is useful for motor control. Moreover, the latest low-cost developments in the field of optical systems allow to extend the field of their application [20]. Data from inertial systems requires additional processing and analysis for determining the position of the foot for each moment of time.

2.3. Optical motion capture system VICON Bonita

VICON Bonita is the latest generation of high-end infrared cameras used in passive optical motion capture systems. Together with Blade software, they allow to create full-featured system for receiving, processing and analysis of human motion.

Practical results are based on system from Institute of Cinema Engineers. System had 10 cameras Bonita 10. Technical characteristics of camera are represented on Table 3. Each camera has a set of infrared LEDs to illuminate the beacons installed on costume. Camera is powered according to the standard 802.3af Power over Ethernet. Power and signal are conducted via a Cat5e cable. This does not affect the quality of the transmitted signal due to the physical characteristics of Ethernet standard, but allows speed up installation of cameras. All cameras connect to a special

switch with 802.3af PoE Ethernet ports. Switch is connected to a powerful computer station for processing of incoming data signal.

Shooting area (Figure 7) is a square with 6 m side, 10 cameras mounted around shooting area according to the scheme indicated in Figure 8. Since the cameras are located at the same height and have a constant focus length there is a blind spot, shaded in Figure 8, reducing working area to a square with 2m sides and increasing chances to lost a beacon from sight. Thus, treadmill was used for gait analysis. Walking in circles does not give a complete data of gait. Diagonal movement is too small, because there are too few diagonal steps, and the first and the last steps are different from others, having another velocity and displacement profiles than steps between them.

Bonita 10 Characteristics	
Interface	Gigabit Ethernet, RJ45
Delay	2 мс
Lightings	Infrared strobe: 68 near- infrared LED (780 nm)
Power	Standard: 802.3af PoE (through Ethernet)
Camera frequency	250 fps
Resolution	1 Mpx (1024x1024)
Working distance	Up to 13 m
Angle of view	26°-70° (Depends on the focal length)
Precision	0.5 mm

Table 3 Bonita 10 Characteristics [16]

Figure 7 Shooting area. Actor in costume, his skeleton in Blade (right) and 3D model based on Skeleton (left)
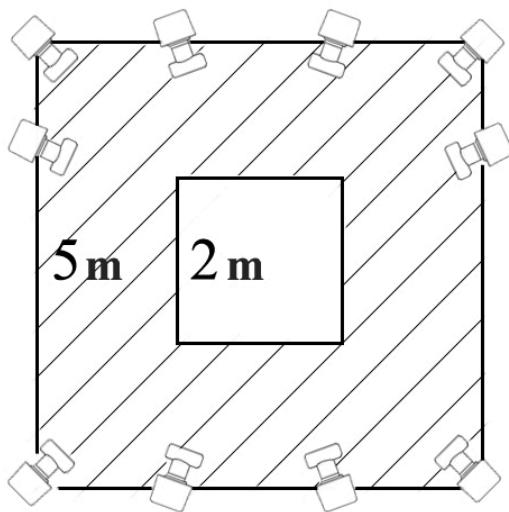

Figure 8 Shooting area scheme. Shaded area is blind spot.

Actor costume is made of elastic material and consists of a jumpsuit, gloves on hands and feet, and hat. Beacons are attached to costume with Velcro. Beacons are located in joints, major surface areas (e.g. abdominals or spine) and head. Together they form a three-dimensional skeleton. Costumes are available in several sizes, because it should fit tightly to prevent movements of the beacons relative to the body.

Before shooting a check of all systems was needed, as well as setting up cameras, strobe lighting and other specific settings for shooting. A special stick is used for camera calibration. After that, all systems are ready for shooting.

2.4. Software of motion capture system - Blade

Blade is a VICON software for motion capture systems. This complex software offers all tools needed to capture motion and work with them in real time. Main objectives of Blade: camera control, video processing, restoration of three-dimensional space, creation of kinematic models of biomechanical objects. To provide greater flexibility Blade proposes using of custom scripts written using HSL (HeroScript Language).

Work starts with creation of project-specific settings and calibration of tools and cameras. This preliminary stage is necessary because it determines the accuracy of future measurements. General plan of work with Blade and optical motion capture system is presented in Figure 9:

Figure 9 The scheme of work with Blade and system of capture of the movement

Main steps – setting up a project and calibration of cameras, the definition and calibration of the skeleton model, capture, post processing and export of data. The most interesting step is capture of the skeleton and data post-processing in Blade. In the future, these data can be used in other three-dimensional packages or in analytical software like MATLAB.

After setup and calibration, staff in a special costume with markers runs in the scene. The human comes to the center of scene and takes the T-pose, when his feet set shoulder-width apart and arms extended to the sides. In this position, all markers are visible and software can quickly

transfer them to a three-dimensional representation of the skeleton inside Blade. After it, the person is free to perform any action within the workspace scene. However, some postures can block markers, which will require some post-processing. The current skeleton is displayed in a three-dimensional window inside Blade (Figure 10). In the same window the relative locations of cameras around the skeleton and location of the coordinate axes can be seen. On the right side are located the points of skeleton and their movement is projected onto each of the planes.
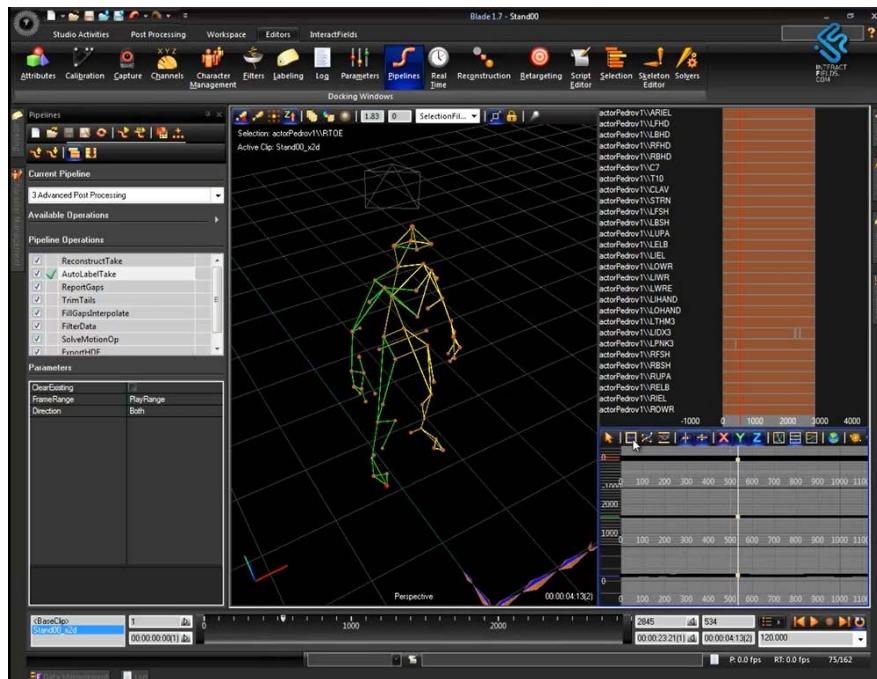
Figure 10 Blade interface

Due to the construction of the treadmill and motion capture system, data loss occurs from losing a beacon. These losses can be compensated by interpolation using Quick Post technology or by hand, which is more labor-intensive over time, however, the result of the movement would be better. The process of post-processing represented in Figure 11.

During motion capture, Blade regardless of processing mode in real time records only two-dimensional streams. The post processing is a reconstruction of data of positions of the markers in three-dimensional space from two-dimensional video streams and elimination of defect data. During capture, some of markers disappear from the field of view of the cameras, this leads to gaps in the trajectories of the markers. In addition, system can be "confused" if two or more markers were near to each other. Blade cannot distinguish the markers from each other. There is confusion of the names inside Blade software. Elimination of these defects is a large part of post-processing data in Blade.
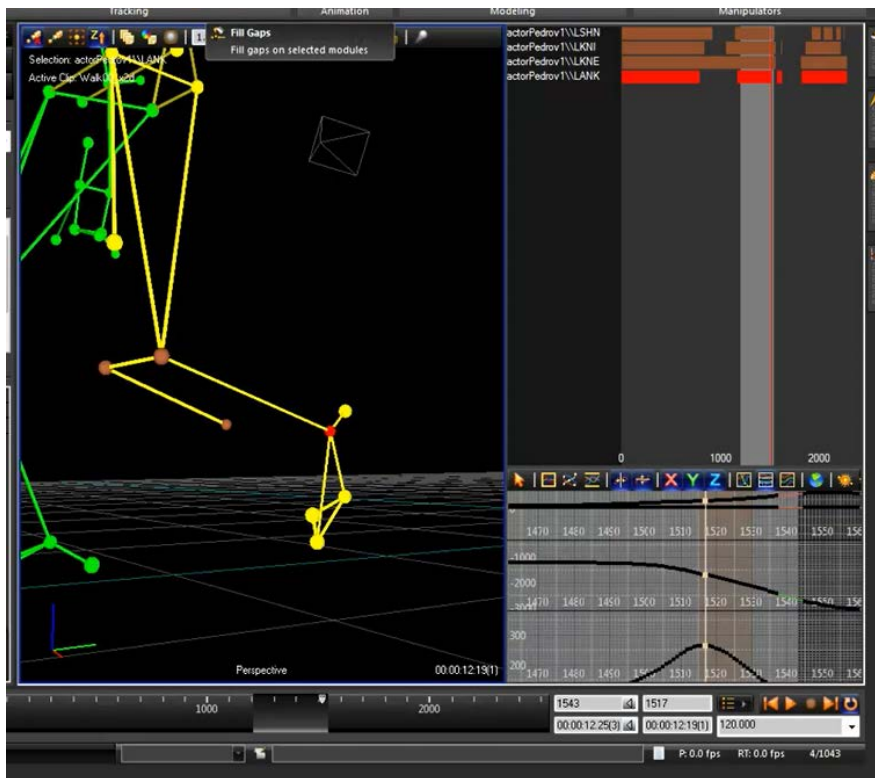
Figure 11 Post-processing in Blade. Operator is looking for the gaps between the profiles and fills them.

Erroneous recognition of the names of the markers can be divided into two types: unrecognized marker and incorrectly identified marker. Unrecognized marker is a kind of error that leads to the appearance of markers without labels (names) in the record. Incorrectly recognized marker leads to the appearance of markers with inconsistency with their labels in the record. Both types of errors are a consequence of the principle of operation of a passive optical system, where the markers themselves do not have a physical identity and are recognized by software, by mutual arrangement. "Cleaning" of data requires iterating over all unrecognized markers and either assigning them labels, or removing, if the marker is reconstructed incorrectly (for example, glare that was recognized by a system as marker). For entangled markers is necessary to select tangled path and swap them.

Once all the markers are in their places, it is necessary to restore the omission trajectories. Blade offers three ways: interpolation of the trajectory; the recovery of trajectories of markers constituting a rigid structure; or the restoration of the position of the marker is calculated by the skeleton. Interpolation is applied to the small gaps, in accordance with the speed trajectory change; otherwise, the motion is too blurry. The second method requires the addition of three recoverable markers moving together. For the third method, it is necessary to calculate the movement of the skeleton; its application is limited to small parts of the trajectory. These cleaning methods in the complex allow to restore almost all the loss of data, but in complex cases (the capture of two

interacting actors, somersaults, fall) require lots of manual work — up to three to four hours for a minute of captured data.
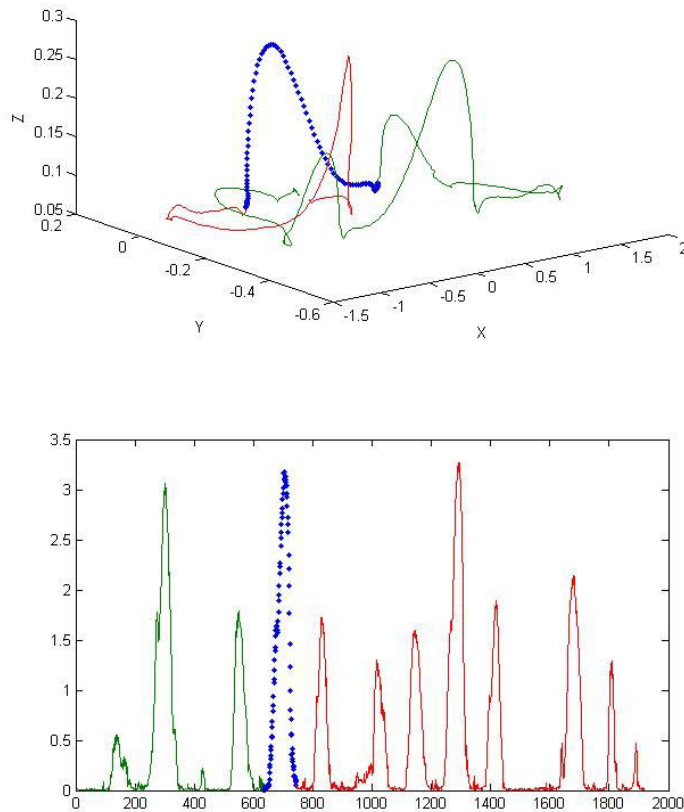

Figure 12 Results of diagonally walking experiment

After correcting all errors, the data is ready for export and analysis. Results data from heel are represented on Figure 12, on graphics obtained in MATLAB. This data is difficult to reproduce, because in the course of the experiment participants had only time to make 2-3 steps between the start and the end, which is not enough to compare and analyze a gait from different people. For practical purposes, the most useful data was obtained in the course of walking on a treadmill (Figure 13), since they are easily reproduced and processed to provide the average value during walking, running or other gait tests. From this data the value of the instep was received, which is necessary for further work.
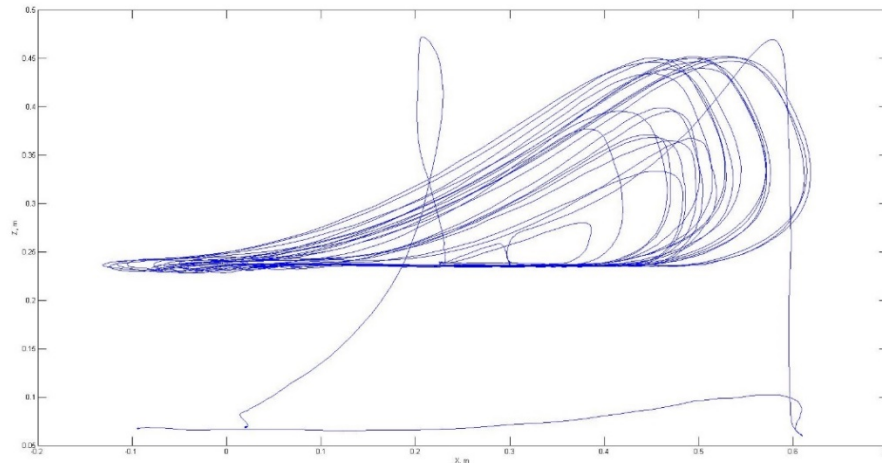
Result (Fig.16) can be represented as an average profile of heel movement, which can be used in practical and experimental tasks.

2.5.Analysis and preparation of experimental data

Data from optical system VICON was chosen as a reference data for control of a plant. Experimental data were recorded from ten subjects during the experiment and were duplicated by a system with accelerometers. As a result of this part is comparison of these systems.

Experimental data was obtained with the optical system represented by the movement of the tokens located at the heel. Data from the optical system is preferred as it represents movements, unlike accelerometers, which give the acceleration. This allows to immediately use this data to control motors without resorting to additional processing, such as integration of acceleration and velocity to obtain the necessary movements.

The peculiarity of the experimental data is that the minimum value is approximately ~60 mm. This is because the beacon is located at a certain height above the earth's surface, thus it is assumed that one of the axes of the plane is on the ground. Also, the data of displacement is projected on a plane perpendicular to the plane of the pelvis; it depicts lifting and lowering of the foot during movement. This approach allows us to apply the data directly to the engine, whereas in the case of three-dimensional accelerometers we will have to understand the position of a point in space.
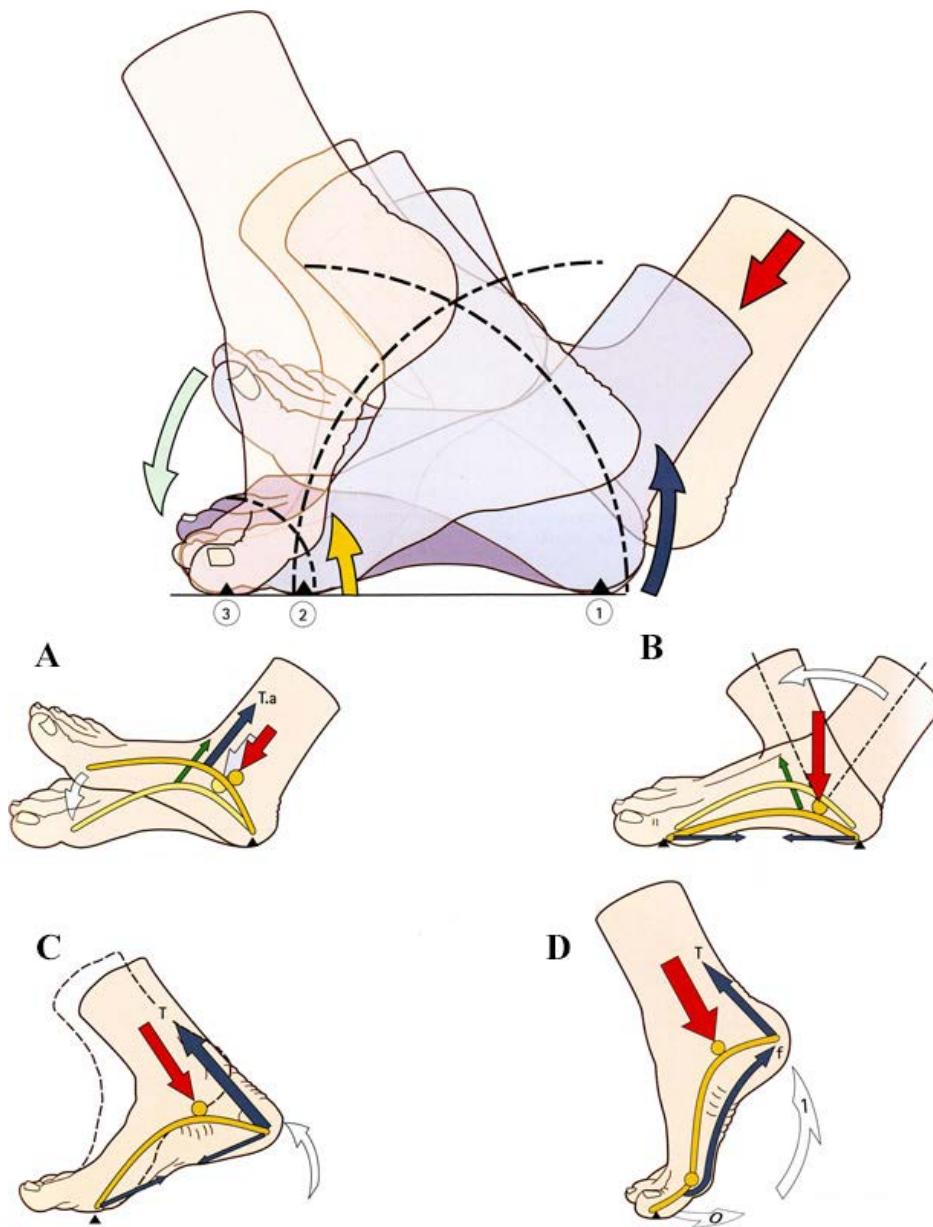
Figure 14 Human foot movements. A – lean on the heel, B – lean on the foot, C – lean on the toe, D - the swing phase of the foot.

The data can be represented as a graph of lifting and lowering of the heel during movement which was received by creating motion graphics on a treadmill, Figure 15. The corresponding cycle of the foot is presented in Figure 14 [3]. Part A corresponds to the lowering of the foot, the beginning of supporting phase, weight transfer on the whole foot. Part B - weight transfer from heel to toe. Part C - reliance on the forefoot. Part D - achieving maximum stack height, the phase transfer of the foot.
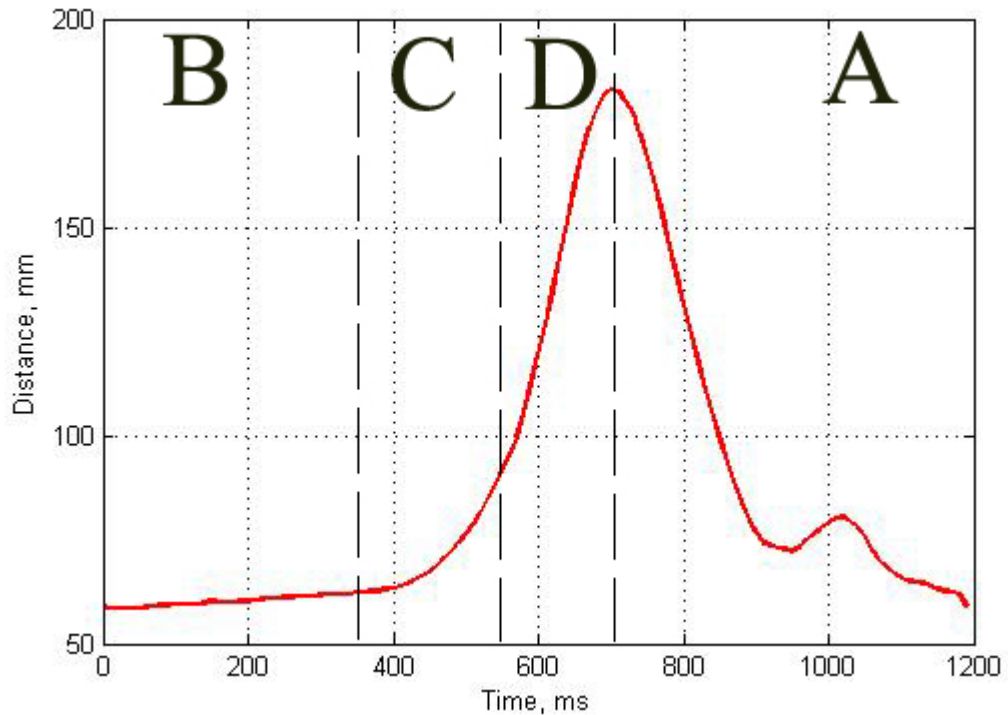
Figure 15 Experimental data for one-step cycle

Duration of each step – 10 ms. Maximal amplitude – 183.23 mm. Difference between maximal and minimal values is 124.8 mm. Thus, the required length of plant racks – 125 mm, taking into account the likelihood of slipping and requirements for anchorage – 150 mm.

It is impossible to observe the exact duration when specifying a discrete movement, as the step is very small. The minimum length of the step is also limited because the engine cannot quickly start and stop.

Motion motors are defined as moving points in the plane, with one engine is a displacement along the ordinate axis, the second along the x-axis. In this regard, acceleration and speed should be selected so that the larger of the values of the engines appropriate for the desired step or was minimized.

In addition, movement of the left and right of the motor must correspond to the movement of a person's legs, so for the second motor motion data are shifted by half a step, which can be represented as the following graph in Figure 16:
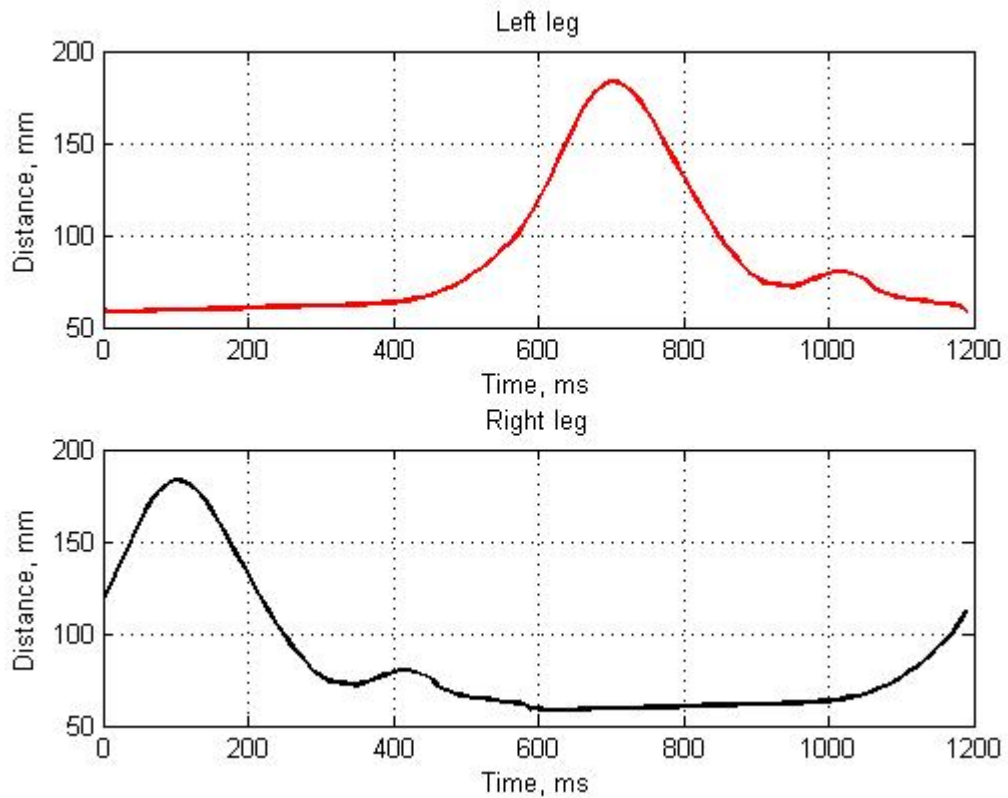
Figure 16 Left and Right engines movements corresponding to the instep of the foot during gait

Motor control with NI Motion Assistant requires the value of the engine turns. Experimentally it was found that the gear rack in one revolution is moved to 21 mm which means that one step is required a maximum of 6 rpm. Data was converted into revolutions based on this relationship.

The result is data on the rotation of the engine, which can be used to control. This can be used as absolute and as relative movement, both methods have their own characteristics. Thus, during the absolute displacement the engines are going to constantly repeat this set of movements. If one or more of the steps are not correct, then this will not affect the overall schedule. Is easier to make changes in the movement for the relative motion; however, a change of one step will shift subsequently to the modified value, resulting in the graph not matching the reference.

3. Control system of Experimental plant
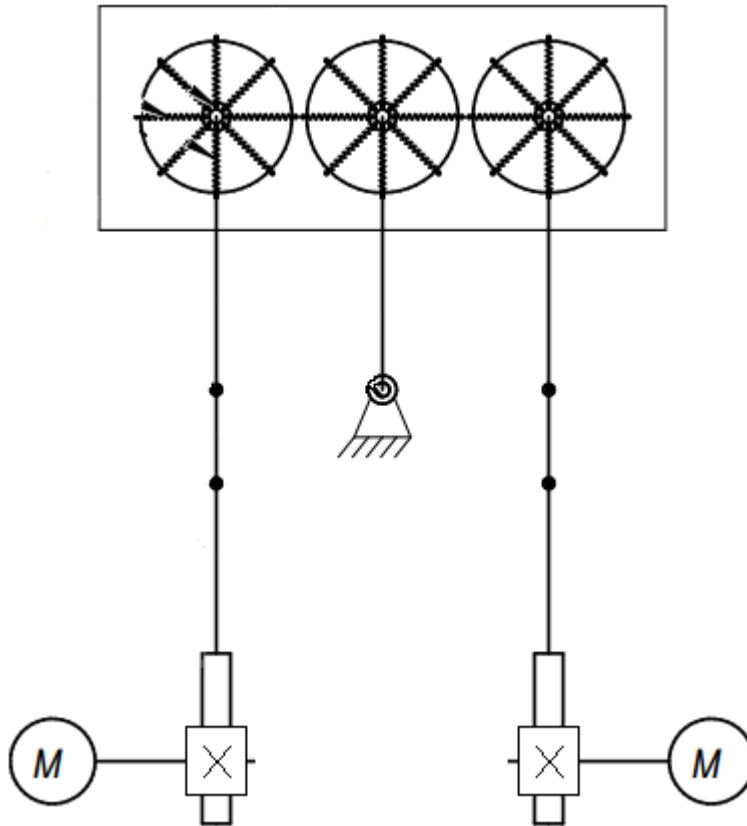
3.1. Plant description

Figure 17 Experimental plant scheme

Practical application of data was made on experimental plant of imitation of the human pelvis movement (Figure 17) [21]. The purpose of creation of this mechanical model is simulation of gait of the person with opportunities of measurement and the analysis of various moving parts of the person. One of the main tasks of creation of the stand is to reduce number of entrance data. Reading the data from many parts of the person is complicated by distinctions in build of people, and, therefore, different distance to the bone device. It especially complicates data collection from people of full build, who can have a shift of sensors in the course of the movement of hypodermic masses and muscles. Thus, the stand can help with the analysis of movements of a skeleton of the person. Further, this stand can be used for creation of stands for preventive treatment of violations of the musculoskeletal device.

Structurally, the geometry of the stand has to repeat shapes of human feet and pelvis. The functional problem of the stand is to move just as human feet and pelvis do in the course of gait move. Structurally the device is made pelvisg on average data on length of male feet and distance between the iliac crest. For the experimental purposes, the stand is made in scale 1 to 2.

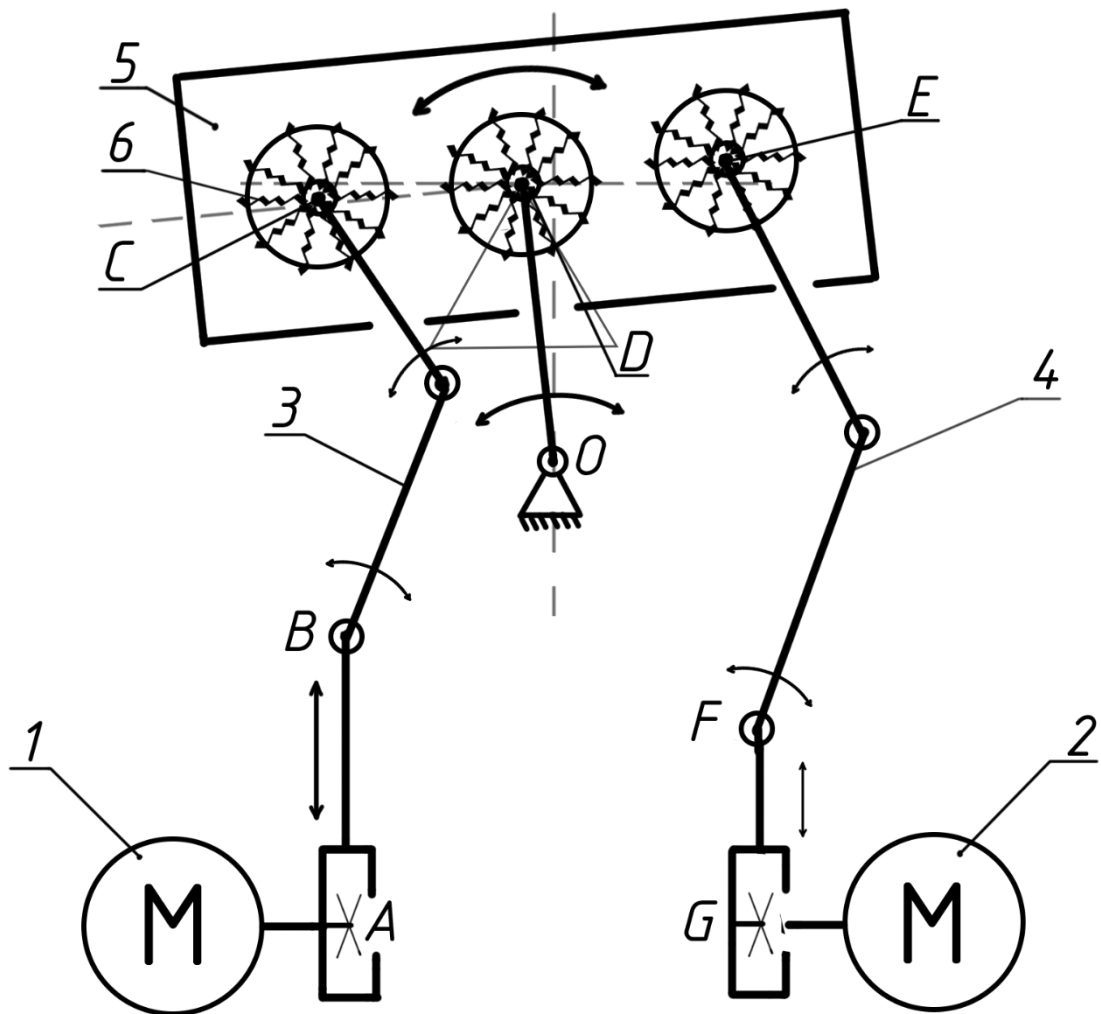Kinematic diagram of the plant is presented in Figure 18:

Figure 18 Plant kinematic scheme

In this scheme, the feet of the man correspond to the mechanical elements located between the points A and B, F and G. These elements with the help of toothed racks connected to the stepper motor (1 and 2 in Figure 18) located at the points A and G. The motions of these motors comply with the movements of human feet during movement. A gear rack moves up and down, allowing transmission of motion through the rotation elements in points B and F, which may make some deviations from vertical displacement, which corresponds to the movements of the knee during movement. Rigid elements 3 and 4 (Figure 18) are used for the transmission of movements from the feet to the pelvis. Any movement of the legs causes the pelvis to twist around the axis of the roller at the point O, while rolling around the point D corresponding to the lowering and raising of the hips during the movement. Joint motion around points D and O result in a motion similar to the rolling of the hips during the movement of the person.

The elastic elements located in points of E and C are the damping elements similar to joint capsules of the person which connect bones and transfer of the movement from one element to another. Also, these elements carry out a role of quenchers of vibration of all system during experiments. And, what is the most important, these elements allow to reduce dependence between the left and right foot.

Rotation elements in points B and F (Figure 18) are adjusted so that the movements of the pelvis following the movements of feet corresponded to the real. Thus, when the gear lath in a point of G or A is lifted as much as possible up, the maximum lowering of the pelvis from the relevant side takes place. It is similar to how the pelvis falls towards a swing leg and rises from the bearing leg.

Also, on the stand there are fastenings by means of which accelerometers will join and the movements of a pelvis and feet be studied. Thus it will be possible to find the movements of bones of feet and a pelvis that earlier was exigeant because of existence of the movement of muscles and fatty masses, and also because of impossibility of fastening of sensors directly on muscles or bones.

The main pluses of the presented plant are a simple design and a large number of parameters for measurement, in the presence of only one input. Change of speeds of step engines is able to afford to create and imitate various gait types, to define violations from reference values, for example, to find lameness. Further, it will allow to use the model in practical tasks, by means of feedback to define gait and by means of engines to correct it towards improvement.

3.2.   Overview of analogs

Analogs of this stand are both mathematical models and the hardware-software complexes (HSC). There is a set of approaches to the solution of such tasks as each task of development of a complex is unique and bears their own purposes. Comparison with mathematical models of other complexes is not very correct as researchers solve a certain set of tasks, having various basic data.

Mathematical models can be divided into several groups:

1) Model for analysis and study of movement. For example, models for medical diagnosis [21] or EMG – based models [22].
2) Models for creating a software and hardware for support the musculoskeletal system, for example, Exoatlet skeleton. Five-flat anthropomorphic mechanism is also an example of such models [23].
3) Models for medical purposes, for example, LokoMat [24].

Design of this stand can be attributed to second and third groups. Apart from similar models, it is necessary to note the presence of similar hardware and software, already widespread and used in medical purposes.

Each complex is based on unique researches which cornerstone the principle of work is. The following HSC can be allocated:

1) Haptic Walker [25] – a restorative complex, which is based on two mobile platforms based on the crank-slider mechanism. A person is fixed over the platforms, and his legs are rigidly fixed with straps. Mobile platforms are designed to mimic the movements of the legs, projected on sagittal plane. Force sensors are installed under the platforms, which provide feedback mechanism. The platforms are independent of each other, allowing them to be programmed in such a way as to simulate various movements. Standard HSC allows only planar motion in the sagittal plane, and the extended one adds 3 degrees of freedom, which allows you to convert the movement in volume. The maximum speed is 5 km/h, which corresponds to the average speed of a healthy person when walking. Special software controls the stand, allowing complete control over the movement of patient records and monitoring the progress, and also displays three-dimensional and two-dimensional models for control a HSC data from PC.

2) G-EO system – the analog of Haptic Walker possessing great opportunities and the smaller size. The main pluses of this stand are a wide choice of additional modules that allow to expand a circle of patients who can use it. The maximum speed on which the system is counted – 2.3 km/h.

3) Gait Trainer 3 and Rehawalk are a family of simulators, which are based on a treadmill with sensors capable of monitoring the condition of gait using sensors built into the platform or cameras that monitor the position of the feet in space. If people are unable to stand on their own feet, it can be hung on a moving platform. Such complexes are designed to improve the parameters of the step, depending on the current state of the person.

4) Balance System 3D – is a system based on deduction of balance of a body. The design is the hand-rail regulated under human height and an elastic mobile platform on which the person tries to balance during training. Also, existence of patient's pain during the inclinations of an elastic surface is checked. Special exercises, for example, achievement of a certain tilt angle of a platform for the allowed time are developed for similar

complexes. These exercises help to increase flexibility of a body, and are suitable for training of a vestibular mechanism.

5) LokomatPro – the Swiss device which operates with the foot by fixing it in special bandages. The person is suspended in stand, and his feet are fixed and further move on a racetrack according to the programmed examples of gait. Software helps to trace a condition of gait and to bring adjustments for each patient. The most advanced Lokomat version has force sensors, the automated systems of the analysis, opportunity for addition of turns of a body during gait, individual settings for each patient and an assessment of physiological drawing of walking. It makes Lokomat the most advanced hardware-software complex in the sphere of rehabilitation of patients with the musculoskeletal system diseases, which has impact on the cost of this complex and stirs it to a wide circulation.

6) Zander mechanical exercise machine [26] – a group of the mechanotherapeutic exercise machines developed in the XIX century by the Swedish orthopedist Gustav Zander. These exercise machines imitated the movements of a pelvis during walking. The patient, sitting down in them, trained muscles of a back and buttock area. The most known exercise machine is "saddle" which could move mechanically or with engines. Zander called the process of work with the exercise machine "mechanotherapy" and "massage". These exercise machines are interesting due to simplicity of design that makes them the inexpensive analog of the complexes described above.

The described systems were chosen because they're already widely used for a long time in therapy of real patients, in addition to Zander trainers, which now exist only in Yessentuki. The main disadvantage that unites these used systems are their complexity and cost. These factors do not allow a wide spread of robotherapy. The spread of such systems could increase the performance of the treatment of patients with disorders of the musculoskeletal system.

3.3. Controller and engines description

National Instrument MID-7602 was used as the motor controller. This controller allows to connect up to two engines, but it is limited in scope on the instructions of movements. This controller works only in a straight line, which makes it difficult to assign a continuous motion, which would correspond to the experimental data. Due to this fact, movement has been divided into discrete steps longer than 20 ms. Technical characteristics of the controller are shown in the table on Table 4:

Driver type	IM481H – modular hybrid, bipolar chopper
Work frequency	20 kHz
DC bus voltage	24 V
Phase current	0.2-1.4 A
Microsteps	x2, 4, 8, 16, 32, 64, 128, 256
	x5, 10, 25, 50, 125, 250
Voltage	90-138 V/204-264 V, 47-63 Hz
Current	1.5 A, 230 V
	3 A, 115 V

Table 4 NI MID-7602 controller technical characteristics

Front panel of controller has settings for Microsteps and phase current. The metal cap contains switches that change multiplier of Microsteps in binary or decimal system (Figure 19):
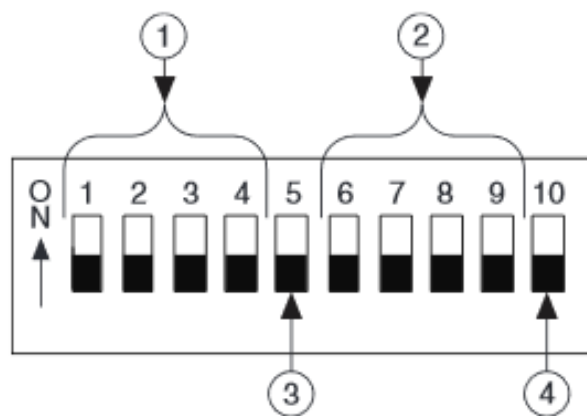
Figure 19 Control panel for micro-stepping and phase current

On Figure 19 :1 – controls the maximum phase current, 2 – multiplier control of microsteps, 3 – current control (to reduce engines heat, when there is no movements), 4 – polarity switch (not used in this controller).

Also, the front panel have a controller switch, engines switch and control LED. The front panel depicted in Figure 20. 1 – Fuse; 2 – Voltage switch; 3 – Controller switch; 4 – power LED; 5 – Engines switch; 6 – 9 – Current and micro-steps control for each engine; 10 – LEDs status for engines:
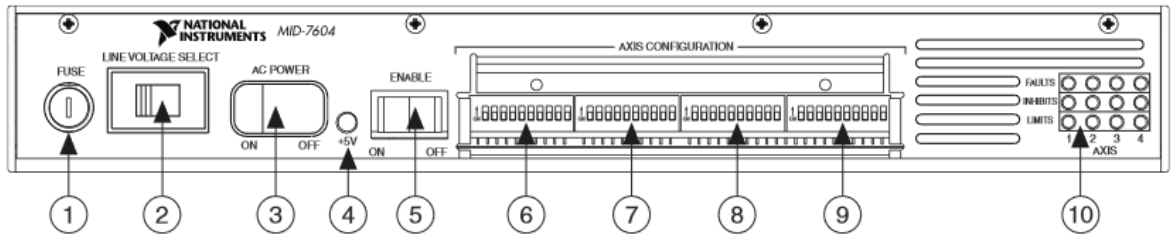
Figure 20 MID7602 front panel

Rear panel has connections to connect a computer controller, additional devices, sensors, motors and controller power supply. To connect and control from computer a specific PCI-E board is used, which connects to the motherboard of the computer and connects with an insulated wire to the controller.

Optimum Maschinen Germany stepper motors are used as engines that transmit motion by means of a toothed connection to the rack and to the plate, which imitates pelvis movements in frontal plane. Stepper motors were chosen for their accuracy in the task of motion. Technical characteristics of motors are represented in Table 5.

Minimal angle	1.8°
Torque	2.2 Nm
Current	3 A/phase
Voltage	2.5 V

Table 5 Optimum motor characteristics

3.4.   Software for motor control NI Motion Assistant

A special role in the quick setup and management is played by the use of overall ecosystem of devices and software. This allows the most flexibility to use the available device and to configure the data exchange between them.

For initial motor control software was used National Instruments Motion Assistant. It is part of LabVIEW, which allows importing the program in LabVIEW and working with it through visual programming.
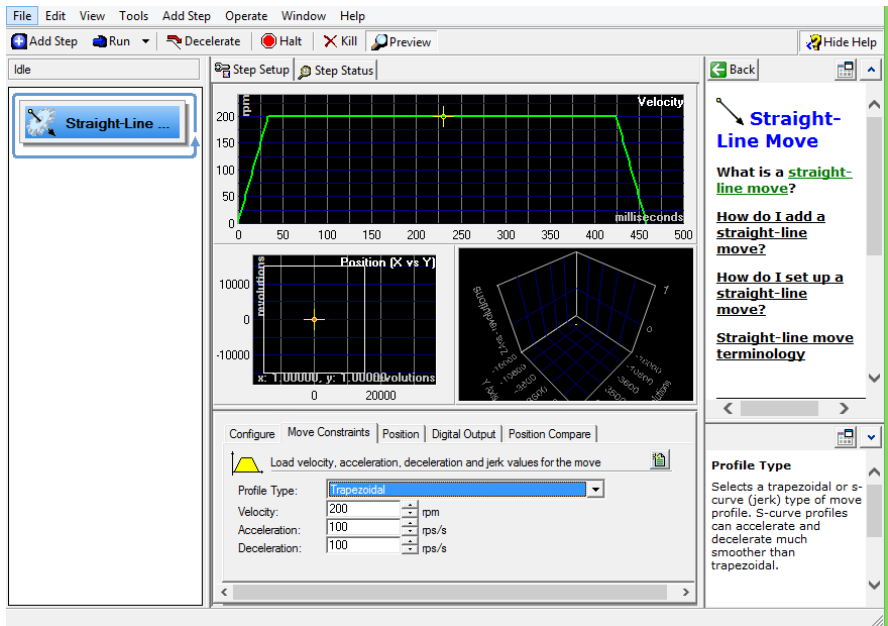
Figure 21 Interface of NI Motion Assistant

Common interface NI Motion Assistant is presented on Figure 21. It can be divided into several areas. Top panel is menu and control operation of the motor, in this area can be added or removed steps, and running the program. Left pane is added steps. In the center is a visual representation of the step and the bottom step setting, such as speed or type of the profile step. In the right part of the window is help.

There are several types of steps that can be assigned to the engines. The interface to add the step is shown in Figure 22. However, the controller MID 7602 does not allow to use non-linear motion, therefore the data are divided into n steps, each of which is recorded separately in the program. Movement along the contour also allows you to set up a schedule to move through a table from MS Excel or text file.
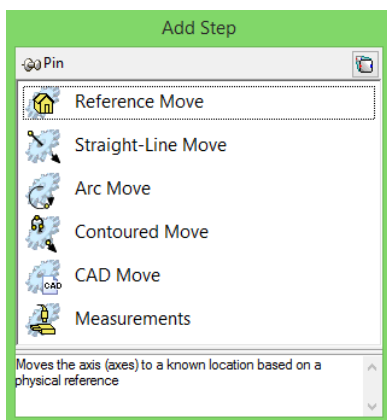

Figure 22 Add Step window

After adding a step, they must be configured. The axis to be used is selected, as well as the movement units (e.g., rotate or microstepping), the type of determination of the position (absolute or relative), and the type of profile. The speed and acceleration, which would correspond to the necessary time of step, are empirically chosen. Set up a step is also displayed visually (Figure 23).

Thus, all steps, velocity and acceleration are added in the program. After making all the steps, program can be used in a single cycle or infinite, which allows users to work with a stand and get some experimental data. However, the inconvenience of entering and changing steps bring some difficulties if it is necessary to change the complete profile of the gait.

Since the code of NI Motion Assistant may be generated in C code or chart LabVIEW, the above problems can be solved by using a text or spreadsheet data that can be used as input in LabVIEW.
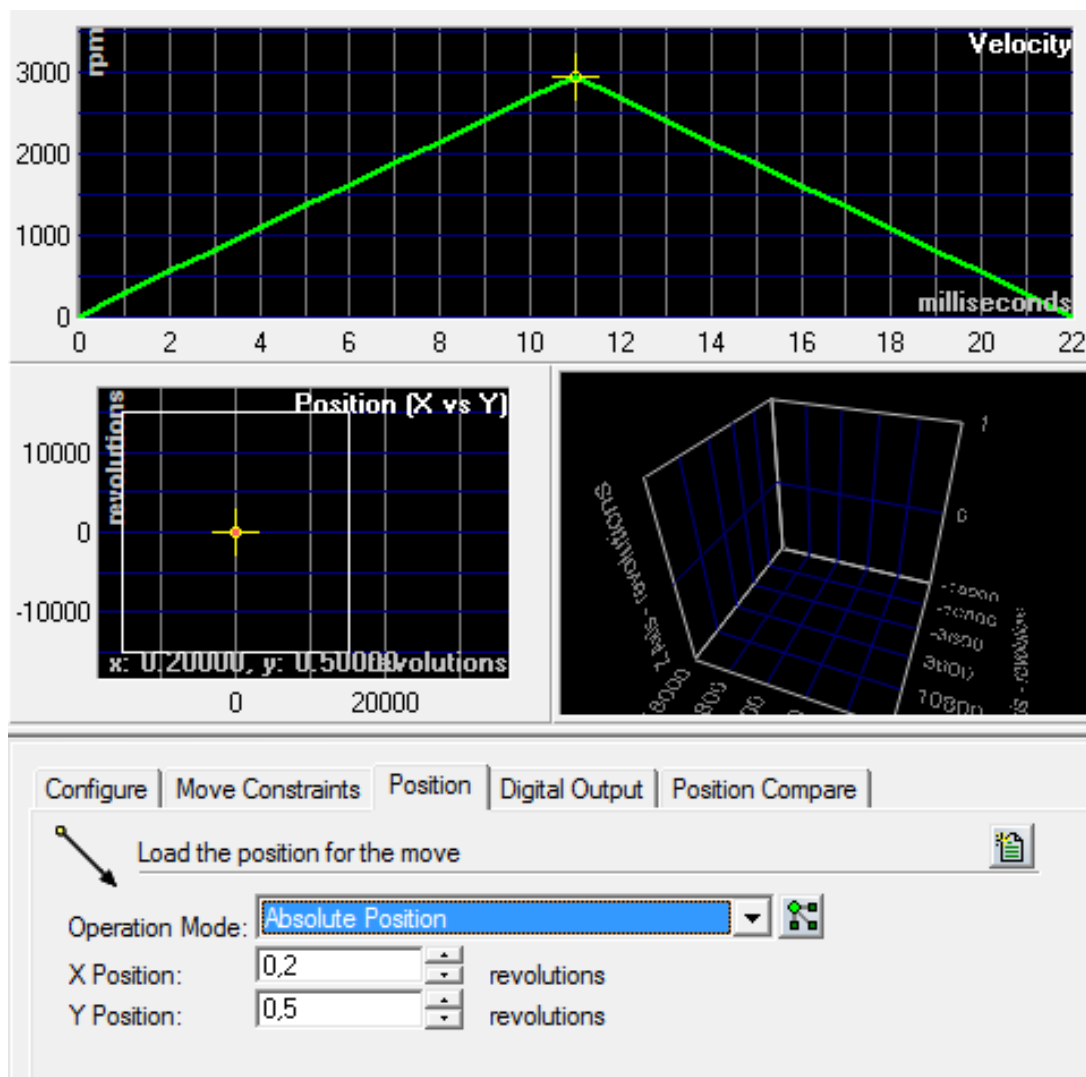

Figure 23 Visual display of configured steps. Specified the profile of the current step, and its position relative to the reference axis

3.5.   Software interface based on NI LabVIEW

NI LabVIEW is a National Instrument development environment of visual language G. LabVIEW is widely used in enterprise and manufacturing systems of collection and analysis of data, for management of technical systems and processes. Visual programming language allows writing programs quickly and effectively. The effectiveness of LabVIEW is also expanding due to the large number of standard libraries that support a huge range of hardware and software from different manufactures. The list includes libraries for working with standard interfaces (e.g. RS-232, Ethernet or TCP/IP), robot control and machine vision systems, generation and analysis of digital signals. The main criticism relates to the closed state of source code of LabVIEW, as well as limited support of non-Windows devices.

Programs written in LabVIEW are the control panel of the device and are called a virtual appliance. They consist of two parts: the internal representation in the form of flowcharts, and the external in the form of a visual interface. The visual interface consists of a panel with controls – buttons, switches, scales, panels. Block diagram is a functional device of the virtual device. Here the reception and output of data, analysis, and control structures and functional units is made. All of this comes together through communication lines.

After importing from Motion Assistant, we obtain the block diagram of the program, which is a sequential execution of each step. This option is not convenient to build the program in LabVIEW, because we need each step to assign your variable. The program should run in a loop, receiving data from a table and also be able to control the device through a visual interface.

The basic requirements for the program: user-friendly interface, the ability to quickly edit the variables, the ability to save and load text data, and graphical display of the current profile. The final visual result interface can be seen in Figure 24:
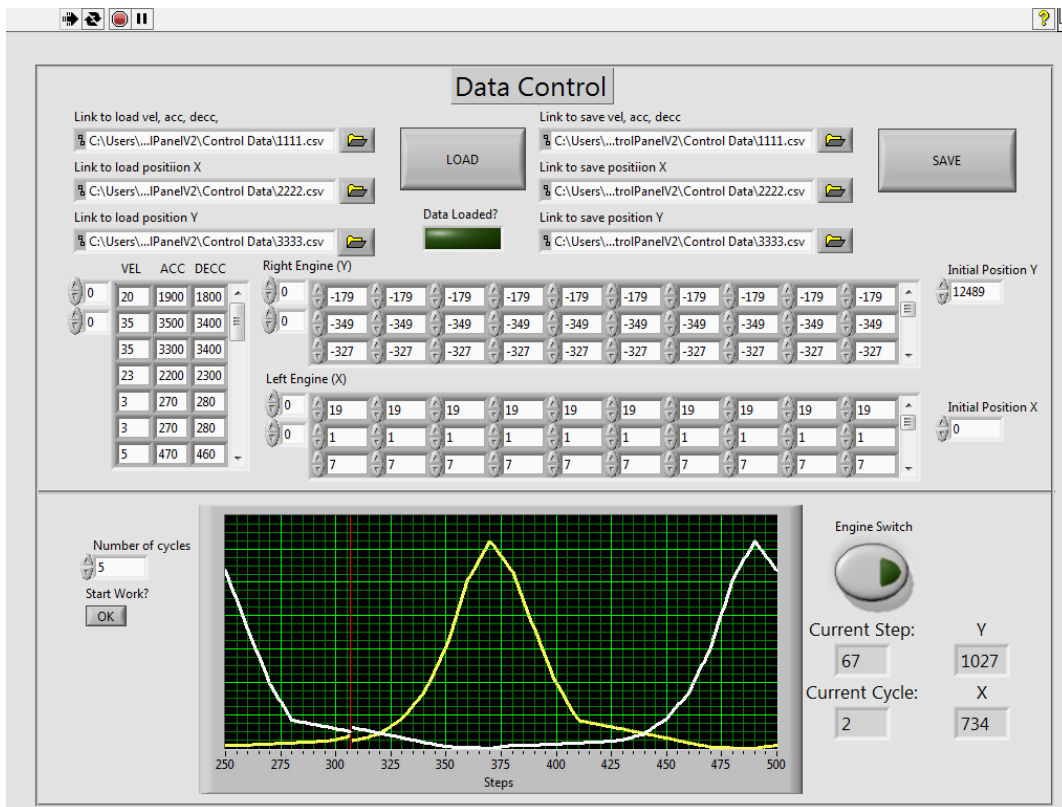
Figure 24 Dashboard plant control

The General principle of the program can be presented in the form of a block diagram depicted in Figure 25. After starting the program the profile data is entered, as well as information on velocities and accelerations of each step. This can be done by downloading a text or tabular data file or manually entering data into a table. After entering the data, you can save them to a file. Further data is checked for correctness, values are checked, and line lengths of the vectors, if data are not correct, you will need to enter them again to continue.

If the data is correct, the engines initialize and execution of a program cycle begins. During a cycle the data in each row is sequentially input to the engines. Upon completion of one cycle, check for the number of cycles if the cycle is set to one, the program stops its execution, otherwise the value of the cycle is reset, and the program continues its execution.

Such an interface has sufficient flexibility and extensibility, whereby it can be further supplemented with feedback and data analysis, for example.
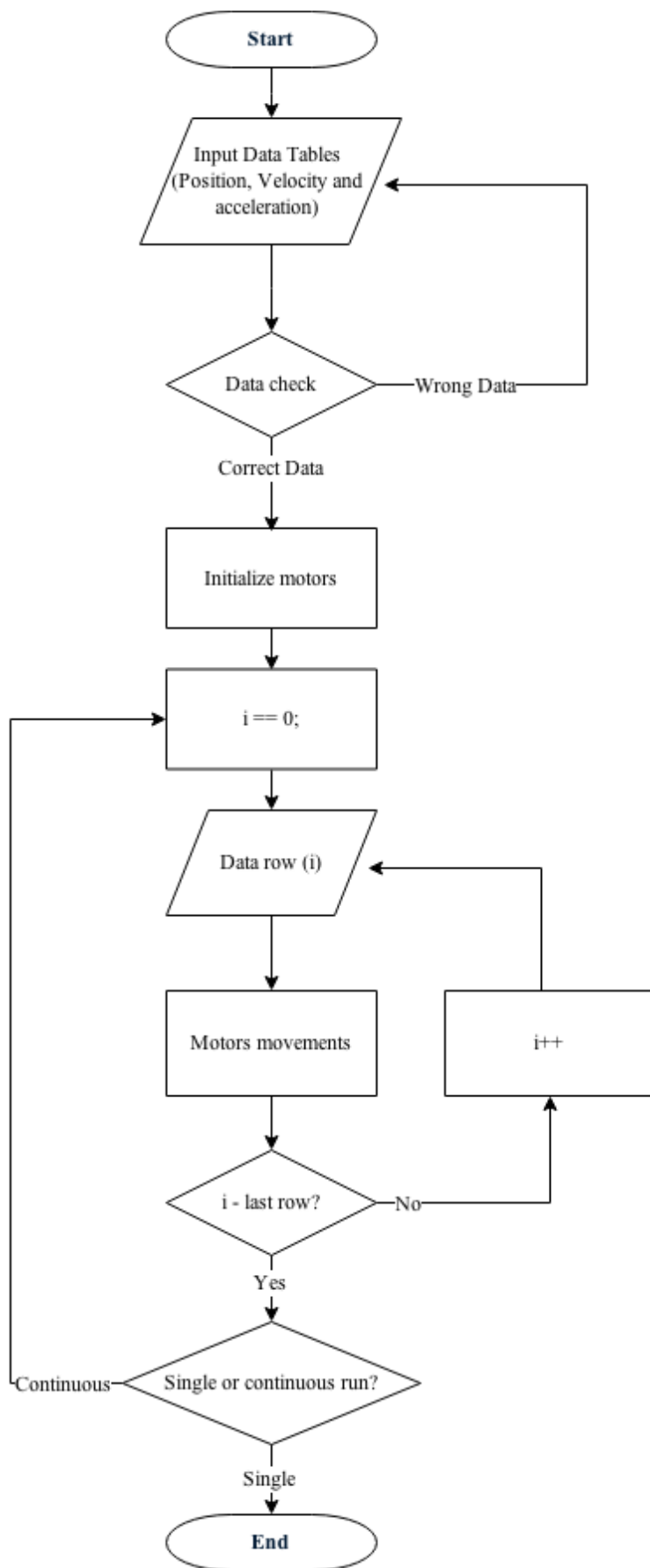
Figure 25 Simplified program working cycle

3.6. Feedback realization

Feedback is needed to monitor movement of the system and making changes to the control of the experimental plant, if there is such a need. Feedback can be implemented in several ways, as in the case of a software implementation, and use of various equipmen.

Since a large part of the used hardware and software is from National Instrument, it is convenient to use LabVIEW to implement feedback. For these purposes the already implemented interface for management of the stand can be used. However, the transfer software interface to another programming language would increase flexibility and opportunities for feedback. In addition, restrictions on multitasking in LabVIEW do not allow you to use the maximum opportunities from the feedback. The most likely languages for development are C++, C# or Java. This approach allows to expand the number of devices to manage a pilot plant. For example, it will be possible to manage using tablet or smartphone through a remote server, configure tests and collect data.

A camera, inertial sensors or sensors of linear displacement can be used as the sensor. Most preferred are the linear displacement sensors, due to their speed, accuracy, and no need for additional processing. Machine vision requires additional processing, the CPU time, and has a precision less than the linear displacement sensors. However, this method does not require additional changes made to setup, and analysis can be implemented from Vision Builder AI program. Inertial sensors are the least preferred option for implementation feedback, primarily because of the output, secondly, because of additional post-processing, which introduces additional processing.

General block diagram of the feedback is presented in Figure 26. Bold blocks are feedback, which was added to the General flowchart of the program. Here is the general implementation without specifying each step.

At this stage of the work the feedback is not significant, as there will be refinement and further study of the plant and its work. As working at construction of device approaches the end, the functionalities of the software based on LabVIEW can be expand and the necessary sensors can be added.

Feedback is an important element of the program control, since its presence allows to use the plant for the purposes of prevention of patients or to explore ways to improve gait in people with disorders of the lower body. The method of implementation and accuracy as a software interface and sensors depends on the output result obtained by the stand.
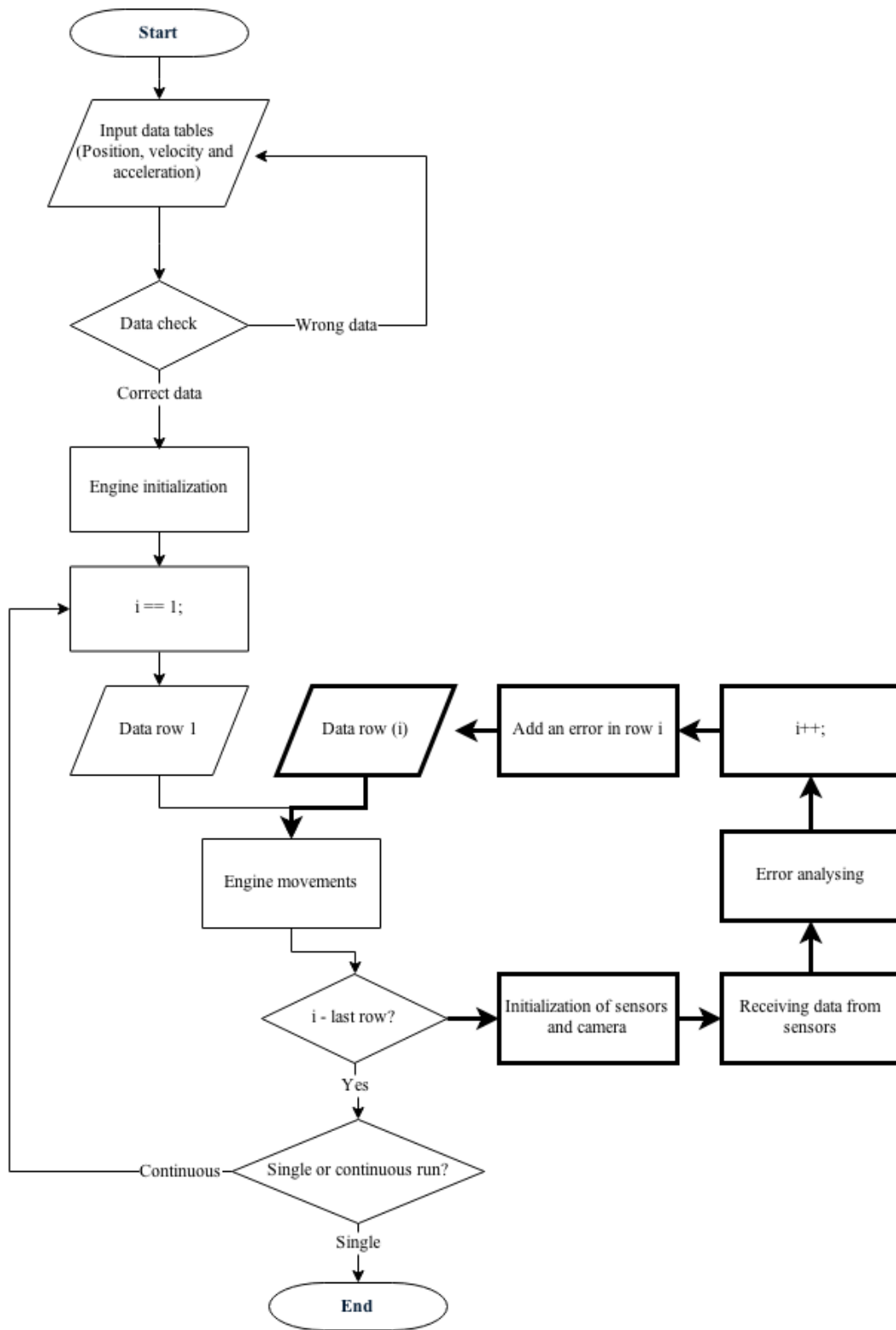
Figure 26 Simplified program working scheme with feedback

4. Measuring and analysis of plant movement

After programming engines, it is necessary to ensure that the stand is moving as needed. There are many methods of determining linear motion. The most affordable and fastest way is machine vision. This method is powerful for setting up and analysis; there is a wide range of quality and inexpensive equipment. The linear displacement sensors are more accurate than machine vision, however, such equipment requires additional placing at the facility. Linear sensors are also more expensive. Nevertheless, for the implementation of feedback they are more preferred because the data from these sensors are obtained faster and more accurately. Also, it is possible to use accelerometers, but this method requires additional processing of the data, because not all of the accelerometers provide data of the movements.

4.1. Linear movements measurement methods

Linear movement can be defined in many ways, both directly through the definition of linear movement, and by analyzing and processing of other data, such as velocity and acceleration. The first group consists of linear displacement sensors. The second group - of accelerometers and machine vision.

There are many types of linear encoders [27], depending on the conditions of use and the required accuracy. A wide range allows to choose the desired sensor while minimizing changes to the system. Next types of sensors can be highlighted:

1. Sensors which determine absolute position based on magnetostriction. They have no contact with the surface, and no wear-measuring element.
2. Sensors based on the photoelectric scanning. They have very high precision. Measured steps are up to 0.1 µm and an accuracy is up to 5 microns. Used in applications requiring high resolution and accuracy.
3. The radar sensors type measuring distance using a laser beam. These systems are good because they do not require additional installation, have high accuracy and long distances to measure.
4. Encoders with cable drum have small size and average precision. Do not require specific installation.

Thus, the linear displacement sensors have a high accuracy, wide opportunities on installation and allow you to immediately obtain the necessary data. When used as a feedback sensor, their main advantage is that they do no need additional hardware for signal analysis of the

sensors data. However, another method was chosen for measurement due to the construction of plant and assembly.

Machine vision is an area of computer vision, gaining popularity in the industrial and manufacturing sectors. Due to the rapid growth of computer power and low cost, computer vision is rapidly and widely distributed in the industrial sector. Main methods of using machine vision are the work on the conveyor. The ability to perform tasks such as counting objects, reading identification numbers, search defective parts allow to increase production capabilities and improve quality control. Also, machine vision can be used in such a specific task as the definition of the displacement or distance between objects.

The main advantages of such systems are speed of deployment and the ability to jump quickly to a solution of the desired task. Furthermore, the large range of equipment allows you to choose the most accurate option for current conditions. The camera should have a matrix with a large resolution and a large physical size of the matrix for the task of determining movements and displacement. This will increase the accuracy of the measurements. However, more powerful equipment will be required for image analysis.

The main difficulty in the use of machine vision to determine the displacement is to establish the necessary relationship of pixel length, and setting the scene. Setting the shooting scene is fundamental, since the accuracy of determination of objects and the speed of analysis of a scene depends on it. This requires the use of additional equipment or additional scene elements, such as a grid on which to tune the ratio of pixels to length.

This method was chosen as the main, due to its simplicity and speed of deployment. SmartCamera with the necessary optics was selected as a main tool, with its own processor. The scene was lit with using gas-discharge fluorescent lamps. Setting the pixel length was performed using a millimeter grid and ruler.

Another way of determining movements is the use of accelerometers. The main advantages of this approach is high accuracy, small size, which allows the use of multiple sensors at once, and the possibility of remote analysis. Cons of this method: it requires additional computations, which requires additional capacity. In addition, in the case of three-axis accelerometers it is required to determine the acceleration and displacement in one of the planes. This method was used to study the movements of the upper part of the stand.

4.2. Post movement estimation

To solve the problem of determining the displacement of the rack (Figure 27) the method of video analysis was chosen. This method was chosen as the most accessible, quick to configure and requires no modifications to plant.

National Instrument SmartCamera NI1764 was selected as a camera. The main advantage of this camera is the built-in CPU, which allows us to analyze the video directly on the camera without using the power of the computer, which reduces the hardware requirements.
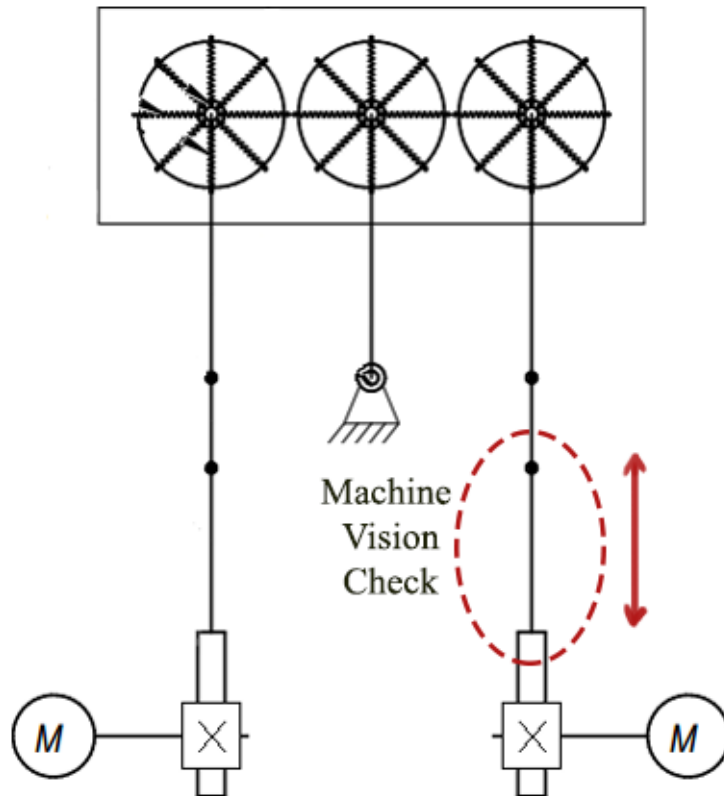

Figure 27 Area of estimation of displacement of racks

Technical characteristics of camera are represented in table on Table 6:

Processor	Main – 533 MHz PowerPC; Co-processor – 720 MHz DSP
Memory	System – 128 МБ Store – 128 МБ
Matrix	CCD matrix. Resolution: 1280x1024 px Color depth – 8 bit (B/W) Frequency – 13 fps

	Possible a partitial image capture
Interface	Ethernet – 2x10/100/1000; RS232
Light	Possible to connect and control an external lighting
Software	National Instrument Vision Builder AI LabVIEW
Working temperature	0 – 45 °C
Housing material	Metal

Table 6 NI SmartCamera NI1764 characteristics [28]

The use of two processors can speed up specific filters and algorithms. Additional DSP processor can speed up linear filters, spectral analysis, non-linear processing, and adaptive filtering (image processing, pattern recognition) [29]. Power is the first processor selected with the need to handle large images. Thus, the work on the analysis of the image may be carried out only by means of the camera.

Since the camera uses a black-and-white matrix, there is no need to convert an image; it is necessary only to use lighting and camera settings to choose an optimal contrast and brightness to identify objects of interest.

NI Vision Builder AI was used as the software. This package is part of LabVIEW that allows you to fully use the camera as an element of feedback. In addition, the NI Vision Builder AI allows you to quickly configure the cameras from National Instrument, to carry out the necessary analysis and then export what you created in VB AI program in LabVIEW. Exported program can be used as part of a program during the creation of feedback.

Using Using hardware and software from a single vendor carries many advantages, since they all are tied to the overall ecosystem, which reduces requirements for the development and commissioning of communication between equipment. All the data from the hardware can be obtained by the standard LabVIEW package without bringing in additional libraries.

The interface of the NI Vision Builder AI is depicted in Figure 28. The program window can be divided into 4 areas.

Figure 28 Interface of NI Vision Builder AI

Zone 1 – menu and program management, in this field can be selected the scale of the image, the number of iterations of the program, turning on and off the lighting area of interest and objects of interest.

Zone 2 – area of the image received from the camera, it shows the current or last image obtained before stopping the program. In this area can be selected an area of interest which will be analyzed.

Zone 3 is a block representation of the program being used, you can see what the unit is doing a task, their current properties, as well as checking the correct execution of the block. Each unit has two status: Pass and Failed. In the case of Pass unit operation occurs in normal mode, in case of Failed emergency occurs. For example, if the unit Detect Objects block loses one of the objects, then the next block Geometry will generate an error, because you will not be able to calculate the required values.

Zone 4 – blocks and their properties. This field provides the means of receiving, processing, analyzing, and data recording, which are used when creating programs for surveys.

For motion analysis has been made a small program whose purpose was to detect objects of interest in the image, to determine their position in space and compute the distance between them. The analysis scheme is presented on Figure 29:
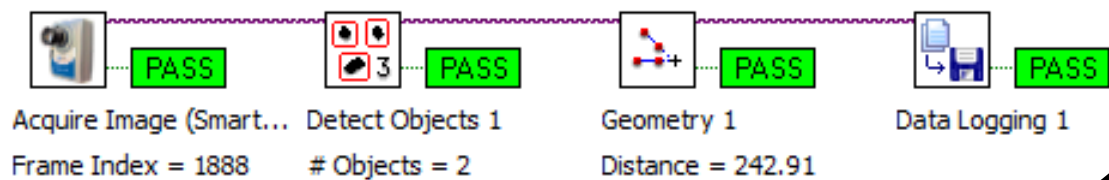
Figure 29 Analysis scheme based on NI Vision Builder AI

The analysis process was divided into the following steps:

1. **Getting image**. In this step it is necessary to empirically determine the parameters of the camera and optics, so that objects of interest are clearly stood out objects of interest. Parameters such as sharpness, contrast, brightness affect not only the accuracy but also the speed of image processing. Empirically, it was determined that the processing speed is significantly reduced, if the objects of interest are not sufficient contrast. In the case where the camera settings do not help, you need to improve the external environment, for example, to increase the coverage of the scene. For unambiguous allocation of objects of interest the discharge lamp was taken, with which was covered the area of interest. Since part of the active metal reflect light in the process of lighting, black paper strips were applied to objects for them to reflect less actively, thus a great contrast was created to accurately determine the position of objects of interest, and also to increase the processing speed of the camera.

2. **Analysis of objects in the image**. This step clearly defines the region of interest of the image, allowing you to increase the speed of analysis and avoid false positives (Figure 30). The darkest rectangular objects in an image were selected as objects to be analyzed. Each object was assigned a unique identification number. If the image is several such objects, we need to choose those that interest us. This can be done in the next step, which evaluates the distance between objects. However, it is necessary to provide a precise definition of the objects in the image during the whole process, as the loss of the object, and then re-detection means changing its identification number, which makes further analysis of distances impossible. This can be avoided by avoiding foreign objects of interest in the frame, then even after the loss of the object and its rediscovery the distance will be determined accurately.
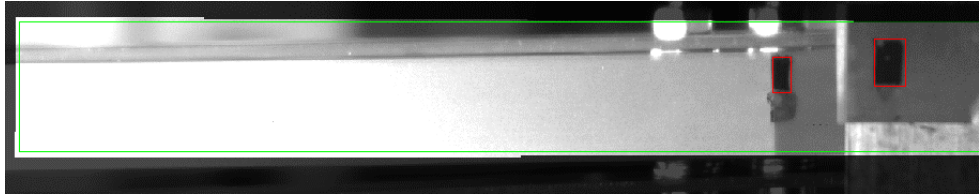
Figure 30 Highlighted field of interest in the target image

3. **Estimate the distance between objects**. In this step, the objects of interest were selected by their identification. A method for calculating the distance between objects is determined. It may be the estimate of the distance between the centers of mass (Z in Figure 31), or the minimum distance between objects (X in Figure 31). Calculated distance is displayed on the image in the interface of the NI Vision Builder.
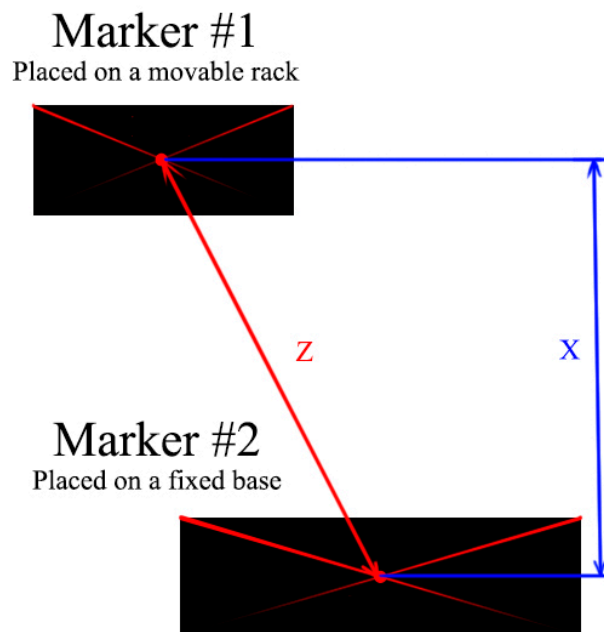

Figure 31 Distance between objects of interest

4. **Writing data to a file**. At this stage should be selected the data that should be preserved, the method of saving data, and the type and form of presentation. In the course of the work the data was recorded on the camera memory to a text file. The following data were selected for recording: the Number of examined objects, the frame Number, Time, Time between frames, the frame Status and the Distance in pixels. This format is convenient for further analysis in MATLAB.

Thus, as a result of the use of machine vision the graphs describing rectilinear motion of the rack were obtained. More than 20 experiments were conducted with survey of experimental data.

The lighting and camera settings were changed, as well as the camera position, the arrangement of labels on the stand, and methods of determining distances. After analysis the best results were selected, in which there was no loss of pixel data. These results can be seen in Figure 32:
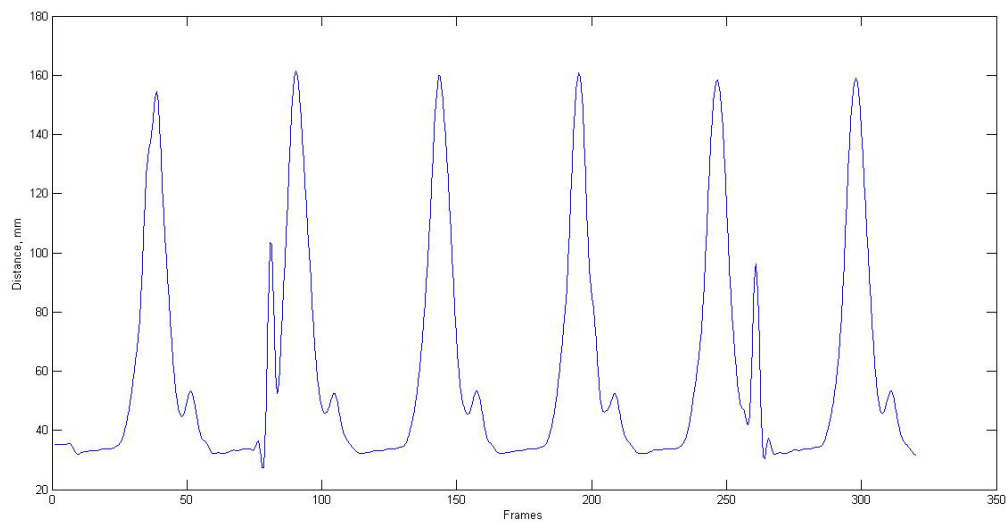

Figure 32 Movements of racks

Anomalous spikes in the graph are associated with temporary loss of objects from the area of interest that may be caused by sudden change of contrast or brightness of the image, with the result that objects cannot be defined or will be defined by other objects caught in the lens.
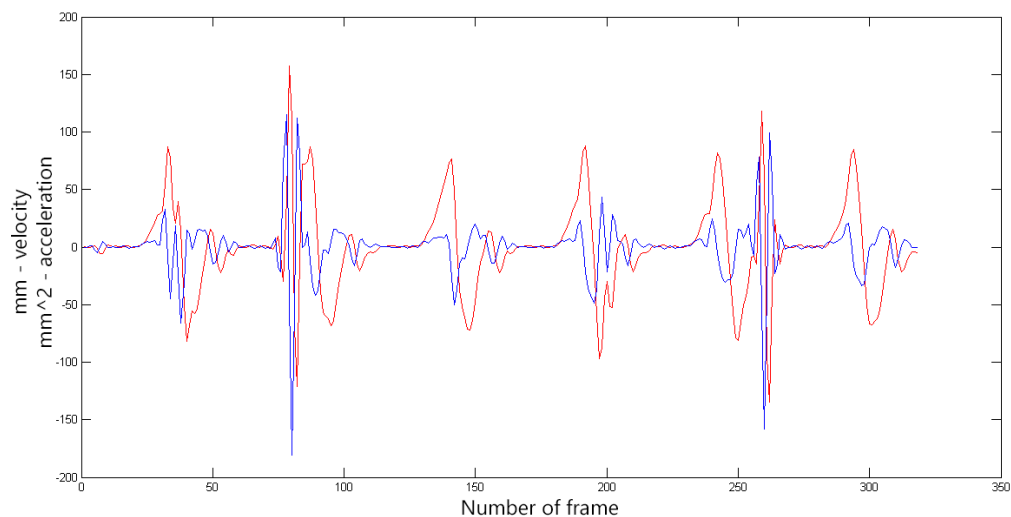

Figure 33 Velocity and accelerations of racks

The acceleration was obtained from the analysis of the movements of the rack shown in Figure 33. They also can highlight the repeatability of the experiment and highlight the cycles of movement of the rack.

To assess the movement of the rack it is necessary to compare the data obtained experimentally with the reference data. To do this, cycles of the step were selected from the experimental data, and their average profile was calculated. This profile was used for comparison with the reference. The comparison of experimental and reference data are presented in Figure 34:
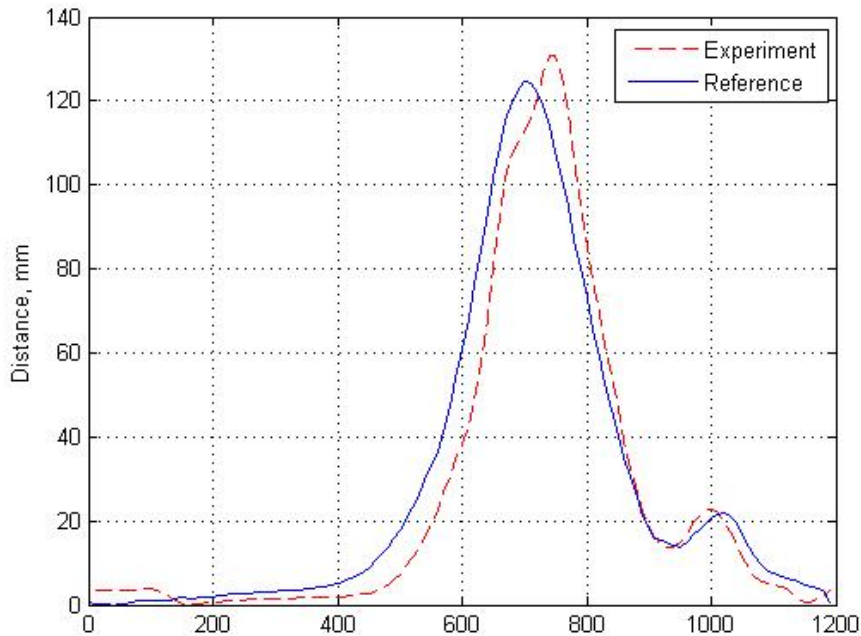

Figure 34 Comparison of experimental (dash line) and reference (solid line) data of heel instep

The graph shows that the profile has the same highs and lows as a reference, but there is a small difference in time. Such differences do not exceed 5% of the reference data and are related to the selection of accelerations and velocities for points, as well as non-ideal mechanical and electromechanical systems. Speed and acceleration were chosen so that the theoretical value for step time are equal to a certain intervals; however, these theoretical values do not match the practical obtained from the engine.

However, from this data we can conclude that the deviation of the profile from the reference is minor and allows us to continue further experimental work on the stand.

4.3. Movement analysis using accelerometers

Analysis of the movement of the plate [30], which repeats the movements of the pelvis, was performed using pairs of accelerometers with gyroscopes. Accelerometers were installed on the plate according to Figure 35. There were several types of tests, the α angle as well as the weight of the plate and speed step were changed. Total there were 27 different sets of experiments, each of which lasted for 300 seconds.
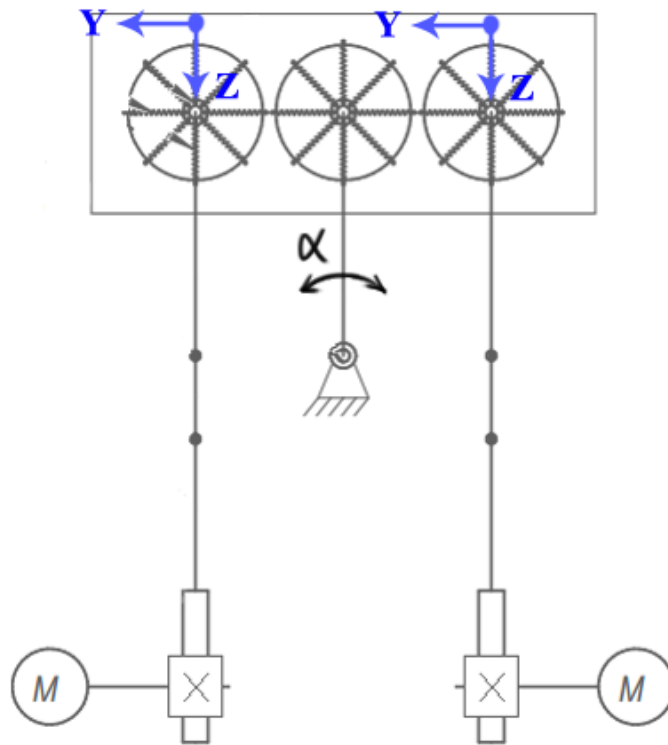
The set of parameters was as follows: angles: 4.8, 6.4 and 8.0 degrees; Weight of the plate with sensors and equipment: 1.686, 1.37 and 0.926 kg; Length (speed step) – 21, 25, and 35 ms. These data were combined and there were conducted 27 experiments with different parameters.

For the analysis it was necessary to process the data from the accelerometers, integrating them into the movement and comparing it with the movements of the real movement of the pelvis while walking. Original data obtained accelerometers are shown in Figure 36.

To exclude noise, the data was passed through a Fourth order Butterworth low-pass filter [31]. It is possible to obtain a curve of accelerations devoid of noise during the interval of the experiment. Filtered acceleration is shown in Figure 36 with thick black line. In addition, it is worth noting that these accelerations have the component of gravitational acceleration, which depends on the angle of rotation sensor and which must be deleted later.

Also, a comparison between two acceleration sensors and the curve derived from the average acceleration values of the two accelerometers was made. The result is shown in Figure 37. Acceleration sensors are represented black and blue lines, the difference between them is highlighted in yellow shaded area, the red line represents the average value of the acceleration. For further analysis and calculations there will be used only the average value of the acceleration.
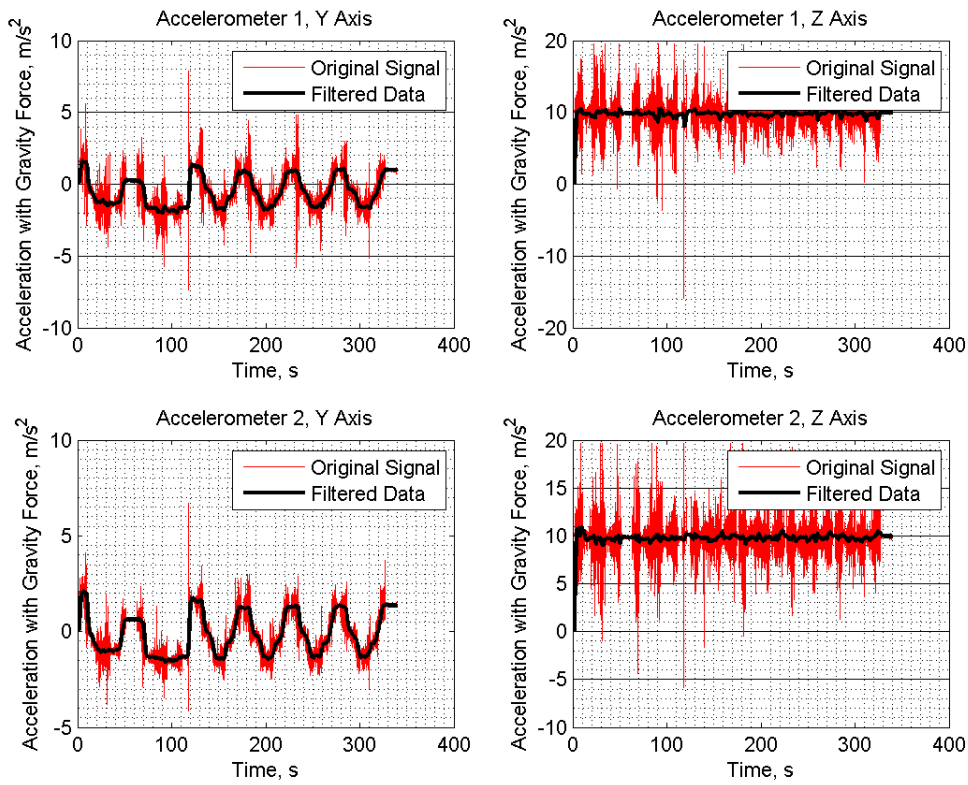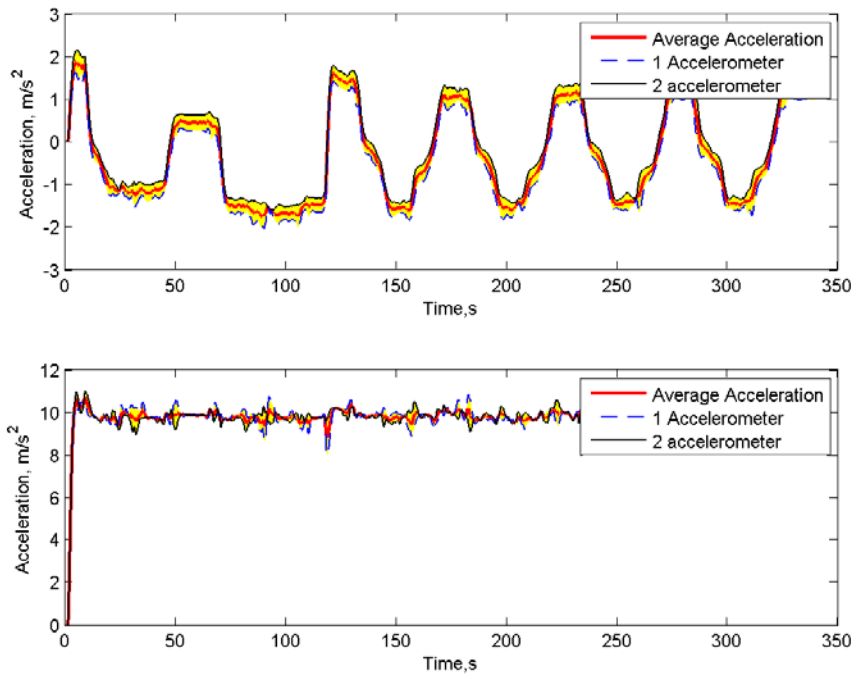
Figure 36 Acceleration data along Y and Z axes

Figure 37 Comparison of the sensors on the axis Y, and Z. The yellow colored area between the first acceleration sensor and the second is a difference. Red line - average value of the acceleration

To eliminate gravitational acceleration it is necessary to know the angle of rotation of sensor during the test. For values of the angle was used data from the gyroscope (Figure 38). Angular rate from gyro need to be numerically integrated to receive a rotation angle sensor along the axis X, directed through the plate. The rotation angle is represented in the right part of Figure 38. The thin black line shows the original data from the integration. There can be seen a zero drift, because of which the angle is distorted continuously, so that the sensor does not return to its initial position.
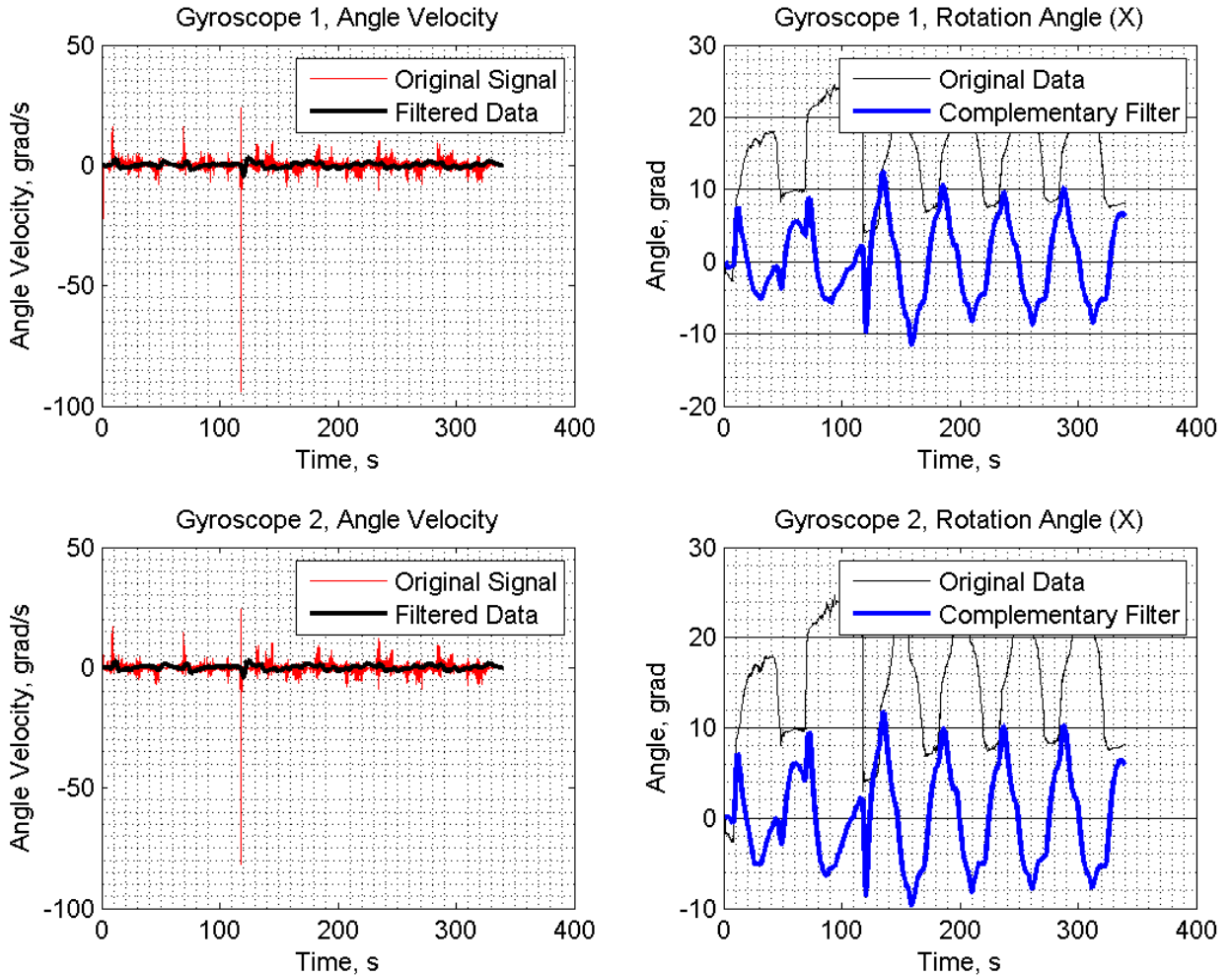

Figure 38 Data from gyroscopes. At the left - angular speeds of the sensor 1 and 2. On the right - an angle of rotation, original and passed via the filter

Complementary Filter was put to eliminate the zero drift [32] (Equation 1), which is the sum of the data of the gyroscope and accelerometer. This method is an analog of a Kalman filter, but has a higher performance and greater simplicity [33]:

$$\text{Ang}(i) = W * (\text{Ang}(i-1) + \text{Gr} * \text{dt}) + (1 - W) * (ACC * \text{dt}) \qquad (1)$$

In this equation: Ang - the angle at which the sensor is rotated; W - weight coefficient determined by experiment, for this experiment was selected 0.98; Gr - gyro data for a small period of time; ACC - accelerometer data.

This filter helped to eliminate drift of the gyroscope by incorporating the values of the accelerometer. Filtered values of the angle are indicated in Figure 38 on the right side with the thicker blue line. These data are necessary to assess the component of the gravitational acceleration on the axes, as well as allowing to estimate the angle of inclination of the plate, which has an amplitude of about 10°. This value is twice the value tilt of the pelvis, which is 5°. In the future, it is need to make adjustments that would fix the moment.

After assessing the rotation of sensor it is possible to estimate the component of the gravitational acceleration projected on the axis. The results are presented in Figure 39.
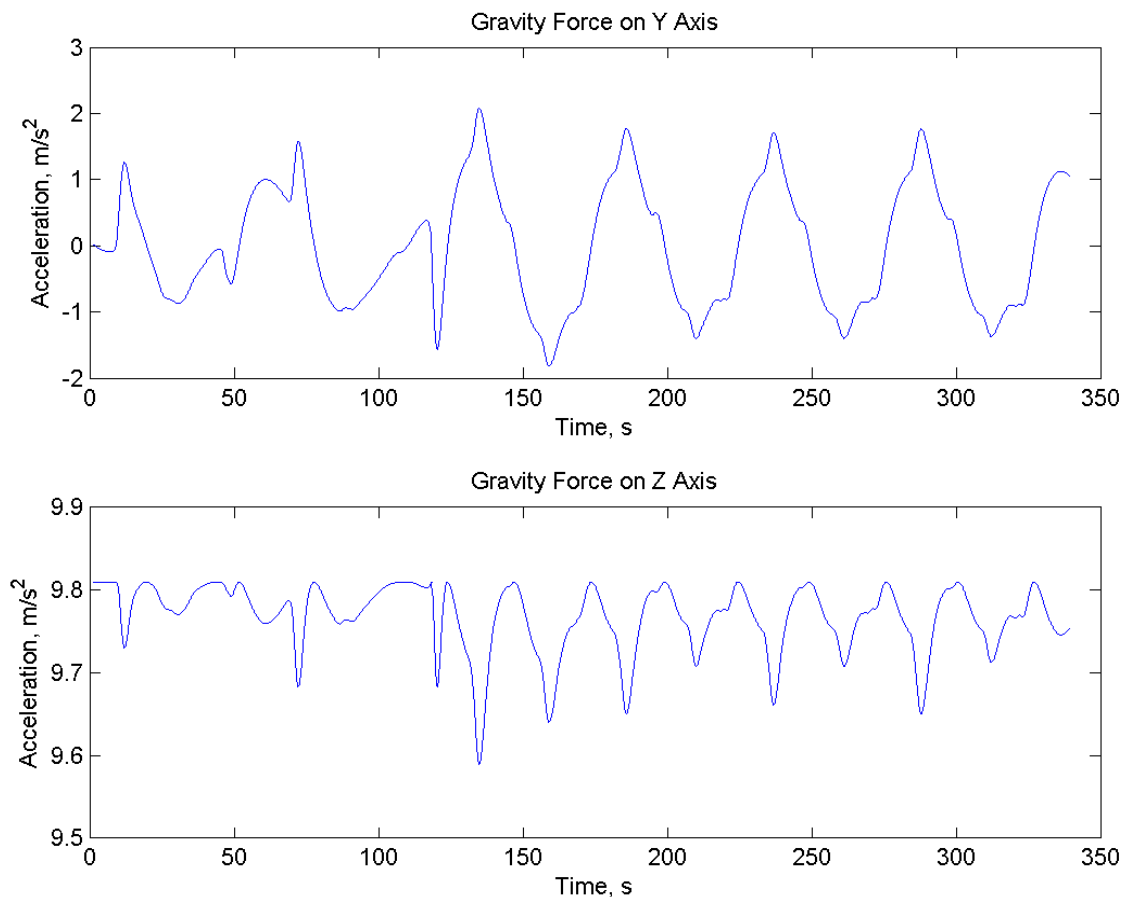

Figure 39 Gravitational acceleration, projected on the axes

After deleting the component of the gravitational acceleration from the acceleration, the actual acceleration of the stand was obtained. The data were further omitted to exclude noise through a low pass filter Butterworth. The results of this processing are presented in Figure 40:
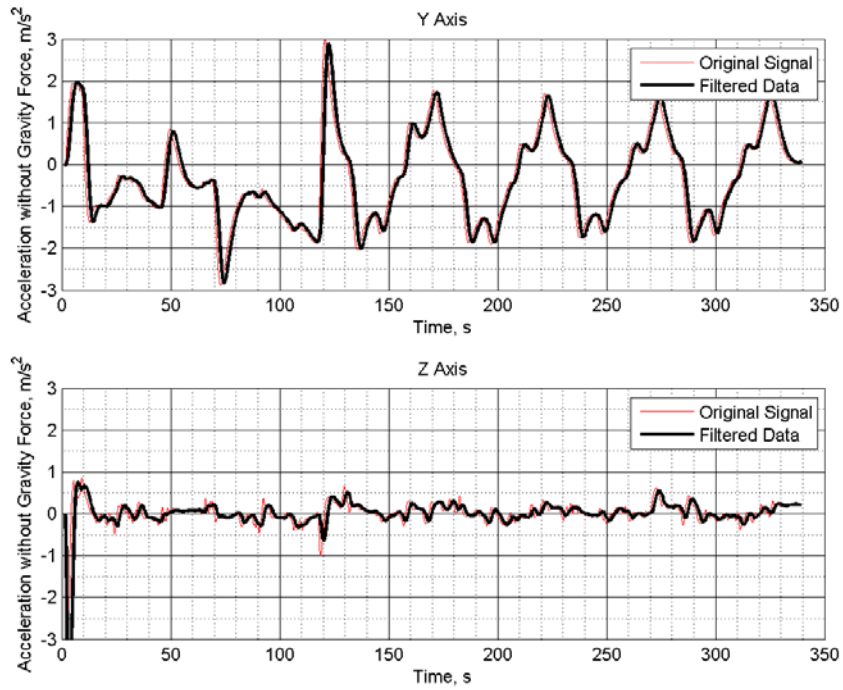
49

Figure 40 Acceleration without Gravity Force

The integration of these accelerations allowed to obtain velocity and displacement of the plant that are required for movement analysis. The values of velocities are shown in Figure 41:
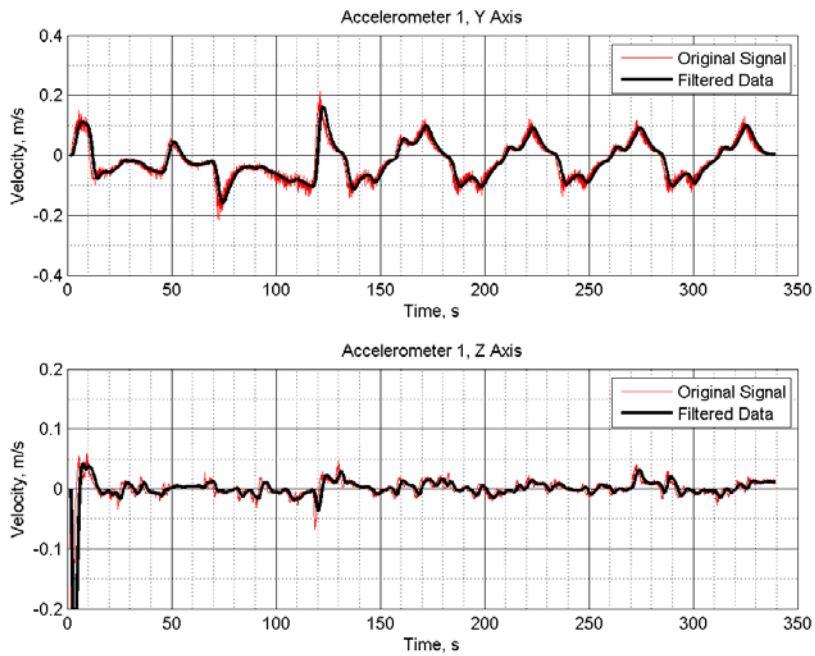

Figure 41 Velocity on each axes

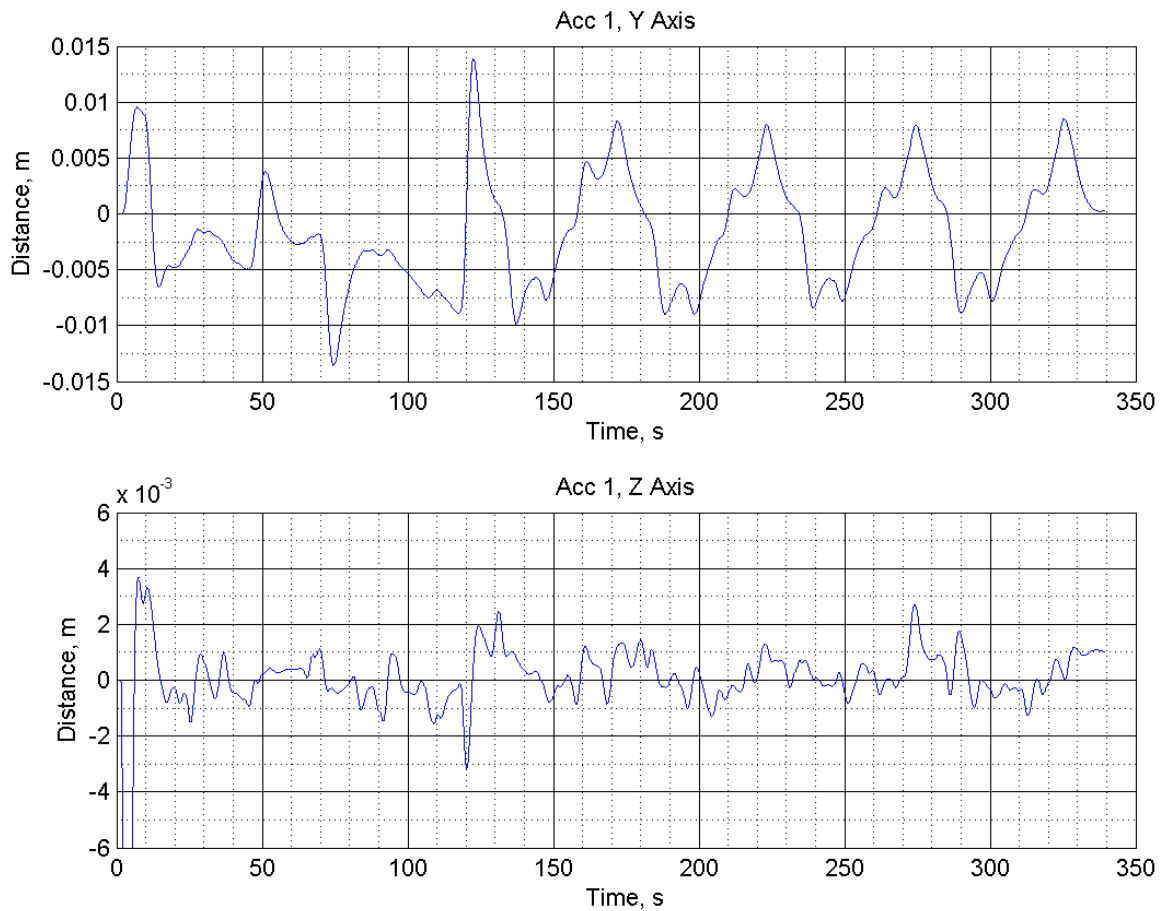The displacement values are presented in Figure 42:

Figure 42 Moving of the plant, projected on the axis

The abnormal surge along the Z axis on all graphs is associated with transients, since the beginning of the accelerometer values of acceleration on all axes are set to zero, whereas at the beginning of the experiment the harsh acceleration of the free fall is set. This surge does not interfere with the analysis of results as repeatable results are present during the second half of the experiment.

Movement data, which were obtained at different values of the angle, but the same other parameters, were analyzed. The results are presented in Figure 43. Based on the data, a small change of available angle (1-2 degrees) does not depend on the length of displacement. In all experiments, the displacements are in the range of from -15 to 15 mm. This result is slightly smaller than the real value of the pelvis, which moves in the horizontal axis for about 40-50 mm.
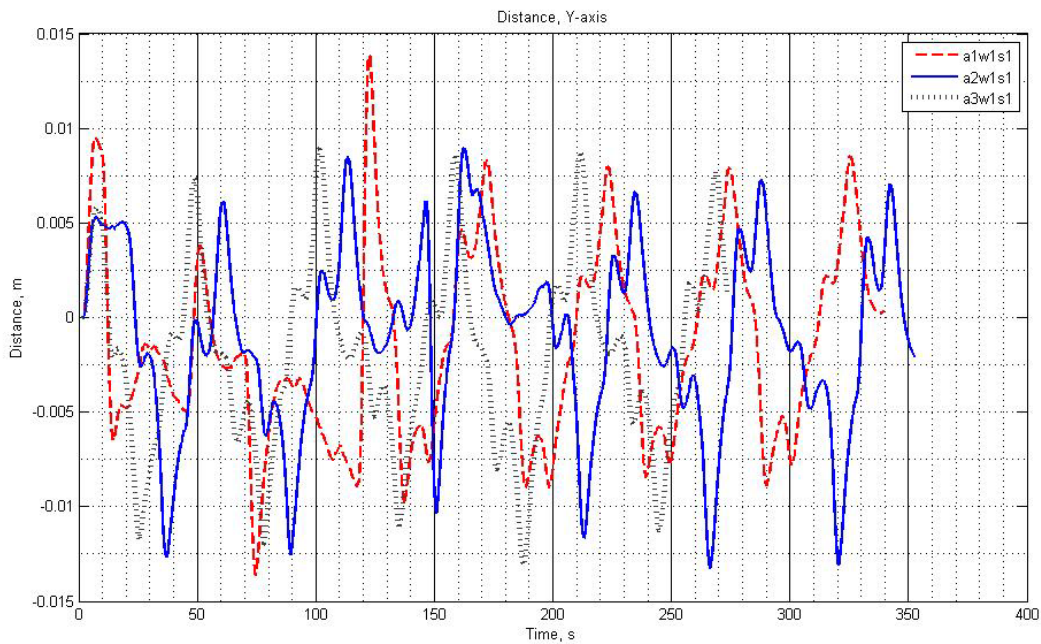
Figure 43 Comparison of displacement results along the Y-axis at different values of the angle, but the same speeds and weight

At the same time, the results of the Z-axis is negligible (Figure 44) and are 5-8 mm, much less than the 40-50 mm at the actual pelvis. In this case, the value of acceleration and the Z-axis can be significantly distorted by elastic springs which connect the rack with the plate, which complicates the collection of data on the Z-axis. However, we can draw conclusions that the plate needs more mobility along the Z-axis.
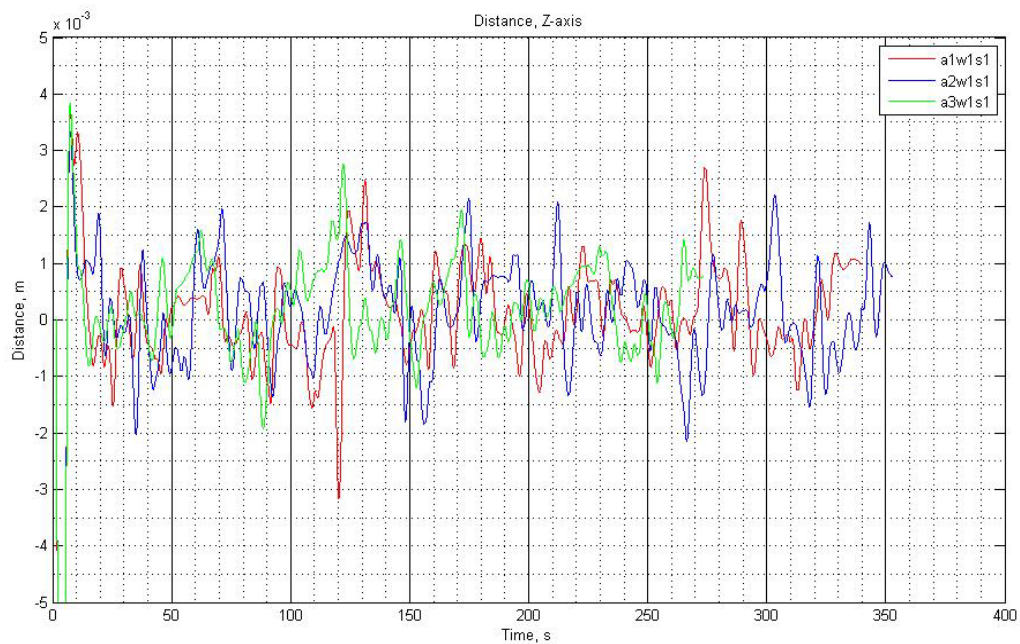
Figure 44 Comparison of the results of the Z-axis at different values of the angle, but the same velocities and weight

There following conclusions from these results were made:

1) It is necessary to increase the mobility of the plate in vertical axis to make movements more consistent with the real movements of the pelvis;
2) Increase of the available rotation angle increases the mobility in the horizontal axis; however, current values are close to the reference movements of pelvis;
3) Changing of the weight and velocity of step has weak influence on plate movements.

Discussion

Conclusion

Existence of requirement in inexpensive rehabilitation device resulted in need for carrying out researches and development. Diploma is part of such researches. During work was made a control system for plant. Was realized a work from a choice of input data to the analysis of movements of stand on compliance to reference data.

Experimental evaluation of motion capture systems has shown that the choice of the system depends primarily on the financial possibilities and output data. Both systems are perfectly suited for the analysis of human gait; however, it is necessary to consider the purposes for which the output data will be used. Optical systems are good as an input for movements systems, since there are no long-term operations and preparations for using these data. Inertial systems are good for the evaluation of complex movements. They provide more facilities and capabilities in the evaluation of running, because there is no limits for using a treadmill or real jogging track. Experiments can be made in any settings and conditions.

In this paper, VICON optical system based on Bonita 10 cameras have been chosen for receiving a reference data for humans. Primarily this was done through the convenience of the output data. The output is represented by the displacements projected on the axes and after quick and simple treatment can be used as an input and reference data for the experimental system simulating the movements of the hip of the person. In the case of the inertial system, additional processing is required, which adds additional errors from numerical integration or sensors drift.

Reference data of the movement of the foot is used as input for the experimental plant of pelvis movement simulation. Two methods of control were considered: first – based on NI Motion Assistant and second – based on LabVIEW. While NI Motion assistant provides more comfort during initial setup, LabVIEW has much greater flexibility. Since the work involves constant changes in the step characteristics, the interface has been developed in the LabVIEW to conduct and control experiments. The main disadvantage of Motion Assistant is a difficult and long change of each step, especially in presence of a sufficiently large gait cycle. In created interface based on LabVIEW, the tables solve this problem with settings of step length, speed and accelerations.

Programmed plant was analyzed for compliance with a given reference motion. First, there has been made the analysis of the movement of the racks in the corresponding to a reference data, and then the analysis of the movements of the plate corresponding to the movement of the real pelvis in a front plane. Analysis of racks movements was conducted with the help of machine

vision based on cameras and software from National Instrument as the most quick and simple to set up. The average result of the movements of racks, from different experiments with different sets of characteristics, deviates from the reference not more than 5%, which is within normal limits. This error is related to the peculiarities of experimental selection of speed and acceleration.

Accelerometers were used for receiving movements of the plate. Analysis of plate movements in the frontal plane showed that the plate oscillates similarly to the inverse of the pendulum and like a real pelvis. However, fluctuations in the vertical axis are much smaller than fluctuations of the real pelvis. To resolve this problem the angle of rolling of the plate must be increased, which allows to increase mobility in the horizontal and vertical plane.

Future Work

Further work is necessary to analyze the stability of plant, reduce oscillation and increase smoothness of movements. Replacing the stepper motors with DC motors or brushless DC motors will help to increase the smoothness of movements as well as to expand the range of possible step speeds. Software interface should be modified and supplemented with additional functions, for example, feedback that can be useful for control movements. In addition, another programming language can be used for software, like Java, C++ or C#. This step can increase a functionality of software and bring new many devices for controlling the stand, for example, smartphone of tablet PC.

Feedback feature is a cornerstone to use the study of gait and use in rehabilitation. Feedback will allow to track changes in the motion profile in real time and correct it if required. Thus, patients will be able to learn the correct gait. The researchers were able to study the influence of external forces and opportunities to return the profile to the reference view. Multitasking support by a programming language is necessary for feedback. This restriction disturbs further use of LabVIEW. However, when using powerful hardware, further work in LabVIEW is possible. It is necessary to analyze possibilities of the existing programming languages, their pluses and minuses, and to choose the most suitable.

The second step of introduction of feedback is the choice of sensors. There is a big range of available sensors, with different opportunities and a ratio accuracy/quality. Stand accuracy, speed of work of feedback, need for additional processing will depend on a choice of sensors. It is necessary to carry out comparison of the available sensors (machine sight, the linear sensor, the accelerometer) and to choose the most suitable.

Furthermore, the plant can be used to study the movements with different profiles of legs movements, which is associated with problems of the musculoskeletal system, or as a preventive simulator that imitates the actual movement of the pelvis and allows massaging the muscles of the back and pelvis.

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Appendix 1. LabVIEW program block diagram
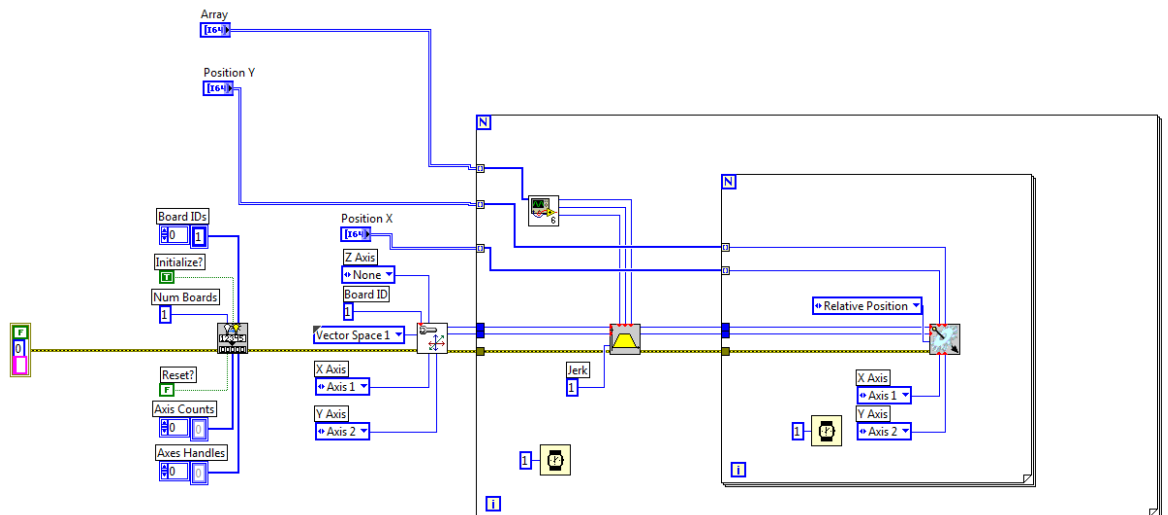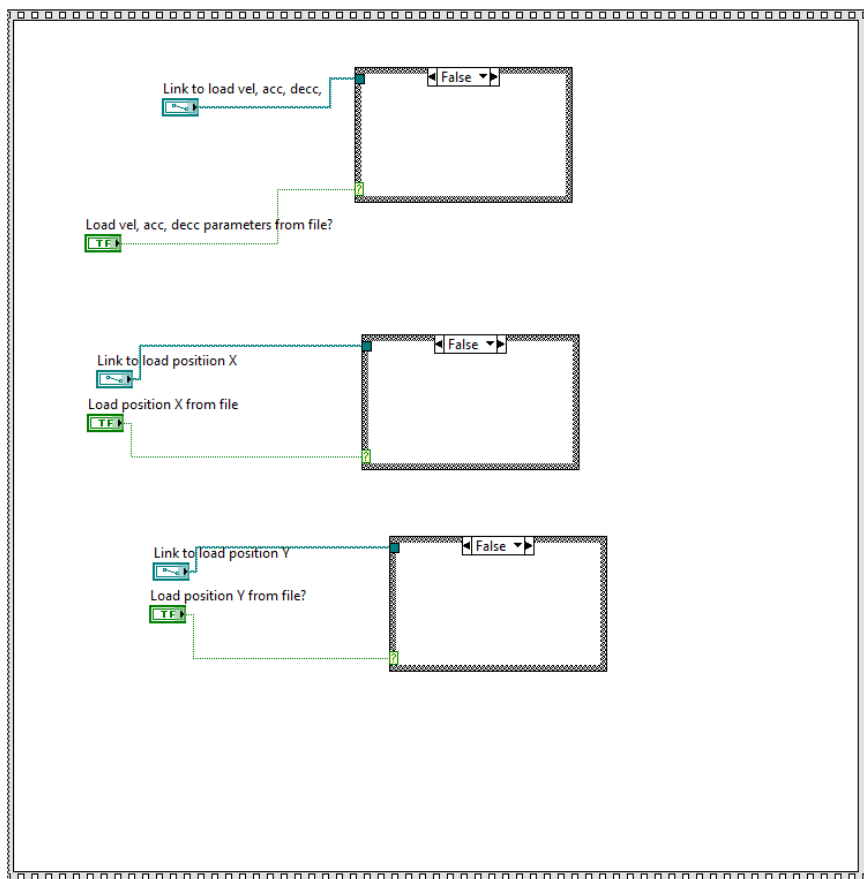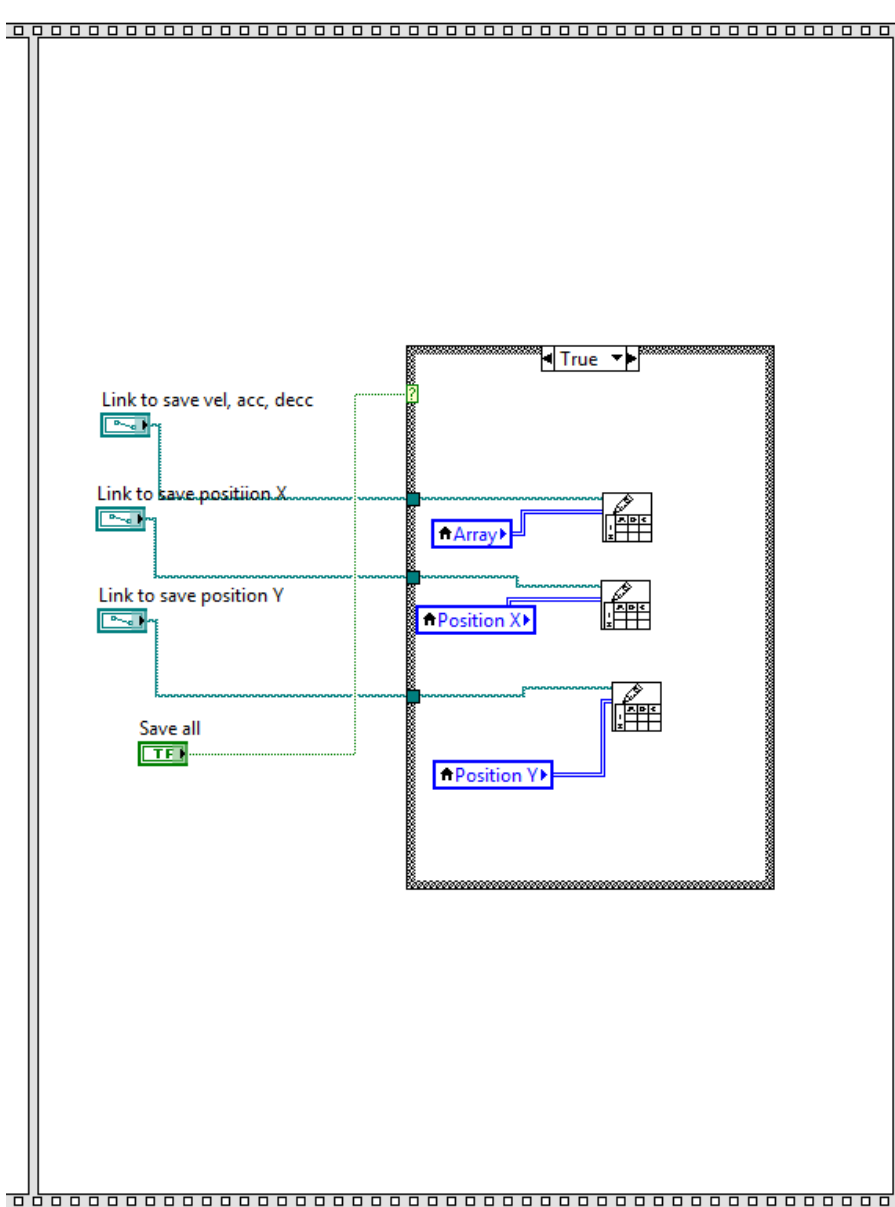
Appendix 2. MATLAB code for accelerometers data analysis.

AnalysisAllData.m – file to analyze the data in a loop:

```matlab
%FAST Analysis of ALL DATA!!! (NEED AT LEAST 10 MINUTES)
close all;

path = 'AccData'; %Path to analysing data ('.' - for current
folder)
for j = 1:3
    for k  = 1:3
        for l = 1:3
            name = ['a' num2str(j) 'w' num2str(k) 's'
num2str(l)]
            DataAnalysisV3(name,path);
        end
    end
end
```

ExpCompare.m – function to compare the received data:

```matlab
function ExpCompare(exp)

close all;
load HB.mat
load LB.mat
[m n] = size(exp);
color = ['r','b','g','y','c','k']; %Coloring graphics

%Create plot for speed
figure;title('Acceleration, Y-axis');
hold on;
for i=1:m
    load([exp(i,:) '\' exp(i,:) ' - AverageAcceleration']);
%Loading data
    load(['AccData\' exp(i,:)],'time'); %Loading Time Data
    plot(time,ACCYM,color(i));legend(exp);
end
xlabel('Time, s');ylabel('Acceleration, m/s^2');

figure;title('Acceleration, Z-axis');
hold on;
for i=1:m
    load([exp(i,:) '\' exp(i,:) ' - AverageAcceleration']);
    load(['AccData\' exp(i,:)],'time');
    plot(time,ACCZM,color(i));legend(exp);
end
xlabel('Time, s');ylabel('Acceleration, m/s^2');
```

```matlab
%Create plot for speed
figure;title('Velocity, Y-axis');
hold on;
for i=1:m
    load([exp(i,:) '\' exp(i,:) ' - Velocity']); %Loading data
    load(['AccData\' exp(i,:)],'time'); %Loading Time Data
    plot(time,filter(LB,VY),color(i));legend(exp);
end
xlabel('Time, s');ylabel('Velocity, m/s');

figure;title('Velocity, Z-axis');
hold on;
for i=1:m
    load([exp(i,:) '\' exp(i,:) ' - Velocity']);
    load(['AccData\' exp(i,:)],'time');
    plot(time,filter(LB,VZ),color(i));legend(exp);
end
xlabel('Time, s');ylabel('Velocity, m/s');


%Create plot for distance
figure;title('Distance, Y-axis');
hold on;
for i=1:m
    load([exp(i,:) '\' exp(i,:) ' - Movement']);
    load(['AccData\' exp(i,:)],'time');
    plot(time,MY,color(i));legend(exp);
end
xlabel('Time, s');ylabel('Distance, m');

figure;title('Distance, Z-axis');
hold on;
for i=1:m
    load([exp(i,:) '\' exp(i,:) ' - Movement']);
    load(['AccData\' exp(i,:)],'time');
    plot(time,MZ,color(i));legend(exp);
end
xlabel('Time, s');ylabel('Distance, m');

end
```

DataAnalysis.m – function for accelerometers data processing:

```matlab
function DataAnalysisV3(name, path)
close all;
%CONSTANT
G = 9.81; %gravity constant
angleCoef = 180/3.14; %Degree -> Radian Coef
expName = name; %Receive an argument from function
mkdir(expName); %Create a folder for results
```

```matlab
scrsz = get(0,'ScreenSize');
position = [1 50 scrsz(3) scrsz(4)-50];
%%
%LOAD EXPERIMENT FILE:
load([path '\' expName])  %NAME OF EXPERIMENT
load HB.mat  %Load a Highpass filter
load LB.mat  %Load a Lowpass filter

CY1=sum(abs(AY1))/length(AY1);
CZ1=sum(abs(AZ1))/length(AZ1)-1;
CY2=sum(abs(AY2))/length(AY2);
CZ2=sum(abs(AZ2))/length(AZ2)-1;
ACCY1 = (AY1-CY1)*G;
ACCZ1 = (AZ1-CZ1)*G;
ACCY2 = (AY2-CY2)*G;
ACCZ2 = (AZ2-CZ2)*G;

ACCZ1F = filter(LB,ACCZ1);
ACCZ2F = filter(LB,ACCZ2);
ACCY1F = filter(LB,ACCY1);
ACCY2F = filter(LB,ACCY2);

figure('OuterPosition',position);
subplot(2,2,1);plot(time,ACCY1,'r');
hold on;
plot(time,ACCY1F,'k','lineWidth',2);
xlabel('Time, s');ylabel('Acceleration with Gravity Force,
m/s^2');legend('Original Signal','Filtered
Data');title('Accelerometer 1, Y Axis');grid minor;
subplot(2,2,2);plot(time,ACCZ1,'r');
hold on;
plot(time,ACCZ1F,'k','lineWidth',2);
xlabel('Time, s');ylabel('Acceleration with Gravity Force,
m/s^2');legend('Original Signal','Filtered
Data');title('Accelerometer 1, Z Axis');grid minor;
subplot(2,2,3);plot(time,ACCY2,'r');
hold on;
plot(time,ACCY2F,'k','lineWidth',2);
xlabel('Time, s');ylabel('Acceleration with Gravity Force,
m/s^2');legend('Original Signal','Filtered
Data');title('Accelerometer 2, Y Axis');grid minor;
subplot(2,2,4);plot(time,ACCZ2,'r');
hold on;
plot(time,ACCZ2F,'k','lineWidth',2);
xlabel('Time, s');ylabel('Acceleration with Gravity Force,
m/s^2');legend('Original Signal','Filtered
Data');title('Accelerometer 2, Z Axis');grid minor;
print([expName '\' expName ' - AccelerationWithG'],'-dpng');
save([expName '\' expName ' -
AccelerationWithG.mat'],'ACCY1','ACCZ1','ACCY2','ACCZ2')

%%
```

```matlab
clear SY SZ
SY = 0;
SZ = 0;
ACCYM = (ACCY1F + ACCY2F)/2;
ACCZM = (ACCZ1F + ACCZ2F)/2;
%
figure('OuterPosition',position); subplot(2,1,1);
plot(time,ACCYM,'r','lineWidth',2');
hold on;
plot(time,ACCY1F,'--b','lineWidth',1');
plot(time,ACCY2F,'k','lineWidth',1');
ylabel('Acceleration, m/s^2');xlabel('Time,s');legend('Average
Acceleration','1 Accelerometer','2 accelerometer');
for i=1:length(time)-1
    SY = SY +
(abs(ACCY1F(i))+abs(ACCY2F(i))+abs(ACCY1F(i+1))+abs(ACCY2F(i+1))
)/2*(time(i+1)-time(i));
    patch([time(i) time(i) time(i+1) time(i+1)],[ACCY1F(i)
ACCY2F(i) ACCY2F(i+1) ACCY1F(i+1)],'y','edgeColor','none');
end

subplot(2,1,2);
plot(time,ACCZM,'r','lineWidth',2');
hold on;
plot(time,ACCZ1F,'--b','lineWidth',1');
plot(time,ACCZ2F,'k','lineWidth',1');
ylabel('Acceleration, m/s^2');xlabel('Time,s');legend('Average
Acceleration','1 Accelerometer','2 accelerometer');
for i=1:length(time)-1
    SZ = SZ +
(abs(ACCZ1F(i))+abs(ACCZ2F(i))+abs(ACCZ1F(i+1))+abs(ACCZ2F(i+1))
)/2*(time(i+1)-time(i));
    patch([time(i) time(i) time(i+1) time(i+1)],[ACCZ1F(i)
ACCZ2F(i) ACCZ2F(i+1) ACCZ1F(i+1)],'y','edgeColor','none');
end


print([expName '\' expName ' - AverageAcceleration'],'-dpng');
save([expName '\' expName ' -
AverageAcceleration.mat'],'ACCYM','ACCZM','SY','SZ')

%%
clear GYROX1 GYROX2
%Angle velocity filtering
GYROX1 = filter(LB,GX1);
GYROX2 = filter(LB,GX2);
GYROX1 = filter(HB,GYROX1);
GYROX2 = filter(HB,GYROX2);

%Calculate angle
clear ANGX1 ANGX2
ANGX1(1) = 0; %Initial position for angle
```

```matlab
ANGX2(1) = 0;
ANGX1O(1) =0;
ANGX2O(1) = 0;

for i=1:length(time)-1
    ANGX1(i+1)=ANGX1(i)+GYROX1(i)*(time(i+1)-time(i));
    ANGX2(i+1)=ANGX2(i)+GYROX2(i)*(time(i+1)-time(i));
    ANGX1O(i+1)=ANGX1O(i)+GX1(i)*(time(i+1)-time(i));
    ANGX2O(i+1)=ANGX1O(i)+GX2(i)*(time(i+1)-time(i));
end
ANGX = (ANGX1+ANGX2)/2;
%Angle and angle velocity graphs
figure('OuterPosition',position);
subplot(2,2,1);plot(time,GX1,'r');
hold on;
plot(time,filter(LB,GYROX1),'k','lineWidth',2);
xlabel('Time, s');ylabel('Angle Velocity,
grad/s');legend('Original Signal','Filtered
Data');title('Gyroscope 1, Angle Velocity');grid minor;
subplot(2,2,2);
plot(time,ANGX1O,'k');
hold on;plot(time,ANGX1,'b','lineWidth',2);
legend('Original Data','Complementary Filter');xlabel('Time,
s');ylabel('Angle, grad');title('Gyroscope 1, Rotation Angle
(X)');grid minor;
subplot(2,2,3);plot(time,GX2,'r');
hold on;
plot(time,filter(LB,GYROX2),'k','lineWidth',2);
xlabel('Time, s');ylabel('Angle Velocity,
grad/s');legend('Original Signal','Filtered
Data');title('Gyroscope 2, Angle Velocity');grid minor;
subplot(2,2,4);
plot(time,ANGX2O,'k');
hold on;plot(time,ANGX2,'b','lineWidth',2);
legend('Original Data','Complementary Filter');xlabel('Time,
s');ylabel('Angle, grad');title('Gyroscope 2, Rotation Angle
(X)');grid minor;

print([expName '\' expName ' - Gyroscope'],'-dpng');
save([expName '\' expName ' -
Gyroscope.mat'],'GYROX1','ANGX1','GYROX2','ANGX2');
%%
clear GY1 GY2

%Let's calculate g data on Y axis
for i=1:length(time)
    GRAVY(i) = cos((90-ANGX(i))/angleCoef)*G;
    GRAVZ(i) = cos((ANGX(i))/angleCoef)*G;
end
figure('OuterPosition',position);
subplot(2,1,1);plot(time,GRAVY);title('Gravity Force on Y
Axis');xlabel('Time, s');ylabel('Acceleration, m/s^2');
```

```matlab
subplot(2,1,2);plot(time,GRAVZ);title('Gravity Force on Z
Axis');xlabel('Time, s');ylabel('Acceleration, m/s^2');

print([expName '\' expName ' - AxisGravity'],'-dpng');
save([expName '\' expName ' - AxisGravity'],'GRAVY','GRAVZ');
%%
clear REALACCY1 REALACCY2 REALACCZ1 REALACCZ2
%Calculate real acceleration on axis
REALACCY = ACCYM - GRAVY;
REALACCZ = ACCZM - GRAVZ;

figure('OuterPosition',position);
subplot(2,1,1);plot(time,REALACCY,'r');
hold on;
plot(time,filter(LB,REALACCY),'k','lineWidth',2);
xlabel('Time, s');ylabel('Acceleration without Gravity Force,
m/s^2');legend('Original Signal','Filtered Data');title('Y
Axis');grid minor;
subplot(2,1,2);plot(time,REALACCZ,'r');
hold on;
plot(time,filter(LB,REALACCZ),'k','lineWidth',2);ylim([-3 3]);
xlabel('Time, s');ylabel('Acceleration without Gravity Force,
m/s^2');legend('Original Signal','Filtered Data');title('Z
Axis');grid minor;

print([expName '\' expName ' - Acceleration'],'-dpng');
save([expName '\' expName ' -
Acceleration.mat'],'REALACCY','REALACCZ')

clear VY VZ
for i=1:length(time)-1
    VY(i+1)=REALACCY(i)*(time(i+1)-time(i)); %Velocity, Axis Y
    VZ(i+1)=REALACCZ(i)*(time(i+1)-time(i));

end

figure('OuterPosition',position);
subplot(2,1,1);plot(time,VY,'r');
hold on;
plot(time,filter(LB,VY),'k','lineWidth',2);
xlabel('Time, s');ylabel('Velocity, m/s');legend('Original
Signal','Filtered Data');title('Accelerometer 1, Y Axis');grid
minor;
subplot(2,1,2);plot(time,VZ,'r');
hold on;
plot(time,filter(LB,VZ),'k','lineWidth',2);ylim([-0.2 0.2]);
xlabel('Time, s');ylabel('Velocity, m/s');legend('Original
Signal','Filtered Data');title('Accelerometer 1, Z Axis');grid
minor;

print([expName '\' expName ' - Velocity'],'-dpng');
save([expName '\' expName ' - Velocity.mat'],'VY','VZ');
```

```matlab
%%
%Movement Data calculation
clear MY1 MZ1 MY2 MZ2
MY(1) = 0;
MZ(1) = 0;
for i=1:length(time)-1
    MY(i+1)=VY(i+1)*(time(i+1)-time(i))+REALACCY(i)*(time(i+1)-
time(i))^2/2;
    MZ(i+1)=VZ(i+1)*(time(i+1)-time(i))+REALACCZ(i)*(time(i+1)-
time(i))^2/2;

end
%LowPass filter movement data
MY = filter(LB,MY);
MZ = filter(LB,MZ);


figure('name','Movement in Axis','OuterPosition',position);
hold on;
subplot(2,1,1);plot(time,MY);title('Acc 1, Y
Axis');xlabel('Time, s');ylabel('Distance, m');grid minor;
subplot(2,1,2);plot(time,MZ);title('Acc 1, Z Axis');ylim([-0.006
0.006]);xlabel('Time, s');ylabel('Distance, m');grid minor;

print([expName '\' expName ' - Movement in Axis'],'-dpng');

figure('name','Movement in Y-Z plane','OuterPosition',position);
plot(MY,MZ,'r');xlabel('Y-axis, m');ylabel('Z-axis, m');

print([expName '\' expName ' - Movement'],'-dpng');
save([expName '\' expName ' - Movement.mat'],'MY','MZ');
end
```