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Using of LEGO Mindstorms NXT Technology for Teaching of Basics of Adaptive Control Theory ⋆

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Abstract An article describes laboratory plants based on LEGO Mindstorms NXT Technology and made of several electromechanical systems. These plant are used both for research and educational purposes. They allow to study and to compare different identification and adaptive control algorithms. Certain results of application of theoretical adaptive control algorithms for various Lego Mindstorms NXT mobile robots (track, wheel and walking ones) and reaction-wheel pendulum-cart systems are presented in the article.

Keywords: Teaching curricula developments for control and other engineers, cognitive aspects of automation systems and humans, management of competences and knowledge, Lego Mindstorm NXT, mobile robots, adaptive and robust control.

1. INTRODUCTION

"Tell me and I will forget,
Show me and I will probably remember,
Involve me and I will understand"
Konfuciy (450 B.C.)

This article is worth starting with the famous words of the great philosopher. Nowadays students and undergraduates in Russia and probably all over the world show minor interest in exact sciences such as mathematics, physics, informatics and etc. We have to accept the fact that an average level of knowledge in mathematics and physics has been considerably reduced. Why? Probably it is connected with the USSR break-up and with the level of development of Russian economy. But approximately the same problem was announced by the president of the USA, Barak Obama, at the meeting with American Science Academy in 2009. We may discuss the reasons that caused this problem endlessly, but we suppose it is better to look for the ways of changing the situation and the ways of rising of exact sciences status among students and undergraduates. From our point of view attraction or involvement in educational process in particular will make mathematics, physics and informatics popular again. Informatics is, of course, popular, but only as a part of very popular nowadays "informational technologies". Just informational technologies became extremely popular among young people all over the world and in Russia as well. It may be because of young age of informational technologies as science or free working schedule of the specialist who doesn't have to work according to the time-table in the office. What is more, high wages are also attractive for young people as well as romance. It is romantic because young people see on TV or in the cinema how poor programmer-hermit saves the world with single press. And very few of mean level programmers understand that everything is based on mathematics. And our favorite automatic control theory follows mathematics. And there appear the same problems although from our point of view automatic control theory combines mathematics, physics, informatics, electrical technology and electronics. We are the scientific associates and academics of the Control Systems and Informatics department of the National Research (earlier Saint-Petersburg) University of Informational Technologies, Mechanics and Optics (NRU ITMO). Our university is well-known all over the world by the achievements in the field of informational technologies. Different teams of students from NRU ITMO for three times became the winners of the world programming championship. And it seems that the cleverest students study in our university but only being post-graduate stu-

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dents they start to realize that exact sciences such as mathematics are extremely necessary for them for their own development. But the time has gone, they are students no more and they have to learn mathematics from the start. The same conclusions can be made when training for engineers that specialize in the field of control systems development. They also mistakenly suppose they don't need mathematics and physics as they can easily program that will be solving the most important tasks. "What for do we need to know differential equations and Lyapunov Theory?", they ask. How mistaken they are! And how are they later sorry that the time has gone. The students sometimes even take offence at the tutors blaming them for not making the students learn so necessary theoretical disciplines such as automatic control theory.

The reader will reasonably ask us: "Why are you talking about mathematics and control theory all the time? The article has another name!" The thing is that control theory has less romance than its section "Adaptive systems theory". We suppose that it is very romantic to compensate all the indefinite forms of the object and to achieve the desired aim of control. And how pleasant it is to look at the faces of the students who see that a robot constructed on the base of Lego NXT technologies is moving along the indeterminate wall and going around unknown obstacles. Showing to the student the usual tracking systems constructed on the base of direct current motor, of course, may be interesting for somebody. But the true romance is when a student programs controller Lego NXT and his robot makes small wonders when going around unknown barriers.

Figure 1. Students team in work.

Thus, involvement in the training and romance are in the basis of our idea. We think that adaptive system theory being a part of automatic control theory will allow to make control science more attractive for young people. The authors hope that this introduction is enough convincing to motivate the publication of the article. Now we pass to the presentation of the experiment obtained by the authors when teaching the master's degree of the Control Systems and Informatics department of NRU ITMO the discipline "The Basics of adaptive control".

2. EXPERIENCE I

We called this paragraph "Experience 1" as this technique is new for us and new for Russia in many respects. From our point of view there is no sense to discuss theoretical aspects in the limits of this article as they are based on information from the books and articles that have already become classical (Astrom et al. (2001); Bobtsov (2005); Fradkov et al. (1999); Krstic et al. (1995); Monopoli (1974); Narendra et al. (1978); Nikiforov (1999)). All the attention in our article will be given to the laboratory studies based on Lego NXT technologies. Approaches proposed by Bobtsov and Pyrkin will be used as adaptive control algorithms.

It is well known that adaptive systems theory was being developed on the basis of two approaches: direct adaptive control and method that provides provisional identification of unknown parameters of the object (see, for example, Astrom et al. (2001); Krstic et al. (1995); Monopoli (1974); Narendra et al. (1978); Nikiforov (1999)). Our first experiment is the construction of the system of adaptive control of pendulum with inertial hand wheel on the basis of identity approach. Consider a single-mess pendulum that is passively fastened on the rotation axis; inertial hand wheel is located at the end distant form the rotation axis. Fig. 2a shows schematic image of the pendulum with inertial hand wheel on the moving platform.

Design of the mechanical part of pendulum system should be as much as possible simple for quick set-up and strong enough to hold mechanical oscillations and vibration occurred during the experiment. To create a moving platform (cart) we decided to use LEGO - available, easy to use, enough to build strong mechanical moving object of the relatively small size.

Pendulum motion is controlled by means of changing of direction and velocity of inertial hand wheel rotation. In its turn rotation of inertial hand wheel is controlled by direct current voltage setting in the feed circuit of the driving electric motor, mounted together with the hand wheel at the end of pendulum.

Mathematical model (Astrom et al. (2001); Bobsov et al. (2009 a,b); Kolyubin and Pyrkin (2008, 2010); Pyrkin et al. (2010 c,d)) shows physical nature of the mechanical part of the setup that takes place when the system is functioning, and can be described in state of spaces by the following system of differential equations:

$$\begin{cases} \ddot{\theta} + a\sin\theta = -b_p\bar{u}, \\ \ddot{\theta}_r = b_r\bar{u}, \end{cases} \tag{1}$$

where θ is the pendulum angle relative to vertical, θ_r is angle of rotation of inertial hand wheel relative to vertical, a, b_p, b_r are unknown complex parameters of the pendulum system.

It is extremely difficult to bring the pendulum at once from the optional initial state to the specified vicinity by the small control and to stabilize it in the upper equilibrium position (Fig. 2b). In this connection the solution of the formulated task is divided in two steps: pendulum excitation and bringing it to the specified vicinity and stabilization in the upturned position. As the control

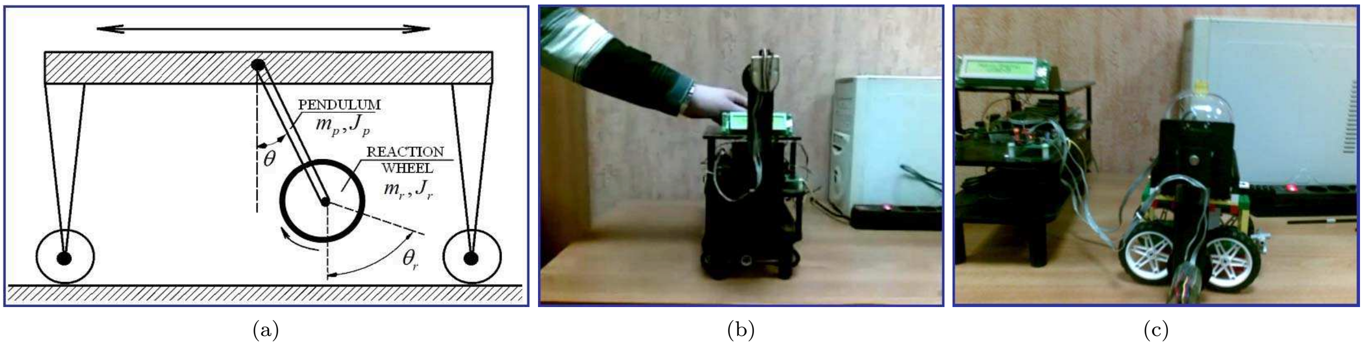


Figure 2. Inertial wheel pendulum on the moving platform.

law we will choose algorithm published in (Bobsov et al. (2009 a,b); Kolyubin and Pyrkin (2008, 2010)). To swing the pendulum and to bring it in the specified position velocity gradient method is applied. This method allows the system to accumulate energy corresponding to the potential energy of the pendulum in the upturned position. With the help of such approach the pendulum enters the specified vicinity with the minimal velocity. The second algorithm based on the modal control method provides the stabilization of pendulum in the upturned position. Such hybrid control system was proposed by Mark Spong already in (Astrom et al. (2001)). However, this approach supposes precise knowledge of all mass-overall dimensions of the system to form control law.

The main differences of our approach are the parametric uncertainty and LEGO based moving platform (Bobsov et al. (2009 a,b); Kolyubin and Pyrkin (2010)). Our approach includes adaptive identity loop in which parameters a, b_p, b_r of the model (1) are estimated in the "online" regime. Obtained on the basis of least square technique estimates are substituted in the excitation and stabilization algorithms. The result exceeds all expectations. Pendulum is oscillating faster and is kept in the upturned unstable position; at the same time the value of three parameters tend to some constant values.

The present setup happened to be interesting for the fundamentally another problem: compensation of the external parametrically not defined disturbance (Aranovskiy et al., (2006); Bobtsov (2008 b); Bobtsov and Pyrkin (2008, 2009); Pyrkin et al. (2010 a,b,c,d); Pyrkin (2010)). To the whole construction, that is easily moving around horizontal plane, disturbing action initiated by the hand and imitating nonregular storm is applied (Fig. 2c). The problem of stabilization of the pendulum lower equilibrium position that is disturbed by the external not measured action in the conditions of delay control is researched (Pyrkin et al. (2010 c,d)). To study the work of algorithms in the delay conditions the buffer is created. This is the buffer in the internal memory of the mechanotronic complex through which control function is transmitted: control signal is put to the buffer entry and output signal of buffer is coming to the control object. The value of imitated delay is determined by the buffer size.

Control law is based on the methods of adaptive estimate of harmonic wave frequency proposed by Aranovskiy, Bobtsov, and Pyrkin (see, for example, Aranovskiy et al. (2007, 2010); Bobtsov (2002); Pyrkin et al. (2010 a); Pyrkin (2010)). In the present laboratory setup an algorithm of identification of disturbing action is programmed. The algorithm has robust properties with respect to nonregular parts of disturbance. The algorithm of disturbance compensation generates control signal supplied to the motor in order to retort disturbance and to keep the pendulum in the stable vertical position without oscillations.

3. EXPERIENCE II

Consider the classical track control problem. Lego NXT mobile robot with full-track drive is used as plant. Any object, for example, a book, can be a tracking object (Fig. 3). Ultrasonic sensor installed in the model measures the distance to the book. Control algorithm compares the current distance with the given distance and forms a control signal to the servodrive in accordance with the tracking error $e(t)$.

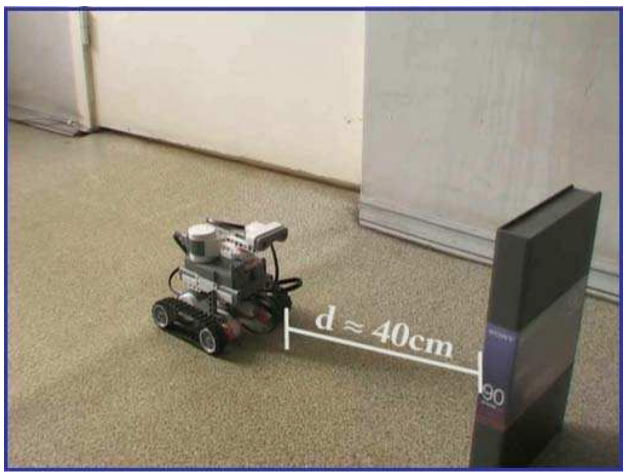
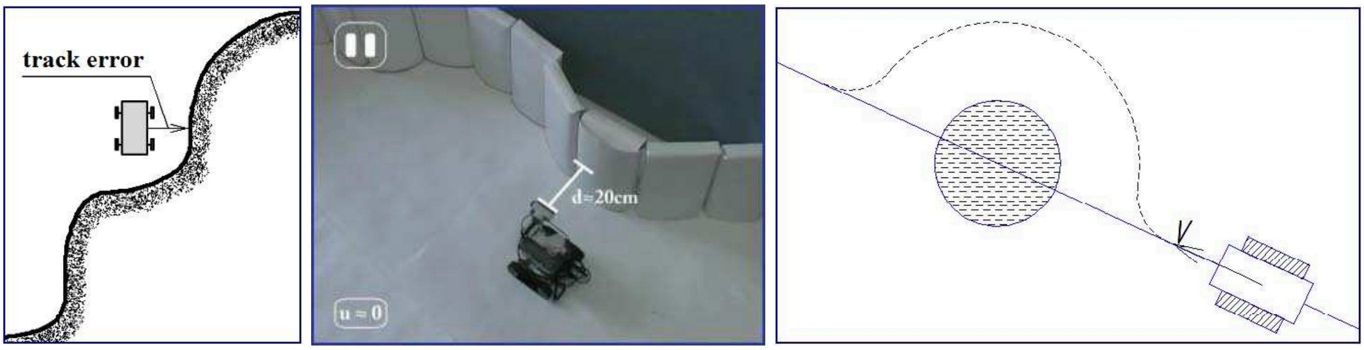


Figure 3. Holding of the given distance.

Control law is of the form:

$$u_1(t) = u(t), \quad u_2(t) = u(t), \tag{2}$$

where u_1 and u_2 are control signals input directly to servodrives. To calculate control signal $u(t)$ we will apply the method called "consecutive compensator" published in (Bobtsov (2004, 2005); Bobtsov et al. (2005); Bobtsov and Nagovitsina (2006); Bobtsov and Nikolaev (2007); Bobtsov and Pyrkin (2007); Bobtsov et al. (2008); Bobtsov and Nikolaev (2009)):



(a) (b) (c)

Figure 4. Motion of mobile robot along indeterminate trajectory.

$$u(t) = -k\alpha(p)\xi_1(t), \tag{3}$$

$$\begin{cases} \dot{\xi}_1 = \sigma\xi_2, \\ \dot{\xi}_2 = \sigma\xi_3, \\ \vdots \\ \dot{\xi}_{\rho-1} = \sigma(-k_1\xi_1 - k_2\xi_2 - \ldots - k_{\rho_1}\xi_{\rho-1} + k_1 e), \end{cases} \tag{4}$$

where number $k > 0$, $\alpha(p)$ is a hurwitz polynomial at the degree $\rho - 1$, where ρ is a relative degree of the chosen model of robot motion, number $\sigma > k$, coefficients k_i are calculated in accordance with demands of asymptotic stability of system (4) at zero input. As a possible way of setting up the parameters k and σ we will increase their values until the following condition is fulfilled (Bobtsov et al. (2008)):

$$|e(t)| < \delta_0, \forall t \geq t_1, \tag{5}$$

where positive number δ_0 is given by the control system developer. To set up the parameter k we will use the algorithm:

$$k(t) = \int_{t_0}^{t} \lambda(\tau)d\tau, \quad \lambda(t) = \begin{cases} \lambda_0, & for\ |e(t)| > \delta_0, \\ 0, & for\ |e(t)| \leq \delta_0, \end{cases} \tag{6}$$

$$\sigma(t) = \sigma_0 k^2(t), \tag{7}$$

where numbers $\lambda_0 > 0$ and $\sigma_0 > 0$.

Now consider the problem of mobile robot adaptive control along to unknown trajectory (Figs. 4b, 4c). We constructed Lego NXT mobile setup with full-track drive that has ultrasonic range sensor. The sensor measures the distance to the wall along which the motion is occurring. The wall curvature is not defined in advance. Walking towards the wall mobile robot defines the distance to it, compares the value with the given value and forms control signals on the drives on the basis of tracking error. Control law is of the form:

$$u_1(t) = u_v(t) + u(t), \quad u_2(t) = u_v(t) - u(t), \tag{8}$$

where u_1 and u_2 are control signals input directly to servodrives, function $u_v(t)$ is chosen proportionally to the velocity of the robot on the direct site of the trajectory, function $u(t)$ brings in mismatch between the drives and it makes robot to turn left or right. To calculate control signal $u(t)$ we will use the algorithm (3)–(7).

Let us make the task for the robot more difficult and put on his way an external barrier (Fig. 4c). The robot is moving along the given trajectory and observes the barrier on his way. Coming to it within some range robot begins to drive around it keeping the given distance to the barrier. Coming closer to the main trajectory robot starts to taxi to it leaving the barrier behind. When moving along the given trajectory algorithm (3)–(8) can be used but we should take into account the condition that tracking error should be available for measurements. The same approach is used for building the algorithm of driving around the barrier at the given distance. Thus, this task uses the same approach (3)–(8) for building of hybrid control system but with different by nature measured signals: the first algorithm allows the robot to move along the given trajectory, the second one is to drive around fixed barriers.

4. EXPERIENCE III

Let us make the task more difficult again, and let us suppose the robot has only two wheels (fig 5a, 5b). At first, we have to make robot stand stably in vertical position, so it is necessary to solve the problem of stabilization of unstable equilibrium position. When solving this problem we can draw an analogy with upturned pendulum (see. Fig. 2b). Then it is interesting to solve the already mentioned classic track control problem (see Fig. 4b), but for the two-wheeled balancing robot. Control law is of the combined form:

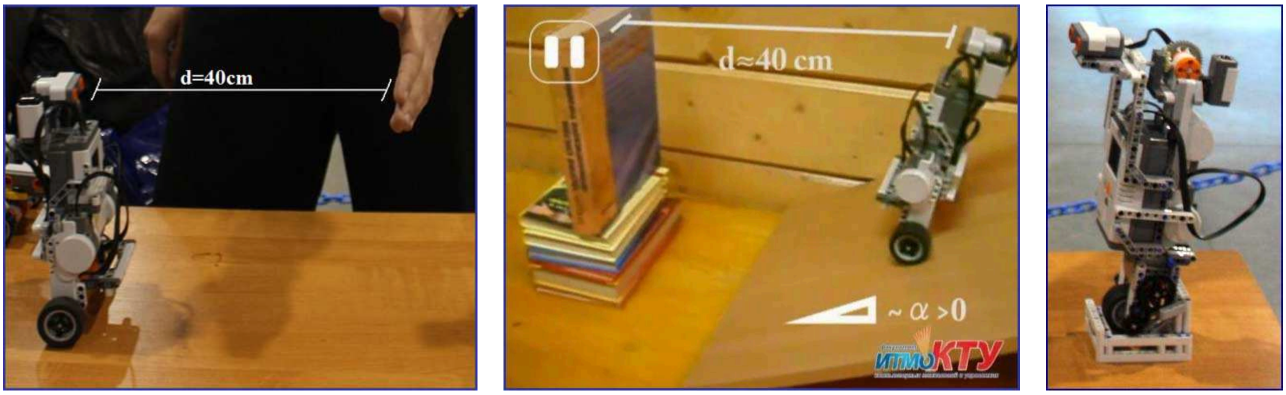
$$u_1(t) = u_s(t) + u(t), \quad u_2(t) = u_s(t) + u(t), \tag{9}$$

where algorithm u_s is calculated taking into consideration stabilization of the setup, function $u(t)$ is chosen in the form of (3)–(7), as in the experiment II for the full-track stable robot. Figure 5a shows the result of using the combined control. The robot stands in the vertical position and keeps the given distance equal to 40 cm to the object. Figure 5b shows more difficult experiment: the surface, where robot is balancing, is tilted, and the tilting angle is slowly changed, at that the robot keeps vertical position and the given distance to the barrier.

To complicate the task the student will be offered to study the algorithms described in the experiments I–III from the point of view of the task in which two-wheeled robot is moving along the indeterminate trajectory. Another interesting and rather complicated task is keeping an equilibrium for one-wheeled robot (see Fig. 5c). Together with the tracking and control tasks relative to indeterminate trajectory this experiment has to solve the problem of vertical position stabilization.

5. EXPERIENCE IV

Let us make one more step together with the walking robots to attract the students in the adaptive control



(a) (b) (c)

Figure 5. Two-wheeled and one-wheeled mobile robots.

(a) (b)

Figure 6. Bipedal walking robots.

(Fig. 6). Figure 6a shows the result of solving the classic problem of tracking for the object (folder in this case) at the given distance. We have to mention that the task of this experiment is complicated by nontriviality of the robot. First of all, it is necessary to make the robot walk forward and backwards. Then we can study the task of tracking similarly to experiments II and III. To solve this problem method of "consecutive compensator" is used: algorithm of the form (3)–(7).

Figure 6b shows the first trial example of two-legged walking robot which legs have three controlled degrees of freedom. We can draw an analogy with the man's leg that has a knee and a foot. At present this robot can remember motions that are shown to it at the stage of "learning" and then reproduce them. The robot can stand up and makes the first steps. Within the limits of laboratory work the students will be offered to study adaptive algorithms that provide stable straight moving along the horizontal and tilted surface, already described tracking of the object, walking along indeterminate trajectory and going around barriers at the given distance.

This experiment is specially mentioned at the end of the article as coordinated control of such multichannel system is the most difficult task. However, students' intellect and quick wit don't allow them to give up in front of such uneasy task.

6. CONCLUSION

"The limits of sciences are like horizon:
the closer to them you come,
the further they move aside"
Pier Buast

The article comes to an end but everything is just starting for us and our students. We have attracted the students and made our science romantic and interesting for them. They responded and now are setting the new problems to us, initiate us as the scientists and make us formulate new algorithms of adaptive control. Students feel themselves the hosts of the department where we work and we are their tutors who are searching for new opportunities of realization of their ideas. We have shown them several examples, and received great number of ideas regarding the development in response. Now our department is preparing for the partial reconstruction. At present we have walls, desks, blackboards, chairs, computers and multimedia screens. But the students want to have Wi-Fi transmitters and receivers, grounds for robots and etc. It seems to us that our department turns from classic academic establishment to comfortable house. Let it be this way! Let not only tutors, following the great Konfucij, attract the students, but the whole establishment help us in this uneasy, but extremely important matter.

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