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PhD THESIS

Development of a legged robotic structure for even and uneven environments

-Summary-

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Table of content

SUMMARY

The PhD thesis "**Development of a legged robotic structure for even and uneven environments"** is the result of a sustained activity of study and research.
This paper deals with the locomotion problem of the legged robotic structures in even and uneven environments. After a detailed research of the state of the art I have identified and analyzed many robotic structures from this category. Some were the subject of previous scientific research and others are available for purchase. Inspiration for all these structures is clearly the biological world.

Chapter 1: ***Introduction***

In the first chapter was identified as a major problem maintaining the stability of the legged robotic structure during locomotion. For such a structure to be considered stable it is necessary that the projection of the center of mass has to be inside the support polygon determined by the leg tips on the ground at the time. The minimal shape of the support polygon that ensures the stability of the robot is a triangle (isostatic equilibrium). Legged robots are more stable when more legs are on the ground on a given time. An immediate effect is a decrease in speed. Unlike structures with fewer legs, hexapod robots in some conditions remain stable even if the locomotion stops accidentally.

Legged robots are used especially for uneven terrain. In these environments can be identified 4 fundamental types of obstacles: inclined plane, step, ditch and crest. A separate category of obstacles is represented by stairs. The complexity of these obstacles in relation with the fundamental ones is given by an increase number of parameters. The analysis of these types of obstacles for a legged robot represents a step forward in their integration in service areas. Locomotion on a stair is a current topic in today's literature where are made efforts in development of legged robotics under all aspects.

Also in the first chapter are presented the major advantages and disadvantages of legged robots in relation with other classes of mobile robots (wheeled or tracks). In the same chapter are defined the performance criteria imposed for the robot. The most important constraints imposed to the robot are: maintaining the robot's body parallel with the ground and maintaining the maxim height of the robot's body in relation with the ground or obstacle.

Chapter 2: ***Modeling of the robotic leg***

The fundamental and crucial element for robot performance is the leg. The insect legs are one of the most studied models for a robotic leg. In the second chapter are studied most of the aspects of the robotic leg. The chosen model of the leg was a 3 DoF open kinematical chain and were derived the kinematical (using Denavit – Hartenberg algorithm) and dynamic model (using Euler – Lagrange method).

Although the servomotors used for joint actuation allow a rotation of 180 degrees the domain was limited by the mechanical construction of the joint and by limiting the workspace intersection of adjacent legs.

Chapter 3: ***Analysis of fundamental types of obstacles***

One of the major advantages of the legged structures to those with wheels is in the case of the locomotion over an uneven terrain, characterized by lack of continuous contact surfaces. The variety of land surfaces that a legged robot can overcome is extremely vast, but the obstacles on these surfaces can be classified in four main categories: inclined plane, step, crest and ditch. In chapter 3, in addition to these four main categories were also introduced two types

of complex obstacles: straight stair and spiral stair, that are more difficult to overcome and which are also the subject of this paper.

All these types of obstacles are analyzed in this chapter, are defined the specific parameters and are evaluated their influences on locomotion strategies that were further elaborated.

Chapter 4: *Graphical user interface for functional simulation of the hexapod robot*

Mathematical modeling and computer aided simulations have become a common practice in scientific research. These instruments allow the study of the evolution of real systems under various conditions, also enabling the estimation of complex systems performances, for which analytical solutions are hard to find. The fourth chapter presents a part of the Matlab programming language which is used for graphical and behavioral simulation of the hexapod robot. In this language has been implemented direct kinematic model, inverse kinematic model, the dynamic model of the hexapod robot's leg and workspace analyses of a leg. Also, in Matlab was designed a simulation interface for the hexapod robot using the GUIDE editor. It was made a detailed description of this editor and of the graphical elements used for creating the entire simulation platform whose functionality is also described. This interface allows the simulation of locomotion over obstacles using models which were previously built for the hexapod robot, the stability analyses in case of failure occurred at leg level and also the robot's stability analysis during locomotion with different strategies. The communication between the software platform and the experimental model of the hexapod robot is made trough the ArduinoMega 2560 development board with microcontroller Atmel – AVR.

Chapter 5*: Hardware structure of the hexapod robot*

Detailed analysis of graphical behavior simulations of the robot over the types of obstacles outlined above had an important role in dimensioning the experimental model of the hexapod robot which has been designed and built. In the fifth chapter are presented in detail the stages covered and the problems encountered during the construction of this experimental model. A starting point for the design and construction was the critical analysis of several legged robots that were on market and we had access to. Of all the models considered only two structures partially met the criteria of research in this paper. The two candidate commercial robotic structures were BH3 and A-POD. In the end, the starting point for the design and construction of a new hexapod robotic structure was the BH3 model, available in the laboratory where I conducted research. Based on several elements of the BH3 structure there have been designed first the CAD models of the robot's feet and body. In the design process of the experimental model of the hexapod robot were performed three successive versions using various solutions and constructive materials. This chapter also describes the operation of electric servomotors fitted to the 18 joints of the robot. Besides mechanical structure and operations, the hexapod robot also has a leading system which consists of: Arduino Mega2560 development board based on an Atmel – AVR microcontroller, the control board of the 18 servomotors (SSC-32) also carried around an Atmel – AVR microcontroller, the power supply for all the servomotors, a LCD display and six force sensors. In this chapter is also presented the Arduino IDE programming environment used for programming the development board Arduino Mega2560.

Chapter 6*: Control of the robot over the main types of obstacles. Experimental results*

In the sixth chapter are described the control of the robot's locomotion over the four main types of obstacles and the details of experiments conducted both in graphical simulation as with the built model of the hexapod robot. At the beginning of the chapter is approached the issue of approximating the polygonal trajectories using arcs and splines. For the calculus of the points of the imposed trajectory to a leg's tip is used the *interparc* function, which can not be found in the basic package Matlab, but can be obtained from the official website of the product. Next is defined and detailed the architecture of the robot's control system.

Next, it was tested and analyzed how the leg's tip performs different specific locomotion trajectories: linear trajectory, plane curvilinear trajectory and space curvilinear trajectory. This was first tested in the created simulation environment, and later with real experiences of the built model of the hexapod robot. Lower tracking errors were recorded for plane curvilinear trajectory. Another analysis conducted on the robotic leg was testing its dynamic model using SimMechanics, part of Matlab, to determine the forces and moments that the joints servomotors must develop to preserve the robot stability on the trajectory.

Then was accomplished an analysis of hexapod robot stability under failure occurred in the legs joints and for the horizontal stepping sequences. In the failure mode was observed the robot's behavior when one or more joints break or the command transmitted to them is not properly performed for various reasons. In the second analysis case was observed how the robot's support polygon changes according to the chosen stepping sequence.

After that followed the development and implementation of the locomotion strategies for each type of basic obstacles. The design of these locomotion strategies had as main constraints the criteria initially imposed to the research, defined in the first chapter. The first studied strategy was the locomotion on horizontal plane, the simplest case of robot motion. For the inclined plane type of obstacle was followed the same strategy as for locomotion on horizontal plane. The specific element of the designed algorithm is related to the calculus of Z coordinates of all legs tips so that their position should be correct and should not affect the robot stability during locomotion. It was then approached the step type obstacle, for which it was also designed a proper locomotion strategy. Experiments performed with the real hexapod robot revealed the need to introduce corrections that were not initially identified by performed graphic simulations. They were mainly due to the function of the legs joints close to the limit values and finally leading to adjusting the height of the step on which it can make physic locomotion. For the crest type obstacle was considered the case when its width does not allow simultaneous positioning of two adjacent pairs of legs. A key difficulty that has been solved is the one where the legs positioned on the crest are about to step on the ground. For their locomotion is necessary that the hip joints to be placed above or over the edge of the crest.

For the ditch obstacle type were evolved two locomotion strategies, according to its width. The first strategy is similar to that on the horizontal plane locomotion and allows the passage of a ditch of small width. The second strategy allows the robot to cross an almost double wide ditch. An important note about this strategy is that in certain sequences the middle legs are placed above the ditch, so there are no longer considered support points for the robot. It becomes very important the order of the locomotion of the legs so that the robot does not lose its stability.

Chapter 7*: Robot control over complex types of obstacles. Experimental results*

In chapter seven of this paper are examined two cases of particular obstacles, with greater complexity: the straight stair and the spiral stair. The escalation of these obstacles requires locomotion strategies that contain several stages for adjusting the position of the robot, including cyclical correction of its height while preserving the body's horizontality so that the process could continue regardless of the number of stairs. Furthermore, for the spiral stair type obstacle it was designed a cyclic shift orientation algorithm of the robot, without which the climbing would be impossible. The shape of the spiral stair used to simulate locomotion was obtained from helical curve.

Chapter 8*: Conclusions and personal contribution*

The last chapter is dedicated to conclusions, personal contribution brought by this paper in author's opinion. Also, in special section are advanced some ideas about future work starting from the present results.

CONCLUSIONS

This paper is part of the development trends of legged mobile robotics. It has been insisted on developing locomotion strategies and control algorithms for the built hexapod robot.

Chapters 4, 5, 6 and 7 are virtually the results of the efforts made by the author of this thesis in recent years, with a high degree of originality.

Note that, following the implementation of all the algorithms in the robot's control system have appeared differences between the graphical simulation and the experiments with the real robot. The explanations consist of constructive defects due to mechanical engineering, existing motions in the kinematical chains, features of transmissions of the numerical controls supplied by the robot's control system to the joints and the limited power of the servomotors that were used.

PERSONAL CONTRIBUTIONS

The main contributions brought by this paper in author opinion divided into chapters are:

- **Chapter 2:** ***Modeling of the robotic leg***
    - Development of the direct kinematical model for the chosen leg structure using Denavit – Hartenberg algorithm.
    - Development of the inverse kinematical model for the leg of the hexapod robot.
    - Development of the dynamic model using Euler – Lagrange method
    - Workspace analysis of the leg with highlighting its shape and its extreme points
- **Chapter 3:** ***Analysis of fundamental types of obstacles***
    - The study of the four main categories of obstacles (inclined plane, step, crest and ditch), with highlighting the most important dimensional relations that will become the bases for developing locomotion strategies.
    - The study of particular types of obstacles (straight stair and spiral stair) for determining the mathematical relations that quantify the locomotion process specific for the hexapod robot
- **Chapter 4:** ***Graphical user interface for functional simulation of the hexapod robot***
    - A detailed analysis of GUIDE editor with pointing its principal functions and predefined block that can be used for building a software interface for functional simulation and control of the robot
    - Designed of an interface for functional simulation and control of the robot leg
    - Designed of an interface for functional simulation and control of the hexapod robot for locomotion analysis over the four main types of obstacles (inclined plane, step, crest and ditch) and also over particular types of obstacles (straight stair and spiral stair)
    - Implementation of the capability for offline testing (through simulation) and online testing (using the real model) for the leg
- **Chapter 5*****: Hardware structure of the hexapod robot***
    - Making of CAD model used for design and implementation of the hexapod robot leg
    - Successively more natural foot variants (using different materials and constructive solutions), their testing and demonstration of specific limitations.
    - Realization of several CAD models for hexapod robot body.
    - The construction of several physical robot body variants, their testing, demonstration of specific problems arising and their successive removal.
    - Functional analysis, modeling and design graphics for the six leg tips, aiming to maximize the surface area of contact with the ground in order to improve general stability and control locomotion.

- **Chapter 6*: Control of the robot over the main types of obstacles. Experimental results***
    - Redesigning software server-client providing communication between the PC and the experimental model of the robot**.**
    - Design and construction of the robot system designed around the Arduino Mega2560 development board and the control board 18 actuators SSC-32, both controlled by Atmel AVR-microcontrollers.
    - Leg tip control for trajectory tracking of a required linear form, flat and curved curve in space.
    - Development of the locomotion strategy for walking on a horizontal plane and the associated necessary algorithms for the control system of the robot.
    - Development of the locomotion strategy for all the 4 main categories of obstacles (inclined plane, step, crest and ditch).
    - Development of all the algorithms necessary for controlling the hexapod robot during locomotion over the 4 main types of obstacles.
    - Critical analysis of all the solutions obtained by graphical simulation and the results of experiments carried out with the hexapod robot model over these obstacles.
- **Chapter 7*: Robot control over complex types of obstacles. Experimental results***
    - Development of locomotion strategies for overcoming complex obstacles like straight stair and spiral stair.
    - Development of all the algorithms necessary for controlling the hexapod robot for a normal evolution in the case of these obstacles.
    - Critical analysis of all the solutions obtained by graphical simulation and the results of experiments carried out with the hexapod robot model over these obstacles

FUTURE WORK

In terms of further development opportunities are foreseeable at this time three directions:

- In terms of the experimental model of the hexapod robot would be useful to amend the soles of the feet attached to design the robot so that stepping on the inclined plane tilted to be right. This would improve the general stability in all control locomotion strategies.
- For more exact control of desired horizontality of the body, it would be useful to provide the robot with sensors for the determination of its tilt (accelerometer, inclinometer, IMU-Inertial Measurement Unit). Attaching a video camera and the development of a system of management which would include recognition of facilities would permit identification of the type of obstacle, its dimensions and the adoption of more complex control locomotion strategies based on those developed thus far. Also, the attachment of sensors for detection of unanticipated obstacles would increase intelligence level available to the experimental model of the hexapod robot.
- In terms of graphical simulation interface is considering improving the algorithms designed for all the obstacles presented, improving communication between the PC and the experimental model of the robot with new functionalities, behavioral simulation in an environment with traits and characteristics as real as possible.

BIBLIOGRAPHY

[1] Adam El, Sayed Auf, Mösch F., Litza M., *How the Six-Legged Walking Machine OSCAR Handles Leg Amputations*, Proceedings of the 9th International Conference on Simulation of Adaptive Behaviour, Rome, Italy, 2006.

[2] Amol Deshmukh, *Robot Leg Mechanisms*, B.Tech. Seminar Report, Department Of Mechanical Engineering Indian Institute Of Technology, India, 2005.

[3] Appin Knowledge Solutions, *Robotics*, Infinity Science Press LLC, Hingham, Massachusetts, New Delhi, ISBN: 978-1-934015-02-5, 2007.

[5] Ayers J., Witting J., *Biomimetic Approaches to the Control of Underwater Walking Machines*, Philosophical Transactions of the Royal Society, Series A, vol 365, nr. 1850, pp: 273-295 DOI:10.1098/rsta.2006.1910, ISSN: 1471-2962, 2007.
[6] Barragán, Hernando, *Wiring,* Wiring unknown University de los Andes, Jan 2007, http://wiring.org.co.
[7] Carbone G., Yatsun A., Ceccarelli M., Yatsun S., *Design and Simulation of Cassino Hexapod Robot*, Proceedings of the 13th WSEAS International Conference on SYSTEMS, pp:301-307, ISSN: 1790-2769, ISBN: 978-960-474-097-0, 2009.
[8] Cadets Lento J., Huson Z., *Development of Leg Control Mechanisms for a Radially Symmetric Octopedal Robot*, Proceedings of The National Conference On Undergraduate Research (NCUR), Virginia Military Institute, Washington and Lee University Lexington, Virginia, Aprilie 21 - 23, 2005.
[9] Cappelletto J., Estévez P., Grieco J. C., Medina-Meléndez W., Fernández-López G., *Gait Synthesis in Legged Robot Locomotion Using a CPG-Based Model*, Bioinspiration and Robotics: Walking and Climbing Robots, ISBN:978-3-902613-15-8, pp: 544, I-Tech, Viena, Austria, Septembrie 2007.
[11] Clark Haynes G., Rizzi Alfred A., *Gaits and Gait Transitions For Legged Robots*, Proceedings of the 2006 IEEE International Conference on Robotics and Automation, Orlando, Florida, ISSN **:** 1050-4729, Print ISBN**:** 0-7803-9505-0, pp:1117-1122, DOI:10.1109/ROBOT.2006.1641859, Mai 2006.
[13] Dalvand Mohsen M., Moghadam Majid M, *Stair Climber Smart Mobile Robot (MSRox)*, Autonomous Robots, vol.20, no.3, pp:3–14, DOI: 10.1007/s10514-006-5364-4. ISSN: 0929-5593, 2006.
[14] Davis Timothy A., Kermit Sigmon, *MATLAB Primer – 7th Edition*, CHAPMAN & HALL/CRC, ISBN: 1-58488-523-8, 2005.
[16] Dominik Belter, Piotr Skrzypczynski, *A Biologically Inspired Approach to Feasible Gait Learning for a Hexapod Robot*, International Journal of Applied Mathematics and Computer Science, vol.20, no.1, pp:69–84, DOI:10.2478/v10006-010-0005-7, 2010.
[17] Duggal S.K., *Surveying, Second Edition*, Tata McGraw-Hill Publishing Company Limited, New Delhi, vol. 1, ISBN: 0-07-053470-5, 2004.
[19] Figliolini G., Ripa V., *Kinematic Model and Absolute Gait Simulation of a Six-Legged Walking Robot*, Proceedings of the 7th International Conference CLAWAR, pp:295-303, Print ISBN: 978-3-540-22992-6, DOI: 10.1007/3-540-29461-9_87, 2004.
[21] Gonzalez de Santos P., Garcia E., Estremera J., *Improving Walking-Robot Performances by Optimizing Leg Distribution*, Journal of Autonomous Robots, vol. 23, no. 4, pp:247 – 258, DOI:10.1007/s10514-007-9045-8, ISSN: 0929-5593, 2007.
[23] Guardabrazo T.A., Gonzalez de Santos P., *Mass Distribution Influence on Power Consumption in Walking Robots*, Proceedings of the 7th International Conference CLAWAR, pp:295-303, Print ISBN: 978-3-540-22992-6, Online ISBN: 978-3-540-29461-0, DOI: 10.1007/3-540-29461-9_50, pp:511-518, 2004.
[26] Jazar Reza N., *Theory of Applied Robotics.Kinematics, Dynamics, and Control*, Springer, New York, Dordrecht Heidelberg London, Springer Science+Business Media, LLC2006, ISBN: 978-1-4419-1749-2, DOI 10.1007/978-1-4419-1750-8, 2010.
[32] Krysztof Walas, Dominik Belter, Andrzej Kasinski, *Control and Environment Sensing System for a Six-Legged Robot*, Journal of Automation, Mobile Robotics and Intelligent Systems, vol.2, no.3, pp:26-32, ISSN:1897-8649, 2008.
[35] Manchester Ian R., Uwe Mettin, Fumiya Iida, Russ Tedrake, *Stable Dynamic Walking Over Uneven Terrain*, International Journal of Robotics Research, vol.30, no.3, pp:265–279, ISSN:0278-3649, DOI: 10.1177/0278364910395339, 2011.
[37] Martin Görnerand, Gerd Hirzinger, *Analysis and Evaluation of the Stability of a Biologically Inspired, Leg Loss Tolerant Gait for Six-and Eight-Legged Walking Robots*, IEEE International Conference on Robotics and Automation, Anchorage, Alaska, USA, pp:4728-4735, ISBN:978-1-4244-5040-4, 2010.
[38] **Mănoiu – Olaru Sorin**, Nițulescu Mircea, Stoian Viorel, *Hexapod Robot. Mathematical Support for Modeling and Control*, Proceedings of the 15th International Conference on System Theory Control and Computing, Sinaia, Romania, vol.1, pp:329-335, ISSN: 2068-0465, ISBN:978-973-621-322-9, 2011.
[39] **Mănoiu – Olaru Sorin**, Nițulescu Mircea, *Basic Walking Simulations and Gravitational Stability Analysis for a Hexapod Robot using Matlab*, Annals of University of Craiova, vol.8(35), no.1, pp:44-56, ISSN:1841-0626, Editura Universitaria, Craiova, Romania, 2011.
[40] **Mănoiu – Olaru Sorin**, Nițulescu Mircea, *The Modelling of the Hexapod Mobile Robot Leg and Associated Interpolated Movements While Stepping*. Proceedings of the 16th International Conference on System Theory Control and Computing, Sinaia, Romania, ISSN: 2068-0465, ISBN:978-606-834-848-3, Octombrie, 2012.
[41] **Mănoiu – Olaru Sorin**, Nițulescu Mircea, *Hexapod Robot Leg Dynamic Simulation and Experimental Control Using Matlab*, Procc of 14th IFAC Symposium Information Control Problems on Manufacturing INCOM, Bucuresti, Romania, vol.14, no.1, pp:895-899, DOI:10.3182/20120523-3-RO-2023.00335, 2012.

[42] **Mănoiu – Olaru Sorin**, Nițulescu Mircea, *Hexapod Robot Locomotion Over Typical Obstacles,* Proccedings of Automation Quality and Testing Robotics AQTR 2012, Cluj Napoca, Romania, pp:422-427, ISBN: 978-1-4673-0701-7, Mai 2012.
[43] **Mănoiu – Olaru Sorin**, Nițulescu Mircea, *Matlab Simulation Interface for Locomotion Analysis of a Hexapod Robot Structure*, Proceedings of the 16th International Conference on System Theory Control and Computing, ICSTCC 2012, Sinaia, Romania, ISSN: 2068-0465, ISBN: 978-606-834-848-3, Octombrie, 2012.
[44] **Mănoiu – Olaru Sorin**, Mircea Nițulescu, *Matlab Simulator for Gravitational Stability of a Hexapod Robot*, Romanian Review Precision Mechanics, Optics and Mechatronics, Editura CEFIN, Bucuresti, Romania, no 39, pp:157-162, ISSN: 1584-5982, 2011.
[45] **Mănoiu – Olaru Sorin**, Nițulescu Mircea, *Hexapod Robot. Virtual Models for Preliminary Studies*, Proceedings of the 15th International Conference on System Theory Control and Computing, ICSTCC 2011, Sinaia, Romania, vol.1, pp:335-341, ISSN: 2068-0465, ISBN:978-973-621-322-9, Octombrie, 2011.
[46] **Mănoiu – Olaru Sorin**, Mircea Nițulescu, *Stability Analysis Software Platform Dedicated for a Hexapod Robot*, Proccedings of 18th International Conference on Control Systems and Computer Science, CSCS-18, Bucuresti, Romania, vol.1, pp:385-390, ISSN: 2066-4451, 2011.
[47] **Mănoiu – Olaru Sorin**, Mircea Nițulescu, *Stability Analysis Software Platform Dedicated For A Hexapod Robot*, Advances in Intelligent Control Systems and Computer Science, Springer Berlin Heidelberg,Germania, vol.187, pp:143-156, ISSN: 2194-5357, 2013.
[56] Pinto Carla M.A., Diana Rocha, Santos Cristina P., *Hexapod Robots: New CPG Model for Generation of Trajectories*, Journal of Numerical Analysis, Industrial and Applied Mathematics, vol.7, no.1-2, pp: 15-26, ISSN:1790–8140, 2012.
[58] Reas Casey, Fry Ben, *Processing.org: A Networked Context for Learning Computer Programming*, ACM SIGGRAPH, 2005.
[59] Register Andy H., *A Guide to MATLAB Object-Oriented Programming*, Chapman & Hall/CRC, ISBN-13: 978-1-58488-911-3, 2007.
[60] Roger Quinn, Toy Ritzmann, Stephen Philips, Randall Beer, Steven Garverick, Matthew Birch, *Biologically-Inspired Micro-Robots:Volume 1, Robots Based On Crickets*, Tehnical Report, Case Western Reserve University, Cleveland, OH 44106-7222, Mai 2005.
[61] Roland Nourbakhsh, Illah R. Siegwart, *Introduction to Autonomous Mobile Robots*, The MIT Press, Cambridge, Massachusetts, England, ISBN 0-262-19502-X, 2004.
[66] Thiago Augusto Ferreira, Armando Carlos de Pina Filho, Aloísio Carlos de Pina, *Modelling A Hexapod Robot by Means of CAD Techniques,* The 9th Brazilian Conference on Dynamics, Control, and their Application, DINCON'10, June, 2010.
[68] Vidoni R., Gasparetto A., *Efficient Force Distribution and Leg Posture for a Bio-Inspired Spider Robot*, Robotics and Autonomous Systems, vol. 59, pp:142–150, ISSN: 0921-8890, DOI: 10.1016/j.robot.2010.10.001, 2011.
[76] Funcția interparc: http://www.mathworks.com/matlabcentral/fileexchange/34874-interparc
[84] Pagina oficială a editorului Matlab – GUIDE: http://www.mathworks.com/discovery/matlab-gui.html
[85] Pagina oficială a programului SOLIDWORKS: www.solidworks.com
[88] Pagina oficială a plăcii de dezvoltare Arduino Mega2560: http://arduino.cc/en/Main/ArduinoBoardMega2560
[91] Programul Matlab – SimMechanics: http://www.mathworks.com/products/simmechanics/
[101] Robotul hexapod BH3: http://www.lynxmotion.com/c-33-bh3.aspx
[119] Senzorul de forță circular: http://www.robofun.ro/senzori/forta/senzor_apasare_circular
[120] Servocontrolerul SSC – 32: http://www.lynxmotion.com/p-395-ssc-32-servo-controller.aspx