Mechatronic demonstrator for testing sensors to be used in mobile robotics functioning on the inverted pendulum concept

L Sandru[1], V Dolga[1], C Moldovan[1] and D Savu[1]

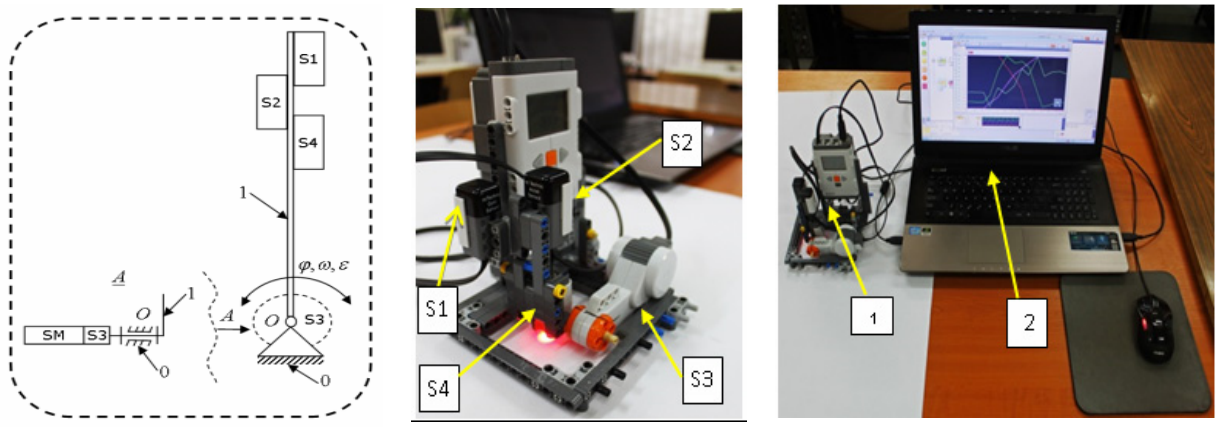
[1]Mechatronic Department, University Politehnica Timisoara, Timisoara, Romania

E-mail: sandru_lucian2002@yahoo.com

Abstract. As the educational system is evolving, there are a lot of Mechatronic demonstrators used in schools and universities to demonstrate some technical, theoretical principle and analyzing new concept to apply this studied information, build practical hardware parts. The idea of using mobile robots for different applications is very common today. For choosing the best hardware and software configuration for the mobile robot it is necessary to make a documented analysis of the environment in which the mobile robot will perform. In our demonstrator we want to collect information from an optical sensor what can be used to maintain stability in a mobile robot equilibrium reading the reflected light from a surface. After hardware build we make a particularity study to see how optical sensors response in different ambient light and surface. To show some reference point we are collecting data from gyroscopic, accelerometer or rotation sensors.

1. Introduction

Element (1) is actuated by S3, a sensor-actuator system in order to produce the rotation angle φ of the element with respect to the base. On (1) are mounted the following sensors, S1 – an inclinometer/accelerometer, S2 – Gyroscopic sensor and S4 – Optical sensor. The assembly is connected to a Lego Mindstorm NXT platform to facilitate the data acquisition and to relay it to a PC.



(a) (b) (c)

Figure 1. (a) Front view; (b) Experimental setup: S1- gyro sensor, S2- acceleration sensor, S3 – rotation sensor, S4 – optical sensor; (c) Experimental setup (1) and PC (2).

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

The main objective of the experiments was the comparative analysis of the sensor outputs S4 and S3. We want to analyze the sensor output with respect to the inclination angle to the horizontal and the reflective media. In the same time, data from the gyro and accelerometer is recorded for an enhanced motion analysis. The behavior of the optical sensor was analyzed in junction with diverse reflective surfaces.

The experiment was conducted in the Sensors and Actuators Laboratory at the Department of Mechatronics. In figure 1 is shown the developed mechatronic demonstrator device.

The experimental setup uses the NXT2 IDE and hardware. These have the following technical specifications according to [4],[7],[8],[9],[10]:

- Microcontroller ARM7 32-bit
- Memory: 256 Kbytes FLASH, 64 Kbytes RAM
- Microcontroller AVR 8-bit
- Memory: 4 Kbytes FLASH, 512 Byte RAM
- Bluetooth
- USB Connection to PC (12 Mbit/s)
- 4 Input ports (for sensors)
- 3 Output ports (for actuators)
- Graphic LCD display with 100x64 pixel resolution
- Sound resolution 8-bit

The characteristic parameters for the servo and sensors are presented in [5], [6]:

- The actuator has an internal rotation sensor. This sensor offers the possibility to accurately control the motor's position. The rotation sensor's accuracy is ± 1 degree. The actuator can be commanded to rotate for a number of degrees, but also to complete a number of rotations.
- The light sensor is constructed using a LED and a photo sensitive diode. In case the LED is turned off, the sensor analyzes the environmental light, in case the LED is on, the sensor analyzes the reflected light and converts it into a percentage number [%].

The NXT2 platform offers ease of use and thus is recommended for demonstrative stands. Other researchers have benefited of this features, researchers such as [11], [12], [13], [14].

2. Description of data acquisition

To produce the test stand and perform the data acquisition from the four sensors, following actions were realized:

- All sensors were connected to the Lego NXT2 platform at ports 1,2,3 and port A respectively. Through Port A are routed the power and command signals for the actuator and also the angle feedback signal from S3. The NXT2 was also connected to a PC via an USB cable.
- The LEGO MINDSTORMS NXT-2 Programming IDE [1] allows the following settings:
    - allows for 0.65s recording of the sensors when element (1) is moving
    - data acquisition frequency set at 20Hz
    - preset delay of 0.04s at the start of the data acquisition before the start of motion of element (1)
    - The NXT Programming IDE allows for sensor calibration. This feature was used in our application, the information from the optic sensor was compared to the maximum value and scaled proportionally [2]
- The working procedure included 10 test runs for the same experiment in the same working conditions, data acquisition and statistic analysis
- There were selected a number of 10 different reflective surfaces to analyze the signal from the optic sensor
- The motion of element (1) if made of: an angular rotation φ in a preset direction; 1s pause; inverse rotation by the same amount $-\varphi$ to the initial position

3. First Experiment. Unique swing of the optic sensor with respect to the reflective surface.

For the acquisition, processing and representation of the signals were used Lego Mindstorms Education NXT-2 Programming IDE [1] and MS Excel [3]. For our experiment the important data are collected from: internal time clock – in seconds, light sensor value – in %+ (relative light). In table 1 we are represent an set of collected data.

Table 1. Table with collected numeric data.

Time [s]	Light_p1_1
0,000	64,0
0,078	63,0
0,108	63,0

In table 1 are shown the following: sensor=Light Sensor – sensor type; units= %+ unit of the sensor signal; Time = time period for the collected data; Light_p1_1 – name for values from S4 (Light sensor, p1 – port name; 1 – first recorded set of data).

For the datasets from sensors S1, S2, S3, S4 in time interval t[s], in table 2 and 3, for each parameter is the unit specified in brackets, with the following: Time – time interval in which data is acquired, starting from 0 with unit [s]; gyro sensor (S1) – with unit [°/s] (degree/second); acceleration sensor on Z direction (S2) – unit [G] with values +/- 2G; rotation sensor (S3) in the actuator – measures the motor's position in [°] with an error of ± 1°; optic sensor (S4) – a relative illumination value expressed in [%].

In table 2 is shown the acquired data from the file saved in the NXT controller. The file save option is activated through the developed program for the controller. The graphic representation of the data is shown in figure 2. For this data set was used a yellow matt paper.

Table 2. Experiment 1 sensor values.

Time [s]	S1 [° / s]	S2 Z axis [g]	S3 [°]	S4 [%]
0,000	9,0	-6,0	0,0	64,0
0,078	8,0	-5,0	0,0	63,0
0,108	21,0	-59,0	0,0	63,0
0,151	94,0	-3,0	3,6	63,0
0,202	121,0	-12,0	10,8	64,0
0,253	150,0	41,0	18,0	63,0

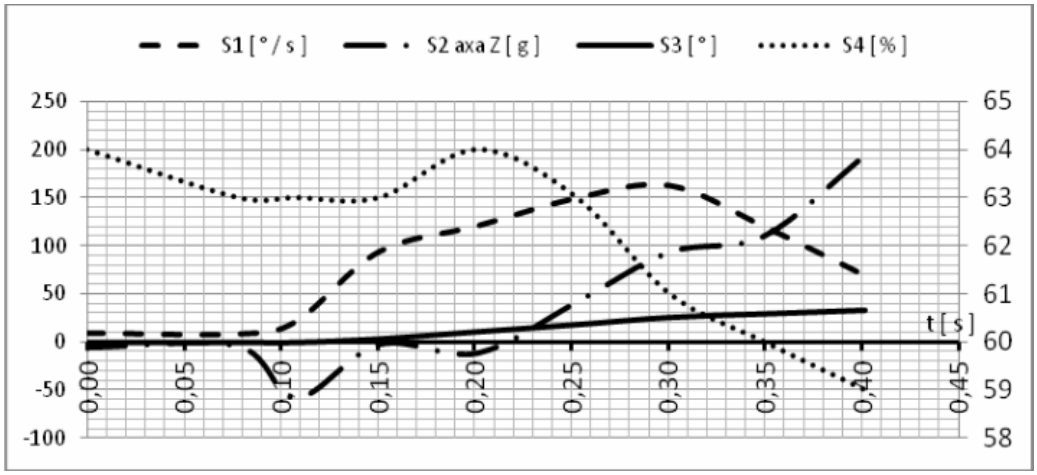


Figure 2. Graphic for parameters S1, S2, S3, S4 in experiment 1.

After the results analysis from S1, S2 and S3 it results that the surrounding environment has no effect in the data acquisition, thus it is shown also an analysis of S4 – optic sensor. This is done regarding the reflective material, time domain and angular motion domain.

In experiment 1 was done a behavioral analysis for S3 and S4 with a yellow matt reflective surface. There were conducted 10 test runs for this experiment. The averaged values are computed in MS Excel and shown in table 3 and figure 3.

Table 3. Averaged values in experiment 1.

Time [s]	S3 [°]	S4 [%]
0,0000	0	63,8
0,1072	1,44	63,6
0,1456	3,24	63,7
0,1921	7,92	63,9
0,2423	15,12	63,7
0,2911	20,88	63
0,3413	28,08	61,5

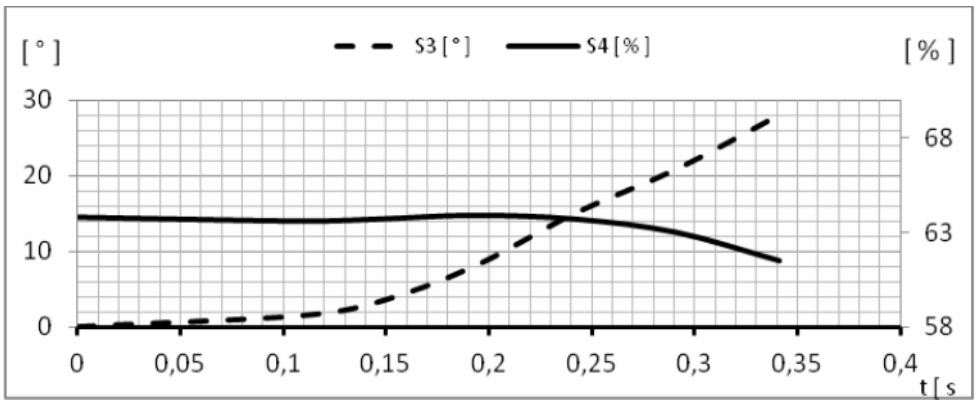


Figure 3. Signals obtained in experiment 1.

From the graphics and data analysis results a general graphical form for the S3 and S4 sensors shown in figure 4. This allows some conclusions regarding S3's behavior. The conclusions are:

- The reflective surface and the environment affect the output signal
- There can be defined some reference values for the results analysis
  - Time instant t0 allows to impose the limits a and b – on the two graphics corresponding to a linear variation of the signal
  - Rotation angle α_0 (about the horizontal) corresponds to point b.
- Relative illumination remains linear between LP1 and LP2 (corresponding to time t0, point a and for a α_0 rotation respectively.
- Following the experiments, relative illumination values were in the interval [35,5-65]% for the 10 reflexive media
- For the experiments in which were used yellow matt paper, bright green matt paper, white matt paper and yellow glossy paper, $LP \in [58,5 \div 66]\%$.
- For the experiments in which were used red glossy paper and white glossy melamine, $LP \in [55,6 \div 62]\%$.
- For the experiments in which were used glossy violet paper, $LP \in [59,4 \div 53,9]\%$

- For the experiments in which were used blue glossy and green glossy paper, $LP \in [35,4 \div 46,7]\%$.
- For the experiments in which were used black matt paper, $LP \in [35,3 \div 36,1]\%$.
- The acquired signals present very good repeatability for each test run
- It is of great interest a numeric analysis for data correlation of sensors S1, S2, S3 and S4 and an information fusing analysis

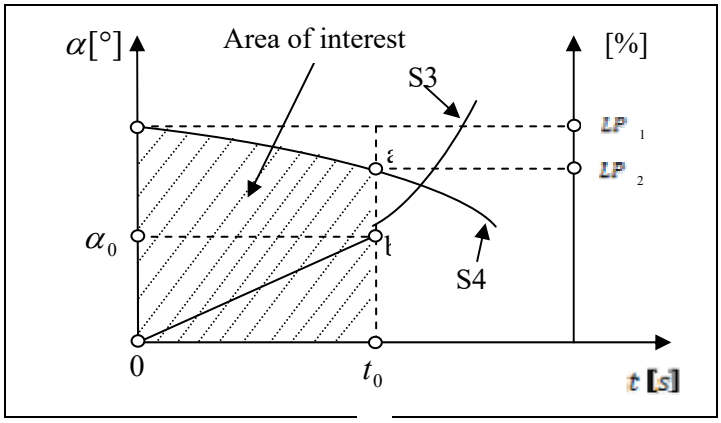


Figure 4. Graphic for values from S4 optic and S3 rotation.

It is of interest the movement domain reduction around the vertical position of the element (1). This results from the main objective, the stability analysis of the stability of an inverted pendulum.

4. Second Experiment. Periodic oscillations of the optic sensor about the reflective surface

The second set of experiment uses the same mechatronic demonstrator – shown in figure 1. In these experiments we want to determine the optical sensor S4 characteristics around the vertical axis - $\alpha = 0$ for element (1) – figure 1. This position corresponds to the stable position of an inverted pendulum.

Element (1) has to swing angle α from the reference value – zero. The reflective surface used in the experiment is yellow matt paper. The experiment was repeated 10 times for statistical processing. Actual angle α is measured by S3, the integrated sensor in the actuator.

Each experiment had duration of 6 seconds. This value was preset through the Lego NXT programming IDE [1]. The sampling rate was set to 25 Hz. Experimental data analysis was done according to table 4.

Table 4. Cycle of experiments.

Rotation domain of α	With surrounding light (daylight)	Without surrounding light (daylight)
$\alpha_1 \in [-30°; +30°]$	Experiment exp_11 / figure 7	Experiment exp_12/ figure 6
$\alpha_2 \in [-10°; +10°]$	Experiment exp_21 / figure 9	Experiment exp_22/ figure 8
$\alpha_3 \in [-5°; +5°]$	Experiment exp_31/ figure 11	Experiment exp_32/ figure 10

The experiments done in surroundings without light were designed to show the influence of the surrounding – noisy light. The experiment was conducted by introducing the demonstrator in a closed cardboard box.

The signals from sensors S1, S2, S3 and S4 are presented graphically in figure 5. The motion is periodic with a period of 0.7s. In the same time S4 values remain relatively constant. The signal from the gyro shows also periodicity – figure 5. In table 5 are presented sample values in the way that they are memorized by the controller ant retrieved on the PC.

The signal from the accelerometer sensor shows correlation with the gyro. From the graphics there can be seen a difference of signals from sensor S4 during the two semi periods in the motion cycle.

This aspect is accentuated when the signal is presented at a different scale – figure 10 and 11. The relative light intensity from S4 remains in a specific interval for each experiment.

Table 5. Signal fragment of acquired data in exp_11.

Time [s]	S1 [^{0}/s]	S2 axe Z [g]	S3 [°]	S4 [%]
0	8	4,5	0	68,1
0,0787	7,8	4,4	0	68
0,1081	8,1	2,7	0	68
0,1381	13,2	-19,2	2,88	68,1
0,2547	108,4	31,5	14,04	69
0,2845	98,1	59,9	17,64	69
0,3169	94,1	39,7	20,88	69
0,3469	95,8	72,1	23,4	68,9
0,3769	96,9	67,4	25,2	68,1
0,4069	98,5	84,3	28,08	68
0,4375	97	101,4	31,32	67,7
0,4678	50,3	181,1	32,4	67,7

The experiments exp_31 and exp_32 have shown high sensor stability for $\alpha \sim \pm 6°$ relative to the vertical axis.

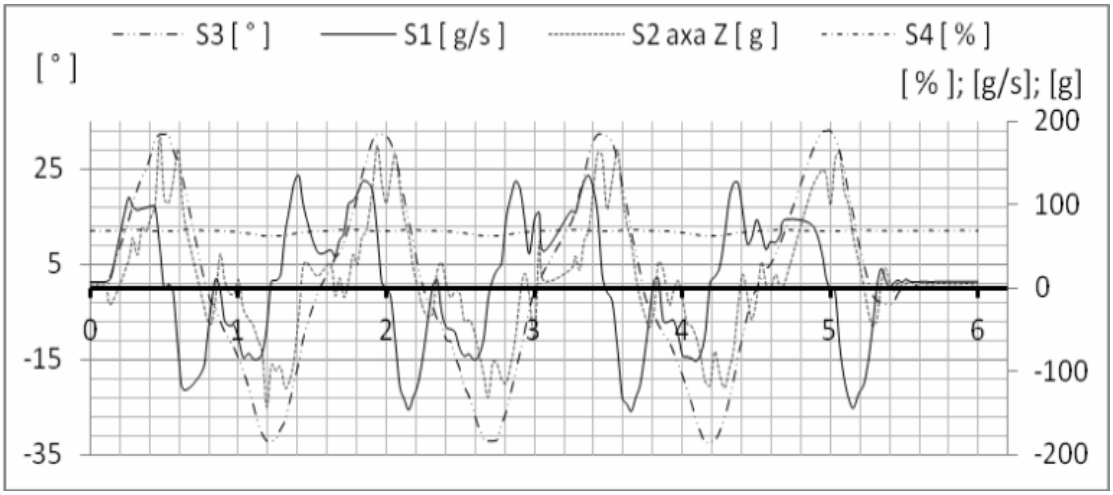


Figure 5. Signals from S1, S2, S3, S4 in exp_11.

For the clearer observation of the acquired signals, in figures 6 to 11 are presented only signals from the optical sensor with and without ambient light, signals from S1 and S2 have no effect in this experiment.

In figures 7,9,11 we developed a set of experiments in an environment with ambient light. There can be seen a difference between the signal from the optic sensor on the duration of the two semi periods of the motion cycle. To further investigate the causes we performed another set of experiments in an closed, light free environment – figures 6,8,10.

There can be seen periodicity of the optic signal and a accentuation of this with each semi period. To further increase the reliability of the analysis of correlation between the two signals, the experiment was restrained to domain $\alpha \in \approx [+10°;-10°], \alpha \in \approx [+5°;-5°]$ in the light free environment

In figures 8 to 10 are presented the two signals from the position sensor S3 and optic sensor S4 for a cyclic motion. The signal from the optic sensor shows periodicity but the amplitude is lower than in the previous cases.

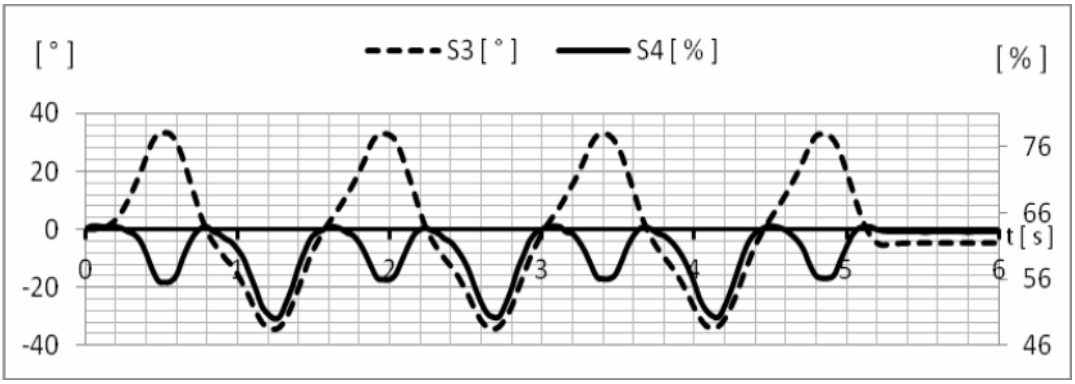


Figure 6. Signals from S3 and S4 in exp_12.

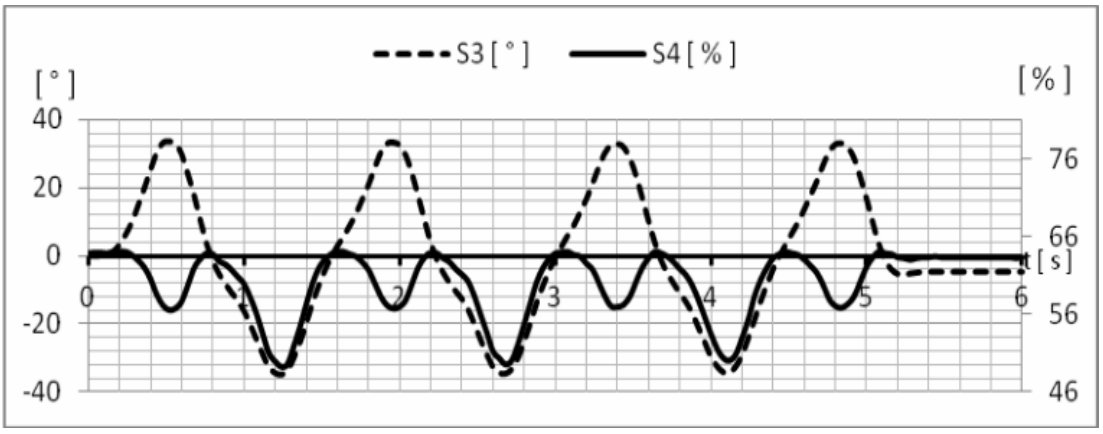


Figure 7. Signals from S3 and S4 in exp_11.

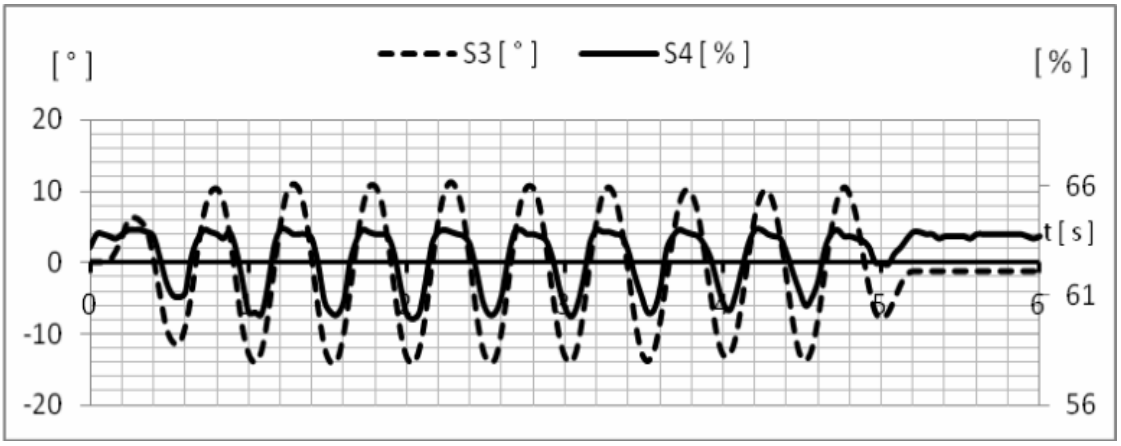


Figure 8. Signals from S3 and S4 in exp_22.

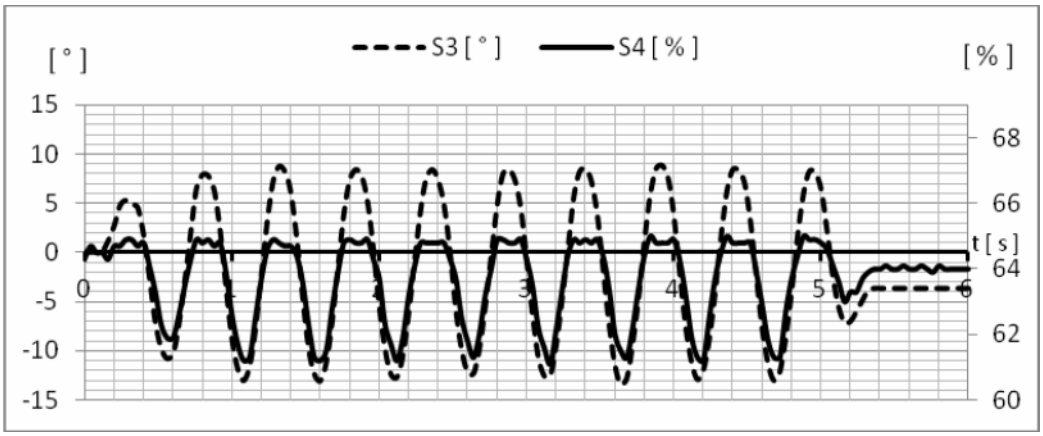


Figure 9. Signals from S3 and S4 in exp_21.

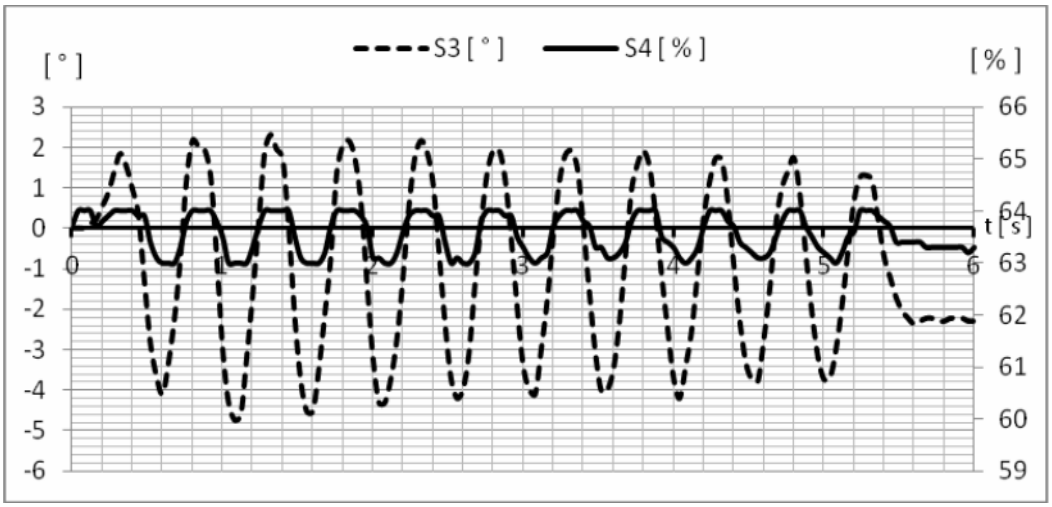


Figure 10. Signals from S3 and S4 in exp_32.

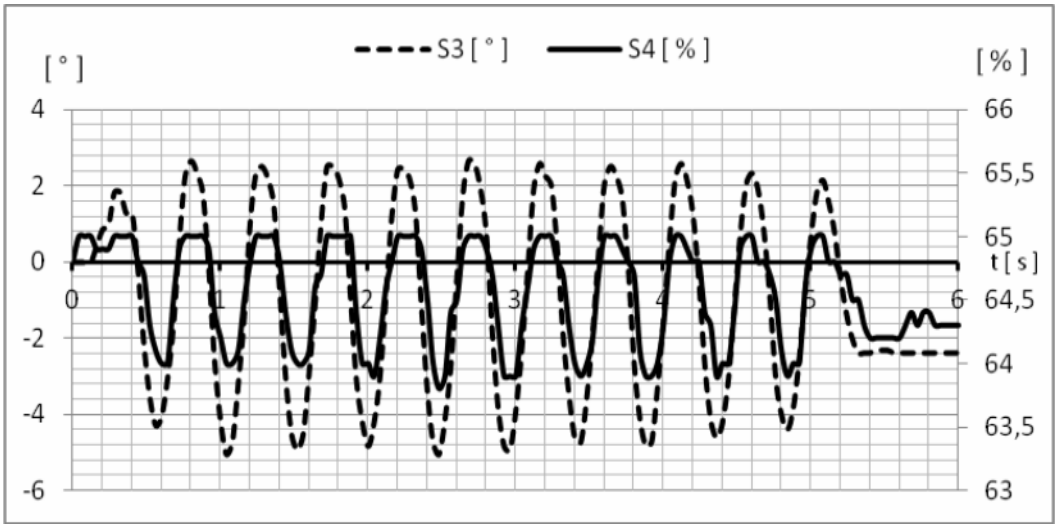


Figure 11. Signals from S3 and S4 in exp_31.

In figure 12 are presented processed signals for the cases in the analysis, to underline the observations that were imposed.

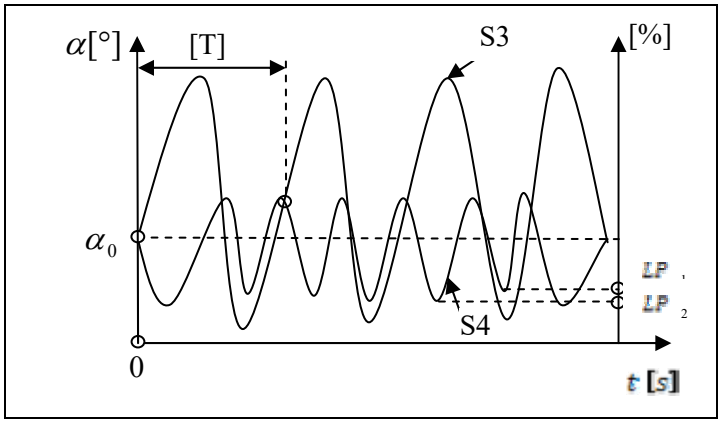


Figure 12. Characterization of signals from S4 si S3.

During one period of the variation of rotation sensor signal take place 2 variations in the existing limits [LPMax-LPMin]. In each experiment the variation is different, these values are shown in table 6.

Table 6. Extreme values for LP [%].

Angular range [α]	With ambient light [%]	Without ambient light [%]
$\alpha_{Max - Min}$ [±30°]	64-49,2	64-50
$\alpha_{Max - Min}$ [±10°]	65-61,1	64-59,9
$\alpha_{Max - Min}$ [±5°]	65-63,8	64-63

5. Conclusions

The experiments allow the following remarks: The direction of movement can be determined by analyzing the variation of sensor S3; Lowering the oscillation angle for the optic sensor and signal acquisition allows to underline the dependence to the motion; For the optic sensor, the signal acquired in ambient light differs from the signal with no ambient light on the same reflective surface; In the range $\alpha \in [+5°; -5°]$, where the inverted pendulum should be controlled, good sensibility of the light sensor can be reached for reflected signals in both directions $\alpha \in (+; -)$ of the equilibrium position; These results are a real help. In future studies, we want to build a humanoid robot, which uses electric signal, from the optical sensor to maintain equilibrium balance, applying invert pendulum concept.

6. References

[1] ***http://www.generationrobots.com/media/Lego-Mindstorms-NXT-Education-Kit.pdf (acc.01.16.2016)
[2] ***http://www.terecop.eu/downloads/appendix_1.pdf (acc.01.16.2016)
[3] *** https://support.office.com/en-us/article/Basic-tasks-in-Excel-2010 (acc.01.16.2016)
[4] *** http://botbench.com/blog/2013/01/08/comparing-the-nxt-and-ev3-bricks/
[5] ***http://www.philohome.com/motors/motorcp.htm
[6] ***https://www.teachengineering.org/collection/umo_/lessons/umo_sensorswork/umo_sensors work_lesson05_presentation_v2_tedl_dwc.pptx
[7] Gonc A, Lima J and Costa P 2006 Rapid prototyping of mobile robots extending Lego mindstorms platform in Madrid *7th IFAC Symposium on Advances in Control Education*
[8] Valera A, Weiss M, Valle´s M and D´ıez J 2006 Proposal of a low-cost mobile robot control laboratory experiment in Madrid *7th IFAC Symposium on Advances in Control Education*

[9] Gawthrop P and McGookin E 2006 Using Lego In Control Education, Plenary Lecture in Madrid *7th IFAC Symposium on Advances in Control Education*
[10] Behrens A, Atorf L, Schwann R, Ballé J, Herold T and Telle A 2008 First Steps into Practical Engineering for Freshman Students Using MATLAB and LEGO Mindstorms Robots *Acta Polytechnica* **48**
[11] Garcia-Cerezo A, Gomez-de-Gabriel J, Fernandez-Lozano J, Mandow A, Munoz V, Vidal-Verdu F and Janschek K 2009 Using LEGO robots with LabVIEW for a Summer School on Mechatronics *ICM 2009 IEEE International Conference* pp 1-6
[12] Gawthrop P and McGookin E 2004 A LEGO-based control experiment *IEEE Control Systems Magazine* **24** pp 43-56
[13] Grega W and Piłat A 2008 Real-time Control Teaching Using LEGO MINDSTORMS NXT Robot *IMCSIT International Multiconference Computer Science and Information Technology* pp 625-628
[14] Heck W, Clements N and Ferri A 2004 A LEGO experiment for embedded control system design *IEEE Control Systems Magazine* **24** pp 61-64