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Cyber-Physical Laboratory Based on LEGO Mindstorms NXT - First Steps

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Abstract— **A description and first implementation results for a "Cyber-physical laboratory" project performed jointly by the students of St.Petersburg State University and those of St.Petersburg Phys&Math Lyceum 239 are presented. The goal of the project is to create a complex of robotics and mechatronics networked devices based on LEGO Mindstorms NXT for application in universities and in high schools.**

INTRODUCTION

During last few years a growing interest in the so called "cyber-physical systems" (CPS) was observed. A CPS is understood as a system with closely interacting computational devices and objects of real physical world. A CPS integrates computing, communication and storage capabilities with the monitoring and/or control of entities in the physical world, and must do so dependably, safely, securely, efficiently and in real-time [1,2]. The key feature distinguishing CPS from more common embedded systems comes from networking these devices. The US National Science Foundation (NSF) has identified cyber-physical systems as a key area of research, aimed at deep integration of physical and cyber design.

On the other hand, in the 1990s a great interest in application of information and control methods was observed in physics. An intriguing fact was discovered that even weak control in feedback form applied to a physical system may dramatically alter the dynamics and properties of the system, e.g., chaotic motions may be transformed into periodic ones [3]. This and other applications (control of lasers, plasma, particle beams, quantum systems) lead to rapid growth of a new field on the borderland between physics and control theory (cybernetics). It was named "Cybernetical Physics" [4,5,6]. Cyberphysics is fundamental for cyber-physical systems, it is aimed at determination of limits and possibilities of changing behavior of physical systems by means of control.

New practical problems demand both for new theory and for new design and education means. Fortunately, development of computer technologies lead to creation of convenient computation and communication environments, supporting design and education. One of the recent milestones on this way is LEGO Mindstorms NXT (further sometimes called LEGO for brevity).

Among different laboratory platforms for implementation of control design methods the LEGO Mindstorms NXT system has at least three advantages. Firstly, it is good for education: because LEGO is a well-known toy, students already have a basic knowledge of its use and construction methods; therefore, they are ready to begin robot construction at the very start of the course. Secondly, it provides good possibilities for creating wireless networks vie Bluetooth connection. The last but not the least, it is low cost: The standard 8527 Lego Mindstorms NXT system consisting of the NXT brick with 4 input and 3 output ports, based on the 32-bit ARM7 microcontroller; 3 motors, 4 sensors (light, touch, sound and ultrasonic) and more than 500 assorted Lego bricks cost less that US$300. The system allows construction of various shaped and sized robots, mechatronic devices and other embedded systems. Therefore it attracts a growing interest as a tool for teaching introductory courses and projects in control design, mechatronics, robotics, embedded systems, etc. and a number of very exciting projects are conducted all over the world. Summarizing, LEGO provides an environment for exciting creative collaboration of teachers and students in process of a cyber-physical system design.

In this paper we describe the first results of an experiment aimed at organizing such a collaboration among undergraduate students of St.Petersburg State University and high school students of St.Petersburg Phys&Math Lyceum 239. The first stage of the project called "Cyberphysical Laboratory" started in September, 2008 and finished in December, 2008. In the next two sections motivation of both

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parties is described. Some particular projects conducted by small student groups are described in Section III.

I. University Approach

The first LEGO Mindstorms NXT 8527 sets arrived at the Department of Theoretical Cybernetics in the beginning of 2008. In spring semester opening of a club for first and second year students was announced. During club hours both students and teachers were mainly examining new opportunities provided by using new learning environment for studying mechanics and control. In April, 2008 a few robots were presented at the **show of robots** during the "Math-Mech week". Perhaps, it was helpful for students to choose department for their specialization. Note that in the case of Math-Mech (the Faculty of Mathematics and Mechanics) students start specialization from their third year. As a result a group of 12 third year students motivated for active work in robotics entered the Department of Theoretical Cybernetics in September, 2008. What is unusual for mathematics students, they were interested not only in theoretical study of cybernetics, but also for practical work aimed at creation of robots and other cybernetics devices. In fall semester such a practical work was organized at the Laboratory "Control of Complex Systems" of the Institute for Problems of Mechanical Engineering. Students were split into teams of two persons and a task of design and simulation of a mathematical model of a robot (or other cyber-device) was proposed to each team. Implementation and simulation of models was to be done in MATLAB-Simulink environment. Implementation of the models in LEGO was planned as the next step. The challenge of such an arrangement both for students and for teachers was shortage of time (2-3 hours per week) and the need to learn/teach basics of control theory and MATLAB simultaneously with practical work. On the other hand, it increased motivation and added passion and competitive spirit to the project. However, both students and instructors were not experienced in building LEGO constructions. A key role to overcome this problem played by collaboration with the high school students from the Robotics Club of Lyceum 239.

II. High School Approach

The idea of joint project with university was in the air. An experience of a few years of teaching robotics in secondary schools revealed decrease of interest in building LEGO constructions in senior year students (age 15-17). The reason lies in their orientation to university entrance exams and focusing on mathematics and physics rather than robotics. At the same time middle age students (age 10-14) are mostly interested in robotics as a big game, with no serious scientific interest. The question was: how to increase interest in robotics of senior year students and how to motivate them to learn it more seriously, based on solid knowledge of math and programming?

Such an understanding came simultaneously with information about first attempts of using LEGO Mindstorms NXT at Math-Mech of SPbSU. We noticed that complexity of the tasks in the University and in the Lyceum was almost the same. Attempts to attack university tasks could get children interested in robotics and more familiar with their future profession. After getting acquainted personally in May, 2008 the authors of this paper agreed about collaboration. First stage of the project (1.5 months) consisted in fostering skills of building LEGO constructions (for juniors) and teaching basics of programming in Robolab 2.9 environment (for seniors). The peculiarities of club learning - some "knowledge diffusion" and "mutual teaching" – lead to increase of efficiency of education.

For juniors we used Lego 9632 «Science and Technology» set and studied techniques of connecting the LEGO bricks, mechanical transmission, alternate/reciprocal motion, inertia, friction, etc. A good practice was creating robots for Sumo contest [8].

Senior students studied programming in Robolab 2.9 using 9797 Lego Mindstorms NXT sets. Typical tasks included: walking of a robot over the room, detection and extrusion of the objects out of the circle, moving along a complex trajectory with obstacles, etc. Basic programming blocks including procedures, variables, concurrent processes were studied during solving practical tasks. A special attention was paid to work with sensors (calibration, noise reduction) which is an important part of programming for embedded systems.

Fig. 1.

An interesting and important task is design and testing of controllers. Using proportional, integral and differential controllers can improve quality in a number of applications. The ideas were coming from cooperative work with university students and later these standard controllers have become a key theme when studying robot control algorithms. One application was implementation of a robot, tracking the black line which is robust with respect to changes of illumination. Control algorithm was based on the P-controller with input signal, proportional to the difference of the two light sensor signals. Another task – motion along a nonideal wall was solved using only one (ultrasonic) sensor and a PD-controller. Programming and testing of the above controllers has demonstrated superiority of P- and PD-controllers compared with relay controllers studied before.

Testing tasks included motion along trajectories with hill, complex turns and crossings. It was in November when the first meeting of high school and university students took place.

III. Cooperation: Cyber-physical Laboratory

The concept of joint project was formulated as follows. A team typically consists of two university students (U-students) and two high school students (S-students). U-students solve robot control tasks with the help of instructors and simulate the system models in Simulink. S-students create robot constructions and implement, jointly with U-students robot control algorithms created by U-students. There were also a few teams consisting only of S-students solving vibrational mechanics problems and a few teams of only of U-students solving problems not requiring creation special LEGO construction. The list of the projects included: **1) robot-byciclist, 2) cart-pendulum system, 3) robot-acrobat, 4) predator-pray system "lion-antelope", 5) robot-cartographer, 6) robot-driver, 7) system seeking a beacon, 8) system of mobile robot formation control, 9) Kapitsa pendulum, 10) robot-segway.**

The projects have various level of complexity and the levels of their completeness during a semester also vary. For some tasks the algorithms should be created by students, while for others students have to read and understand an article, typically in foreign language. Consider some projects in more detail.

IV. Sample Projects

Project 1. Robot-byciclist. In 1968 the Head of Department of Theoretical Cybernetics of SPbSU Prof. V.A.Yakubovich proposed first formal mathematical definition of adaptive system [9]. Self-learning of robot-bicyclist was examined as one of examples. The problem is in that the bicycle may be unstable, and in some cases – nonminimum phase. Later the robot-bicyclist problem has become a sort of benchmark for demonstration of different adaptive control methods [10,11]. However no experiments of robot controlling a bicycles were reported. The first LEGO-based bicycle (to be more precise – motorcycle, since pedals were not realized) was built by the S-students A.Fedotov and M.Golev, Fig.2. Later it was modified by U-students A.Selivanov and A.Stepanov, Fig.3. In both cases the design included two auxiliary wheels to avoid falls. Two algorithms were implemented and simulated in Simulink: Yakubovich's "strip" adaptive control algorithm [10] and Astrom's algorithm [12], Fig.4. Implementation in LEGO was done in RobotC language [13].

Fig.2.

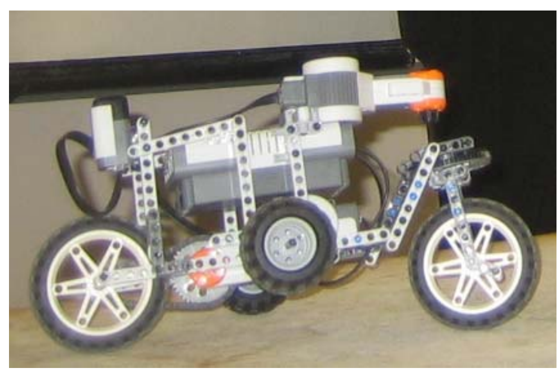

Fig.3.

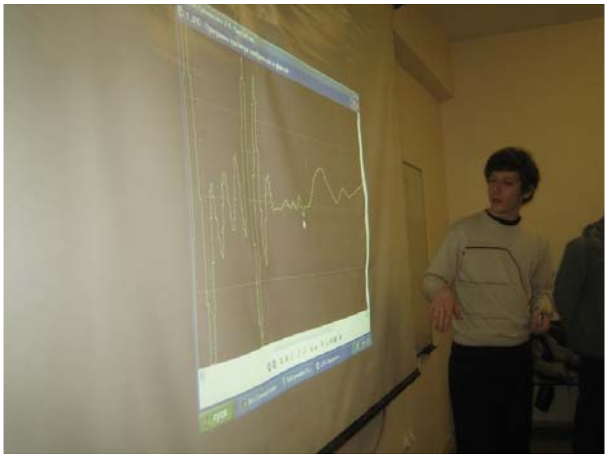

Fig. 4.

Project 2. Cart-Pendulum System.
Cart-pendulum is a standard benchmark for illustration and comparison of different control algorithms when teaching control theory. The design of S-students Olga and Anna Bogdanova, see Fig.5 is based on [14] while algorithm of speed-gradient swinging control and stabilization in the upper equilibrium was designed by U-student V.Krylov based on results of [15]. Control algorithm was implemented in Robolab 2.9 and RobotC. The control system used measurements of the deflection angle and angular velocity provided by accelerometer and gyro sensors produced by HiTechnic company [16].

Fig.5.

Project 3. Pursuer-target system. The idea is also borrowed from the first works of V.A. Yakubovich on self-learning robots [17]. The system is close to ‘robot-grasshopper’ [17] and got the name ‘Lion-Antelope’.

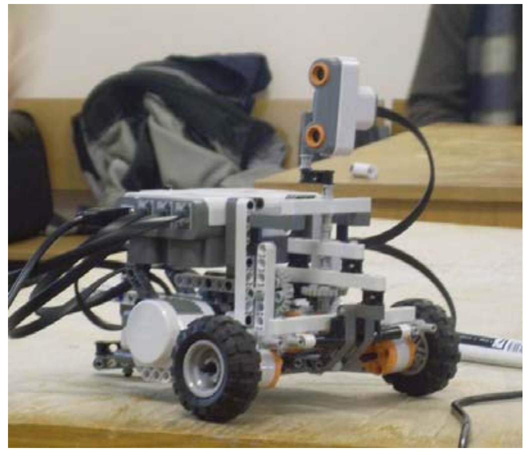

Fig.6.

The Lion, see Fig.6 is scanning surrounding space with constant angular velocity by the ultrasonic sensor and periodically defining current coordinates of the Antelope. It is assumed that the model of Antelope’s motion is known up to a finite number of parameters (e.g. it is moving along an unknown circle with unknown yet constant angular velocity). Then, according to algorithm developed by U-students E.Belova and O. Zheleznyak Lion can estimate these parameters and catch Antelope in the predicted point, even in the case when Lion’s speed is less that the one of Antelope’s.

Project 4. Kapitsa pendulum. This example was proposed to the 12-14 years kids in the Robotics Club as a task for self-solution. It is well known that in the end of the 1940s Russian physicist, future Nobel Prize winner Piotr Kapitsa surprised his colleagues by experiment with a rod eccentrically mounted on a horizontal motor shaft. The demonstration showed that the upper unstable equilibrium of the swinging rod (pendulum) can be made stable by sufficiently fast vibrations of the pivot. The experimental results were explained both by Kapitsa himself who developed his method of ``effective potential" [18]. The above mentioned and other results started the development of a new field in mechanics called "Vibrational mechanics" with numerous applications in science and technology [19]. Without mentioning any mathematical description of the system, children were suggested to find a reasonable combination of all parameters ensuring the desired effect.

Note that they already had necessary LEGO building skills and knowledge in mechanics: gear ratio, alternate/reciprocal motion, friction avoidance, etc.The motor was chosen as the Power Functions Medium Lego Technic motor with speed 185 rpm (with battery supply 7,2V). Using trial and error method, the gear ratio was chosen equal to 25 or 27, wich ensures the vibration frequency about 77 Hz.

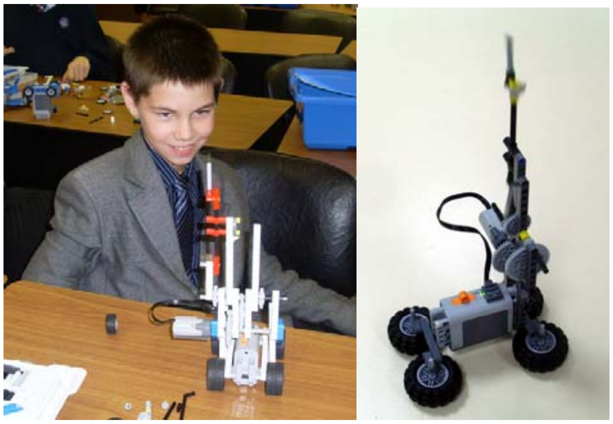

Fig.7.

As a result the experiment was successful. Even a novelty was proposed: Vasily Tobias of 14 created a pendulum with two degrees of freedom which is easier to stabilize, see Fig 7. Andrej Pyatygin created another version of Kapitsa pendulum and a two-rotor vibration set-up. These devices were demonstrated at the International Workshop on vibrational mechanics in November, 27, 2008 in IPME, St.Petersburg and got high evaluation by participants. Particularly, the two-rotor set-up allows one to demonstrate self-synchronization phenomenon for two rings, supported by planetary rotation.

Project 5. Formation control. An important peculiarity of cyber-physical components is their ability to communicate with each other via wireless networks. Such an ability is essential for groups (formations) of ground or aerial vehicles, flocks of artificial insects and other complex systems that are often called multi-agent systems. Behavior of complex systems can be examined when studying simplified systems built in the LEGO Mindstorms NXT environment. Our first experiments of such kind were conducted in 2008 by V.V.Shiegin in the Control of Complex Systems Lab with participation of the SPbSU students. In Fig.8 the system consisting of three autonomous LEGO carts with light and ultrasonic sensors, communicating through Bluetooth. The task of each cart is to find the light source and to approach it until the prespecified distance is reached. The command to start motion is sent over the network by the leader cart providing coordinate-shift synchronization. Videos showing the experiments can be found in YouYube [20].

Fig.8.

LEGO carts provide an interesting platform for studying and testing mobile robot (unicycle) formation control algorithms which attract a lot of interest in control literature, see e.g. [21]. In addition, limited communication speed allows an instructor to pose some interesting problems of control under communication constraints which are typical for cyberphysical systems. Many problems of such kind are still open for nonlinear nonholonomic systems like unicycles and are of interest for research as well as for education,

V. Conclusions

Realization of the first stage of the project “Cyberphysical laboratory” provided evidences of usefulness of LEGO Mindstorms NXT for design and implementation of various controlled mechanisms, robotic and mechatronic devices aimed at prototyping, studying cyberphysical phenomena and teaching in the areas of embedded systems, cyber-physical systems and cybernetical physics. LEGO Mindstorms NXT meets main education and professional orientation demands of high school students focusing on automation, control systems, robotics, etc. The ‘resonance’ effect of mutual amplification of interest and understanding during collaborative work of university and high school students seems to be most important and impressive.

Future work should be aimed at improving performance of created cyber-physical systems and expanding the park of laboratory equipment.

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REFERENCES

[1] http://en.wikipedia.org/wiki/Cyber-physical_system
[2] Lui Sha, Gopalakrishnan S., Xue Liu, Qixin Wang. Cyber-Physical Systems: A New Frontier. IEEE Intern. Conf. on Sensor Networks, Ubiquitous and Trustworthy Computing, 2008. SUTC'08, 11-13 June 2008 pp.1 – 9.
[3] Ott T., Grebogi C., Yorke G. Controlling chaos. Phys. Rev. Lett. 1990. V.64 (11). pp.1196-1199.
[4] Fradkov A.L. Cybernetical Physics: From Control of Chaos to Quantum Control. Springer-Verlag, 2007, 242p.
[5] Fradkov A.L. Application of cybernetical methods in physics. Physics-Uspekhi, 2005, V. 48 (2), pp.103-127.
[6] Fradkov A.L. Control applications in physics: from control of chaos to quantum control. (Invited Plenary Lecture). Preprints of the 3rd IFAC Workshop "DECOM-TT 2003", Istanbul, June 26-28, 2003, pp.47-48.
[7] LEGO Mindstorms NXT http://mindstorms.lego.com/
[8] TexLUG LEGO Robotic Sumo Contest. http://www.davidjperdue.com/competitivemindstorms/rule_set.htm
[9] Yakubovich V.A. Theory of adaptive systems. Soviet Physics Doklady, 1969, V. 13, pp.852–855; Adaptive Systems with Multistep Goal Conditions. Soviet Physics Doklady, V. 13, pp.1096-1099.
[10] Fomin V.N., Fradkov A.L., Yakubovich V.A.. Adaptive Control of Dynamical Plants. Moscow: Nauka, 1981.
[11] Bondarko, V. A. and V. A. Yakubovich. The Method of Recursive aim Inequalities in Adaptive Control Theory. *Int. J. Adaptive Control and Signal Proc.*, 1992, V. 6, pp.141-160.
[12] Astrom K. J., Klein R.E., Lennartsson A. Bicycle Dynamics and Control. IEEE Control Systems Magazine, 2005, V.17, (7), pp. 26-43.
[13] Robot C. Home page. http://www.robotc.net/
[14] Gawthrop, P., E. McGookin. A LEGO-Based Control Experiment, IEEE Contr. Syst. Mag., vol. 24, no. 5, pp. 43-56.
[15] Andrievskii B.R., Guzenko P.Yu., Fradkov A.L. Control of nonlinear vibrations of mechanical systems via the speed gradient method. Autom. Remote Control, V.57, No 4, 1996, pp. 456-467.
[16] HiTechnic www.hitechnic.com
[17] Yakubovich V.A. On a problem of self learning to purposeful behavior. Autom. Rem. Control, 1969, 8.
[18] Kapitsa P.L. Dynamic stability of a pendulum with oscillating suspension point. Zh. Exper. Teor.Phys., 1951, V.21 (5).
[19] Blekhman I. Vibrational Mechanics. Singapore: World Scientific, 2000 (In Russian: 1994).
[20] http://www.youtube.com/shiegin
[21] Marshall J.A., Broucke M. E. and B. A. Francis. Pursuit formations of unicycles. Automatica, V. 42 (1), 2006, pp.3-12.