Design of biped robot walking with double-support phase

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Abstract

The main idea of this dissertation is development of walking strategy of biped robot with prolonged double support phase in step cycle. Technical purpose of this work is an upgrade of leg's construction of biped robot Rotto in order to lighten it using an electrohydraulic actuator with flexible gear. Scientific objective is design of stable biped walking algorithm with step cycle stabilization during double support phase. Force controlled electrohydraulic actuator is developed. Stabilization system for planar robot using position control of robot's mass center is developed and implemented. Stabilization system for biped robot in the double support state is built using kinematical constraints for realization of compliant features of robot. Stable dynamic walking strategy with stabilization in the double support state is developed and implemented in biped robot Rotto. Performance of developed actuator, control and stabilization systems are simulated and proved experimentally.

Kurzfassung

Die Hauptidee dieser Arbeit ist die Entwicklung von Laufalgorithmen des zweibeinigen Roboters mit Doppelstützphase im Schrittzyklus. Technisches Ziel ist die Modernisierung der Konstruktion von Roboterbeinen mit Einsatz des elektrohydraulischen Antriebs mit flexiblem Getriebe. Wissenschaftliches Ziel der Arbeit ist ein Entwurf des stabilen Robotergehens mit der Stabilisierung des Schrittzyklus in der Doppelstützphase. In dieser Arbeit ist die Konstruktion des elektrohydraulischen Antriebs mit flexiblem Getriebe dargestellt. Das Stabilisierungssystem des vereinfachten Roboters mit Positionsregelung des Schwerpunktes wurde entwickelt und implementiert. Das Stabilisierungssystem des zweibeinigen Roboters in dem Doppelstützzustand wurde mit kinematischen Reflexen für die Gewährleistung der Elastizität des Roboters realisiert. Im Rahmen dieser Arbeit wurde stabile dynamische Gehensstrategie entwickelt und im Roboter ROTTO implementiert. Die Eigenschaften des entwickelten Antrieb-, Steuer- und Stabilisierungssystem wurden simuliert und experimentell geprüft.

Schriftliche Erklärung

Ich erkläre hiermit, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe; die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sind als solche kenntlich gemacht.

Insbesondere habe ich nicht die Hilfe einer kommerziellen Promotionsberatung in Anspruch genommen. Dritte haben von mir weder unmittelbar noch mittelbar geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen.

Die Arbeit wurde bisher weder im Inland noch im Ausland in gleicher oder ähnlicher Form als Dissertation eingereicht und ist als Ganzes auch noch nicht veröffentlicht.

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Contents

Chapter 1. Introduction and Statement of the Problem

1.1 Introduction

Implementation of dynamic walking by biped robots remains one of the most actual and urgent problems nowadays. This can be explained in many ways. On the one hand, this form of movement on surface occurs most frequently in nature. It is a feature of people, animals, birds and insects. On the other hand, walking is the most energy-efficient form of movement [14].

People and animals demonstrate incredible capabilities of universal adaptive walk in the real life. In order to create robots with similar abilities, their mechanisms should have much more degrees of freedom than they have currently, and actuators in robots should have features similar to muscles of people and animals.

Currently science has no clear and final solution to the problem of biped human-like walking. A lot of scientists and researchers worldwide work on this problem in order to create more efficient, fast and stable walking robots. The works are held towards creation of fundamentally new actuator systems, mechanical constructions, control algorithms and stabilization systems.

Scientific interest of this problem is caused not only by the objective to create an exact copy of human walking. One of the main goals remains application of obtained knowledge, skills and technologies in medicine. Models of movements, control algorithms, actuator systems, joint structures and many more other things can be widely used in creation of active prostheses which are quite frequently used in medicine.

1.2 State of Research in Robotics

At that point a great variety of prototypes of bipedal robots with the ability of dynamic walking is built. It is possible to distinguish between them because they have different constructions, actuator systems, control algorithms and etc. All robots can be classified on the basis of double support phase presence in walking and its duration.

Walking of robots with prolonged double support phase may occur much more often. The reason for this is that this type of walking is much more easily implemented. In the double support a mechanism of a robot as a control object is more controllable, since it has greater support surface than in the single support state. The presence of this kind of state in a step cycle allows stabilizing of a robot and its walking. Such types of gates tend to be similar to sneaking gate of a human. The speed of this type of gait is relatively small. Energy efficiency is also not very high, since energy is consumed on acceleration and deceleration of the robot in every step.

Walking with instantaneous or very short double support phase occurs less frequently but at the same time it is more fast and power efficient. This type of robot walking is harder to implement. The reason for this is the fact that in the single support phase a mechanism of a robot as a control object is almost incontrollable, since it has smaller support surface.

1.2.1 Walking with prolonged double support phase

The best example of a robot with prolonged double support phase is Asimo (Fig.1) [18], [41]. It was designed and developed by Honda in Fundamental Technology Research Center in Wako, Japan. Latest version of the robot, which was created in 2014, has 130 cm height and weight 50 kg, and it has an ability to move at speeds of up to 7 km/h. Zero Moment Point stability criterion is used for the stabilization of the robot.

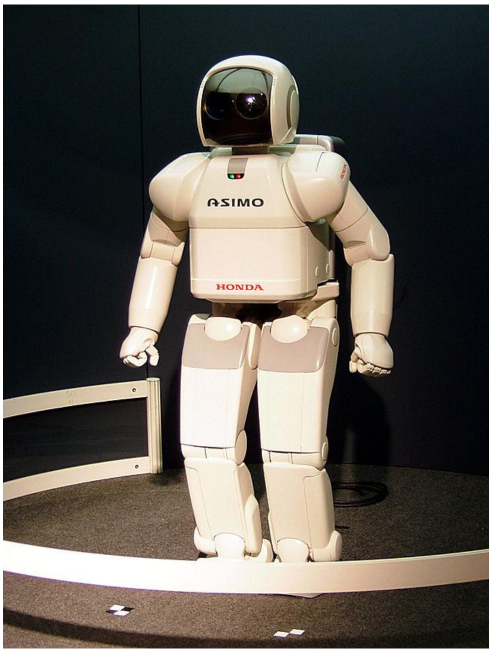

Fig. 1.1 – Honda ASIMO

There is also double support phase in the gait of the robot, in which stabilization of walking step cycle happens with the help of torques in robot’s feet. Moreover, ASIMO can run. During running process there is a phase, in which ASIMO doesn’t have any contact with surface.

Walking of the HRP robot, which was built in Japan [7], [27] can be another example of walking with prolonged double support phase.

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Fig. 1.2 – Robot HRP

Prolonged double support phase is explicitly expressed in the gait of the HRP robot, at the time of this phase step cycle stabilization happens with the help of torques in robot’s feet.

Robots like Johnnie and Lola from TU München [17], [42] also walk with prolonged double support phase (Fig. 1.3).

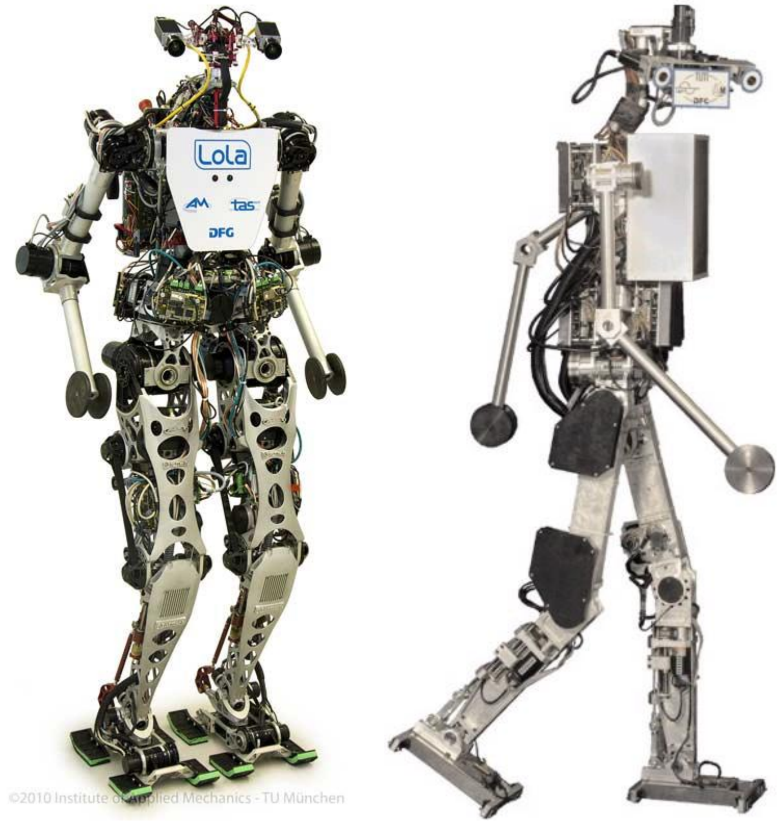


Fig. 1.3 – Robots Johnnie and Lola from TU München

1.2.2 Walking with instantaneous double support phase

One of the first examples of walking with instantaneous double support phase is walking of robot Spring Flamingo [23], which was build in the MIT in 1994 (Fig. 1.4). A special feature of this type of walking is that it is realized in sagittal plane. In order to maintain the robot in balance in frontal plane it is held by a rod and is moving in a circle.

Robot’s feet have very small mass and moment of inertia compared with robot’s body. Knees and feet of the robot are actuated with actuators, which are force controlled. Movements of legs with high dynamics are realized due to lightweight legs, this dynamics considerably exceeds dynamics of its own movement of a mechanism relative to a support foot.

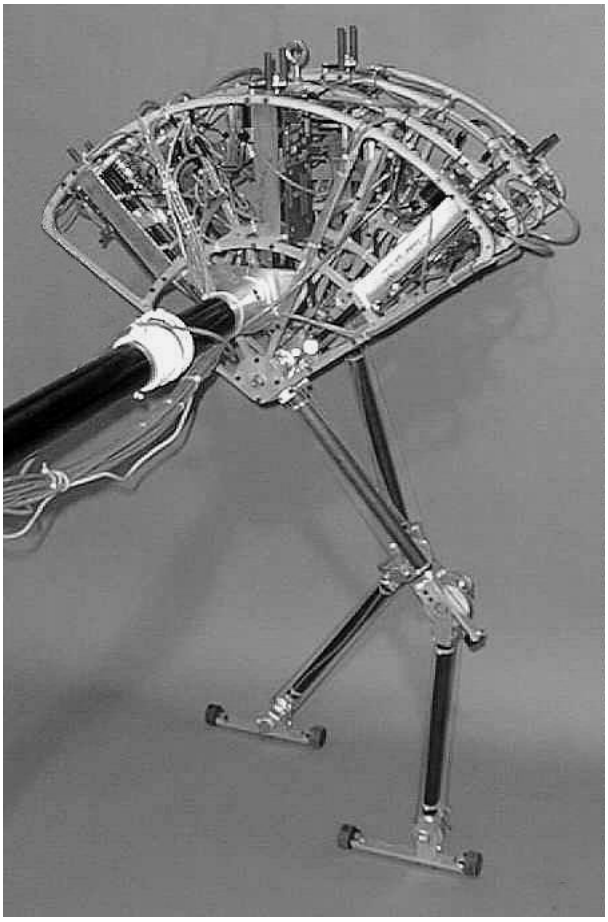


Fig. 1.4 – robot Spring Flamingo

Walking of Spring Turkey [23] from MIT (Fig. 1.5) is also an interesting example of planar walking. This robot also moves in a circle with a help of a rod. But for all that it hasn’t got any feet. Walking also happens with instantaneous double support phase.

Robots Spring Flamingo and Spring Turkey walk in the plane. The task of step cycle stabilization in walking is to move a leg into the position which is consistent with current speed of the robot in due time. In the frontal plane these robots are stabilized with a help of rod.

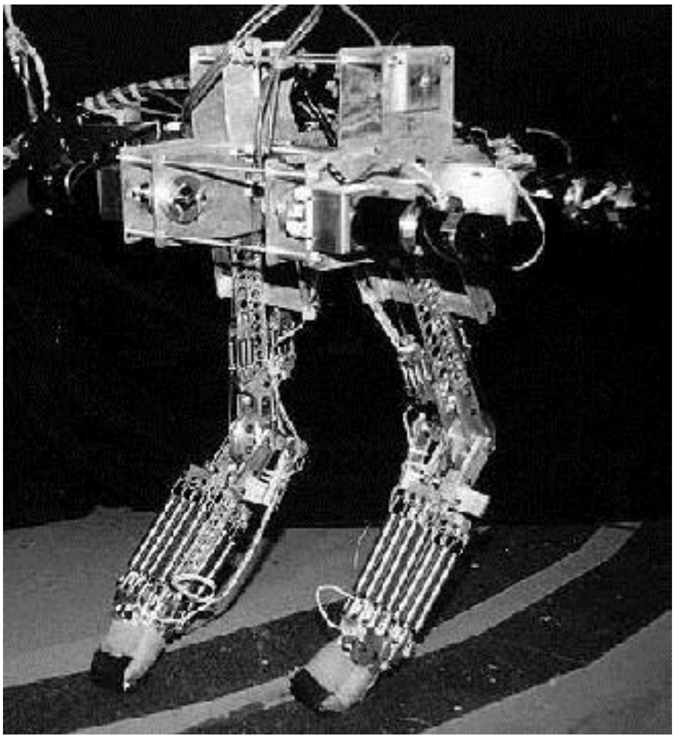


Fig. 1.5 – robot Spring Turkey

Realization of walking of a biped robot in space without any auxiliary leg with instantaneous double support phase is a very difficult task. This kind of walking is most similar to walking style of a human and two-legged animal.

Currently one of the best examples of this type of walking is walking of a biped robot Petman that was built by Boston Dynamics [8].

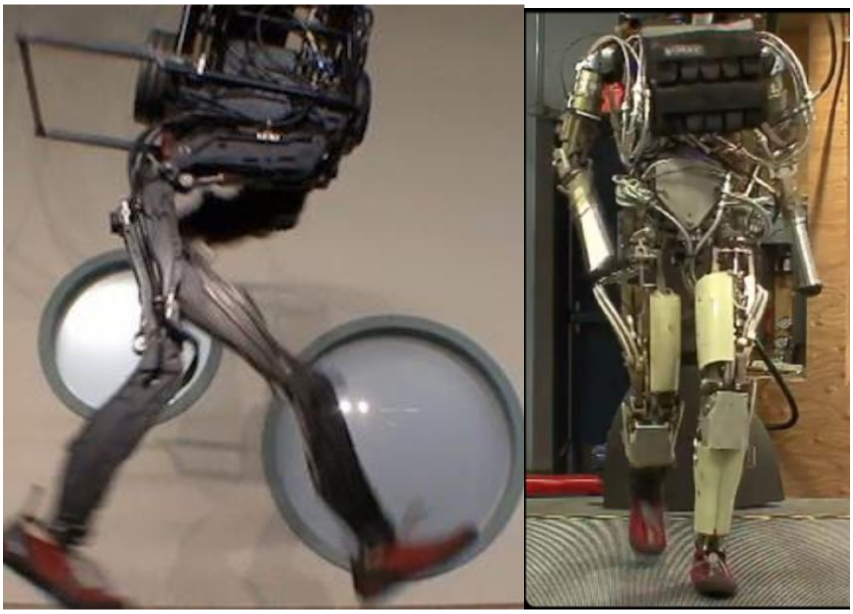


Fig. 1.6 – Biped robot Petman

PETMAN is a robot designed for testing military clothing in conditions that are similar to real life, for example, with the use of real chemical warfare agents.

PETMAN was made public in 2009, but actually only its legs were shown which were mowing somewhere towards. However already at that time robot PETMAN demonstrated remarkable stability: when developers pushed him, he could stay on both his feet and continued to walk.

PETMAN can move fairly fast on smooth or rough country, including stairs, pits and moderate barriers. PETMAN is also able to move at speed of 5.2 km per hour, it’s speed of brisk walking of a human. This robot walks like a human being, it moves its feet in sneakers from heels to toes while walking.

In order to make this robot more stable, there is used the system, which uses gyroscopes and thus helps to orientate in space and to stabilize the position of robot. Due to this system robot can stay on its feet and is able to return to its normal position after kicks or collisions.

1.2.3 Darpa Robotics Challenge

Darpa Robotics Challenge [12] is a prize competition, where one can meet most modern human-like robots. During competitions robots go through a lot of challenges like: walking on surface with barriers, climbing the stairs, work with a hand tool, driving of the vehicle. Robots also do various tasks in situations which can be dangerous for people, for example, rescue operations.

All the robots in the competition are autonomous and have hands with fingers. The main goal for participants is to create an algorithm for problem solving in severe conditions that can threaten lives, and interaction between robots and people. In this study particular attention is paid to video materials that depict walking of robots that participated in the competition. Further one can see the most significant examples.

MIT’s HELIOS (Atlas) was made by the company Boston Dynamics in 2013 [40]. Robot is 195 cm tall and weighs 182 kg. It also has hands with fingers, which are necessary for implementation of various applied operations. This robot is totally autonomous.

Fig. 1.7 – MIT’s HELIOS

There is also double support phase in the gait of the robot, in which gait cycle stabilization happens with the help of moments in robot’s feet. Duration of stride in the single support is approximately 0.7s.

Robot **THORMANG** (Fig. 1.8) was made by Robotis in 2013 [38]. It is 16 cm tall and it weighs 60 kg. It also has hands with fingers, which are assigned to do various operations like: work with a hand tool, opening of the doors, valve rotation, driving of a car and etc.

THORMANG 2 is the upgrade version of THOR-OP (or THORMANG 1) [38]. It is much stronger, faster and more stable than the previous version, although its height and weight is similar to previous one. Modularity is its main feature. ROBOTIS has been providing modular servo actuators Dynamixel and Dynamixel-Pro for a decade. THORMANG 2 is simply assembled with 32 Dynamixel-Pro modules; its hardware and software are very compact and efficient. It allows us to develop a robot in a very short period time and to carry out fixes easily. For these reasons, modularity, we believe, will work well in real-life situations and DRC finals as well. After DRC finals, ROBOTIS is going to merchandise THORMANG 2 to share the DRC experience with other roboticists[38].

Figure 1.8 – Robotis THORMANG

Double support phase is clearly expressed in the gait of the robot, in which stabilization of the robot and gate cycle happens with the help of moments in robot’s feet. Duration of stride in the single support is approximately 0.5 sec. Stride length is circa 15cm.

Robot **HUBO** (Fig. 1.9) was built in 2014 in HUBO-Lab (Humanoid Robot Research Center) [34]. Height of this robot is 180cm and weight is 80 kg.

DRC-Hubo is the latest version of HUBO. HUBO stands for "HUmanoid roBOt". HUBO has been developed since 2002 [34]. DRC-HUBO is the most powerful version among the previous HUBO series. The robot is redesigned to be more powerful and more capable. We rewrote the walking algorithm for the new design. Every joint motor is more powerful. All motors that handle a higher workload now are equipped with air cooling. The hands are stronger to handle various tasks in a disaster situation. It can also transform from a standing position, used for biped walking, to a kneeling pose that is meant for wheeled and fast motion. This gives the robot is uniqueness [34].

Fig. 1.9 – DRC-HUBO

There is double support phase, in which stabilization of walking stride cycle happens with the help of moments in robot’s feet. Duration of stride in the single support is approximately 0.5 sec.

The prototype **WALK-MAN** platform is an adult size humanoid with a height of 1.85m an arm span of 2m and a weight of 118Kg [35].

The robot is a fully power autonomous, electrically powered by a 2KWh battery unit; its body has 33 degrees of freedom (DOF) actuated by high power electric motors and all equipped with intrinsic elasticity that gives to the robot superior physical interaction capabilities[35].

The robot perception system includes torque sensing, end effector F/T sensors, and a head module equipped with a stereo vision system and a rotating 3D laser scanner, the posture of which is controlled by a 2DOF neck chain. Extra RGB-D and colour cameras mounted at fixed orientations provide additional coverage of the locomotion and manipulation space [35].

IMU sensors at the head and the pelvis area provide the necessary inertial/orientation sensing of the body and the head frames.

Protective soft covers mounted along the body will permit the robot to withstand impacts including those occurred during falling incidents [35].

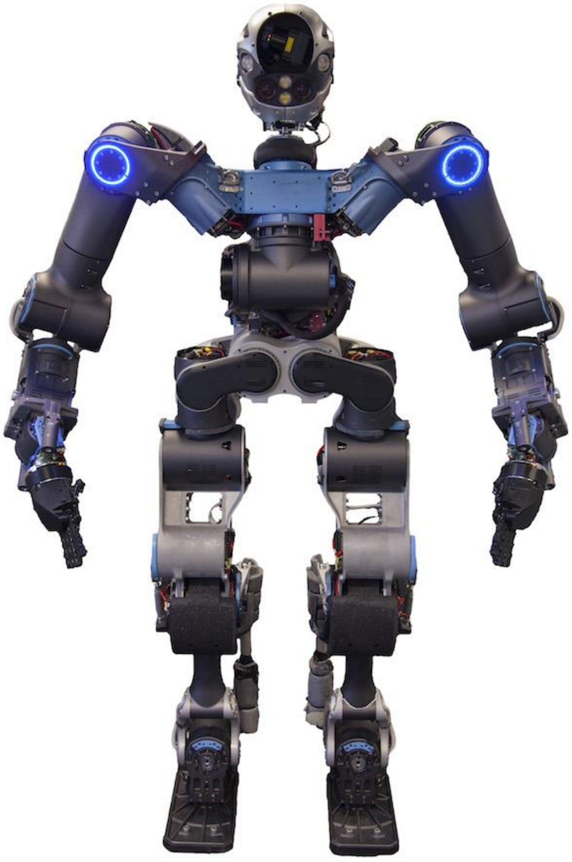


Fig. 1.10 – Walk-Man

Double support phase is well defined in the gait of the robot, in which stabilization of the robot and walking stride cycle happens with the help of moments in robot’s feet. Duration of stride in the single support is approximately 0.5 sec. Stride length is circa 15cm.

Given overview allows us to come to a conclusion that the main tendency in development of biped robots is performing operations that are typical for people and the use of devices designed for people.

Walking of these robots is far from human walking, although it has got rather high characteristics (speed and stride length). Algorithms of walking are mainly based on the use of double support phase for stabilization of the stride cycle. The use of such algorithms allows easier to realize stable dynamic walking of biped robots. In comparison with walking of a human, it reminds about separated steps or sneaking gate.

1.3 Motivation and Goal

Object of the study is robot Rotto [47]. Creation of the robot began in 2009 in «RobotsLab». Its construction and algorithms of walking, which are based on control of periodic oscillation process, were described in previous studies [1], [2], [4].

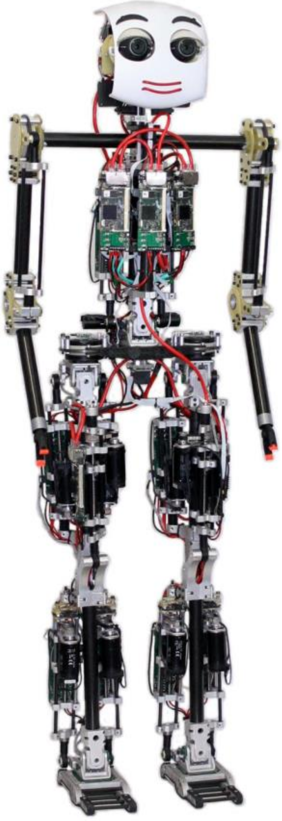


Fig. 1.11 – Biped robot ROTTO

The previous attained results have disadvantages because of big leg mass, it brings disturbances into the work of control algorithm. Suggested control algorithms also don't let compensate disturbances that appear during walking, since double support phase happens in them instantly, but in single support phase it is hard to stabilize the robot.

The technical goal of the paper is to improve robot’s leg construction by equipping it with an electrohydraulic actuator with a flexible drive [16] in order to ease and lessen moment of inertia in legs and to redistribute masses in the mechanical system of the robot.

Scientific purpose of this thesis is to create an algorithm of dynamic walking with double support phase, in which stride cycle is stabilized and disturbances that occur upon contact with bearing surface are compensated.

1.4 Statement of the Problem

From the given technical and scientific purposes of this study following tasks were assigned and following problems were solved:

- Design of an electrohydraulic actuator with a flexible gear, that is force controlled.
- Upgrade of the existing leg construction by equipping it with an electrohydraulic actuator in order to lighten them and to redistribute masses of the robot.
- Design of stabilization system of biped robot for double support state, which is based on control of position of robot’s mass center.
- Creation of an algorithm of dynamic walking with prolonged double support phase, in which occur stabilization of step cycle and compensation of external disturbances affecting the robot.
- Implementation of designed stabilization and walking algorithms on the real robot ROTTO.

1.5 Structure of the thesis

Content of the paper is structured as follows: In Chapter 1 introduction into the topic can be found. Practical importance and scientific relevance are illustrated. State of research in robotics to date is described. Purpose and tasks, which have to be solved, are also explained.

Construction of an electrohydraulic actuator with flexible linear drive is represented in Chapter 2. There is also described a modernized construction of a leg with this actuator.

Practical studies were conducted. They show improvements in the work of a modernized leg.

Chapter 3 is devoted to the construction of an algorithm which stabilizes a robot with the aid of foot that is based on control of a position of mass center. Prototype of a planar robot is described, which was built for synthesis of the stabilization system. Results of experimental studies of the proposed stabilization system are clarified in the conclusion.

Stabilization system of a biped robot in the double support is proposed in Chapter 4. Methodology is introduced that allows realizing compliance of mechanical structure of a robot in relation to bearing surface by means of kinematic relations in the control system. Results of experimental studies of the proposed stabilization system are described in the conclusion.

Chapter 5 describes in detail proposed walking algorithm of a robot, which is based on the use of prolonged double support phase in stride cycle for the stabilization of process. The findings of experimental studies of the proposed walking algorithm are clarified. Conclusions are made in the end of the paper.

Chapter 2. Electrohydraulic actuator. Leg construction upgrade

According to realization of dynamic walking by biped robots, many demands are to be made of its mechanism construction. Within the scope of this work the following requirements have to be met:

- Mechanism of robot should have general definite moment of inertia, which determines time constant of its own movement, and consequently, time of taking a step.
- Legs of robot should be able to move with rather high dynamics, which allows moving legs faster than robot falls.
- Inertial leg features should be such that highly dynamic leg movements wouldn't negatively affect movements of the entire mechanism.

In other words, leg mass under knee should be essentially smaller than mass of the entire robot. Otherwise realization of walking will be bothered by high negative disturbing effect caused by cross-connections in the mathematical model of robot's mechanism.

In this chapter modernization of robot's legs is described, this modernization allows to redistribute location of masses in the mechanism in such a way, that legs become lighter than the entire robot. Modification of the construction of robot's legs is that electrohydraulic actuators with a remote hydraulic drive are used in robot's feet.

Construction of the actuator and the leg with its use are also described. Quantitative changes of inertial features of the leg and results of the experimental research on the upgraded leg are presented.

2.1 Leg's construction of robot ROTTO

Robot's ROTTO leg consists of 3 main elements: foot, shin and hip (see Fig.2.1). Construction is made of carbonic pipes and aluminum joints. Foot is also made of aluminum. In the given construction 5 degrees of freedom are realized. Joints q1, q2 are equipped with actuators, which are force controlled, joints q3..q5 are controlled.

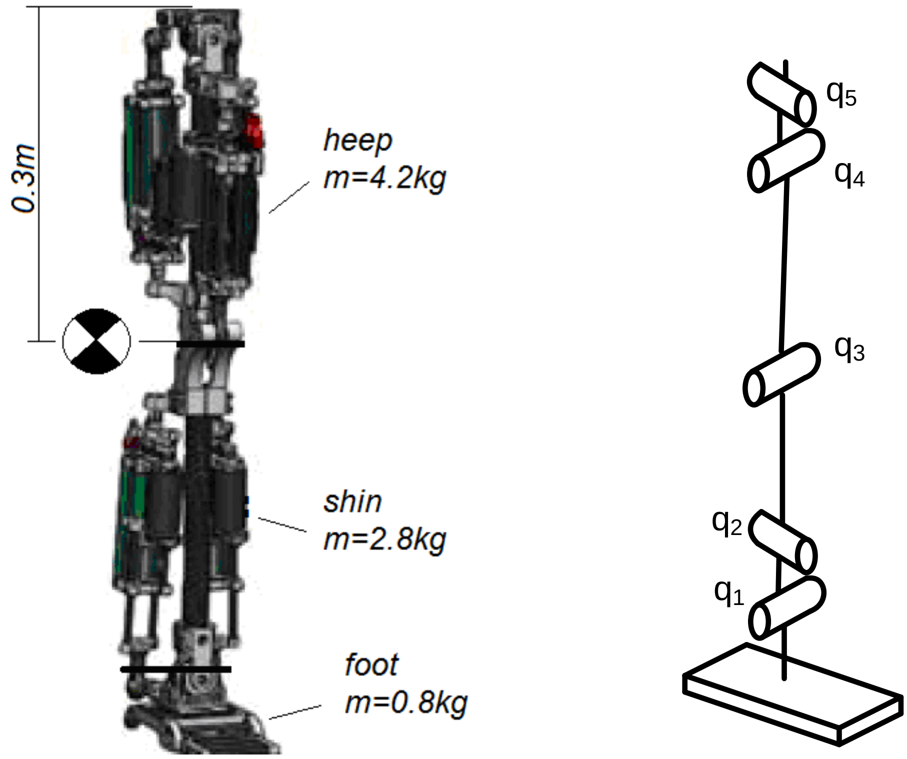


Fig. 2.1 – Robot’s leg and leg kinematic

Disadvantage of the given construction of a robot’s leg is big mass that lies under knees, namely 3.6 kg in comparison with 16.5 kg of full robot’s mass. Leg’s mass center is situated 30 cm further than leg’s suspension point, it sets magnitude of moment of inertia:

$$J_{Leg} = (4.2 + 2.8 + 0.8) \cdot 0.3^2 = 0.7 kg \cdot m^2 \qquad (2.1)$$

Robot’s hip and foot during leg’s movement during walking process execute motions with high speeds, at the same time their big mass and moment of inertia set negative effect of leg’s movements on movement of the entire robot. In Fig. 2.2 reacting moments of bearing in the upper point of leg’s suspension during typical leg movement are presented.

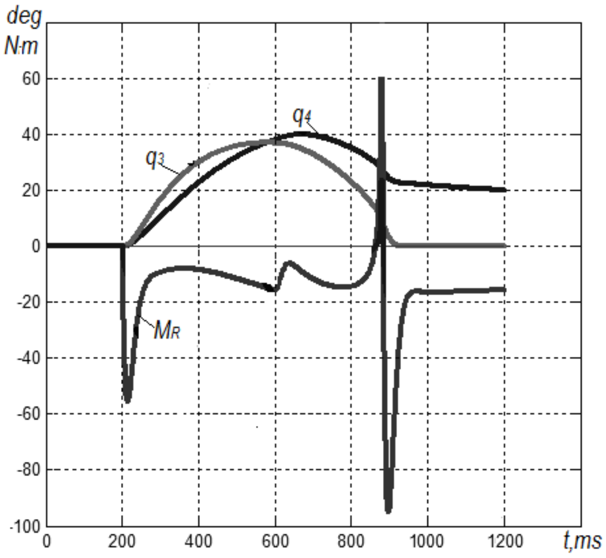


Fig. 2.2 – Reaction moment in bearing of leg

2.2 Electrohydraulic linear drive with flexible gear

In order to reduce negative effect of positive feedback, robot's leg construction was modified. In the robot's foot was used an electrohydraulic actuator with a flexible drive [3], this allowed to lessen mass of robot's leg and to redistribute mass positions in the robot's construction.

The technical capabilities of the transfer of mechanical energy between the different nodes are often limited. There are different mechanisms in which the working body is movable but the drive for constructional reasons must be stationary (e.g. hand devices, robotic joints, etc.). Alternative way to transfer of mechanical energy from the remote drive to the working body is the using of flexible shafts, cables, pneumatic and hydraulic machines, etc. This article describes a pilot version of an electrohydraulic linear drive with a flexible transmission.

The purpose of the work is getting the drive system with follow features:

- low weight of the moving element
- flexible construction
- ability to force control
- high dynamic properties
- simplicity and reliability

This paper proposes the drive design which consists of a linear electric drive and closed hydraulic transmission based on differential cylinders. Used linear drive was built in "RobotsLab" in 2007 and used in the construction of the robot "ROTTO" [30]. Works [11], [22] describe another constructions of serial elastic actuators.

Designed electrohydraulic actuator can be used in the joints of robotic mechanisms, medical prostheses, etc. An important advantage of the developed design is its autonomy compared to classical hydraulic actuator, namely the absence of compressor, valves, pressure accumulator, etc.

2.2.1 Construction of electrohydraulic actuator

Construction of the developed electrohydraulic actuator is shown in Fig. 2.3. The mechanism consists of two main elements: force controlled linear actuator and hydraulic transmission. Drive can run in three modes: position control, force control and position control with a given force. Hydraulic transmission consists of two double acting differential cylinders, whose respective chambers are connected with elastic pipes. An important feature of the proposed system is its arrangement, namely the location of the force sensor. It is located remote from the working cylinder. This makes the system reliable but at the same time causes inaccuracies in the force measurement due to the friction in the hydraulic transmission.

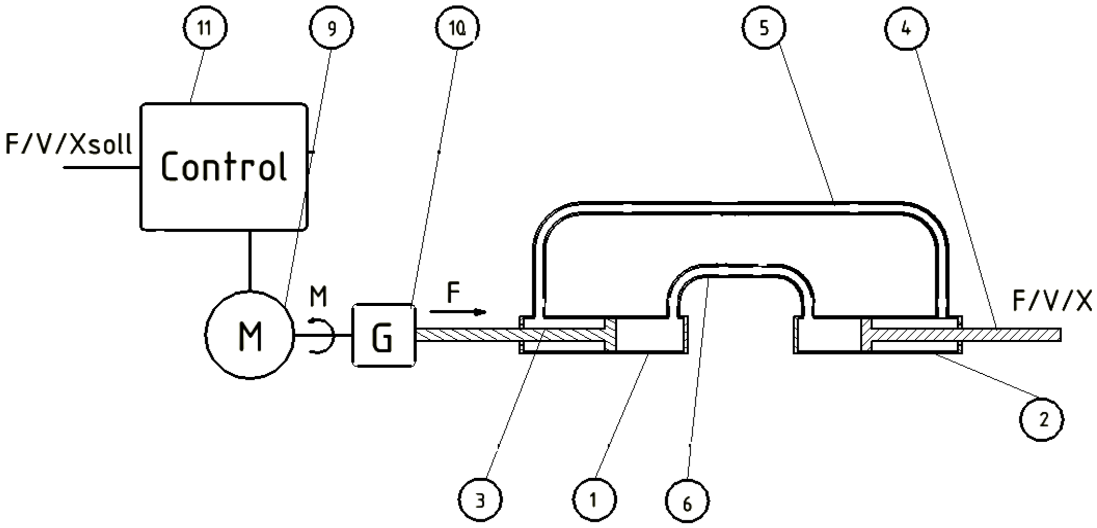


Fig. 2.3 – Construction of electrohydraulic actuator

Here: 1 – main cylinder, 2 – working cylinder, 3 – shaft of main cylinder, 4 – shaft of working cylinder, 5,6 – tube connections, 9 – electric drive, 10 – gear, 11 – control system of actuator

2.2.2 Parameter optimization

To choose the optimal parameters of elements of the electro-hydraulic drive a mathematical model is developed with MATLAB / SimHydraulics [29] (fig. 2.4).

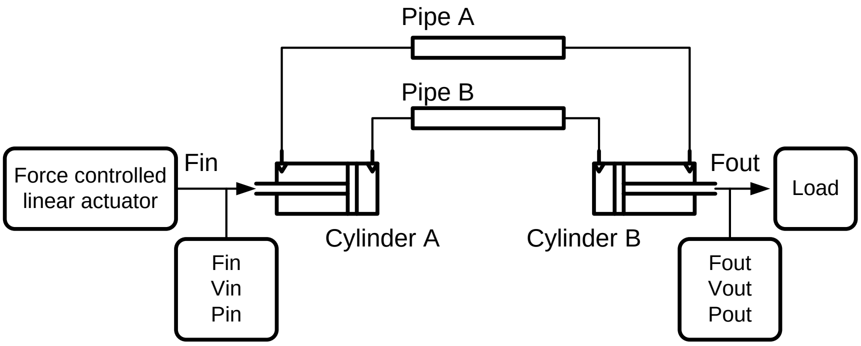


Fig. 2.4 – Simulation model

Based on this model the dependence of top drive motions speed from the parameters of the system is found (fig. 2.5).

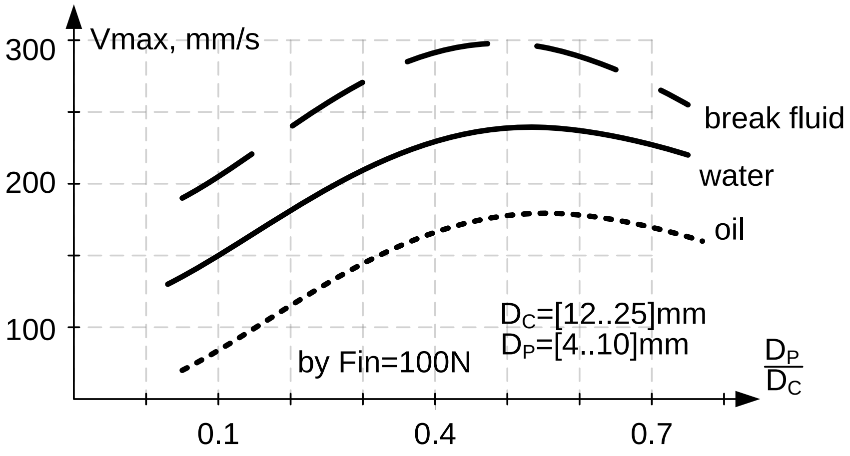


Fig. 2.5 – Dependences of top drive motions speed from the parameters of the system

Proceeding from obtained dependence for the best balance of dynamical and mass properties of the system are choosed the following parameters: cylinder diameter *Dc*=16mm, pipe diameter *Dp*=6mm, water as the working fluid.

Simulation of working out positions with load 50N with cylinders of diameter 16mm and 20 mm is shown in fig. 2.6.

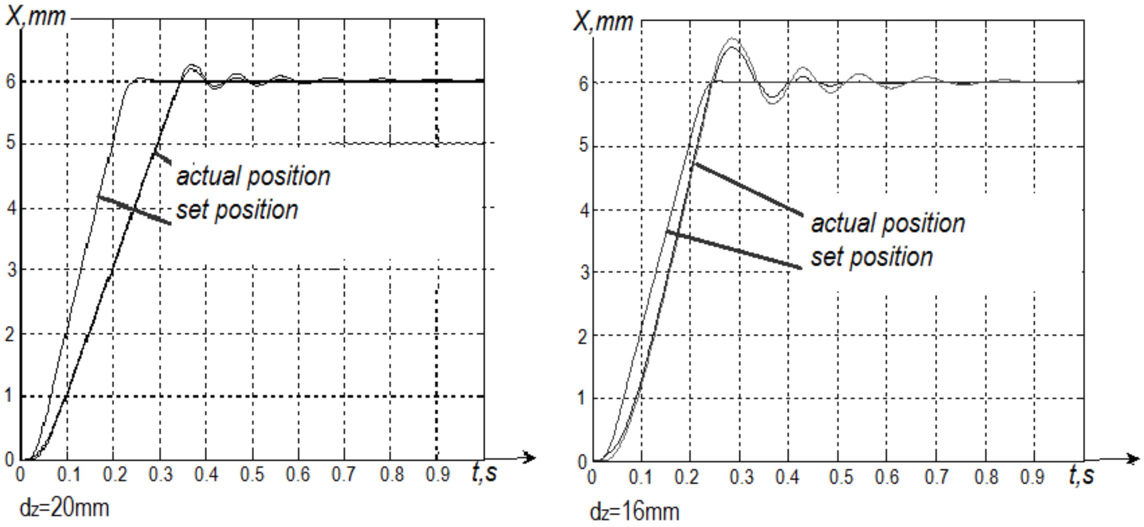


Fig. 2.6– working out positions with the different cylinder diameters

The dynamic of the system is defined by the diameters of cylinders and tubes.

2.2.3 Experiments

Based on the simulation results of the developed system experimental prototype of electrohydraulic drive was built (fig. 2.7).

As the working fluid was used water from reasons of optimality between its fluidity and safety of work with it. Drive control is realized with the real-time interface MATLAB / XPC Target.

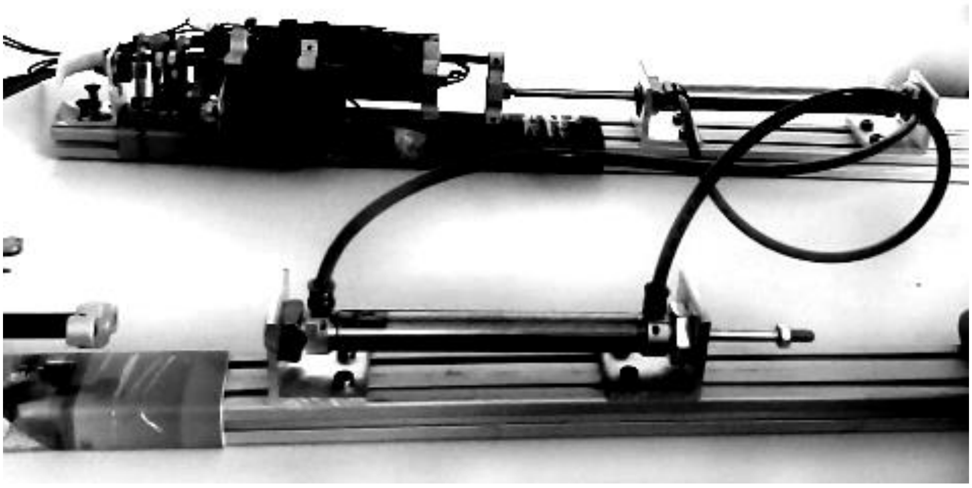


Fig. 2.7– experimental prototype of electrohydraulic drive

The aim of experiment - to determine the quality of the obtained system in two main aspects:

- The dynamic properties of the system (moving speed)
- Quality of force measurement in the proposed drive system

Dynamic properties of the system are presented as working out of positions of the drive with the load and without it (fig. 2.8).

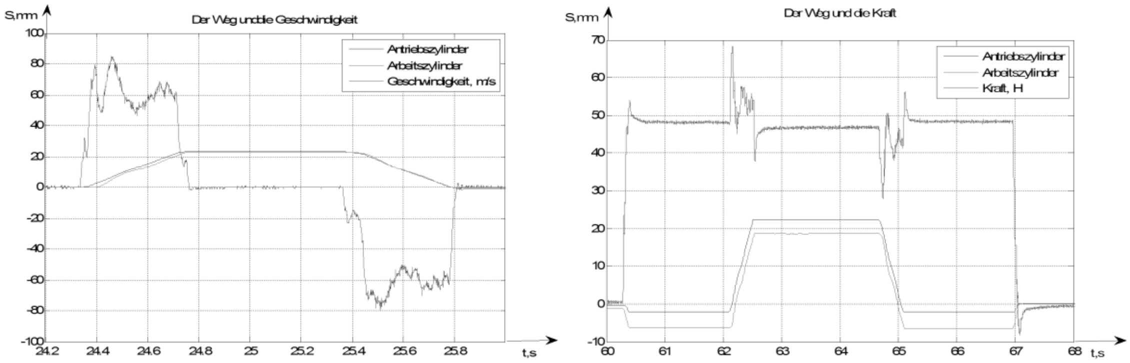


Fig. 2.8 – working out positions with and without the loading

Positioning speed is approx. 60 mm / s. The current load is 50N. Dynamic of the drive is satisfactory, the loss in the hydraulic transmission are acceptable.

In this work also was implemented a virtual spring with the given stiffness used a force sensor. Fig. 2.9 shows a deformation of a virtual spring with stiffness 2N/mm under external loading.

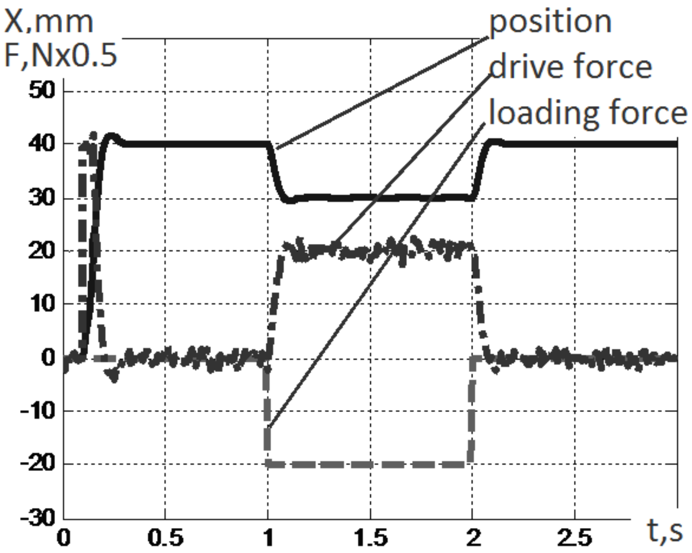


Fig. 2.9– deformation of a virtual spring

Another experiment - positioning with limited force. Fig. 2.10 shows a working out of positions, wherein the actuator is moved under a load. The drive realizes a constant impedance equal 40N.

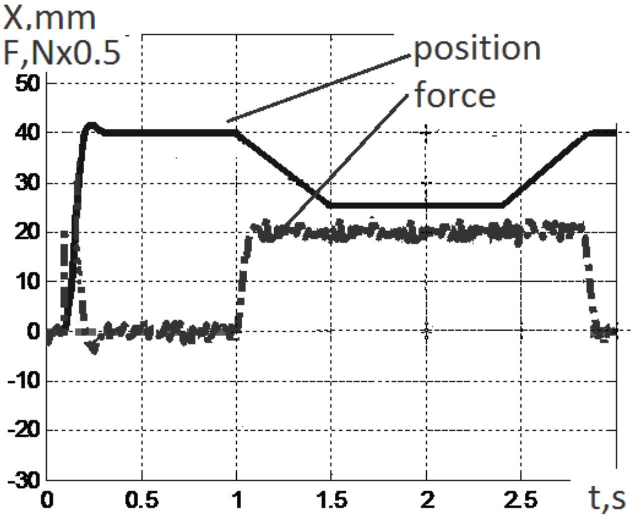


Fig. 2.10 – working out of positions with constant impedance

The force measurement is estimated as the sensor response indications on the pressure from side of the working cylinder (fig. 2.11).

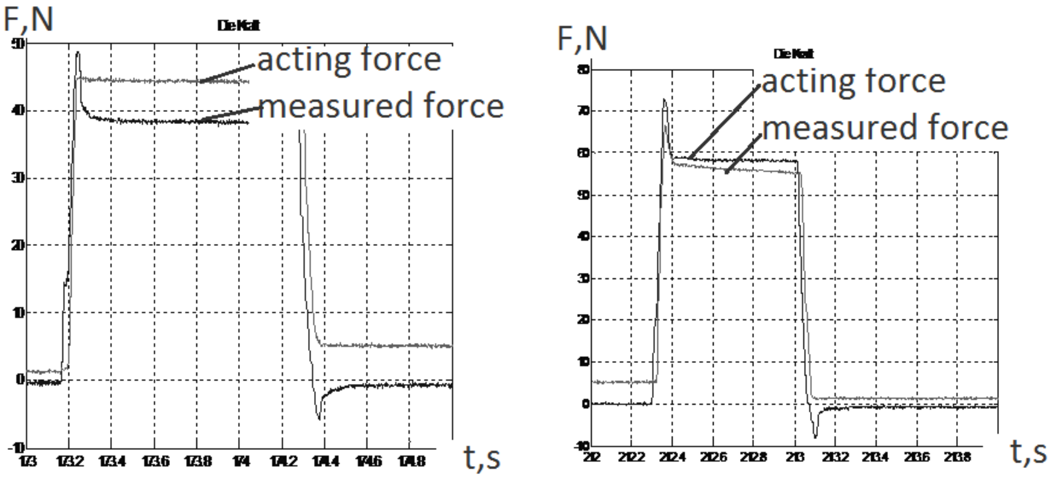


Fig. 2.11 – force sensor response on the pressure from side of the working cylinder

There is a dead zone by a force measurement, which is caused through the friction of the pistons in the cylinders. The magnitude of the dead zone has limits +- 20N (fig. 2.12).

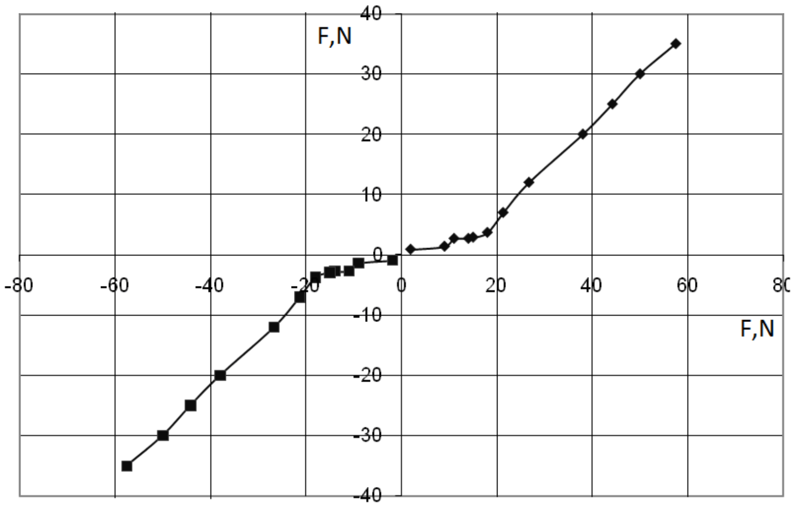


Fig. 2.12– dead zone by a force measurement

2.2.4 Force measurement with a pressure sensor

Dead zone in feedback of force control loop brings negative effect in system’s work. In order to minimize this effect drive system was modernized, and namely: elastic force sensor was replaced by pressure sensors in hydraulic transmission tubes (see Fig.2.13). Pressure value in hydraulic transmission’s tubes is proportional to force that acts on cylinders.

In this configuration magnitude of dead zone while measuring force is equal to magnitude of dry friction force in the working cylinder.

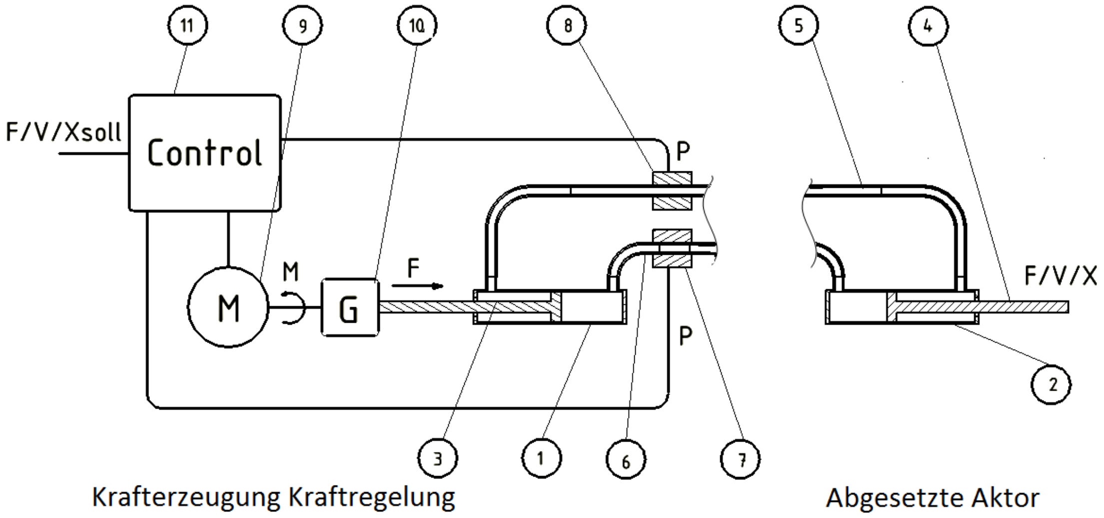


Fig. 2.13 – Electrohydraulic actuator with pressure sensors

Here: 1 – main cylinder, 2- working cylinder, 3 – shaft of main cylinder, 4 – shaft of working cylinder, 5,6 – tube connections, 7,8 – pressure sensors, 9 – electric drive, 10 – gear, 11 – control system of actuator

In the system two pressure sensors Freescale MPX5700GP [16] are used (fig.2.14).

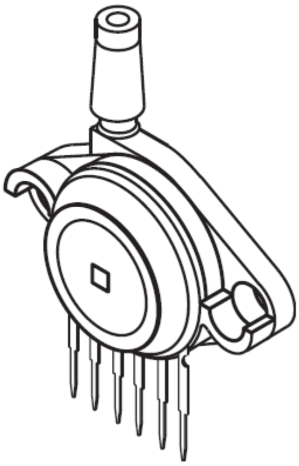


Fig. 2.14 – pressure sensor MPX5700GP

Given sensor measures pressure until 700 kPa, output voltage 0-5V. (fig.2.15).

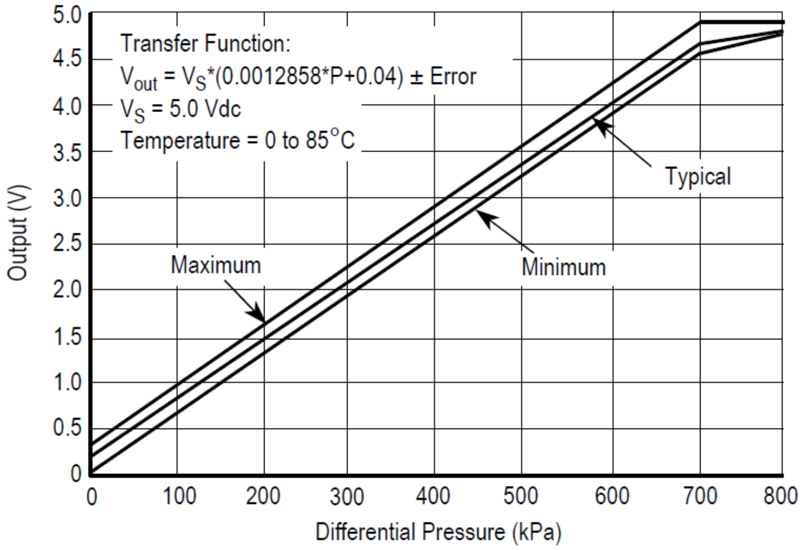


Fig. 2.15 – Output voltage of pressure sensor

Given sensor can measure positive pressure in cylinder's tube. In order to measure force that is applied to cylinders in the hydraulic transmission, two pressure sensors are used that are differentially switched on (see Fig.2.16).

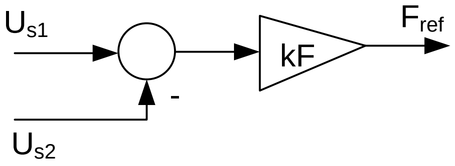


Fig. 2.16 – Differential connection of pressure sensors

Using this method of sensor switching, output characteristic for force measuring in the system was obtained (see Fig.2.17).

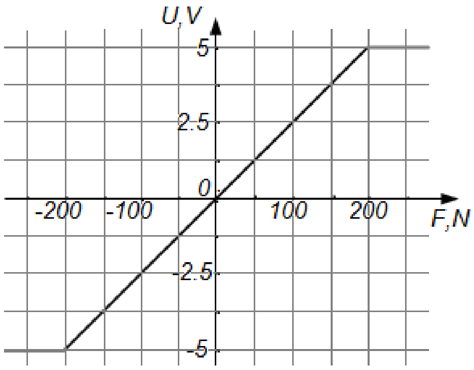


Fig. 2.17 – Force measurement

The usage of pressure sensors allows reducing dead zone.

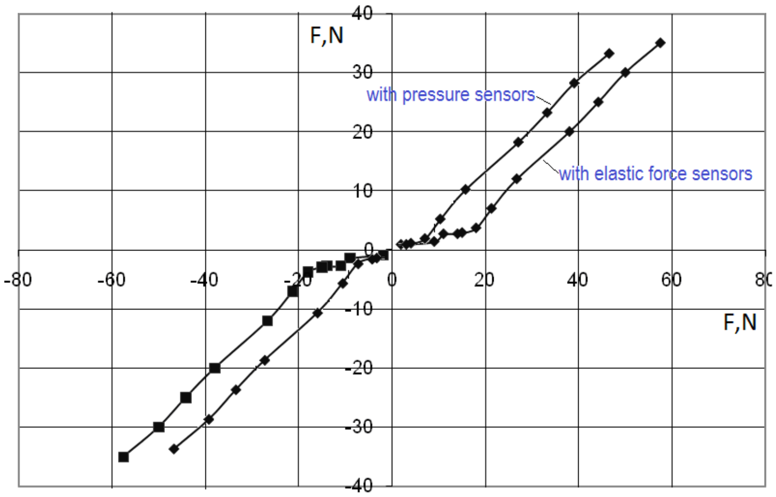


Рис. 2.18 – Dead zone by force measurement with pressure sensors

Force control loop is realized using PD regulator (see Fig.2.19). Parameters of the regulator are empirically chosen.

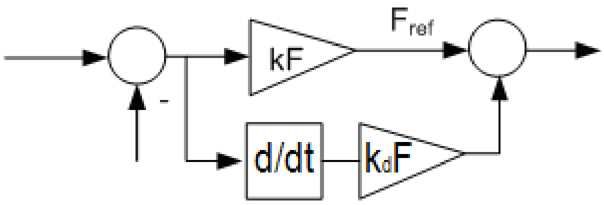


Fig. 2.19 – Force control loop

Force control in this loop lasts for 0.07s. (fig.2.20).

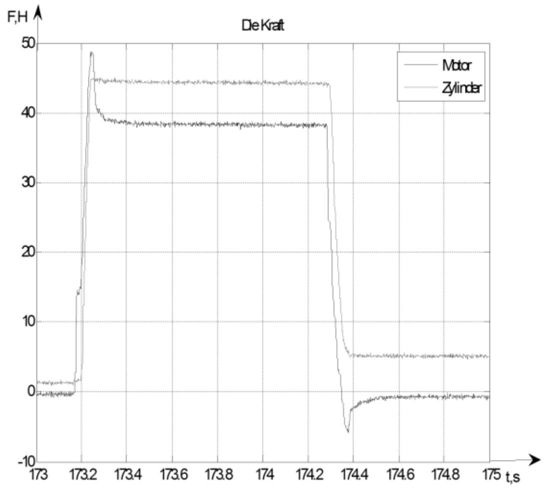


Fig. 2.20 – Force control

2.3 Leg’s construction of robot ROTTO with an electrohydraulic actuator.

Modernization of leg’s construction in the robot ROTTO was made with the help of an electrohydraulic actuator for foot (see Fig.2.21). In addition to this only one degree of freedom q1 is actuated, q2 moves freely.

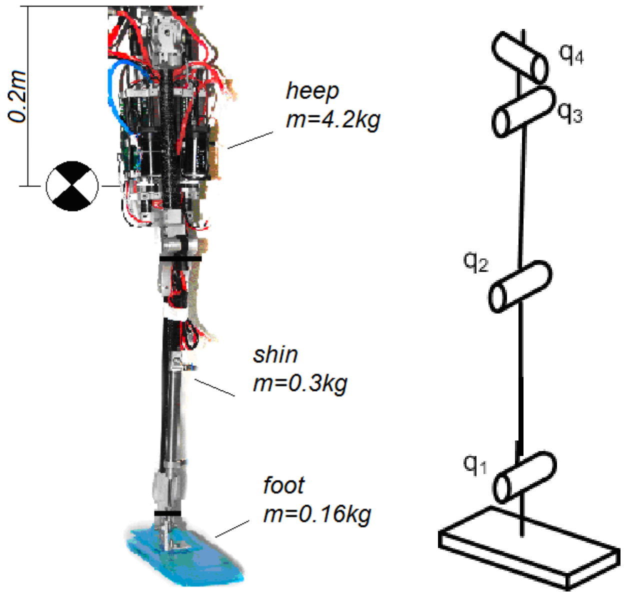


Fig. 2.21 – upgraded leg’s construction and kinematics

Leg’s mass under knee is 0.48 kg, what is essentially less than earlier.

$$J_{Leg} = (4.2 + 0.3 + 0.16) \cdot 0.3^2 = 0.19 kg \cdot m^2 \qquad (2.2)$$

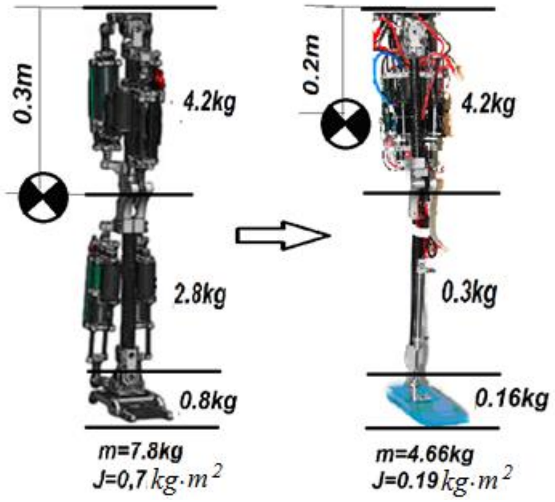


Fig. 2.22 – Comparison of inertial features of leg’s constructions

2.4 Performance simulation of the modernized leg

On the graph (see Fig.2.23) one can see, how force of bearing reaction in joint of leg suspension at mass decrease in the lower part of leg decreases in case of positioning of leg along swing trajectory.

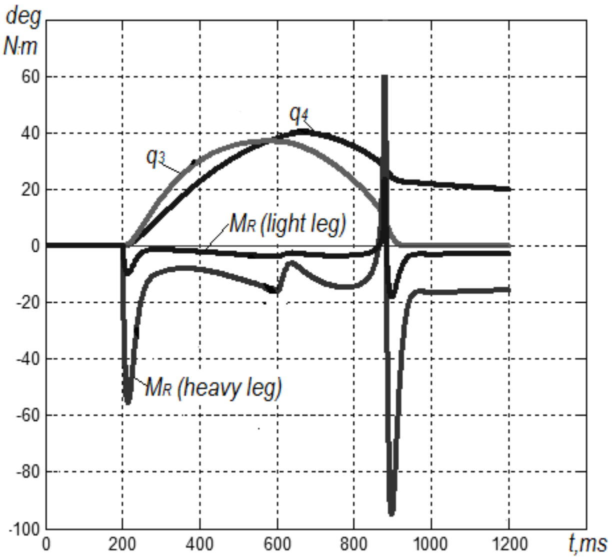


Fig. 2.23 – Reaction moments in bearings of legs

2.5 Summary

The use of an electrohydraulic actuator with a flexible drive enables remote allocation of the drive from the working mechanism. Proposed construction of an electrohydraulic actuator allowed redistribute masses in robot’s legs, make them less inertial. This also gave an opportunity to develop leg’s movement trajectories with lesser disturbances.

The use of fluid pressure sensors in tubes in the actuator construction let us improve actuator’s sensitivity that is regulated by force and also make robot’s feet more compliant and sensitive during the contact with surface.

Proposed construction of an electrohydraulic actuator can be used in various robotic devices, in which an actuator should be situated remotely from the executive mechanism.

Chapter 3. Stabilization of the planar robot

Solving the problem of walking of a biped robot, particular attention should be paid to standing of a robot. During standing in the double support state robot should maintain balance, compensate commensurable external disturbances. Robot must also have an ability to balance itself in unstable conditions. Many works propose different methods of robot's balancing [6], [10], [13], [36].

In order to maintain balance robot needs feet. Robot also needs an active stabilization system that keeps robot in balance with the help of feet. We have built a simplified robot model that depicts behavior of robot in sagittal plane. This model is used at building and testing of robot's stabilization system in order to reduce temporal and financial costs.

Construction of planar robot model is described in this chapter, an analogy is drawn with a biped robot. Further one can see an algorithm of work of robot's stabilization system using feet. At the end results of experiments illustrate how proposed stabilization system functions.

3.1 Problem

A problem was put to maintain the given system in balance.

- A planar robot should stand in balance regardless of surface's elastic properties, its form and orientation, and also regardless of its own mechanical properties. On top of all that lack of equilibrium cannot be tolerated.

- A planar robot should also have a possibility to be position controlled and should be able to move along prescribed movement trajectories. Positioning dynamics should not depend on properties of surface and robot's mechanic properties.

- A planar robot should be able to absorb external disturbances and to stay in equilibrium regardless of support surface properties and other mechanical properties.

3.2 Design of a planar robot

Construction of a planar robot is a simplified construction of a biped robot. At the same time following refinements are made:

- A planar robot illustrates behavior of a robot in incident plane in the case of double support phase and only a projection of a robot in sagittal plane in the case of single support phase.

- Knee of a robot is straightened and fixed.

A planar robot consists of 3 main segments: a foot, a leg and a body. Segments are connected with two joints with revolute degrees of freedom. A joint in a foot can be moved by an actuator with a hydraulic drive. A joint in the pelvis is actuated with a force controlled drive. Construction of planar robot and its kinematics are presented in fig. 3.1.

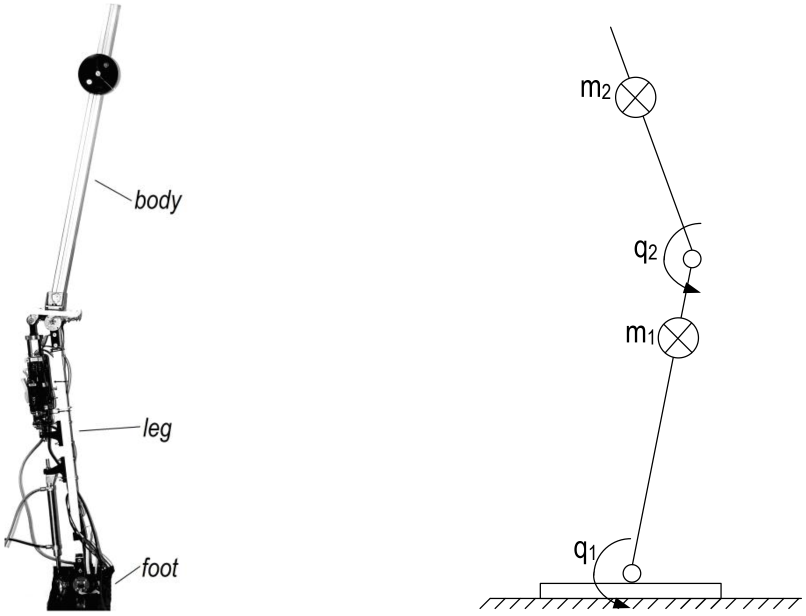


Fig.3.1 – Construction of planar robot and its kinematics

3.3 Control system of a planar robot

Control system of a planar robot should solve 2 main problems: to hold robot’s body in the prescribed position and to maintain the whole robot’s mechanism in the vertical position. Main external disturbing action that can cause a state of instability – overturn torque of gravity force. The idea of controlling such system lies in the fact that we have to identify disturbing effect and compensate it.

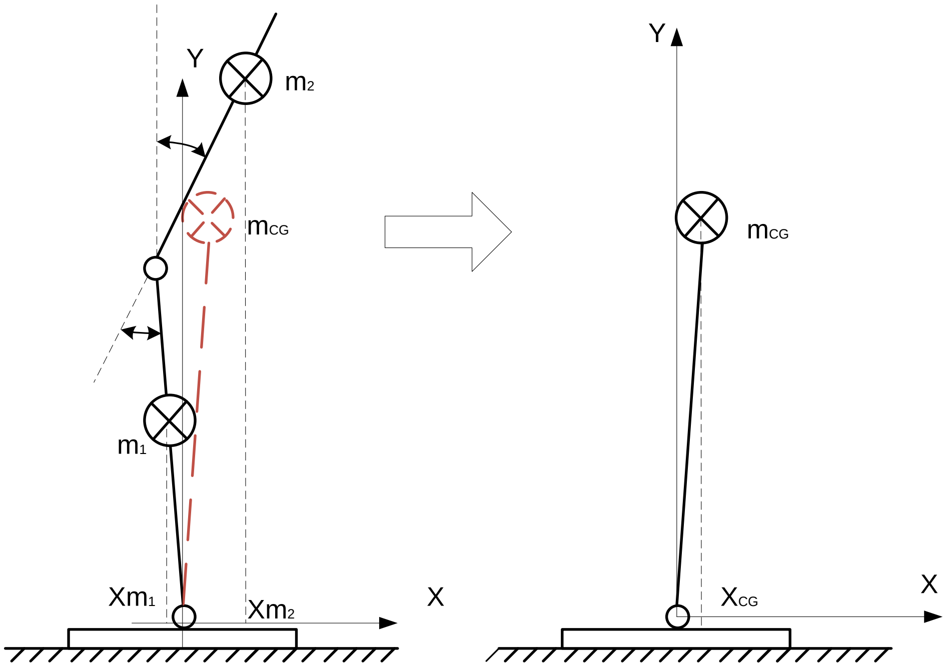


Fig.3.2 – replacement of a dual-mass system with a virtual single-mass system.

Magnitude of overturn torque of gravity force that acts on the robot depends on the robot's mass center with respect to rotation axis in the foot. It can be calculated as follows:

$$M_k = F_k \cdot d \tag{3.1}$$

Here: F_k - value of tangential component of gravity force, that affects robot's mass center, d - distance from robot's mass center to rotation axis in the foot.

$$F_k = m_{CG} \cdot g \cdot \sin(\alpha) \tag{3.2}$$

$$d = \frac{X_{CG}}{\sin(\alpha)} \tag{3.3}$$

After substitution (3.2) and (3.3) in (3.1) we get:

$$M_k = m_{CG} \cdot g \cdot X_{CG} \tag{3.4}$$

Here m_{CG} - mass of robot's mass center, X_{CG} - projection of robot's mass center position on ***x*** axis, are calculated as follows:

$$m_{CG} = m_1 + m_2 \tag{3.5}$$

$$X_{CG} = \frac{X_{m1} \cdot m_1 + X_{m2} \cdot m_2}{m_1 + m_2} \tag{3.6}$$

Here X_{m1}, X_{m2} - positions of robot's masses on ***x*** axis:

$$X_{m1} = d_1 \cdot \sin(q_1) \tag{3.7}$$

$$X_{m2} = l_1 \cdot \sin(q_1) + d_2 \cdot \sin(q_1 + q_2) \tag{3.8}$$

Control system of a planar robot consists of two control loops that regulate the position (Fig.3.3). First of them has to maintain prescribed robot's configuration, in this case it's body's orientation. In the given control loop PD position controller is used. It defines control torque $\mathbf{M_2}$ in joint q_2:

$$M_2 = k_P \cdot e_{q2} + k_D \cdot \frac{de_{q2}}{dt} \tag{3.9}$$

Here e_{q2} - control error:

$$e_{q2} = q_{2\_soll} - q_{2\_ist} \tag{3.10}$$

Controller parameters k_P, k_D of proportional and differential components are chosen experimentally.

Task of the second control loop is to maintain robot in balance with the help of feet and it also has to position projections of robot's mass center within the limits of the support polygon. In essence we represent our two-mass mechanical system as a one-mass system, in which masses of all elements are considered in equivalent mass of robot's center of gravity m_{CG}. Thus, control loop controls the position of virtual one-mass system.

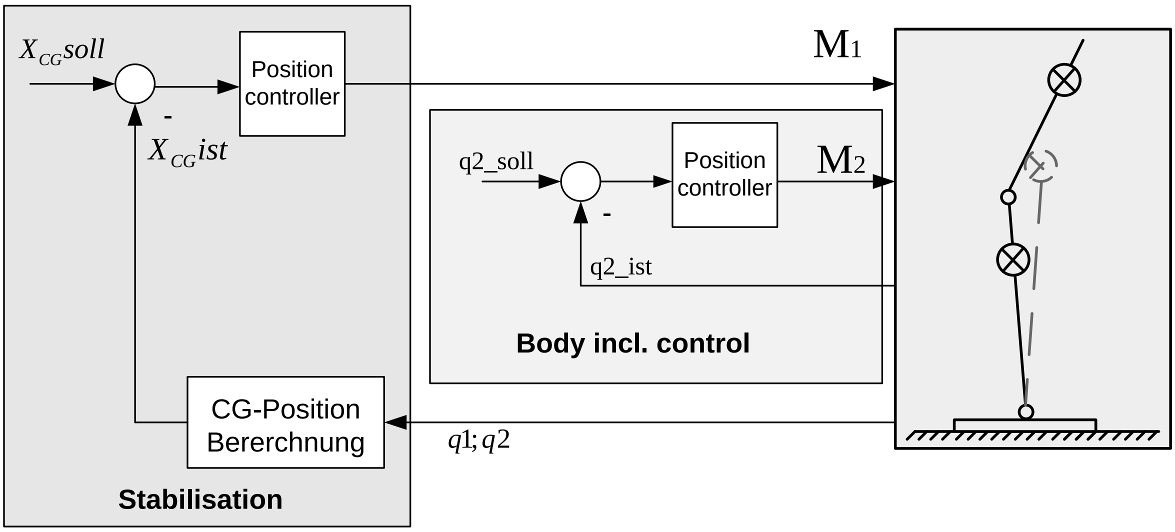


Fig. 3.3 – Stabilization system of planar robot.

PD position controller of robot's center of mass with respect to ***x*** axis is used in stabilization loop. The controller determines stabilizing torque in the robot's foot:

$$M_1 = k_P \cdot e_{XCG} + k_D \cdot \frac{de_{XCG}}{dt} \tag{3.11}$$

Here e_{q2} - control error of robot's center of mass position with respect to rotation axis in the foot:

$$e_{XCG} = X_{CG\_soll} - X_{CG\_ist} \tag{3.12}$$

3.4 Performance simulation of the control system

In order to evaluate performance of proposed system for planar robot stabilization was built a model of this system in MATLAB/Simulink. Simulating the performance of this system is necessary to determine empirically controller parameters in the stabilization system and to check functioning in the following cases:

- Pulling planar robot into the balance from unstable position
- Robot balancing while its configuration is being changed
- Compensation of external disturbances that act on robot
- Positioning of mass center of planar robot along necessary trajectories

3.4.1 Pulling of mechanisms into the equilibrium state from unstable state

Further one can see the case when mechanism of planar robot is inclined from equilibrium state at zero time (see Fig.3.4). Stabilization system is applying torque in robot's foot and tends to pull it into equilibrium state.

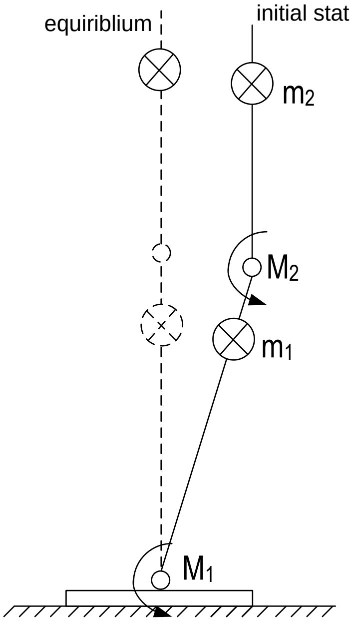


Fig.3.4 – pulling of robot into equilibrium state

Time diagrams of robot's mass center movement show the process of pulling of mass center in the mechanical system of a planar robot into the equilibrium state from unstable position (see Fig.3.5). At zero time mass center of the system is 5 cm away from the state of unstable position. Over a period of 0.8 sec. (duration of transient process) stabilization system pulls the mechanism into the equilibrium state and maintains it in this state.

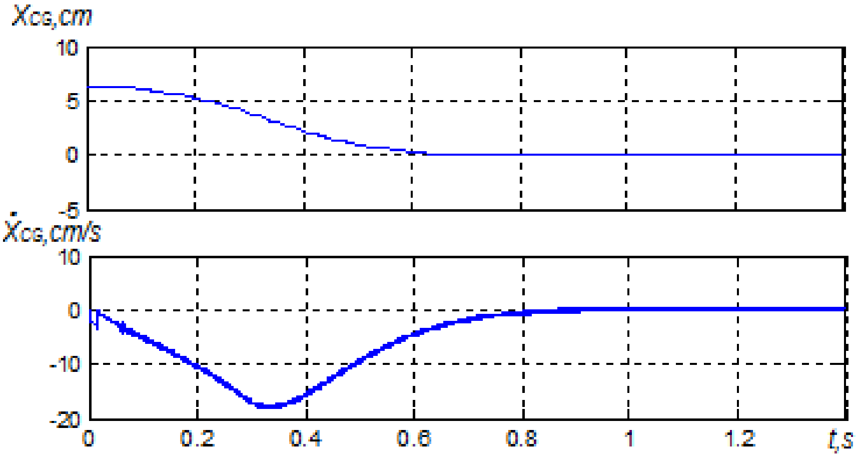


Fig 3.5 – robot's mass center movement

Given movement process is a curve on the phase plane (see Fig.3.6), which starts from the condition of 5 cm at speed 0 cm/s, accelerates, goes through the speed's maximum that is equal to 18 cm/s, then decelerates and goes into zero position with zero speed.

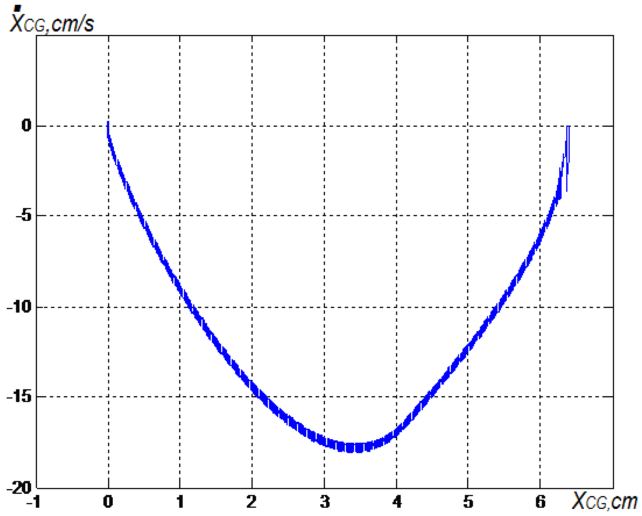


Fig.3.6 – phase diagram of robot's mass center movement at the stabilization

Below one can see time diagrams of angle and angular velocity change in robot's joints during the process of stabilization (s. fig.3.7).

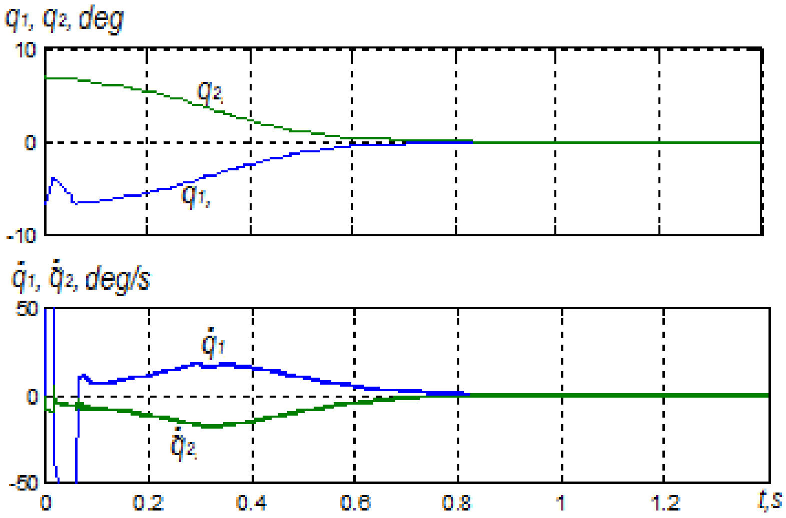


Fig.3.7 – angle and angular velocity in robot's joints during the stabilization

Stabilization system generates torques in robot's joints, that are represented in Figure 3.8.

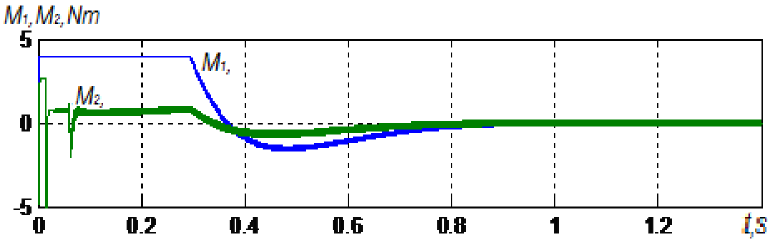


Fig.3.8 – torques in joints of a planar robot during the stabilization

3.4.2 Maintaining robot in balance while its configuration is being changed

In this case we change angle q2 in the robot, in addition to this, stabilization system should maintain robot's mass center above fulcrum, thus keeping mechanism of a planar robot in balance while its configuration is being changed (see Fig.3.9).

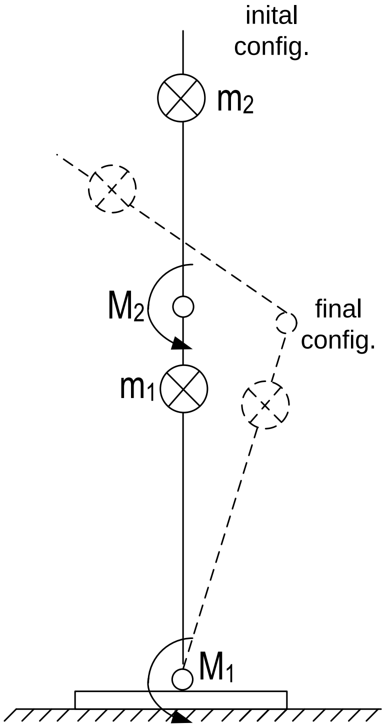


Fig.3.9 – keeping a robot in balance while its configuration is being changed

On the time diagrams (fig.3.10) are represented transient processes of angle and angular velocity in the joint q2 of a planar robot. Robot's upper element turns with respect to the leg through 15 deg for 0.33 s. with constant angular velocity 100 deg/s.

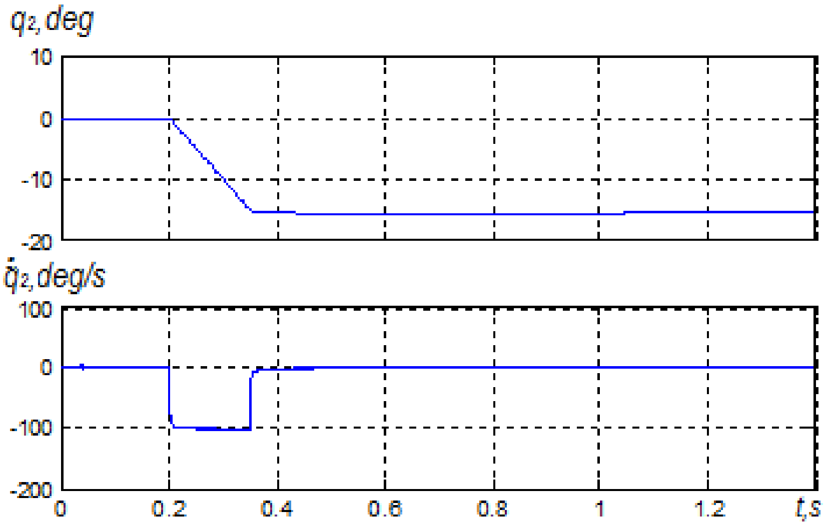


Fig.3.10 – angle and angular velocity in joint q2

Stabilization system tracks incline of robot’s mass center from equilibrium and tends to compensate it with the help of torque in robot’s foot. Transient process of stabilization during the change of planar robot’s configuration is represented below (fig.3.11). Robot’s mass center deviates from equilibrium state for a short moment within the limits of 4mm and then is pulled back into equilibrium state. Range of deviation depends on selected rigidity of controller in the stabilization system, amount and speed of change in robot’s configuration.

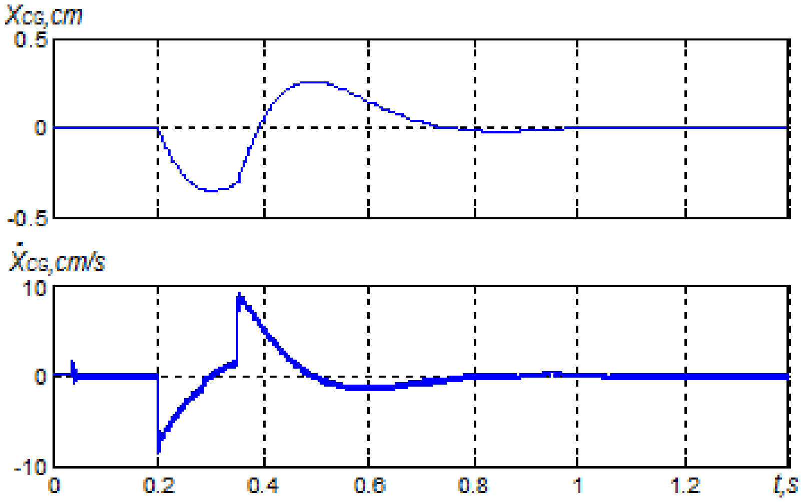


Fig.3.11 – deviation of robot’s mass center from equilibrium state during the change of robot’s configuration.

Deviation of robot’s mass center from balance state while robot’s configuration is being changed on phase plane is a closed loop near equilibrium point in the origin of coordinates (fig.3.12).

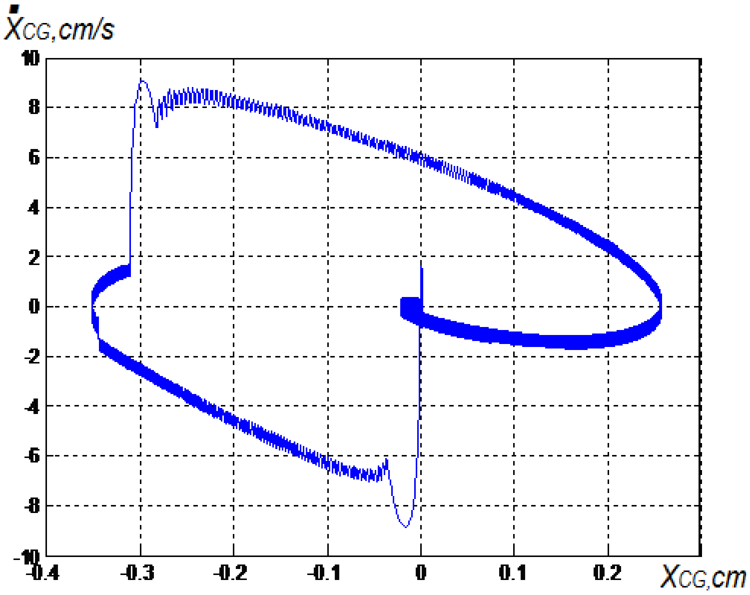


Fig.3.12 – phase diagram of robot’s mass center movement during change in robot’s configuration

Angle q_1 changes in such a way that robot's mass center stays in equilibrium state (fig.3.13).

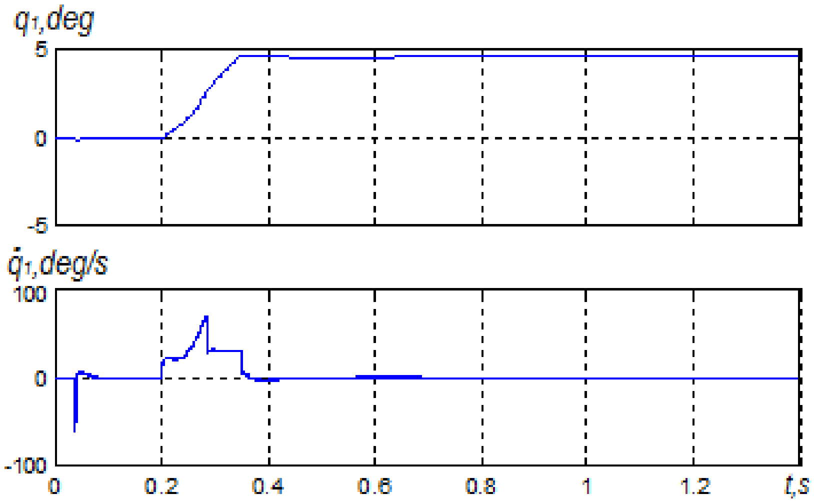


Fig.3.13 – angle change in robot's foot joint during angle change in upper joint.

3.4.3 Compensation of external disturbances

Here we consider the case when disturbing force that acts for a short moment is applied abruptly to the robot, which is in equilibrium and is controlled by stabilization system (fig.3.14). Robot deviates from the equilibrium state, as stabilization system has compliant features.

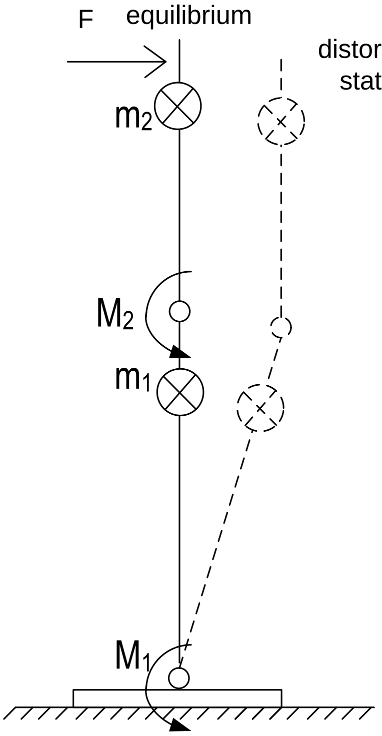


Fig.3.14 – robot's behavior under the action of disturbing force

External disturbing force of 10N affects the mechanism during 0.3 sec. The force is applied stepwise (fig.3.15).

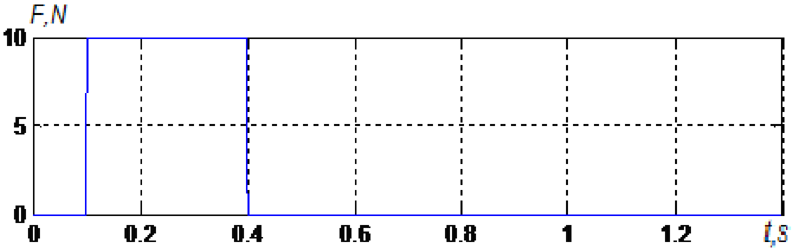


Fig.3.15 – Disturbing force

With all this going on robot's mechanism deviates from equilibrium and stabilization system pulls it back into equilibrium. Time diagrams of robot's mass center movement near equilibrium point are shown in the Figure 3.16.

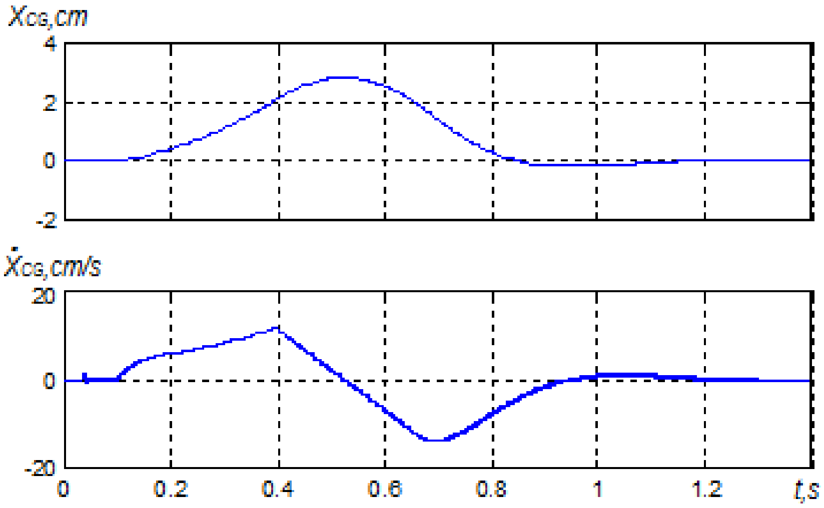


Fig.3.16 – robot's mass center behavior at external disturbing effect

The process of compensation of external disturbances on phase plane is a closed loop, that begins and ends in the point of origin of coordinates (see Fig.3.17).

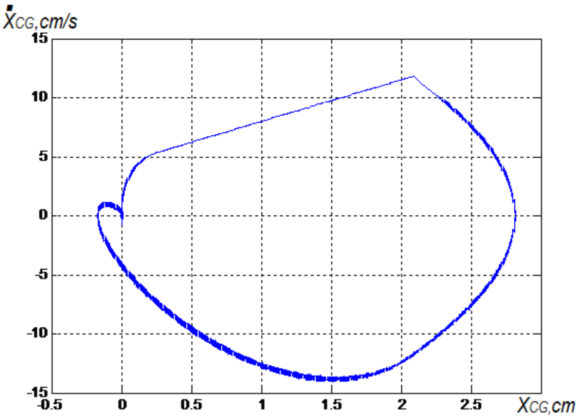


Fig.3.17 – phase diagram of robot's mass center movement during reaction to the external disturbance

Stabilization system maintains robot’s body in the vertical position. Time diagrams of angle and angular velocity changes in robot’s joints during external disturbance are shown in fig.3.19.

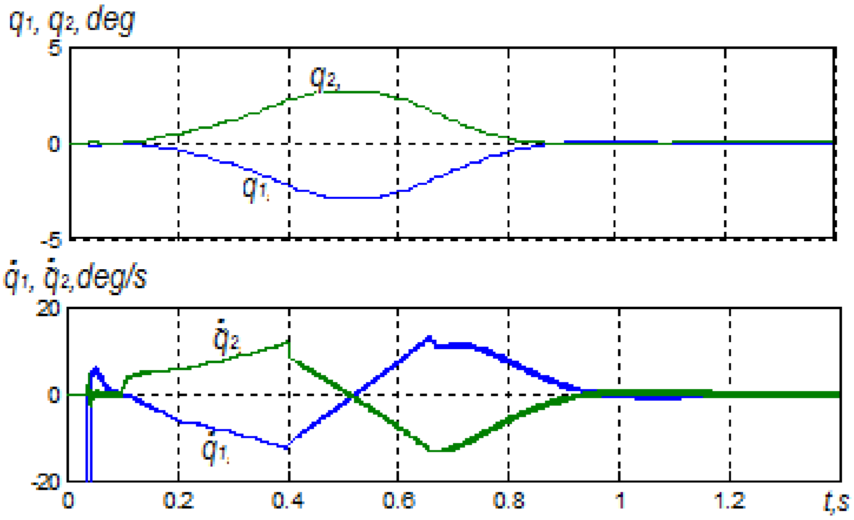


Fig.3.19 – angles and angular velocities in robot’s joints during external disturbance

Stabilization system generates torques in robot’s joints (fig.3.20), which are keeping the robot in balance state and robot’s body in the vertical position

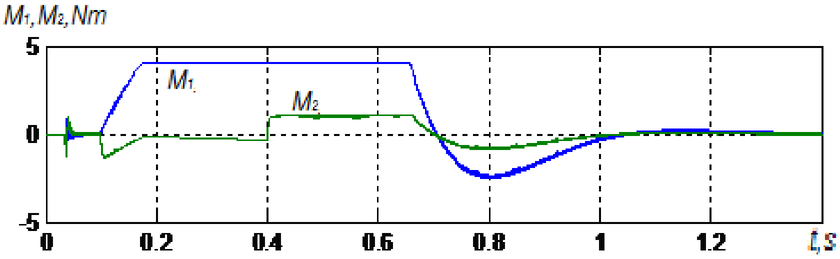


Fig.3.20 – torques in robot’s joints during external disturbance

3.4.4 Positioning of robot’s mass center

Here is taken a look at the case when with the help of robot’s control system we shift robot’s mass center within the limits of support polygon with prescribed speed (fig.3.21). It is necessary in order to have an opportunity to accelerate robot’s mass center during walking.

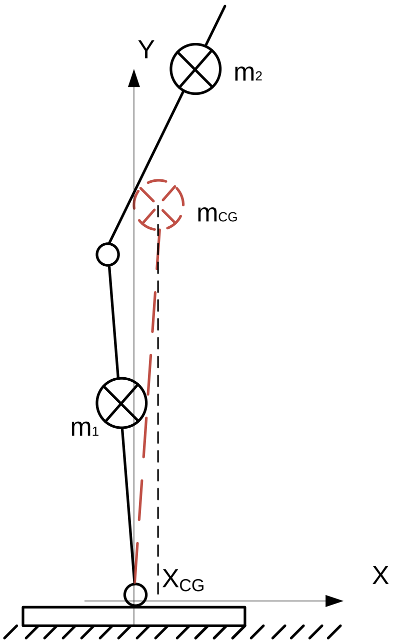


Fig.3.21 – Positioning of robot's mass center

In the given case robot's mass center shifts from equilibrium point for 35mm with constant speed 50mm/s (fig.3.22). The process of shift lasts for 0.75 s. Later stabilization system keeps mechanism in deviated position, compensating static load of gravity force. After this mechanism is pulled back into the equilibrium state.

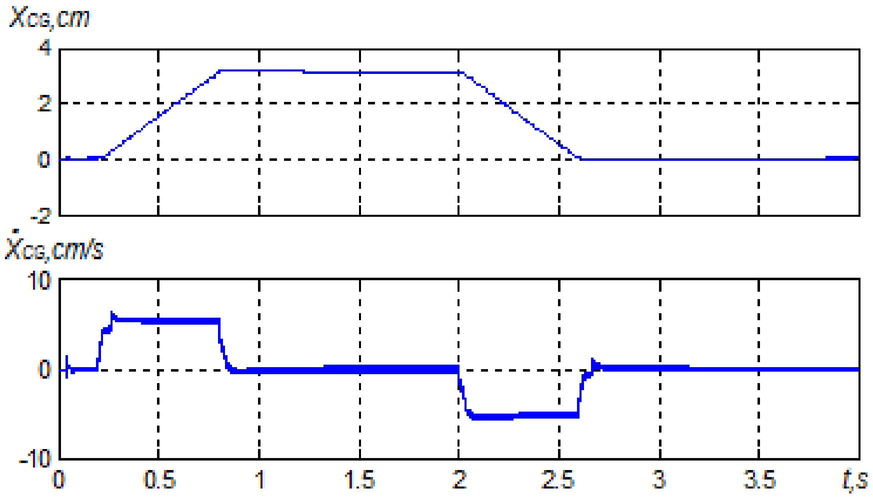


Fig.3.22 – position and speed of robot's mass center

On phase plane the trajectory of robot's mass center movement is a closed polygon, which faces match acceleration, movement with constant speed and deceleration (fig.3.23).

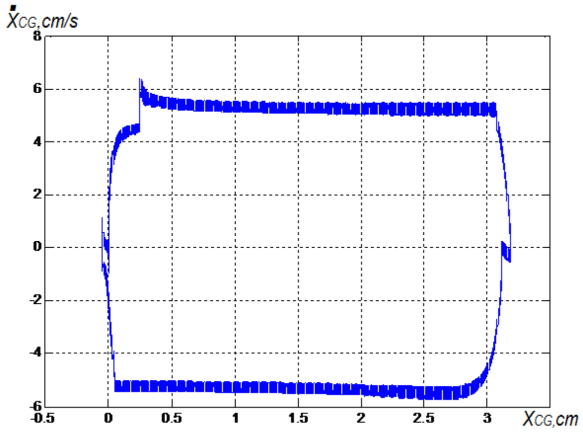


Fig.3.23 – phase diagram of robot’s center mass movement along given trajectory

Timing diagrams of angle and angular velocity changes in robot’s joints for the given case are represented in fig.3.24. Upper element of the robot is supported in vertical position.

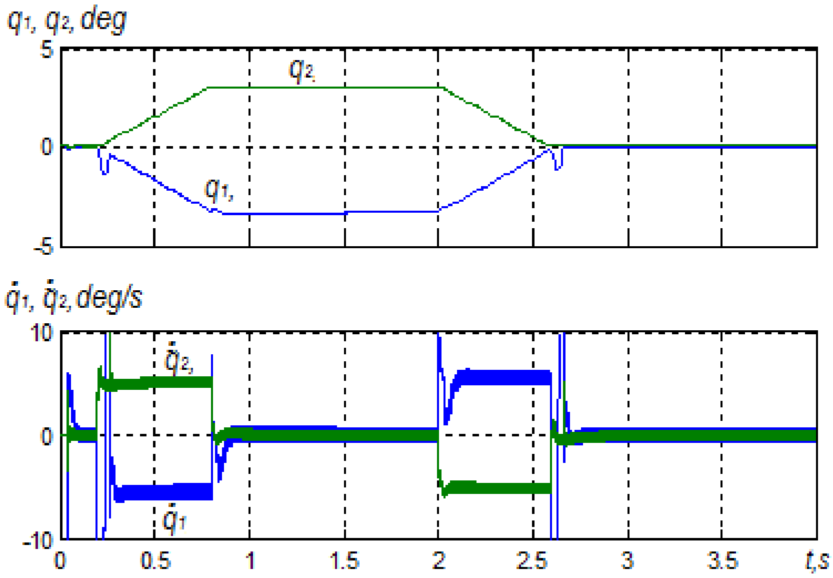


Fig.3.24 – angle and angular velocity in robot’s joints

Stabilization system of a planar robot generates in the joints torques, which are necessary for robot’s mass center movement and for the compensation of static load of gravity force in the declined from equilibrium state (fig.3.25).

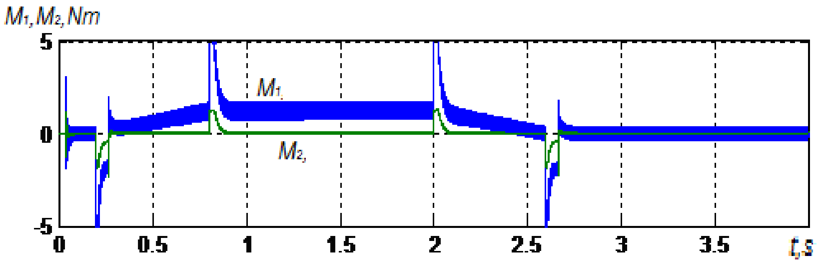


Fig.3.25 – torques in the joints of a planar robot

For all these cases in the control system of a planar robot PD position controllers were used. Controller coefficients were defined empirically: **k_{P1}=5, k_{D1}=2; k_{P2}=3, k_{D2}=1.2.** In the foot joint torque is limited with ±4Nm, in order to prevent robot's "bouncing".

3.5 Experimental research of stabilization system performance

In order to estimate the quality of performance of the developed control system of a planar robot were conducted experiments. Experiments were carried out for 2 cases, firstly: for maintaining robot's balance while its configuration is being changed and secondly, for positioning of robot's mass center.

Experiments were run on wooden horizontal surface. Coefficients of position controllers were chosen the same as in the simulation model of planar robot. In order to conduct experiments real time platform MATLAB/XPC-Target was used.

3.5.1 Balancing of planar robot by the changing its configuration

In this case we change angle q2 in the robot, stabilization system should keep robot's mass center above support point and thus keep the mechanism of a planar robot in balance during the change of its configuration.

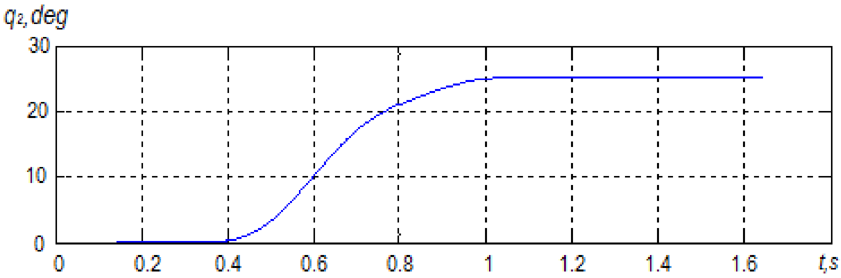


Fig.3.26 – positioning of body of planar robot

Angle q2 is declined 25 deg and robot's mass center slightly deviates from equilibrium state and is kept by robot's stabilization system within the range of ±1cm (fig.3.27).

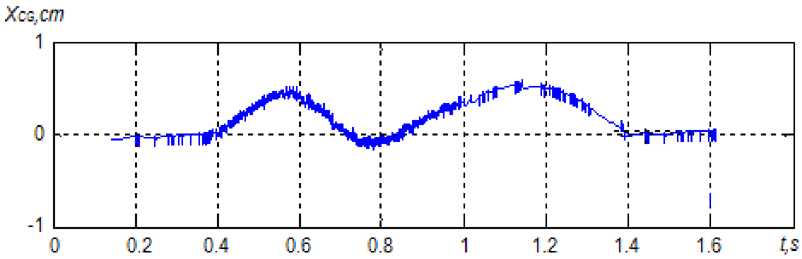


Fig.3.27 – keeping robot's mass center near equilibrium state

Angle q1 while robot’s configuration is being changed changes in such a way that robot’s mass center continues to be in balance (fig.3.28). Kinks of the curve show that robot’s foot “bounces” on bearing surface.

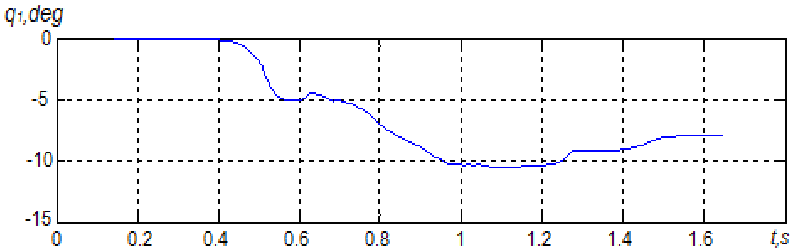


Fig.3.28 – change of q1 angle while changing angle q2

Robot’s control system generates torques in robot’s joints which change its configuration and maintain it in balance (fig.3.29).

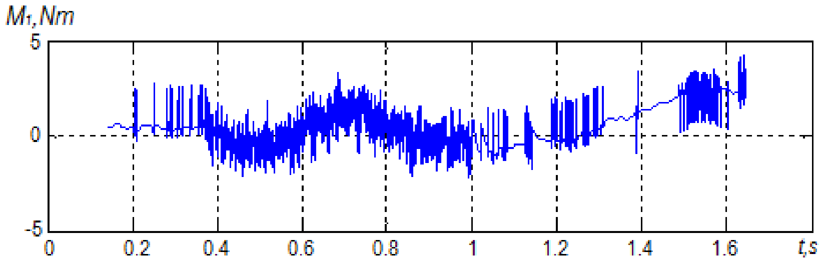


Fig.3.29 – torque in robot’s foot

3.5.2 Positioning of robot’s mass center within the limits of support polygon

Robot’s mass center deviates from equilibrium state for 50mm and stays in this state, and then it is pulled back into equilibrium state (fig.3.30).

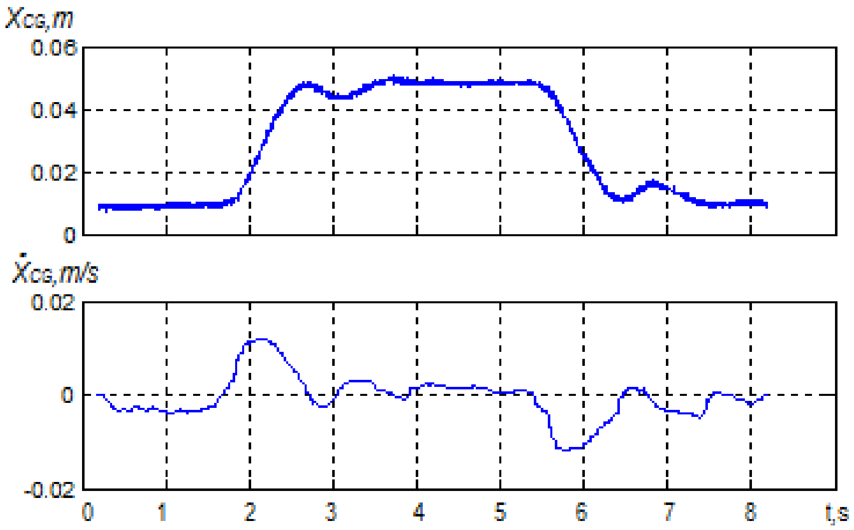


Fig.3.30 – position and speed of robot’s mass center

Change of angles in robot's joints is represented in Fig.3.31. Beats in the curve of joint q1 movement tell us about robot's foot "bouncing" on bearing surface that is caused by contact features of robot's feet. Angle q2 is changed in such a way that upper robot's element stays in the vertical position.

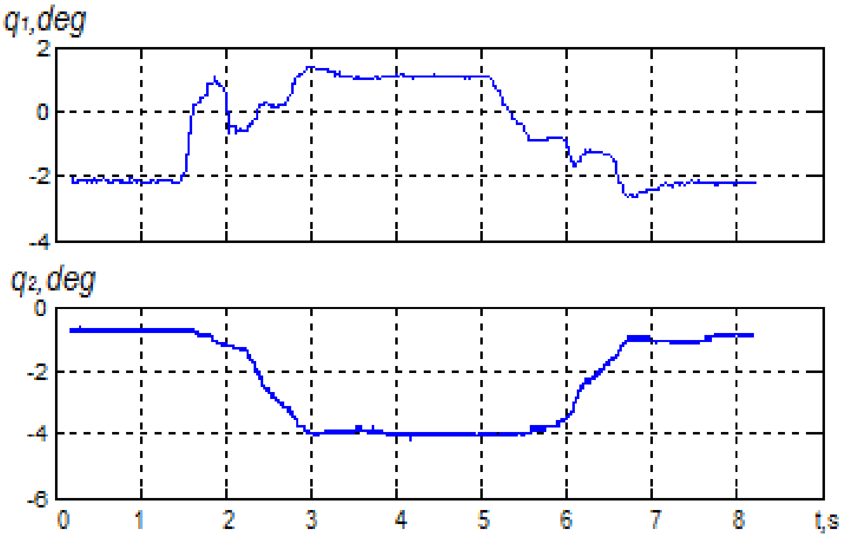


Fig.3.31 – change of angles in robot's joints.

3.6 Summary

At this stage we checked the conception of stabilization system building of a two-mass planar robot with the help of foot. The concept consists of calculation of mechanical system mass center position, interpretation and its control like a one-mass system.

Suggested approach let us make a simple control system, which has 2 closed control loops: for stabilization in gravity force field and for positioning of prescribed mechanism configuration.

Experiments confirm that realized stabilization system allows safely maintain robot in equilibrium state, compensate commensurable external disturbances, shift mass center of mechanism within the limits of support polygon. Suggested technique will be used for the stabilization system of a biped robot.

Chapter 4. Biped robot stabilization in double support state

Method of stabilization of robot’s simplified model was examined in the previous chapter. In works [43], [44], [45], [46] are also different methods of robot balancing described. Now is presented a stabilization system for a biped robot ROTTO.

In this chapter main tasks for stabilization system of a biped robot are determined. Robot’s construction and its kinematics are investigated. Further one can see a stabilization system of a biped robot. Stabilization system is separated in 3 levels for simple understanding.

At the end of this chapter one can see the results of simulation and experimental investigations of functioning of proposed stabilization system.

4.1 Tasks

Stabilization system of biped robot must have following features:

- Stabilization system have to keep a robot in balance regardless of elastic properties of the elements of robot’s construction, regardless of mechanism configuration (length and width of leg position) and regardless of properties and forms of support surface.

- Stabilization system should be able to position robot’s mass center over support polygon, work through various movement trajectories of robot’s center of mass, and also let change mechanism configuration (work through trajectories of each joint), keeping mechanism in balance regardless of features of construction elements and bearing area.

- Stabilization system should also have a possibility to absorb external disturbances, safely keep robot’s mechanism in the double support state and effectively damp a robot at landing from single support.

4.2 Robot's kinematics

Robot's kinematic scheme is represented in fig.4.1. Joints [$q_3 \ldots q_{10}; q_{13} \ldots q_{15}$] are position controlled. Actuators in joints [q_1; q_{12}] are force controlled. Joints [q_2;q_{11}] don't have any actuators and move freely.

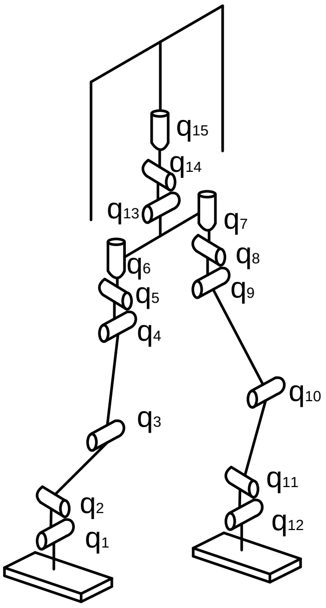


Fig.4.1 – Robot's ROTTO kinematics

4.3 Control system

In the proposed stabilization system is used the technique generated in previous chapter and implemented in planar robot. Robot's mechanism is described as equivalent mass $\mathbf{m}_{CG}$ that is fixed on the weightless rod **S**. Rod on the rotary joint is fixed to the platform lying on the support surface. In this case platform is support polygon of robot's feet.

Virtual joint $\mathbf{q}_S$ allows a rod rotating about **d** axis, which goes through pinning points of hinge joints in robot's feet. Since robot's joints are equipped with actuators with ball-and-screw drive with high gear ratio and are position controlled, then robot's feet have fixed length and cannot be freely deformable. It is defined by the fact that robot's construction is rigid and unyielding. Thus virtual rod can rotate with respect to the platform only around **d** axis, but $\mathbf{m}_{CG}$ moves only in plane **S**. Deviation of $\mathbf{m}_{CG}$ from plane **S** is possible only at detachment of robot's foot from support surface.

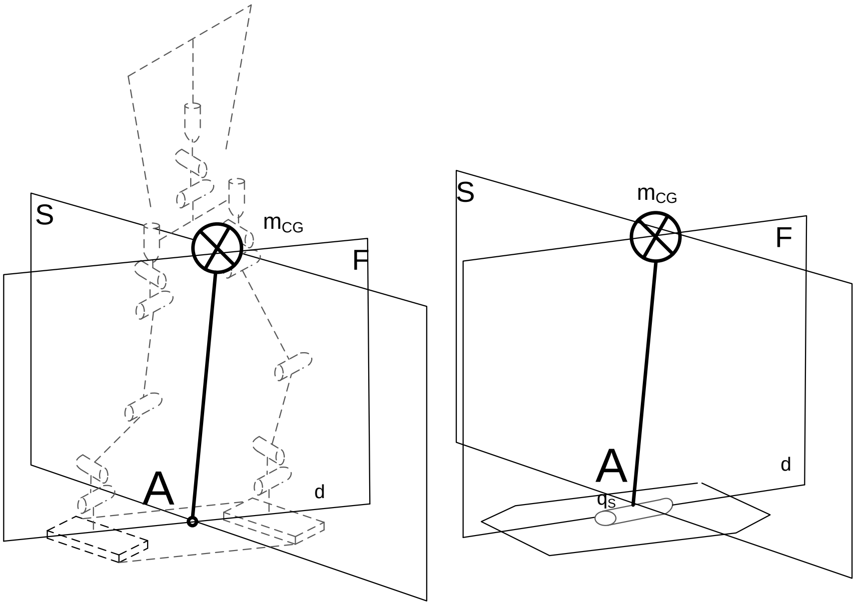


Fig.4.2 – degree of freedom of robot's mass center relative to support surface.

Without compliance/deformability of robot's skeleton in plane **F** is impossible to position, damp or somehow control a mechanism in space and safely keep it in the double support state.

Let's make a mechanism compliant in plane **F**, this will let $\mathbf{m_{CG}}$ to move relative to the platform not in an arc, but on a sphere without removal of virtual platform from surface, in other words in continuous double support state. This compliance is realized with the help of application of following kinematical constraints in robot's control system between leg length and position of mass $\mathbf{m_{CG}}$:

$$\begin{aligned} L_L &= L_0 + dL_L + dL_{ML}, \\ L_R &= L_0 + dL_R + dL_{MR}; \\ dL_L &= k_L \cdot Z_{CG}, \\ dL_R &= -k_L \cdot Z_{CG}; \\ dL_{ML} &= k_M \cdot M_X, \\ dL_{MR} &= -k_M \cdot M_X. \end{aligned} \tag{4.1}$$

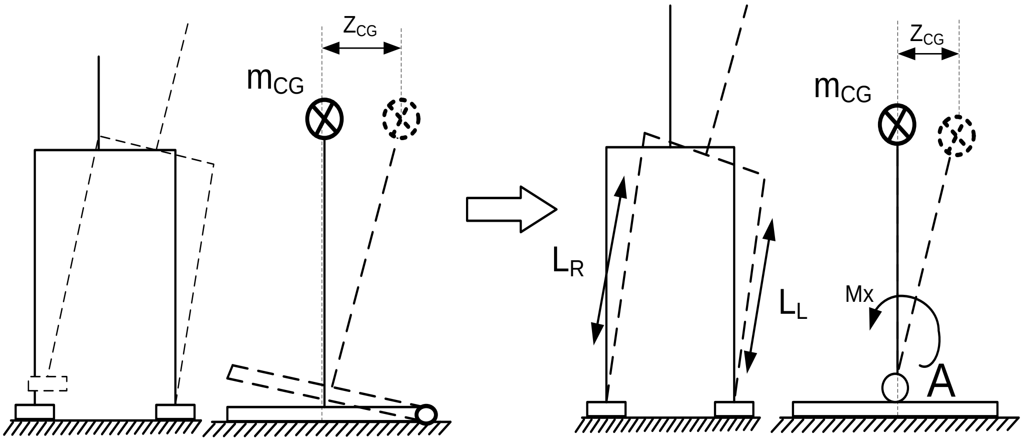


Fig.4.3 – realization of compliance of robot’s skeleton in plane **F**

After the realization of these kinematical constraints we got one additional degree of freedom for robot’s mass center in plane **F**. Let’s go back to the virtual single-mass model: now it can be said that hinge joint has two rotation axis: [qF,qS]. These degrees of freedom are actuated and in them torques [MF,MS] can act. These torques are used as control action for the control system.

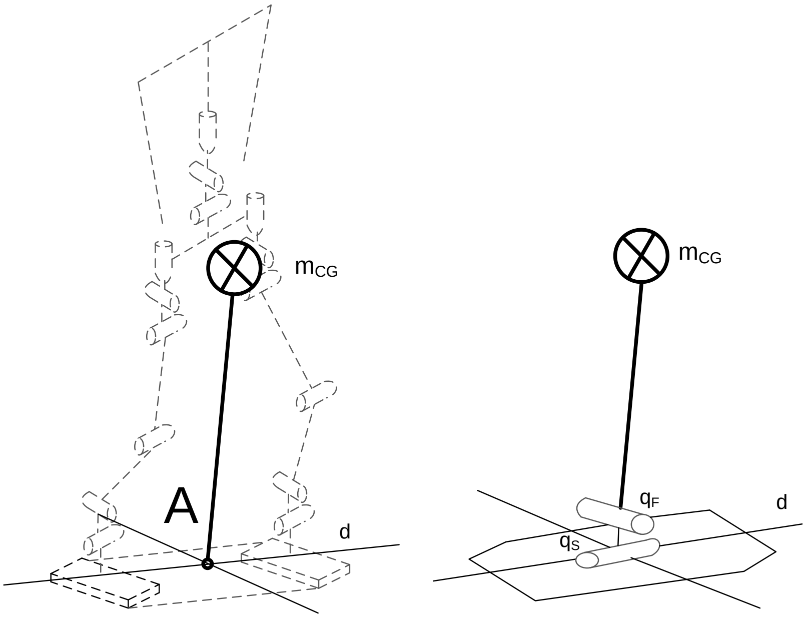


Fig.4.4 – degrees of freedom of robot’s mass center relative to support surface

Projections of position of robot’s mass center on axis **f** and **s** that lie in plane **T** (fig.4.5) were used as coordinates for control. Coordinate system **fs** is turned on angle **β** around axis **y** relative to coordinate system **xz**. Angle **β** is determined by mutual alignment of robot’s feet on support surface.

$$\beta = a\tan 2(X_{F2} - X_{F1}, Z_{F2} - Z_{F1}) \tag{4.2}$$

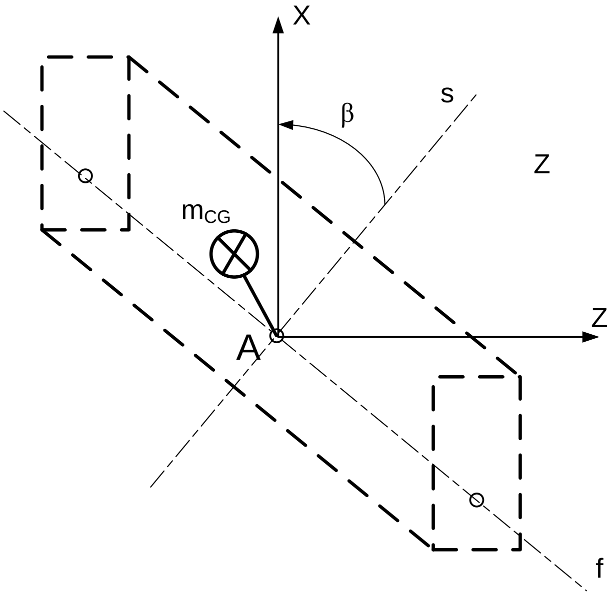


Fig.4.5 – coordinates for control system

When we have a general idea about system's kinematics taking into account kinematical constraints and ways of affecting it, we can implement stabilization system. Stabilization system that is represented in this chapter has a hierarchical structure from three basic levels (see Fig.4.6):

- Actuator control system by position/force
- Kinematical constraints/reflexes
- Stabilization system

Realization of actuator control loops in robot's joints is described in previous chapter. Level of kinematic constraints realizes from robot's legs a virtual platform with virtual joints $\mathbf{q_F},\mathbf{q_S}$.

Upper level is robot's stabilization system. Stabilization system consist of two control loops that regulate projections of robot's mass center on x and z axis (fig.6). PD position controllers are used in control loops. They calculate control torques based on values of control errors:

$$M_Z = k_{PX} \cdot e_{XCG} + k_{DX} \cdot \frac{de_{XCG}}{dt} \tag{4.3}$$

Here e_{XCG} - control error of robot's mass center position along ***x*** axis that is equal to difference of given and actual position:

$$e_{XCG} = X_{CG}\_ref - X_{CG}\_act \tag{4.4}$$

$$M_X = k_{PZ} \cdot e_{ZCG} + k_{DZ} \cdot \frac{de_{ZCG}}{dt} \tag{4.5}$$

Here e_{ZCG} - control error of robot's mass center position along ***z*** axis that is equal to difference of given and actual position:

$$e_{ZCG} = Z_{CG}\_ref - Z_{CG}\_act \tag{4.6}$$

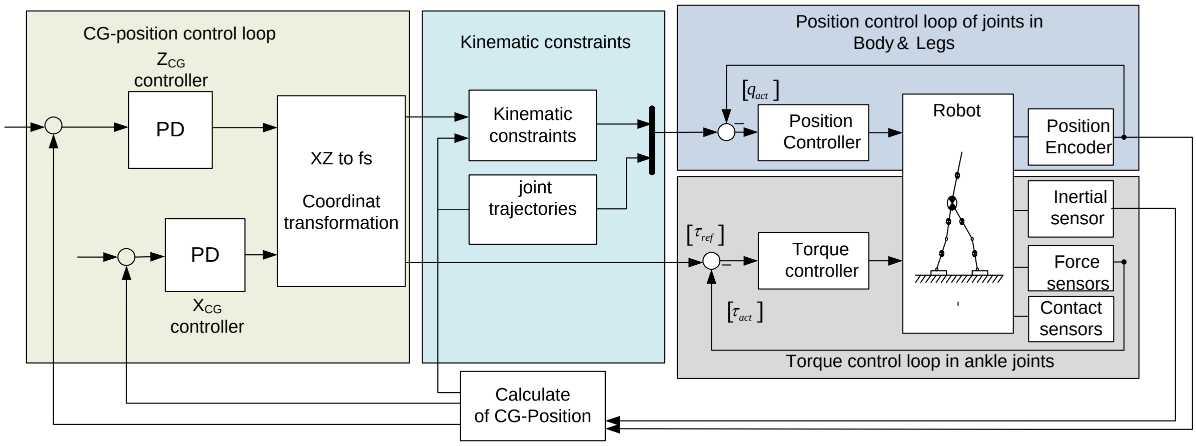


Fig.4.6 – biped robot's stabilization system

Since torques in the virtual platform are applied to the rod around **f, s** axis, then control action should be transformed from coordinate system **xy** into coordinate system **fs** taking into account angle of turn **β**.

4.4 Performance simulation of stabilization system

In order to evaluate performance of proposed stabilization system for biped robot was built a simulation model of this system in MATLAB/Simulink. Simulating the performance of this system is necessary to determine empirically controller parameters in the stabilization system and to check functioning in the following cases:

- Stabilization of robot in sagittal plane
- Compensation of disturbances in frontal plane and maintaining robot in the double support state
- Positioning of mass center movement of robot, its acceleration and deceleration in the double support state

4.4.1 Stabilization of robot in sagittal plane with the help of feet

Here one can see the case, when robot stands in the double support phase. Stabilization system maintains equilibrium. Disturbing force affects robot with impulses along X axis. Stabilization system compensates disturbing effect and keeps robot in balance.

Force Fx=30N is applied to robot's pelvis abruptly and acts over a period of 0.3 sec. (fig.4.7).

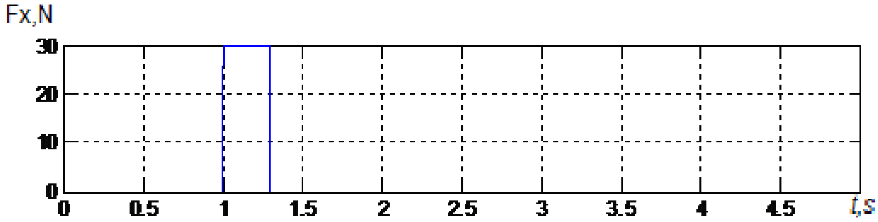


Fig.4.7 – disturbing force Fx

Under the action of this disturbance robot's mass center deviates from equilibrium state and then it is pulled back into balance influenced by stabilization system (see Fig.4.8).

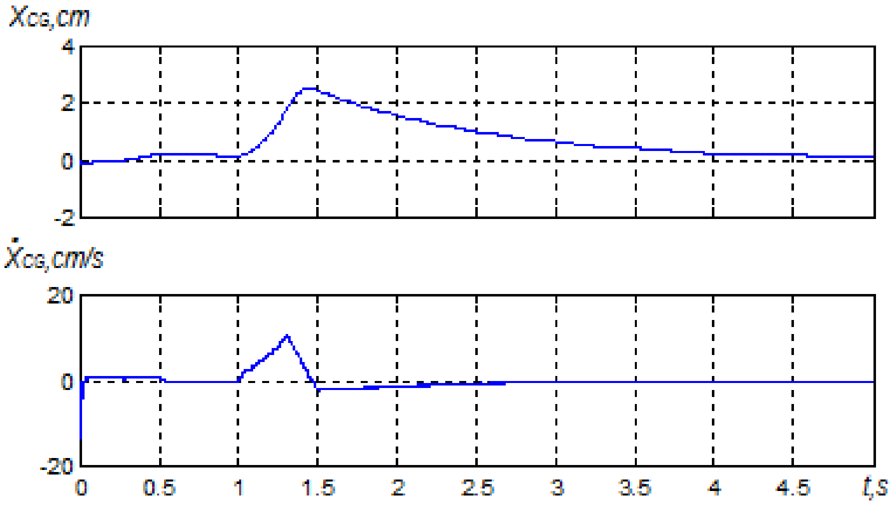


Fig.4.8 – position and speed of robot's mass center along X axis in case of compensation of external disturbance

On phase plane given process is a closed loop with beginning and end in the origin of coordinates (fig.4.9).

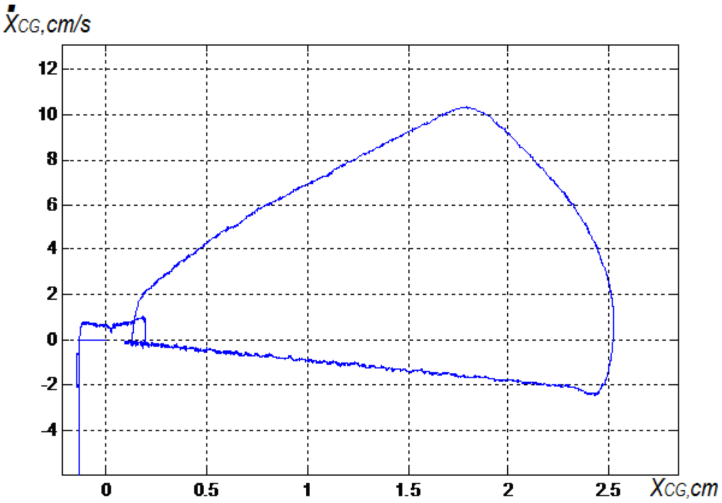


Fig.4.9 – Phase portrait in case of compensation of external disturbance along X axis

Robot’s stabilization system generates control action - torques in robot’s feet, which pull the mechanism back into the balanced condition (see Fig.4.10).

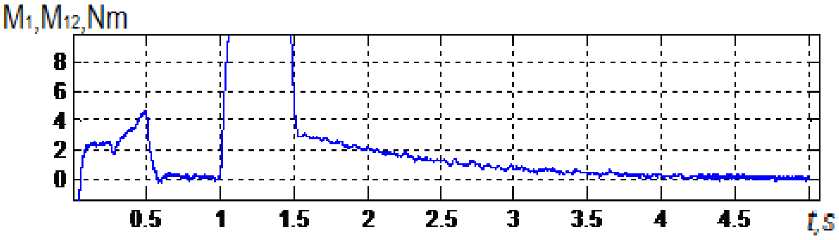


Fig.4.10 – torques in robot’s feet

4.4.2 Stabilization in frontal plane

At first there was described the case when disturbing force abruptly affected robot’s pelvis. Compliant function in robot is switched off, that is robot’s construction in frontal plane is rigid. Robot under the influence of disturbance deviates relative to one leg aside (second raises), then returns to original position affected by gravity force with certain speed, meets the surface, deviates further with respect to the second leg and so on. As a result robot returns into quiescent state after several cycles of such oscillations.

Force Fz=30N is applied to robot’s pelvis abruptly and acts over a period of 0.3 sec (fig.4.11)

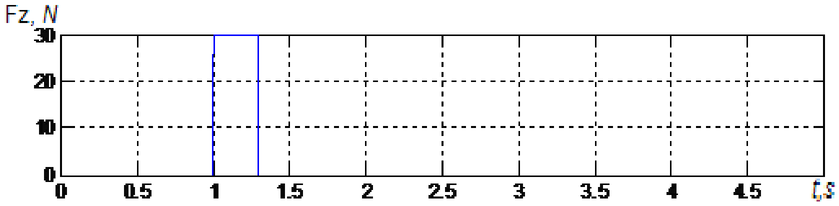


Fig.4.11 – disturbing force Fz

Oscillations of robot's mass center along Z axis fade over in 5 sec. (fig.4.12).

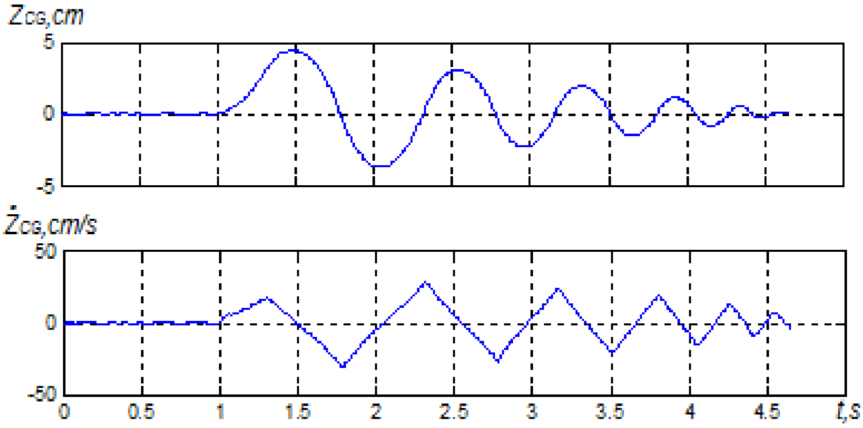


Fig.4.12 – position and speed of robot's mass center along Z axis.

On phase plane this process is a spiral that slowly comes to the origin of coordinates (fig.4.13).

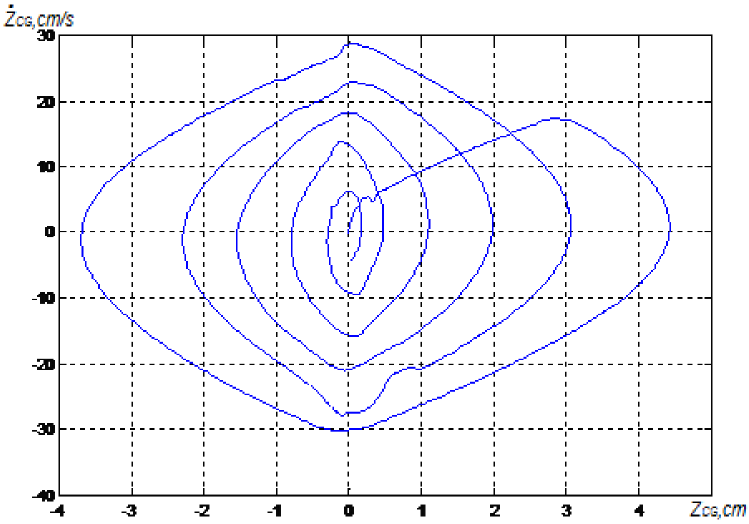


Fig.4.13 – phase diagram for the process of robot's damping in the double support.

With all this robot's contact with surface occasionally intermits (fig.4.14). This factor affects negatively robot's stabilization in sagittal plane, since only one leg has contact with support surface and system's controllability is low.

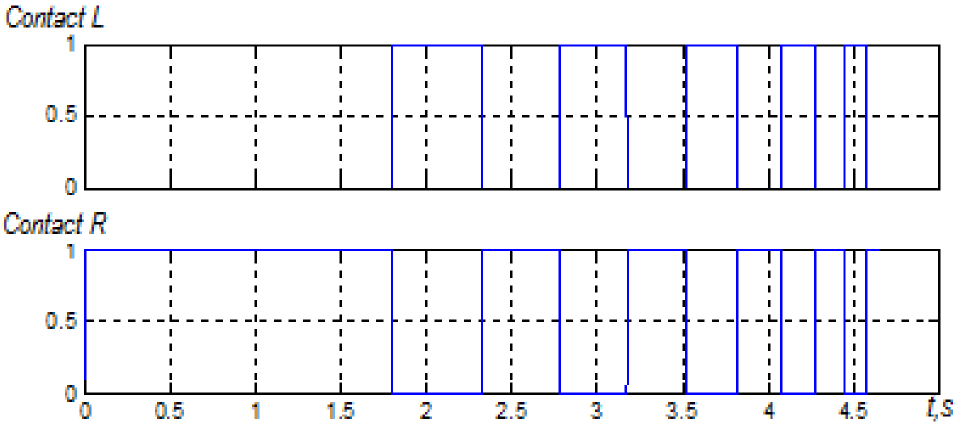


Fig.4.14 – Contact of robot's feet with surface

Now let's assume the case when dependencies (4.1) in robot are switched on and robot's construction becomes compliant in frontal plane relative to the surface. In this case robot's mass center reaction on disturbance happens faster and without oscillations (fig.4.15).

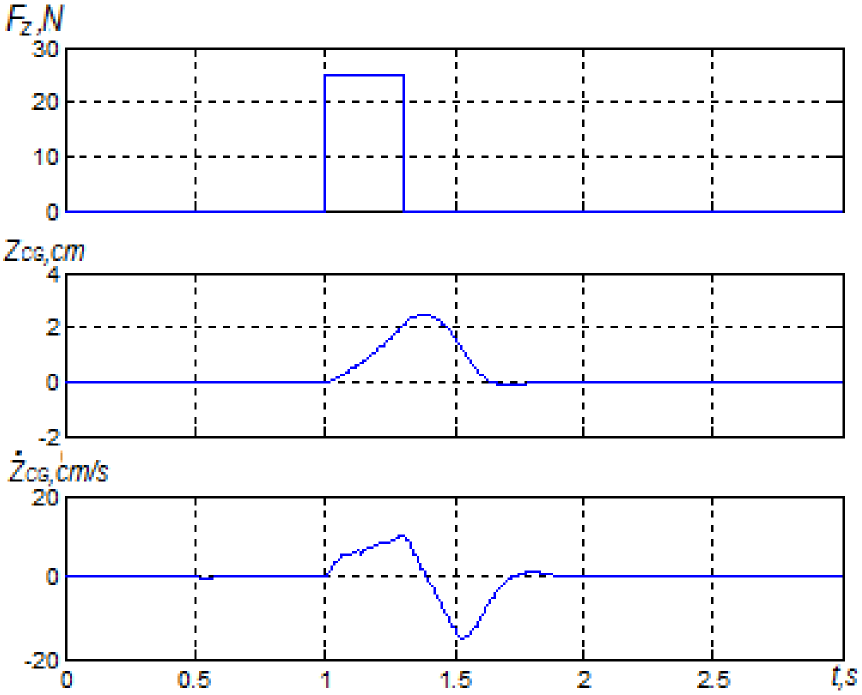


Fig.4.15 – Behavior of robot's mass center at disturbing action in case of robot's compliant construction

On phase plane stabilization process of robot in this case is a loop with beginning and end in the origin of coordinates (fig.4.16).

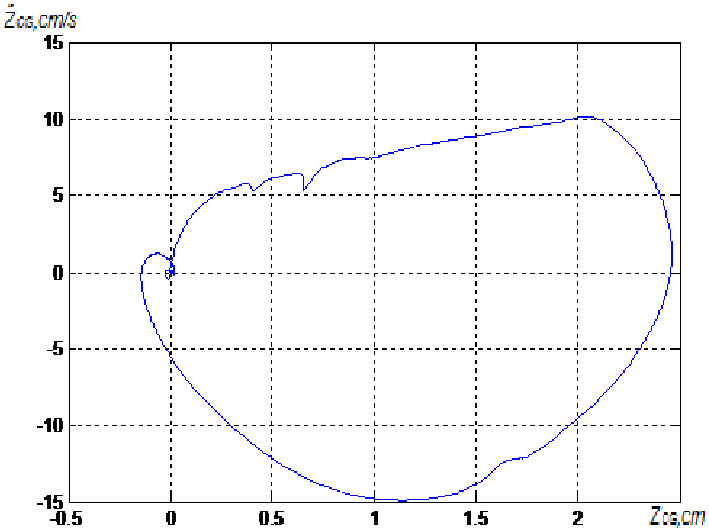


Fig.4.16 – Phase diagram of robot’s mass center movement during the reaction on disturbance in case of robot’s compliant construction.

Robot’s skeleton on top of all that deforms according to dependencies (4.1) (fig.4.17).

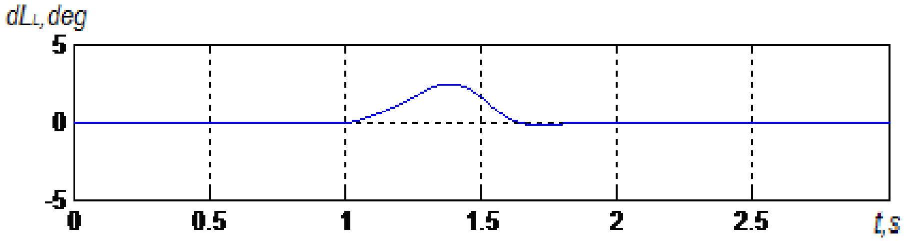


Fig.4.17 – “Deformation” of robot’s skeleton in frontal plane under the influence of disturbance.

Also important is that robot in the given process doesn’t move away legs from surface and always is in the double support (see Fig.4.18). It affects positively stability’s reserve for stabilization system in sagittal plane.

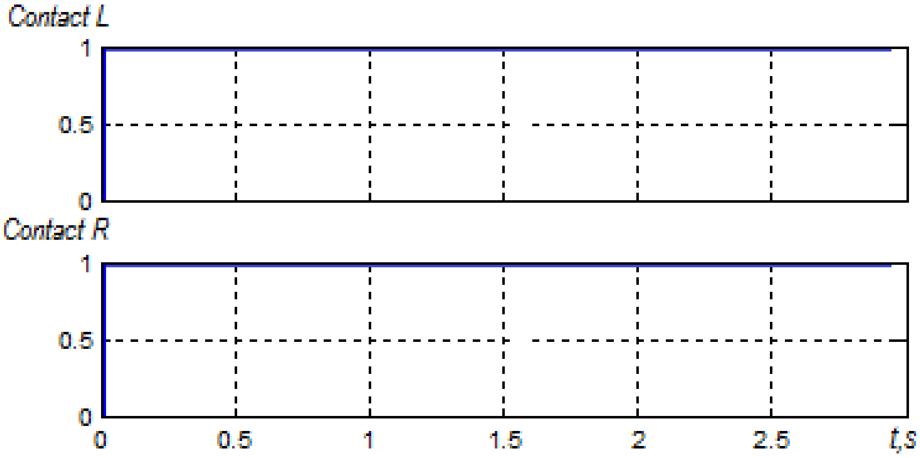


Fig.4.18 – Robot’s feet contact with surface.

Further one can see a process when at the beginning robot's skeleton is "rigid", external force deviates it from equilibrium, then robot returns with certain speed to original position and when robot's second foot has a contact with surface we switch on skeleton's "compliance". As this takes place, robot stops quickly, without any oscillations safely goes into double support state.

Force Fz=30N is applied to robot's pelvis abruptly and acts over a period of 0.3 sec (fig.4.19).

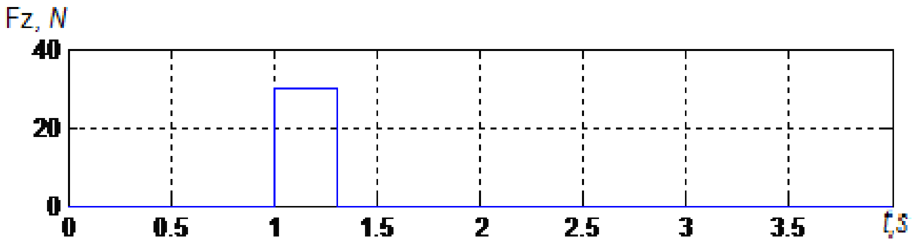


Fig.4.19 – Disturbing force Fz

On time charts (fig.4.20) displacement and speed of robot's mass center along Z axis are shown.

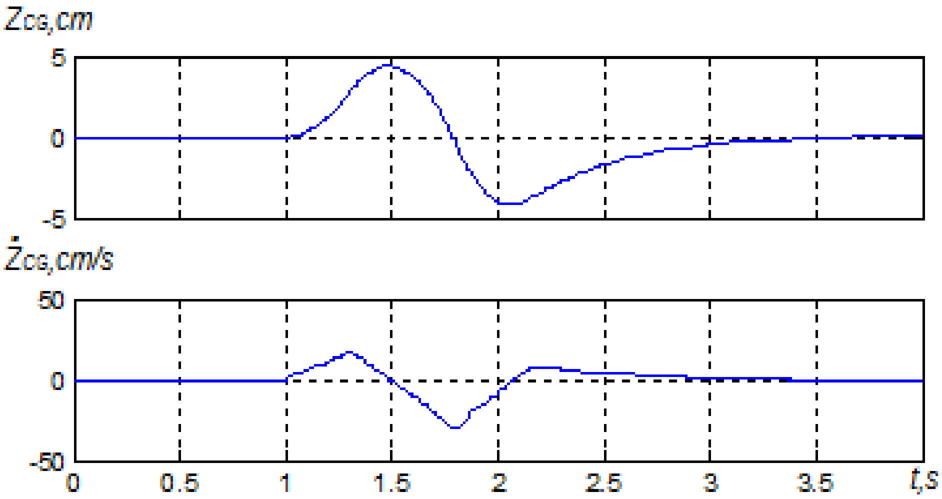


Fig.4.20 – Displacement and speed of robot's mass center along Z axis

On phase plane this process looks like a closed loop with beginning and end in the origin of coordinates (see Fig.4.21).

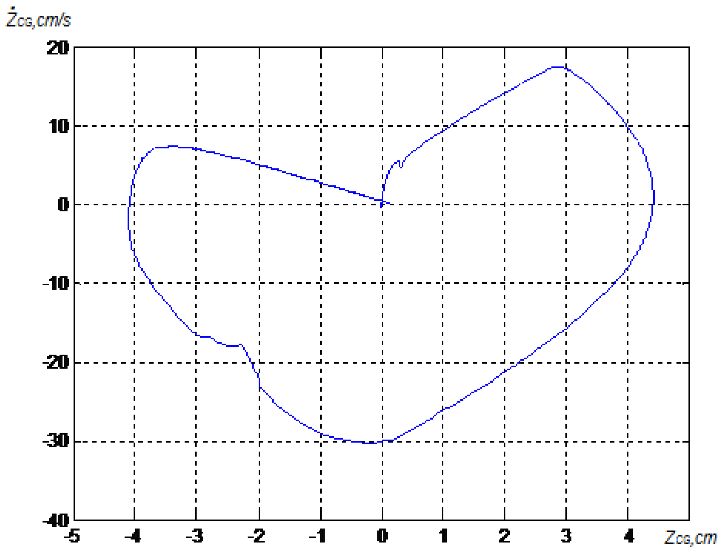


Fig.4.21 – Phase diagram of process of keeping robot in the double support.

Robot’s skeleton in frontal plane deforms as follows:

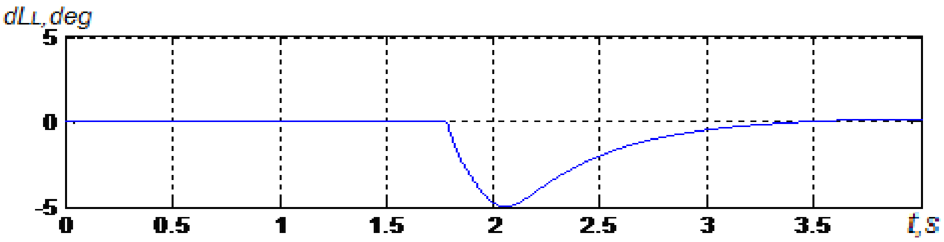


Fig.4.22 – “deformation” of robot’s skeleton when robot meets surface.

Robot’s legs after returning of mass center into equilibrium state have continuous contact with surface (fig.4.23).

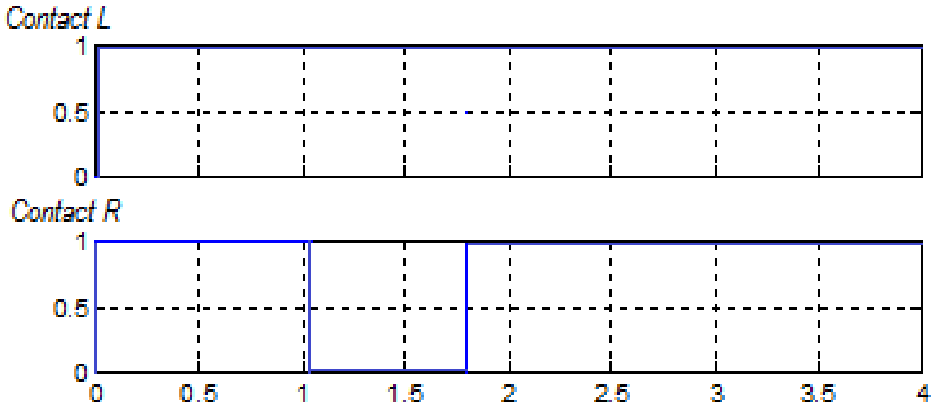


Fig.4.23 – Contact of robot’s legs with surface

The use of kinematical connections (4.1) for robot's skeleton lets us realize robot's stabilization in equilibrium in frontal plane without feet detachment from surface, what affects positively stability's reserve in control system. Also this gives an opportunity to stop robot in the double support after leg has had contact with surface.

4.4.3 Acceleration and deceleration of robot's mass center

There one can see the case when with help of angular torque Mx we accelerate robot's mass center along Z axis until certain set of initial conditions, after this we switch off dependencies (4.1), thus we make skeleton rigid. We set certain initial conditions for robot's mass center, from which it will move along ballistic trajectories (3.1) relative to one of the feet, then it returns back into initial position with certain speed. At the moment when second foot touches support surface we activate dependencies (4.1), and robot's mass center smoothly stops and is pulled back to equilibrium state.

Timing diagram of robot's skeleton "deformation" in frontal plane (see Fig.4.24) consists of 3 parts that determine acceleration of mass center, movement with respect to one foot in the single support state and absorption of impact when second leg meets surface.

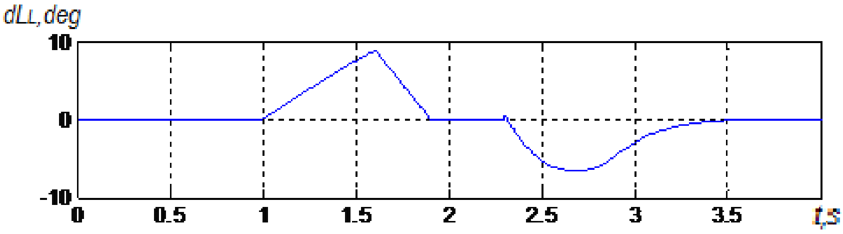


Fig.4.24 – Robot's skeleton "deformation" in frontal plane

Robot's mass center executes motions that are represented on fig.4.25. At the beginning it accelerates, deviates from equilibrium state and then returns to initial position with certain speed, and then is damped in equilibrium state.

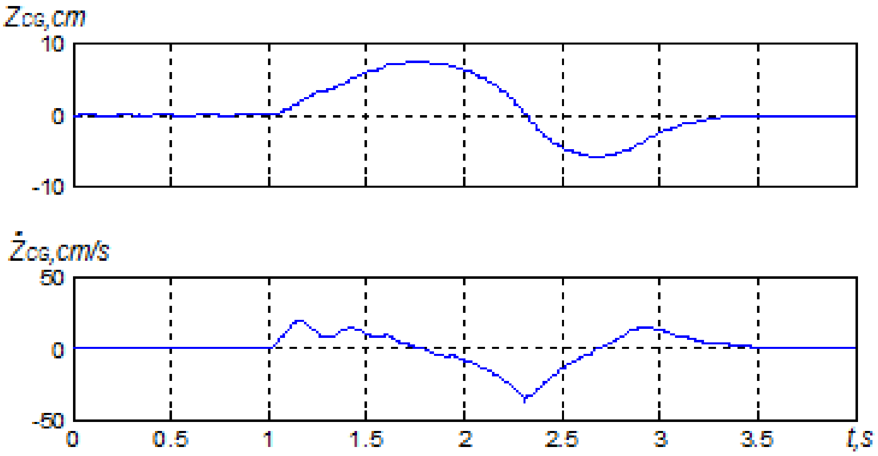


Fig.4.25 – position and speed of robot’s mass center along Z axis.

On phase plane given process is a loop with beginning and end in the origin of coordinates (fig.4.26).

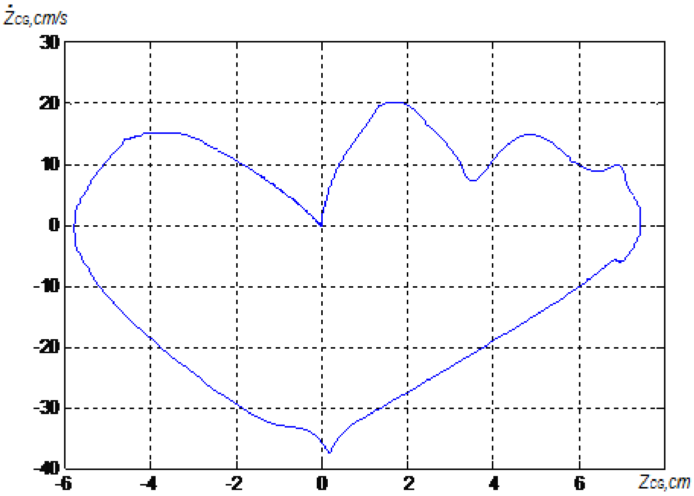


Fig.4.26 – Phase diagram for acceleration-step-damping cycle.

On timing diagrams of robot’s leg contact with bearing surface one can see that robot’s mass center accelerates in the double support, then for some time executes motions in the single support, then is damped and is maintained in balance in the double support state (fig.4.27).

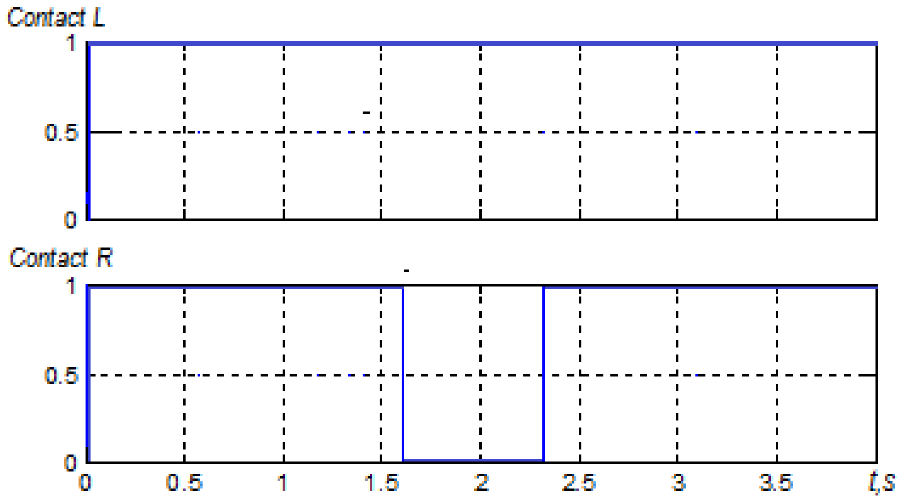


Fig.4.27 – Contact of robot’s legs with support surface

This process is a robot’s step in place. Phase diagram of the process (fig.4.26) shows that step begins and ends with the same set of conditions of robot’s mass center, it means that process can be repeated. Given cycle (acceleration-step-deceleration) will be a basis for the realization of walking of a biped robot that is described in next chapter.

4.5 Experiments

In order to evaluate robot’s performance quality of the stabilization system, experiments with biped robot ROTTO were conducted. Experiments were made for the cases of robot’s stabilization in sagittal and frontal planes in the double support.

4.5.1 Stabilization of robot in sagittal plane with the help of feet

Force Fx=30N is applied to robot’s pelvis abruptly and acts over a period of 0.3 sec. (fig.4.28)

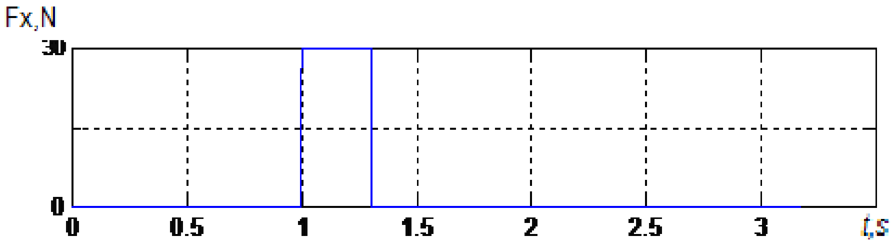


Fig.4.28 – Force Fx

Under the action of this disturbance robot's mass center deviates from equilibrium state and then it is pulled back into balance influenced by stabilization system (fig.4.29).

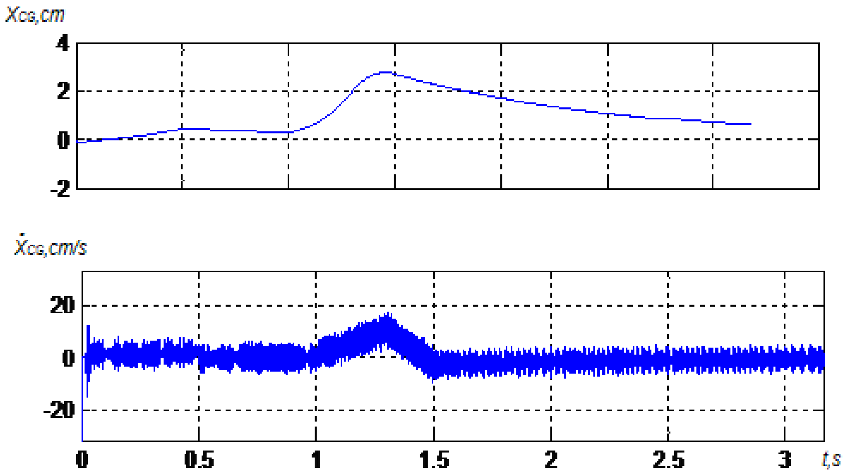


Fig.4.29 – position and speed of robot's mass center along X axis in case of compensation of external disturbance

On phase plane given process is a closed loop with beginning and end in the origin of coordinates (fig.4.30).

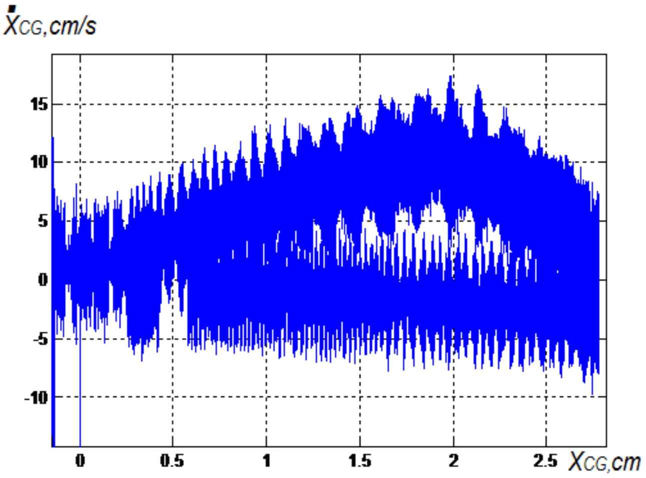


Fig.4.30 – Phase portrait in case of compensation of external disturbance along X axis

Robot's stabilization system generates control action – torques in robot's feet, which pull the mechanism back into the balance condition (fig.4.31).

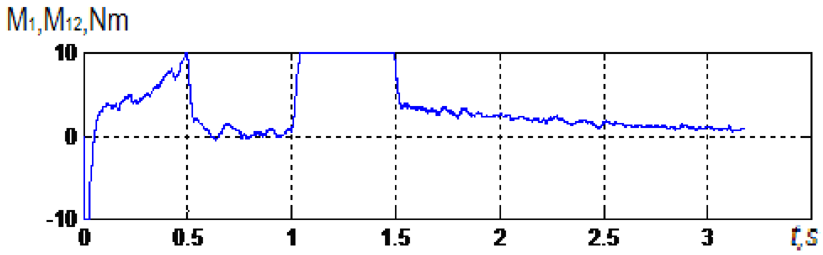


Fig.4.31 – torques in robot's feet

4.5.2 Stabilization in frontal plane

Now let's assume the case when dependencies (4.3) in robot are switched on and robot's construction becomes compliant in frontal plane relative to the surface. In this case robot's mass center reaction on disturbance happens faster and without oscillations (fig.4.32).

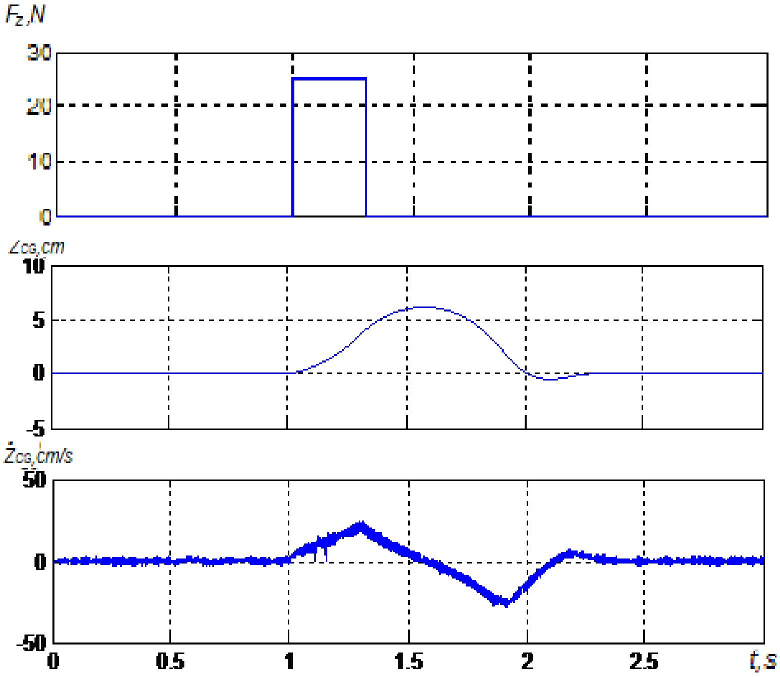


Fig.4.32 – Behavior of robot's mass center at disturbing action in case of robot's compliant construction

On phase plane stabilization process of robot in this case is a loop with beginning and end in the origin of coordinates (fig.4.33).

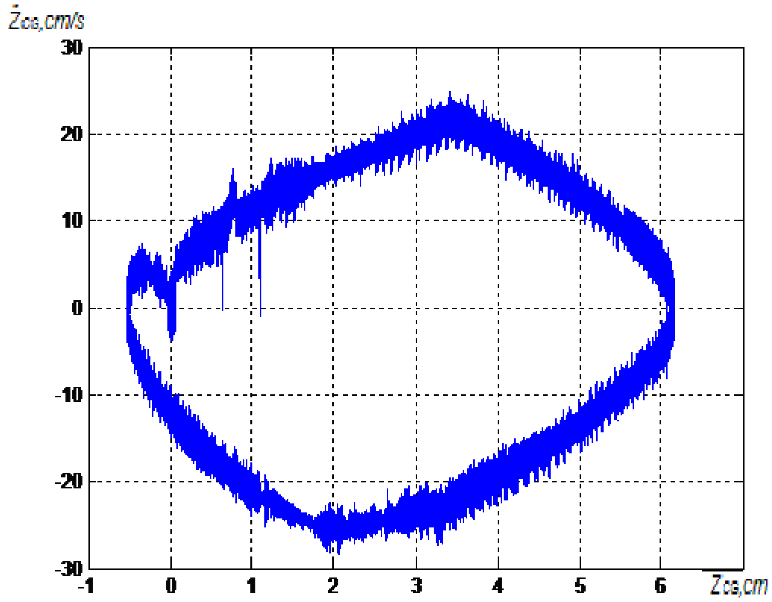


Fig.4.33 – Phase diagram of robot's mass center movement during the reaction on disturbance in case of robot's compliant construction.

Robot's skeleton on top of all that deforms according to equations (4.1) (fig.4.34).

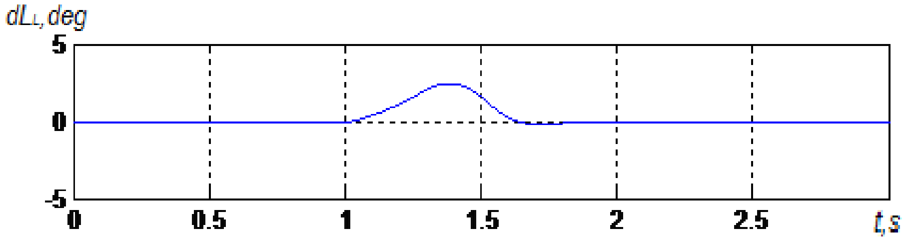


Fig.4.34 – "Deformation" of robot's skeleton in frontal plane under the influence of disturbance.

4.5.3 Acceleration and deceleration of robot's mass center

Robot's mass center executes motions that are represented on Fig.4.35. At the beginning it accelerates, deviates from equilibrium state and then returns to initial position with certain speed, and then is damped in equilibrium state.

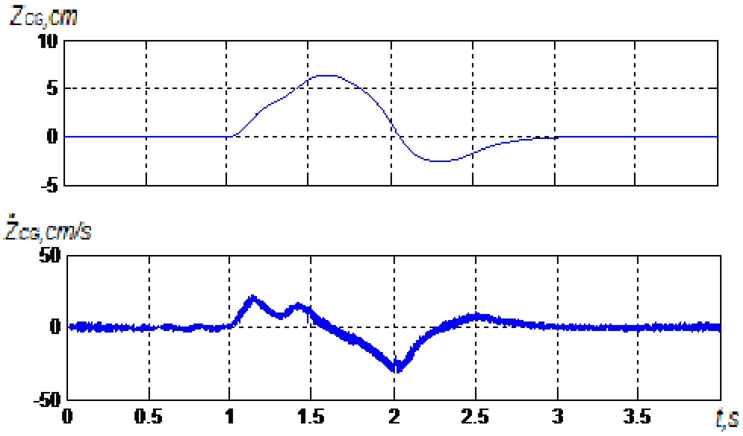


Fig.4.35 – position and speed of robot’s mass center along Z axis.

On phase plane given process is a loop with beginning and end in the origin of coordinates (fig.4.36).

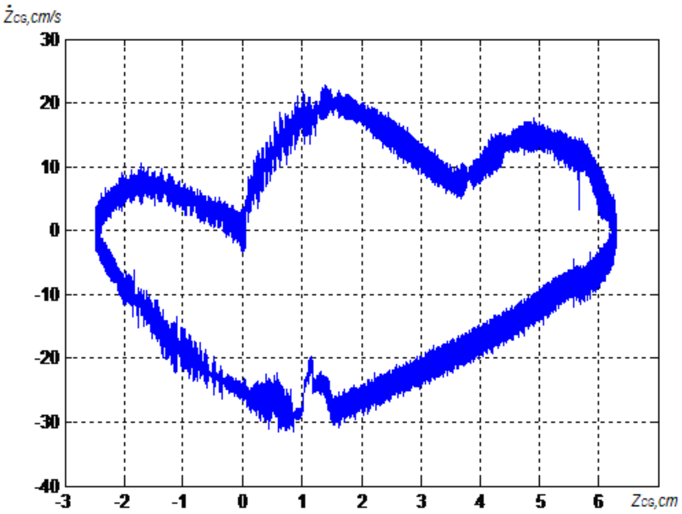


Fig.4.36 – Phase diagram for acceleration-step-deceleration cycle.

4.6 Summary

Proposed stabilization system of a biped robot is based on the evaluation of position of mechanism’s mass center and on keeping it in equilibrium state. Stabilization system realizes also compliant features of mechanical system with respect to support surface. Skeleton’s compliance gives an opportunity to damp robot’s mechanism when it enters in contact with support surface that is being displaced and safely keep it in the double support state.

Kinematic constraints used in proposed stabilization system allow acting torques apply to robot’s center of mass, that allows it’s accelerating to necessary initial conditions.

Possibility of the damping of the robot in double support state after the landing allows keeping the robot to the equilibrium state every time after each step. Acceleration and damping of the robot’s center of mass will be used for the implementation of the step cycle in walking strategy that will be presented in next chapter.

Chapter 5. Walking of a biped robot

Realization of dynamic walking of biped robots still is one of most important problems in robotics. Complexity of the given problem is caused by the complexity of mechanical construction of bipedal mechanisms. Multicoordinate mathematical models cause complexities while building a control system for such mechanisms.

In this chapter process of walking of biped robot is viewed generally. In order to simplify the task robot is viewed as a single-mass mechanic system. In this chapter are also considered robot's movement trajectories while walking, criteria for stable walking. It is also deal with the issue of applying control actions to robot in order to stabilize walking process.

In this chapter concept of walking realization for robot ROTTO is introduced. Proposed concept is based on stabilization of walking process in the double support phase. Results of simulation and experiments, and also evaluation of suggested walking algorithm are presented in this chapter.

5.1 General terms of Walking

Process of bipedal walking as shift of certain mass $\mathbf{m_{CG}}$ along X axis is considered (fig.5.1). Mass $\mathbf{m_{CG}}$ is fixed on rod, which is fixed with help of revolute joint to bearing surface in point **A**. Point **A** moves discretely and interprets the change of robot's support foot. It is influence of movement of swing leg on movement of mass $\mathbf{m_{CG}}$ disregarded. Speeds of mass $\mathbf{m_{CG}}$ stay the same by the changing of support foot. Movement of mass $\mathbf{m_{CG}}$ is defined by influence of gravity force and torques that are applied in support foot to the rod.

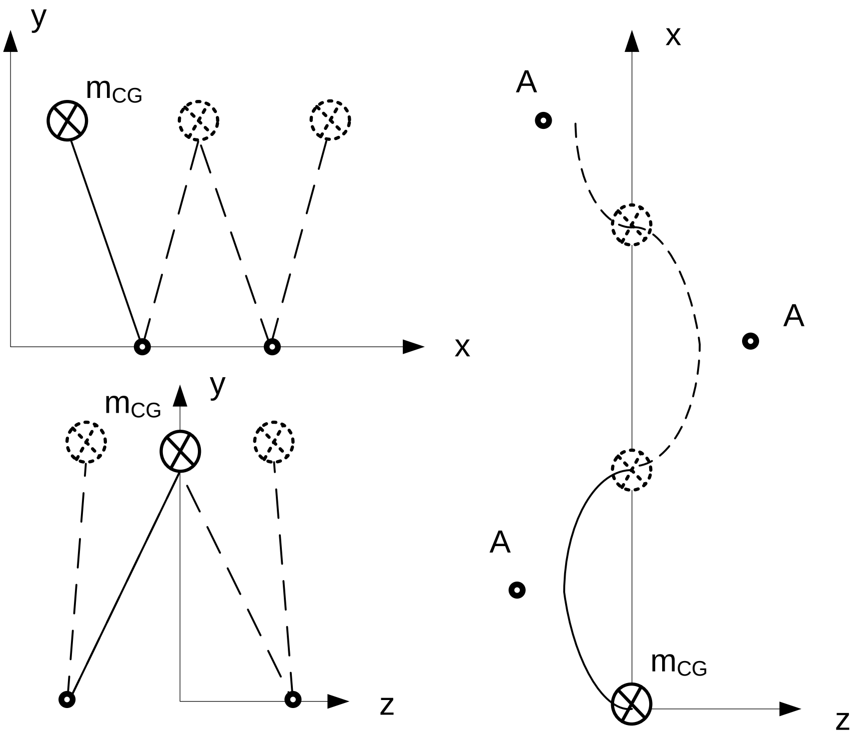


Fig.5.1 – movement of robot's mass center during walking

Let's examine a single step. During pacing it's necessary that robot's mass center moves from the position «0» to position «1», and foot of swing leg moves from position «A» to position «B» (fig.5.2). And also it is important that movement of mass center from the initial position to final position should not happen faster than transfer of foot of swing leg.

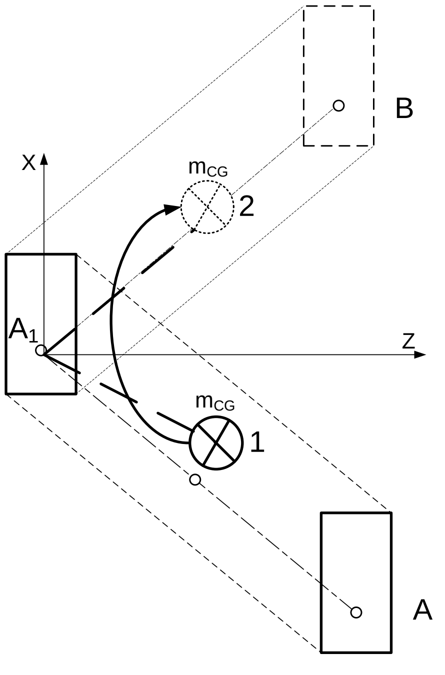


Fig.5.2 – Transfer of robot's mass center during step

Movements of such one-mass mechanical system can be described with following equations:

$$\begin{vmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{vmatrix} = \begin{vmatrix} \dfrac{M_1 + l \cdot m \cdot \cos(q_2) \cdot \left(g \cdot \sin(q_1) + 2 \cdot \dot{q}_1 \cdot \dot{q}_2 \cdot l \cdot \sin(q_2) \right)}{m \cdot l^2 \cdot \cos(q_2)} \\ \dfrac{M_2 + m \cdot g \cdot l \cdot \sin(q_2) \cdot \cos(q_1) - m \cdot l^2 \cdot \dot{q}_1^2 \cdot \sin(q_2) \cdot \cos(q_2)}{m \cdot l^2} \end{vmatrix} \tag{5.1}$$

$$\begin{vmatrix} X_{CG} \\ Z_{CG} \end{vmatrix} = \begin{vmatrix} -l \cdot \sin(q_2) \\ l \cdot \sin(q_1) \cdot \cos(q_2) \end{vmatrix} \tag{5.2}$$

It can also be described with series of phase curves for axis ***x*** and ***z*** that illustrate behavior of this system (fig.5.3):

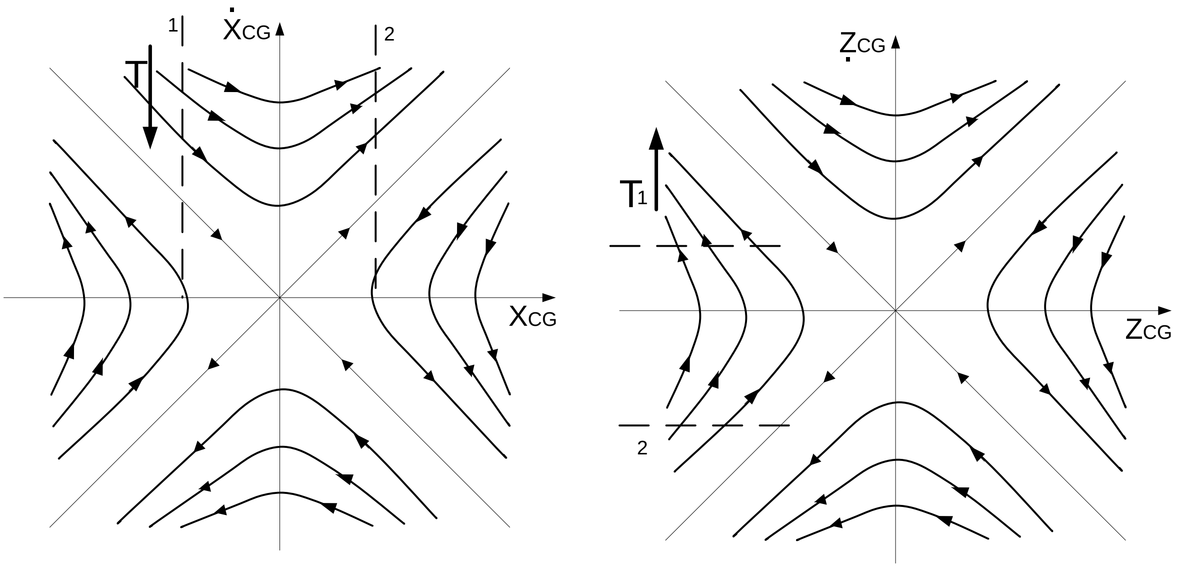


Fig.5.3 – Phase portrait for one-mass system for axis X and Z

Successfully step

At the beginning of step system has vector of initial conditions **[$X_{CG}(t_1)$,$dX_{CG}/dt(t_1)$,$Z_{CG}(t_1)$,$dZ_{CG}/dt(t_1)$].** These initial conditions define further movement of the mass **m_{CG}** (fig. 5.4). In order to take a step successfully it is necessary that initial speeds of mass center match in a certain way initial positions relative to support point.

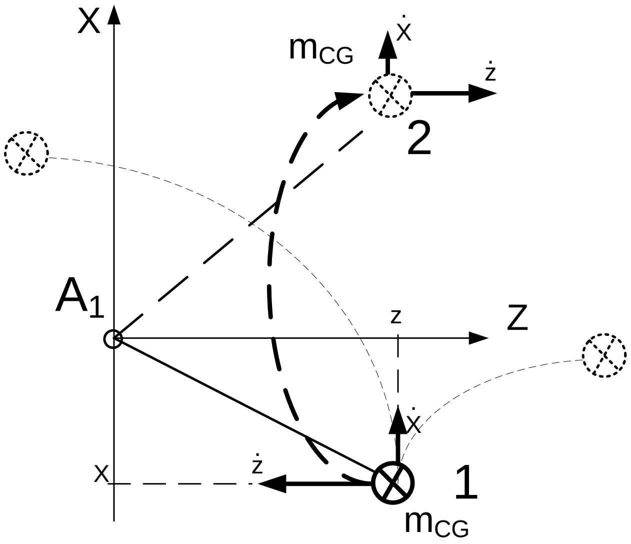


Fig.5.4 – movement of robot's mass center during step
here: 1 – initial conditions, 2 – final conditions

Series of phase curves for our system relative to ***x*** axis is represented in Fig.5.3. It is important that initial states **$X_{CG}(t_1)$,$dX_{CG}/dt(t_1)$** would belong to phase trajectory in upper quarter of phase portrait.

Vector **T** shows that at same initial position of mechanism **$X_{CG}(t_1)$** movement of robot's mass center from position 1 to position 2 will happen faster when initial speed increases. Movement of robot's mass center along **z** axis is represented in Fig.2b. Here one can see that at certain initial states **$Z_{CG}(t_1)$,$dZ_{CG}/dt(t_1)$** robot's mechanism will stay on one feet certain time and then will return in initial position. Value of initial speed **$dZ_{CG}/dt(t_1)$** is defined by time which robot can stay on one foot. This is shown by direction of vector T.

Stable walking

Stable walking can be defined through repeatable phase curves of the CoM movement. Main principles of orbital stability are described in papers [5], [15], [21], [24].

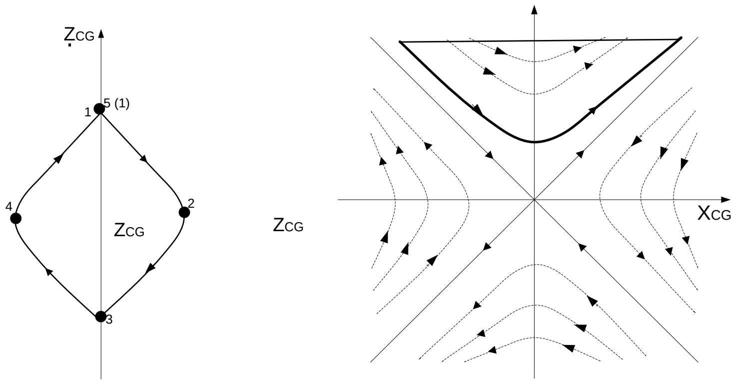


Fig.5.5 – repeatable phase curves of the CoM movement

For the Repeatability of phase curves the following conditions have to be fulfilled:

$$\begin{vmatrix} X_{CG}(t_0) \\ \dot{X}_{CG}(t_0) \\ Z_{CG}(t_0) \\ \dot{Z}_{CG}(t_0) \end{vmatrix} = \begin{vmatrix} X_{CG}(t_1) \\ \dot{X}_{CG}(t_1) \\ Z_{CG}(t_1) \\ \dot{Z}_{CG}(t_1) \end{vmatrix} \tag{5.1}$$

Thus it can be said that during walking it is necessary that with every change of support foot, that is in the beginning of every step, right correspondence between position of robot's support position and its mass center speed have to be provided. This correspondence should predetermine that:

- Robot's mass center moves from position 1 in position 2 along **x** axis
- Robot's mass center does return motion along **z** axis
- Time of movements along Z axis is equal to time of movement along **x** axis, it determines right form of robot's trajectories of mass center movement in plane **xz**.

Necessary initial conditions of each step can be found by optimization method that is described in papers [2].

Stabilization

Research of given mathematical model shows that system is quite sensitive to set of initial states, to impacts by the landing of robot and system must be stabilized by walking. From the above reasoning we can suggest several ways of stabilization of walking process:

1. To control robot’s mass center trajectory with help of torques in robot’s feet in such a way that it would correspond to the position of support point in the next step. Disadvantage of this method is that time constant of control loop for such system is quite big, torque in foot is limited, and system in the single support is hard to control, since robot’s mass center is situated outside the bearing polygon of foot.
2. To transfer leg depending on velocity of mass center respectively to phase portraits of mechanism and thus provide correct initial states for the next step. This method of stabilization is hard to realize because it leads to appearance of positive feedback in robot’s control system. Also delay in following trajectories make this method quite problematic.
3. Foot stabilization in double support phase

5.2 Implementation of biped walking

Following works describe walking organization for biped robots [20], [23], [26], [28], [32], [33], [37], [39]. Implementation of walking of biped robot Rotto is described further. There are three cases of walking presented:

- Planar walking in frontal plane with a rod support
- Planar walking in sagittal plane with a rod support
- 3D walking without a rod support

First two cases are easier to implement in comparison with third case.

5.2.1 Walking in place

There is considered process of robot walking on the spot with instantaneous double support phase. During every step robot deviates relative to support foot and returns back in initial position with certain speed (fig.5.6).

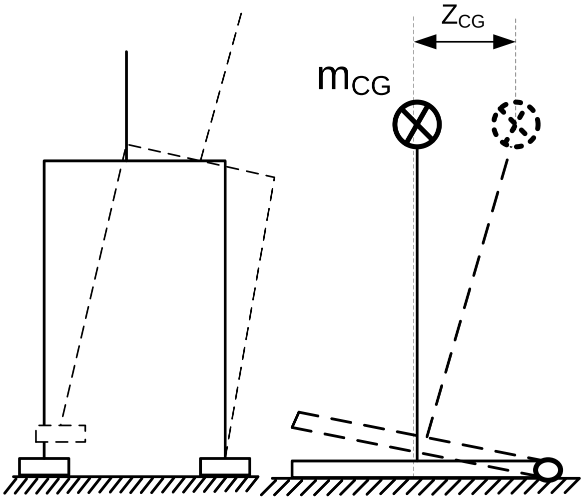


Fig.5.6 – Robot's movement in frontal plane during step

Movement of robot's mass center on phase plane is a curve that connects points 1 and 2 (fig.5.7). This curve belongs to area 1 on phase plane. Depending on value of initial speed in point 1 value of robot's mass center deviation from initial state during step and time of taking a step T change.

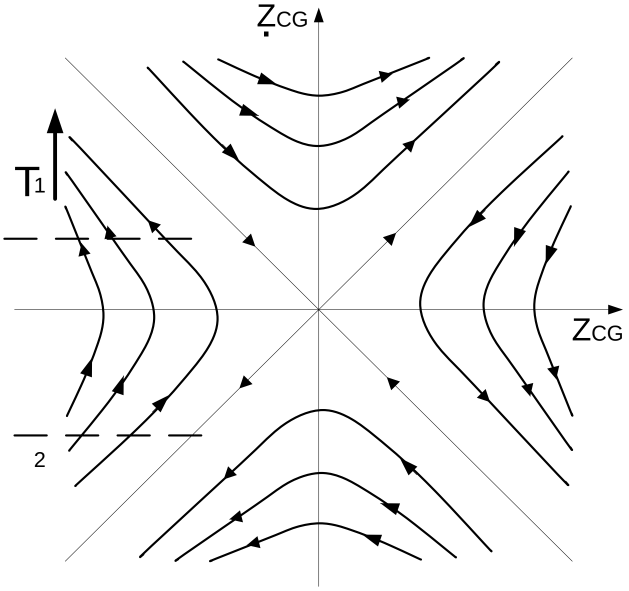


Fig.5.7 – Phase portrait for one-mass system in frontal plane

Sequence of such steps is a periodical oscillation process that is described in [x]. Robot's movement is viewed as movement of mass $\mathbf{m_{CG}}$ fixed on the rod in relation to support point (fig.5.8).

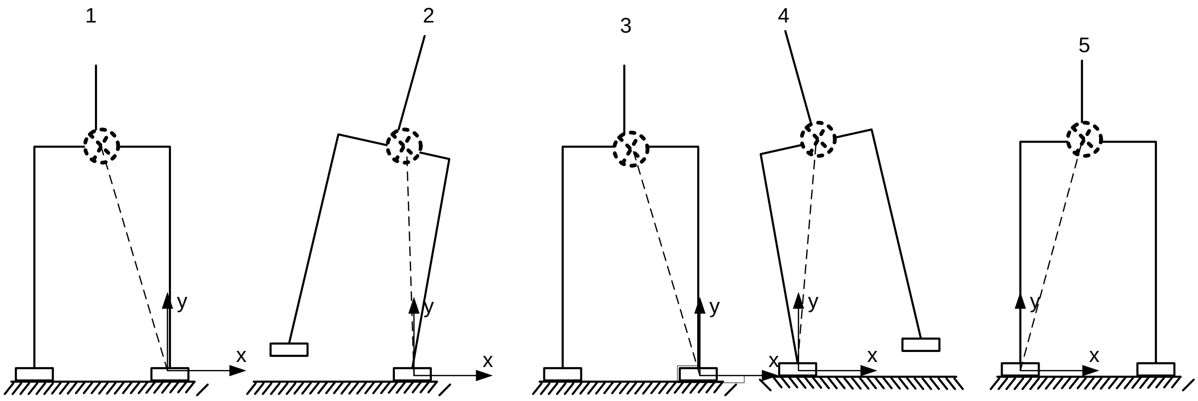


Fig.5.8 – step cycle in frontal plane

Stability of given process lies in repetition of movement trajectories on phase plane (fig.5.9).

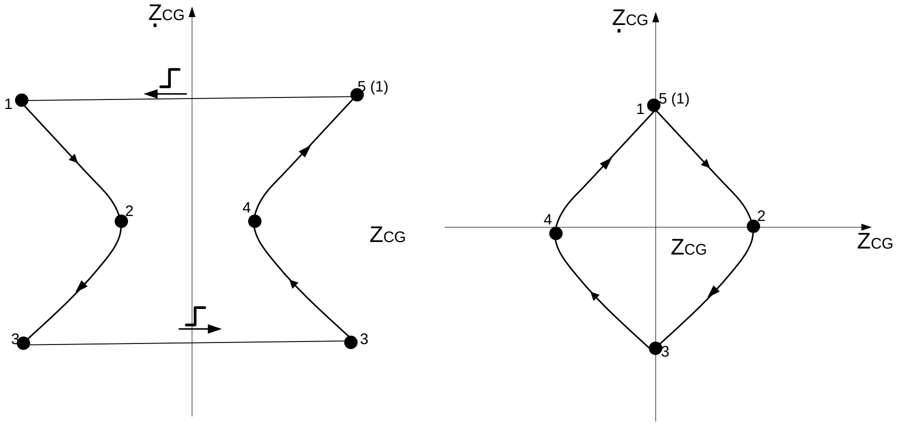


Fig.5.9 – phase portrait of stable walking in frontal plane

Accordingly, it is necessary to mention: for repetition of step cycle in planar walking on the spot following conditions have to be satisfied:

- Vectors of states [Z_{CG},dZ_{CG}/dt] in the beginning of step should correspond to the vector of states[Z_{CG},dZ_{CG}/dt] at the end of step, i.e. in the beginning of next step.
- Criterion of stability during the step: Initial states [Z_{CG},dZ_{CG}/dt] should belong to phase curve that lies in area 1 of phase plane

Simulation of walking on the spot with instantaneous double support phase

Displacement of robot’s mass center is an oscillation process (fig.5.10). Values of states [Z_{CG},dZ_{CG}/dt] at the end of every step are equal to the states at the beginning of step.

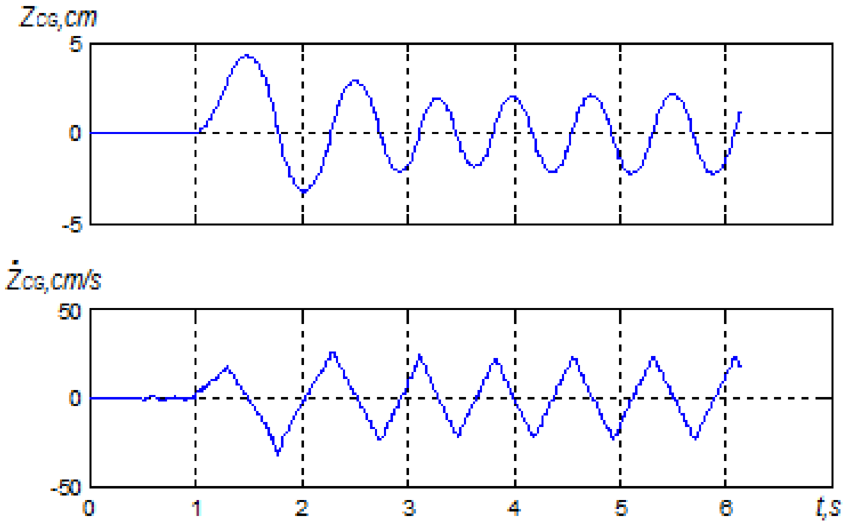


Fig.5.10 – displacement and speed of robot's mass center along z axis during walking on the spot

Phase trajectories on fig. 5.11 show orbital stable walking on the spot.

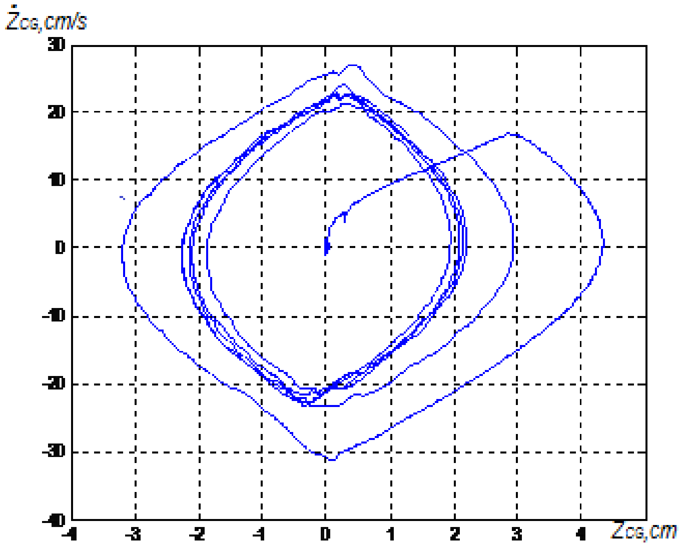


Fig.5.11 – phase portrait of robot's mass center movement during walking on the spot

Walking on the spot with prolonged double support phase

Let's discuss such type of walking on the spot, in which robot accelerates at every step until state that correspond to desired phase trajectory, robot takes a step, and when swing leg has a contact with surface it damps and stops.

At this organization of step cycle phase portrait looks like this

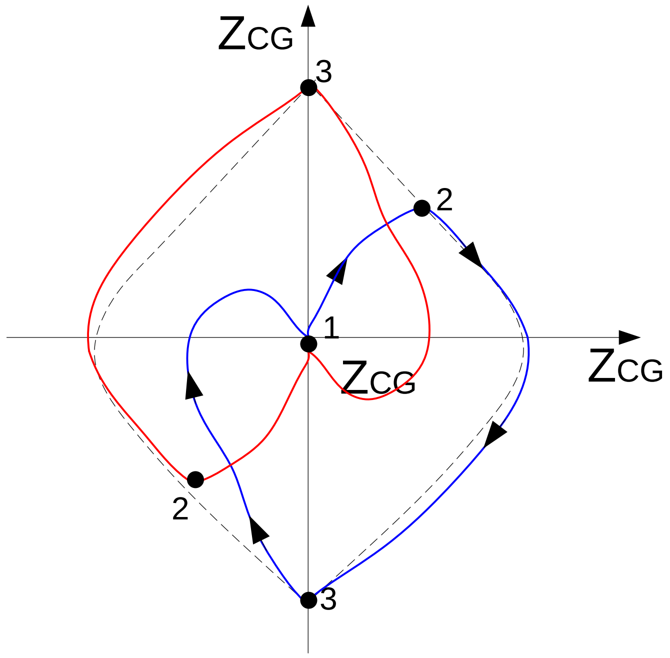


Fig.5.12 – phase portrait by walking on the spot with stops between steps

Advantage of this stride cycle is that robot's states after every step are reduced to zero, after that are accelerated to necessary values. It allows stabilizing of step cycle.

Simulation of walking on the spot in the double support

Time diagram of robot's mass center displacement along z axis (fig.5.13) shows sequence of acceleration-step-deceleration for some steps on the spot. On the speed graph one can clearly see periods when robot is in the quiescent state.

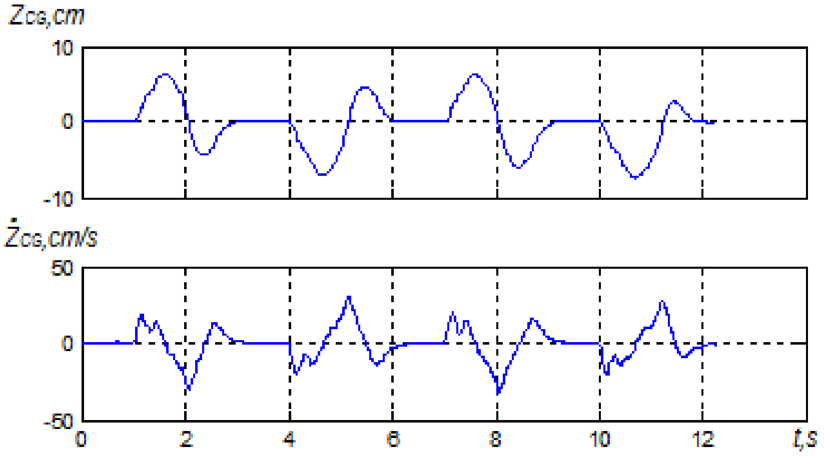


Fig.5.13 – displacement and speed of robot's mass center along z axis while walking on the spot with pauses between steps

On phase diagram it is seen that robot's mass center from quiescent state accelerates to states that correspond to desired phase trajectory, then it moves freely on this trajectory in the single support phase (fig.5.14). Upon contact with surface robot is being damped and it stops in the initial quiescent state. Then the process is repeated. Curves on phase plane occur again, it means that there is an orbital stable walking on the spot.

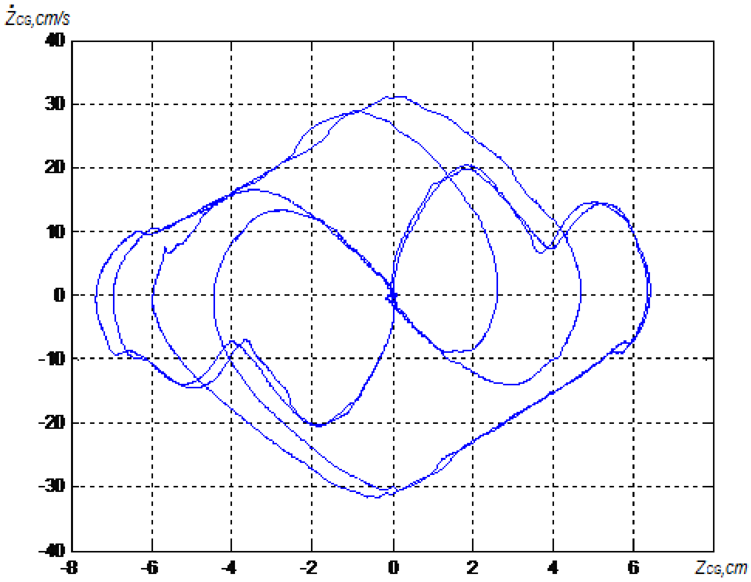


Fig.5.14 – phase portrait at walking on the spot with stops between steps

In this section 2 fundamentally different methods of organization of phase cycle are represented:

- With instantaneous double support phase
- With prolonged double support phase

In the first case for ensuring stable walking process it is necessary that initial states at the beginning of the step [Z_{CG},dZ_{CG}/dt] were such that final states [Z_{CG},dZ_{CG}/dt] would be equal.

In the second case condition of process stability is simplified. It is in fact necessary that robot's mass center would return to initial state at the end of the step, but speed value of mass center doesn't matter, as in the double support phase robot will be stopped.

Thus we can say that presence of double support phase in stride cycle makes walking process simpler for the stabilization, since in the double support mathematical model of robot's mechanical system is easier to control.

5.2.2 Walking in sagittal plane

To begin with, let us consider walking in sagittal plane. The backbone of it in the fact that transferred leg is always ahead of robot's mass center movement along X axis.

Walking process is a movement in plane of certain mass in coordinate system XY, where X_{CG_1} – position of mass center relatively to support point, X_{CG_2} – position of foot of swing leg relatively to mass center, V_{CG} – horizontal component of speed of mass center movement (fig.5.15).

During robot's walking orbit of phase coordinates X_{CG} V_{CG} can be situated in one of three zones (fig.5.16). In zone "1" runs orbital stable walking process, in zone "2" energy of mechanism is too big and robot falls ahead, in zone „3" kinetic energy is insufficient and robot falls back.

The aim of the paper is formation of stable walking, which is characterized by closed orbit of phase coordinates in plane X_{CG} V_{CG}. On the basis of given description following requirements to the process are specified:

1. Orbital stability of the process in zone "1" (fig.5.16).
2. Resistance to external disturbances

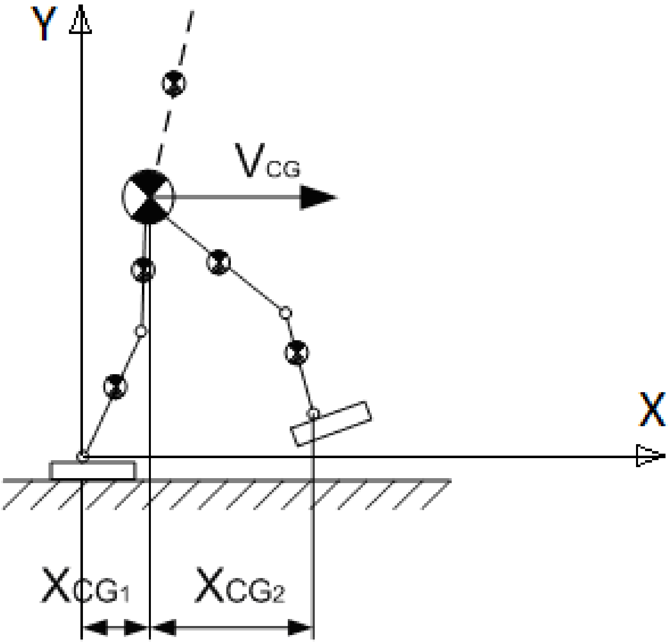


Fig.5.15 – Movement of robot in sagittal plane

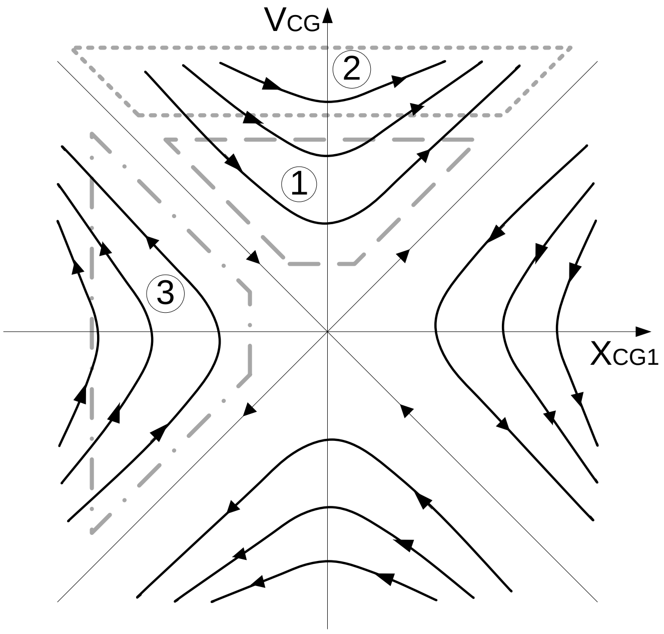


Fig.5.16 – Series of phase trajectories for mechanism in sagittal plane

In order to organize walking of robot in sagittal plane it is necessary that:

- Robot moves ahead along trajectories «1»
- Swing leg moves to the next support point faster than robot moves along trajectories «1»
- ▪ Next support point should correspond to robot’s speed in such way that state vector would correspond to trajectory 1 in the next step.

For the implementation of these requirements it is necessary to arrange walking algorithm.

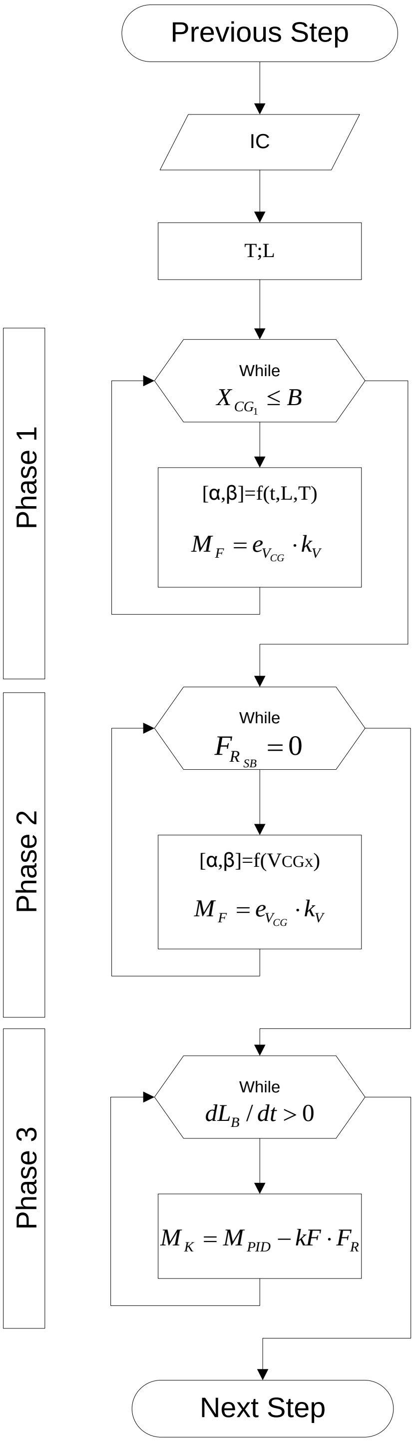


Fig.5.17 – Walking algorithm in sagittal plane

For implementation of walking control system was built (fig.5.18). Control system consists of state machine, robot's stabilization system on phase trajectories and generator of swing leg trajectories.

Current process phase is defined based on values of position and robot's mass center speed relatively to support point and information about contact with surface from force sensors in robot's feet.

Stabilization system maintains robot's movement relatively to support point along desired phase trajectory and secures system's stability to external disturbances.

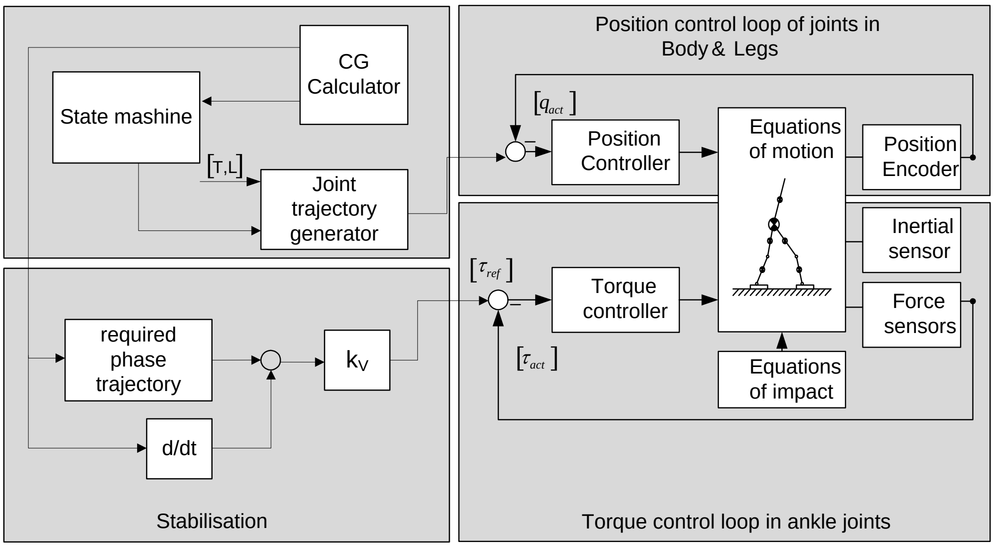


Fig.5.18 – Control system of planar walking in sagittal plane

On fig.5.19 time diagrams of mechanism movement are shown. On Fig.5.20 phase diagram of movement is represented.

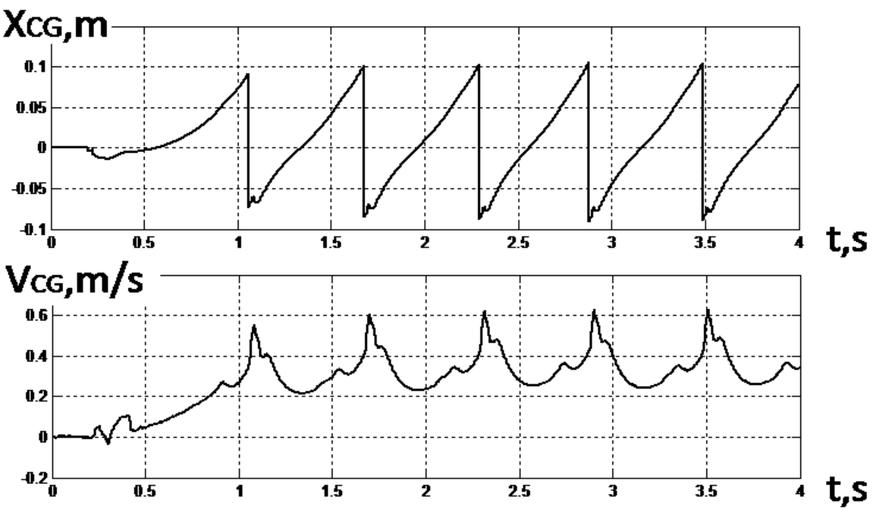


Fig.5.19 – timing diagrams of robot's mass center movement along X axis

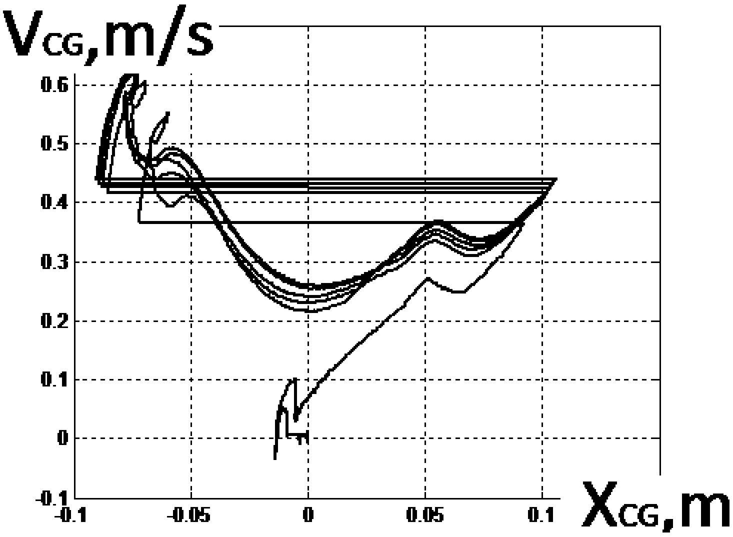


Fig.5.20 – phase diagram of robot's mass center movement along X axis

Using proposed concept it was possible to realize dynamic walking of robot Rotto in a circle with step length 25cm and step duration approximately 0.8sec. Process of walking is represented on Fig.5.21.

Fig.5.21 – Walking of robot Rotto in sagittal plane

On Fig.5.22 time diagrams of mechanism movement are represented. On Fig.5.23 phase diagram of its movement is shown.

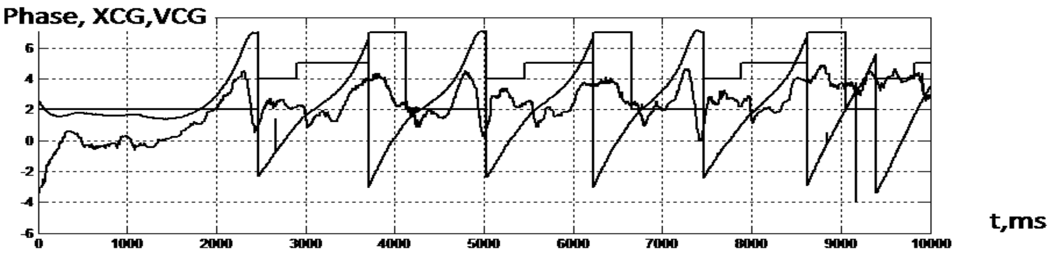


Fig.5.22 – robot's mass center movement along X axis

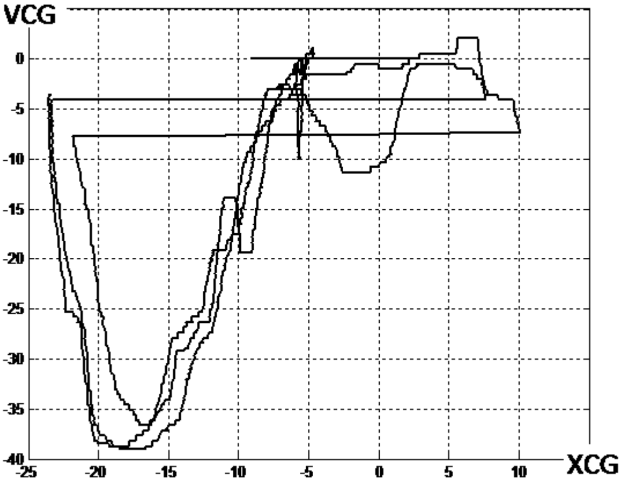


Fig.5.23 – phase diagram of robot's mass center movement along X axis

5.3 Walking in space

In the latest works in our laboratory gaits with instantaneous double support phase were realized. In addition while changing the support foot speeds were distributed quite stochastic. It was large disturbance. It was quite hard to compensate these disturbances in the single support with the help of torques in the feet.

5.3.1 Strategy

In this work is suggested another walking strategy, which based on usage of prolonged double support phase. In the double support phase robot will stop, i.e. speed of mass center will be reduced to zero under influence of control system. After stop robot's mass center will accelerate again to necessary states for stepping in the single support phase.

Step is provisionally divided into 4 intervals: stay, acceleration, step and damping. Every phase of step is characterized by movement trajectories ZCG(t),XCG(t), dZCG/dt(t), dXCG/dt(t) and limit values [ZCG,XCG,dZCGdt,dXCGdt] (fig.5.24).

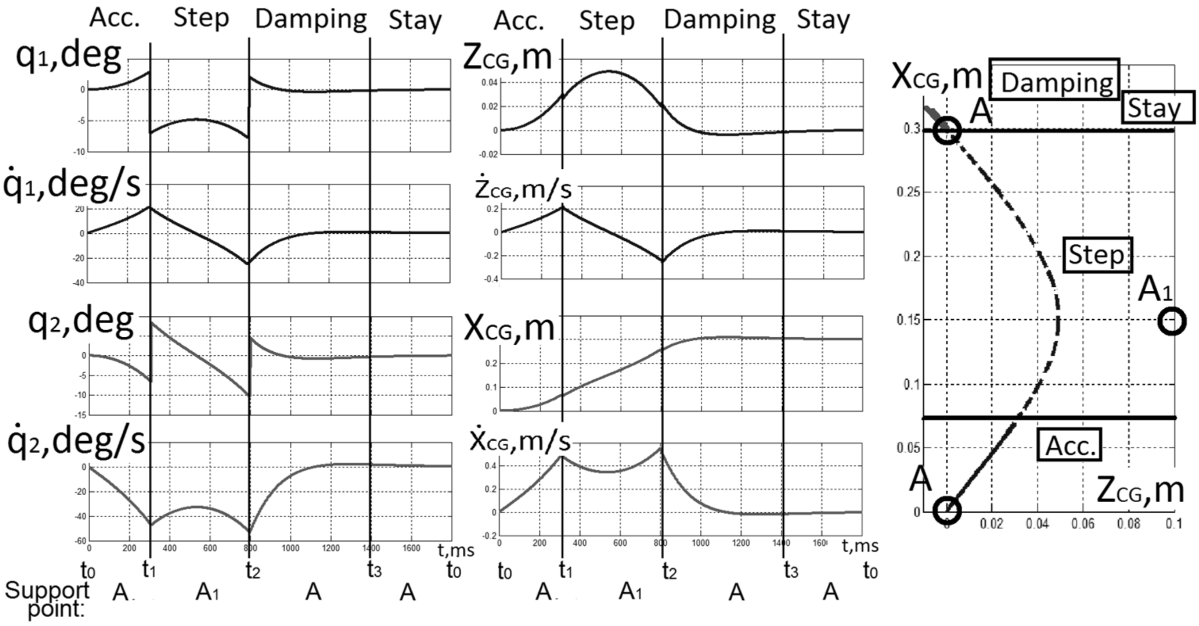


Fig.5.24 – Trajectories of robot's mass center movements during stride cycle with prolonged double support phase

A special feature of this gait is that every step ends with damping phase. Thus robot is in quiescent state like before walking. Let's examine separately every phase of step:

Quiescence. In quiescent state robot stays in the double support phase without any motions under the control of control system. Robot's mass center is kept in center of bearing polygon.

Acceleration. During acceleration (t_0-t_1) robot is still in the double support phase. Robot's mass center accelerates along trajectories (fig.5.24) under the influence of control system. Acceleration trajectories are synthesized offline taking into account acceleration in the double support and ballistic movements in the single support phase. Affected by constant torques **$M_X(t)=M_{XACC}$, $M_Z(t)=M_{ZACC}$** single-mass system in the double support phase is being brought to the states **Z_{CG}**(t_1)=**$0.3Z_{A1}$** with speeds **$dZ_{CG}/dt(t_1)$, $dX_{CG}/dt(t_1)$,** which by movement in the single support phase will bring the system to the states **$X_{CG}(t_2)=L$** at **$Z_{CG}(t_2)=0$.**

Step. After the end of acceleration robot's mass center has states **$[X_{CG}(t_1),dX_{CG}/dt(t_1),Z_{CG}(t_1),dZ_{CG}/dt(t_1)]$**, which determine movement of the system in the single support phase along trajectories (fig.5.22). Swing leg moves along trajectories (see Fig.5.25).

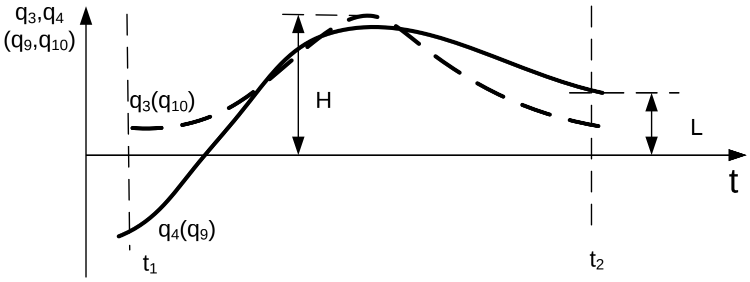


Fig.5.25 – Movement trajectories of joints of transferred leg

Joint movement trajectories of Swing leg are calculated offline by means of inverse kinematics. Parameter **L** corresponds to step length and mass center position in the shifted bearing polygon, **H** – height of leg lifting during transfer.

Damping. After working out of trajectories swing leg of robot meets the surface. Robot's mass center has speeds **$[dX_{CG}/dt(t_2),dZ_{CG}/dt(t_2)]$**, that were acquired during step. On the given stage stabilization system tends to reduce these speeds to zero and kept system's mass center in the center of support polygon. Torques in feet are equal to:

$$\begin{aligned} M_X(t) &= k_P \cdot Z_{CG}(t) + k_D \cdot Z_{CG}(t); \\ M_Z(t) &= k_P \cdot X_{CG}(t) + k_D \cdot X_{CG}(t) \end{aligned} \tag{5.3}$$

Thus stabilization system brings mechanism again to quiescent state.

5.3.2 Control system

Further robot's walking control system is represented (fig.5.26). Main task of this control system is organization of step cycles according to walking strategy that was described earlier. Walking control system consists of following main elements:

- State machine
- Generator of robot's mass center trajectories at acceleration
- Generator of trajectories of robot's joints during leg swing
- Stabilization system of robot in the double support state

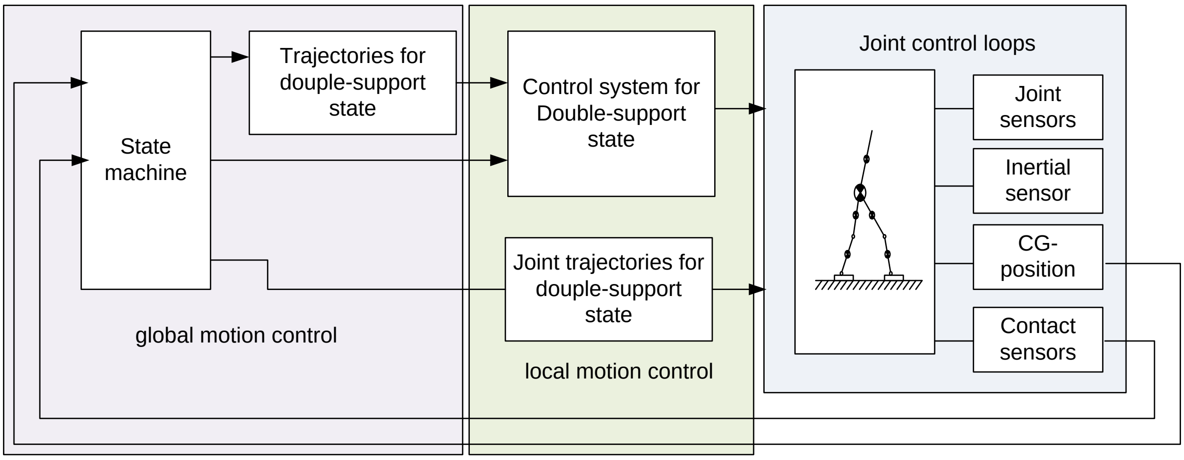


Fig.5.26 – control system of biped robot

Task of state machine is to determine and switch current step phase. State machine operates based on current values of robot's mass center states and information about robot's contact with surface.

Generator of robot's mass center trajectories at acceleration forms robot's movements which bring it to such states that are necessary for moving at stage of single support phase at leg swing.

During movement in the single support phase joints of robot work out trajectories which are necessary for leg swing to the next support point. These trajectories are formed with help of generator of trajectories for single support phase.

Robot's stabilization system in the double support phase is described in chapter 4. Its tasks are to serve trajectories of robot's mass center acceleration and damp robot's mechanism after taking a step and maintain robot in quiescent state.

5.3.3 Simulations of 3D walking

For evaluation of proposed robot's walking concept simulations of control system's performance using contact processing model [25] were conducted.

On the graphs of movement and robot's mass center speed relatively to Z axis (fig.5.27) it is seen that robot stops completely between steps.

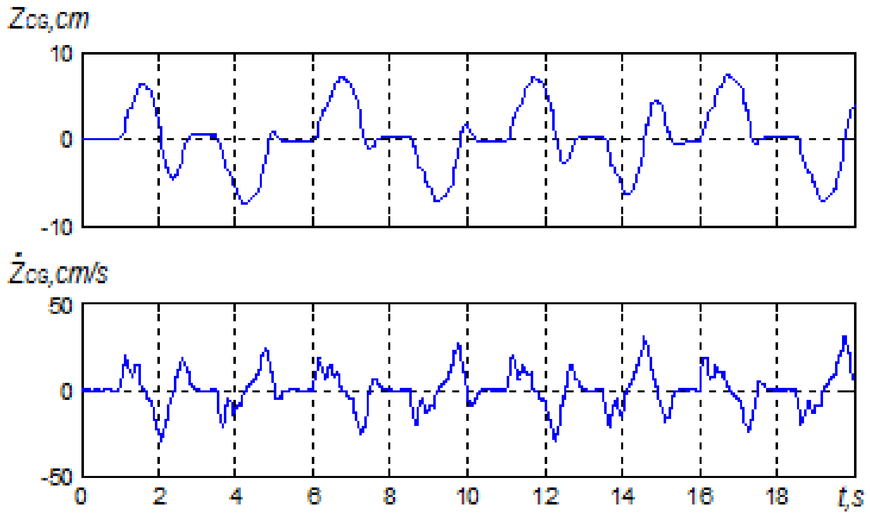


Fig.5.27 – position and speed of robot’s mass center along Z axis

Phase portrait of robot’s mass center movement in frontal plane represents closed repetitive curves. This fact confirms orbital stability of the given process.

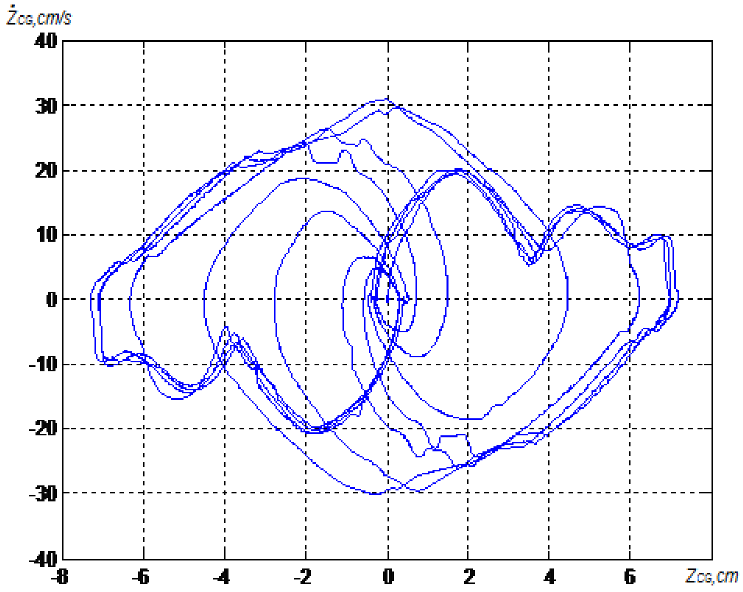


Fig.5.28 – phase portrait of robot’s mass center movements in frontal plane

Robot’s mass center movement in sagittal plane relatively to support foot is represented on Fig.5.29. Step length is approximately 15cm.

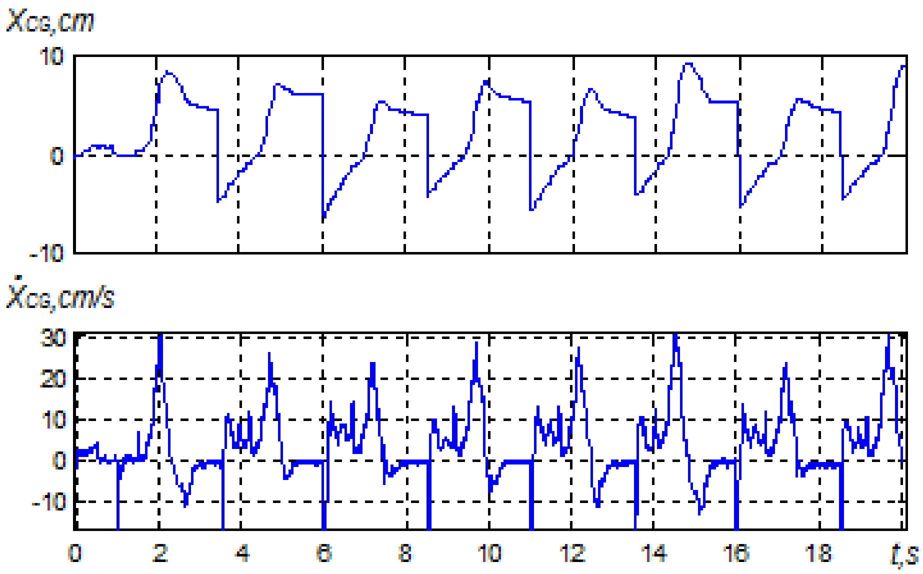


Fig.5.29 – position and speed of robot’s mass center along X axis

Phase portrait of robot’s mass center movement in sagittal plane represents closed repetitive curves. This fact confirms orbital stability of the given process (see Fig.5.30).

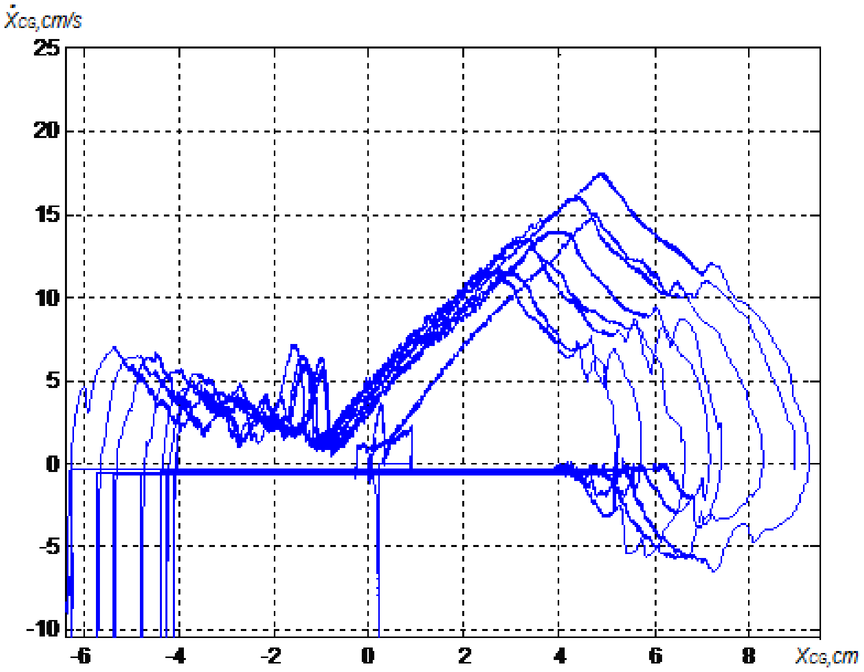


Fig.5.30 – Phase portrait of robot’s mass center movement in sagittal plane

Trace of robot’s mass center movement above support surface is represented on Fig.5.31.

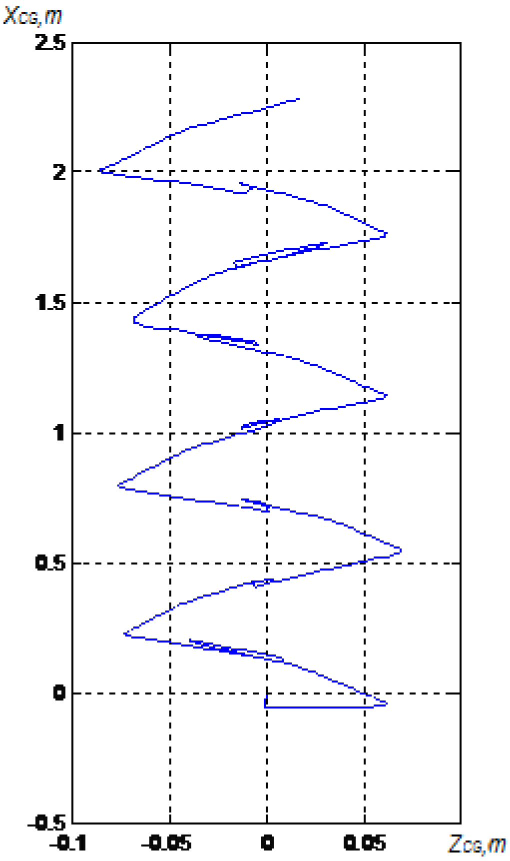


Fig.5.31 – Trace of robot’s mass center movement above support surface

5.3.4 Experiments

Experimental research of performance of robot’s control system was conducted on horizontal support surface. Robot’s mass center movement in frontal and sagittal planes is shown on Fig.5.32a. Graphs are presented also for the results of walking simulation (fig.5.32b) for comparison with the results of experiment.

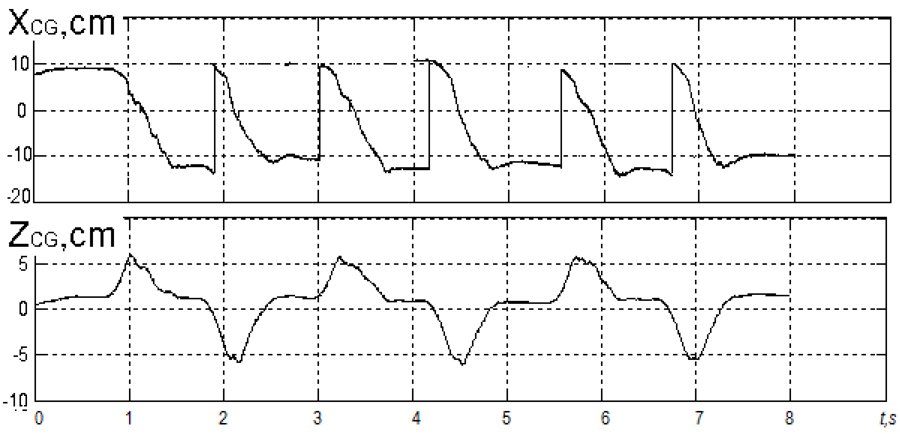


Fig.5.30a – movement of robot’s mass center in frontal and sagittal planes during walking – experiment

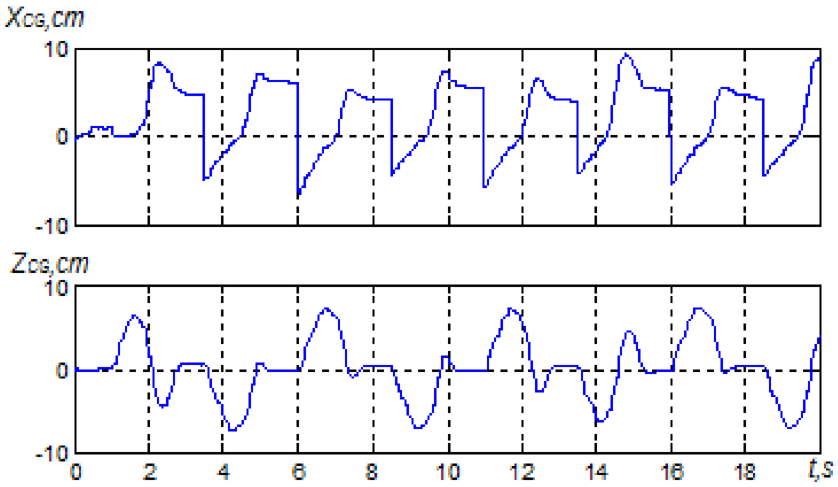


Fig.5.30b – movement of robot’s mass center in frontal and sagittal planes during walking – simulation

Robot’s stabilization system maintains mechanism in balance state with help of torques in robot’s feet (fig.5.33).

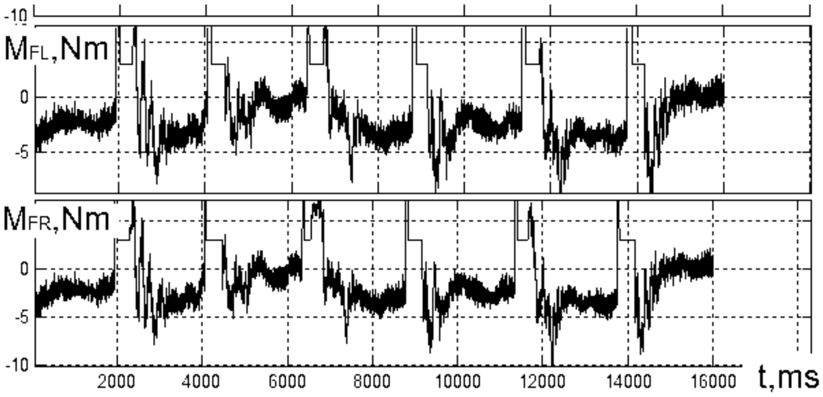
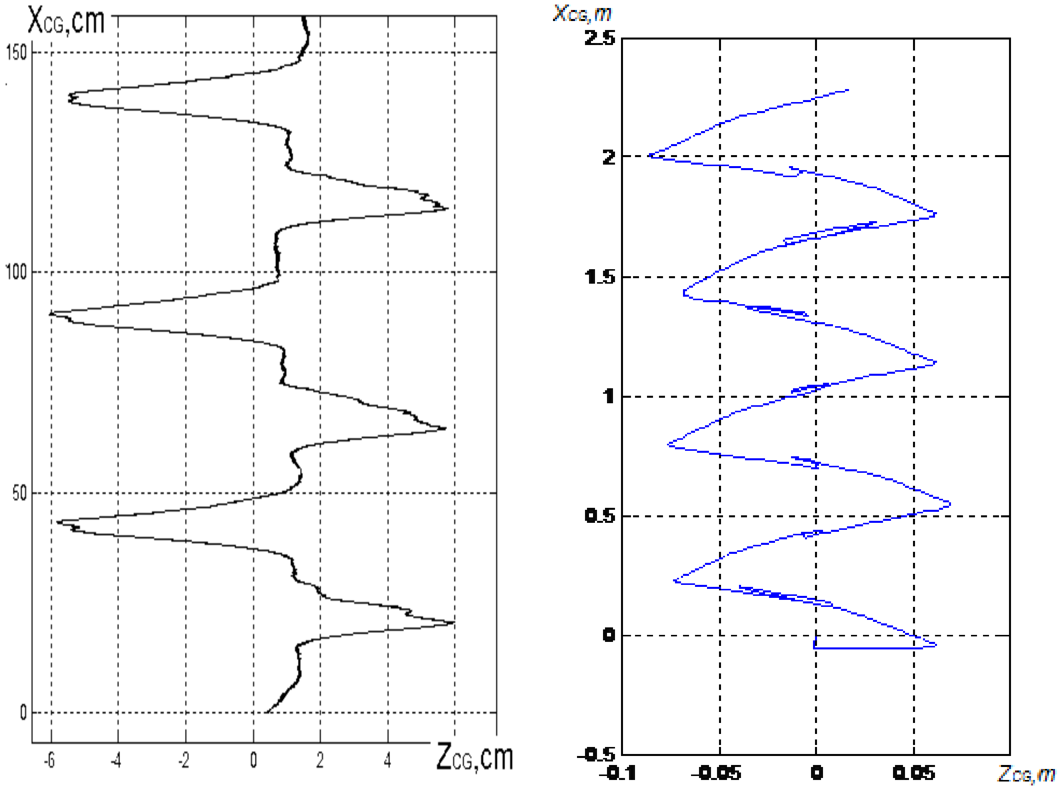


Fig.5.33 – torques in robot’s feet during walking

Trace of robot’s mass center movement above support surface is represented on fig.5.34a for experiment and on fig.5.34b for simulation.



a) b)

Fig.5.34 – Trace of robot’s mass center movement above support surface

Screenshots of robot’s step are shown in fig 5.35

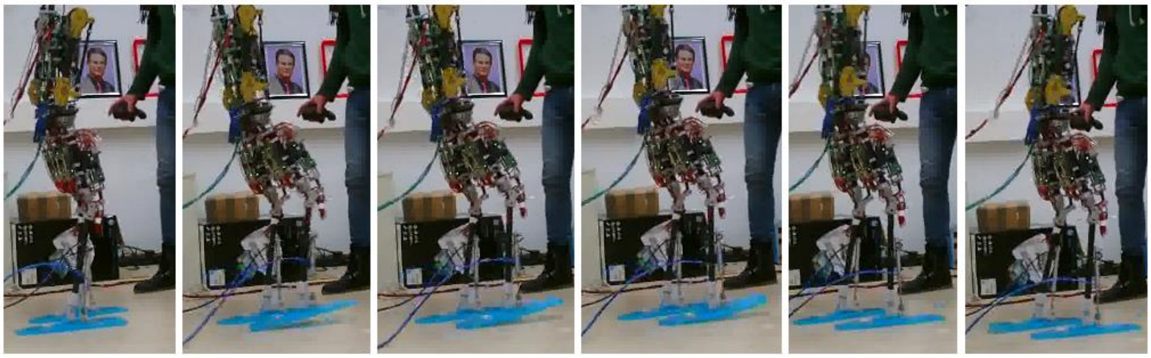


Fig.5.35 – Screenshots of robot’s step

5.4 Summary

Proposed walking method allows us to realize more stable step cycle on account of more stable control system. Here states of robot’s mass center on account of control system in the double support phase after entering in contact always are reduced to given initial states of single support phase.

On the one hand such organization of walking let us minimize disturbances in robot’s control system which were caused by robot’s contact process with support surface at change of support foot. On the other hand there was a complete stop of robot between steps, what causes low walking speed (approximately 0.5m/sec. at step length 25cm) and inefficient use of energy.

In the future improvement of given gait is planned in such a way that damping of robot between steps would happen not until complete stop, but until set of necessary states for taking next step. It will let exclude «stay» phase from step cycle, cut down duration of double support phase and make gait more fast and efficient, but proposed method would be used only at occurrence of big disturbances or at the end of walking.

Conclusion

This thesis describes modernization of construction of legs in the robot ROTTO using implementation of a special electrohydraulic actuator with a flexible gear and algorithm of dynamic walking with stabilization of step cycle during prolonged double support phase.

The use of an electrohydraulic actuator with a flexible remote linear gear allows to lighten mass of robot's legs and to redistribute masses in the mechanical system. It made it possible to realize movements of robot's legs with higher dynamics than earlier and also to lower negative effect of cross-connections in the mathematical model of robot.

Proposed construction of an electrohydraulic drive gives an opportunity to use it in devices, where an actuator should be situated remotely from the last moving element. Advantage of this actuator is that it combines features of an electric drive from the point of view of control tasks and hydraulic drive from the point of view of mass-dimensional features.

This paper also illustrates technique of balancing of a multimass mechanical system using position control of its mass center. This approach let us to build a control system that is easy to understand for a multicoordinate mechanical system with the use of classical control methods and simple PID controllers.

Concept of virtual kinematical constraints is used in the stabilization system, it helps to create elastic properties for a mechanical system with a position actuators, that allows to make a mechanical construction "flexible" and pliant in relation to support surface.

Proposed algorithm of dynamic walking by a biped robot is mainly based on the use of prolonged double support phase in step cycle. Double support phase is used for damping of robot's mechanism after its contact with surface.

Using this approach step cycle by walking can be easily stabilized, as every step in this case ends with similar conditions - speed and position of robot's mass center. On the other hand this gait is less effective compared to gait with instantaneous double support phase, as in every step robot throws its kinetic energy and then wastes energy for acceleration in order to take a next step.

An advantage of this method of stride cycle realization is simplicity and reliability of walking process, simplicity of its implementation, lower requirements to dynamics of robot’s actuators and also to precision of measurements in mechanism speed.

Gait proposed in paper realizes steps of robot with length of approximately 25 cm and step period 1 sec, what is approximately 0.9 km/hour.

Zusammenfassung

Im Rahmen dieser Arbeit, wird die Modernisierung der Konstruktion, von den Beinen des Roboters ROTTO durch den Einsatz von einem speziellen elektrohydraulischen Aktor mit flexiblem Getriebe beschrieben. Dabei wird ein Algorithmus des dynamischen Gehens mit Stabilisierung des Schrittzyklus in der Doppelstützphase dargestellt.

Die Verwendung eines elektrohydraulischen Antriebs mit flexiblem Getriebe, ermöglicht die Gesamtmasse von Roboterbeinen zu reduzieren und die Massen in dem mechanischen System zu verteilen. Daraus folgt, dass die Bewegungen der Roboterbeine mit höherer Dynamik zu realisieren und auch die negativen Auswirkungen von Querkopplungen im mathematischen Modell des Roboters zu verringern sind.

Der elektrohydraulischen Antrieb kann in den Geräten und Anlagen eingesetzt werden, wo ein Aktor entfernt vor dem Endeffektor sich befinden kann. Der Vorteil dieses Aktors ist, die Kombination von Eigenschaften eines elektrischen Antriebs, vom Gesichtspunkt der Regelungstechnik und des hydraulischen Antriebs, bezüglich des Verhältnisses Gewicht/Leistung.

In dieser Arbeit wird eine Methode der Gleichgewichtsunterhaltung des mehrdimensionalen mechanischen Systems, durch Lageregelung des Schwerpunktes betrachtet. Solche Methode ermöglicht das einfache Regelungssystem für mehrdimensionale mechanische Systeme mit klassischem PID-Regler zu entwerfen.

Das Konzept der virtuellen kinematischen Reflexen, ermöglicht in dem Stabilisierungssystem, die elastischen Eigenschaften des mechanischen Systems mit positionsgeregelten Gelenken zu erstellen, um eine mechanische Konstruktion "flexibel" und nachgiebig bezüglich der Stützoberfläche zu erschaffen.

Der Algorithmus des dynamischen Gehens, des zweibeinigen Roboters, ist vor allem auf der Verwendung von einer längeren Doppelstützphase in einem Schrittzyklus basiert. In der Doppelstützphase wird eine Dämpfung des Roboters nach dem Kontakt mit einer Stützoberfläche realisiert.

Solch eine Art von Schrittzyklus erlaubt, dass der Robotergang leicht zu stabilisieren ist. Basierend auf der Idee, welches jeder Schritt mit gleichen Roboterzuständen bzw. Position- und Geschwindigkeitswerten, des Schwerpunktes von Gesamtsystem endet. Von anderer Seite ist solches Gehen wenig effektiv im Vergleich zum Gehen mit sofortiger Doppelstützphase, weil die kinetische Energie in jedem Schritt durch Dämpfung/Beschleunigung des Roboters verloren wird.

Die Vorteile des entwickelten Schrittzyklus, ist die Einfachheit und Zuverlässigkeit des Robotergehens. Eine einfache technische Realisierung dank der niedrigen Anforderungen an die Aktordynamik und an die Messgenauigkeit der Geschwindigkeit.

In Rahmen dieser Arbeit wurde ein dynamisches Gehen des Roboters ROTTO mit Schrittdauer von ca. 1s und Schrittweite von ca. 25cm realisiert, was der Geschwindigkeit von ca. 0.9km/h entspricht.

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