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MECHATRONIC DEMONSTRATORS FOR ROBOTICS

PhD Thesis – English Summary
for obtaining the scientific title of doctor at
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in the Mechanical Engineering PhD field
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The PhD thesis by the title MECHATRONIC DEMONSTRATORS FOR ROBOTICS, aims the development of a theoretical and applicative/experimental support for a group of mechatronic demonstrators in order to highlight the applicability and usefulness of certain modular structures in this approach and the constraints imposed on the control of a mechatronic system – inverted pendulum.

The main objective of the PhD thesis consists of a theoretical and experimental analysis of the inverted pendulum concept for the control of some mechatronic demonstrators.

Based on this research project, to the main objective of the thesis there have been subordinated a series of operational or specific objectives:

- Identify the current state of researches in relation to the approached field, of the related problems, and of the expected doctoral thesis;
- Elaborate a synthesis, a bibliography on mathematical models of the inverted pendulum and its applications in mechatronics;
- Synthesize the bibliography related to the mechatronic demonstrators;
- Materialize the mechatronic philosophy in designing proceed of the demonstrators, based on the inverted pendulum;
- Apply the mechatronic philosophy related to the balance between modeling/simulation and the experiment for mechatronic components in the demonstrator's structure;
- Modeling and experimental analysis of a biped demonstrator;
- Dissemination of research results, highlighting of contributions and future research directions.

The thesis is structured in seven chapters, bibliography and annexes. The approach and the achievement of the objectives are described in the following chapters of the PhD thesis as follows:

Chapter 1 - *Introduction* - describes the field and the research directions in which the current PhD thesis falls. The motivation of the doctoral thesis theme, the main objective and the operational objectives are being highlighted. At the end of the chapter it is presented the structure of the PhD thesis on chapters and their extension.

Chapter 2 - *Current researches on the inverted pendulum and its use in mechatronic systems* - presents a bibliographic synthesis on the inverted pendulum concept, as well as the aspects of integrating the concept of inverted pendulum in maintaining the balance in various systems.

Chapter 3 - *Mechatronic demonstrators and operating principles* - starts with generalities connected to the notion and usefulness of a mechatronic demonstrator. A summary of some benchmarks is inserted in the chapter below. The mechatronic demonstrator is a truly functional system designed to highlight the theoretical and practical aspects of the research in the technical field.

Chapter 4 - *Designing of mechatronic systems and representative demonstrators* – presents the results of the philosophy of mechatronic design through the developed demonstrators. The chapter also presents the case of software integration in a demonstrator - serial robot.

Chapter 5 - *Experimental analysis of integrated sensors in the humanoid demonstrator structure* - is the object of modeling, simulations and experimental analyzes for mechatronic sensorial components in the structure of a demonstrator. There are included work procedures resulted from the experimental analysis and their synergistic use. The experimental results are accompanied by conclusions from the processing of experimental data. The experimental results are accompanied by conclusions from the processing of experimental data.

Chapter 6 - *Humanoid demonstrator modeling and simulation* - reviews the constructive concept of the demonstrator, experimental analysis and modeling, critical analysis of the results.

Chapter 7 - *Final conclusions and personal contributions* - highlights the conclusions that come out of the research activities, reviews personal contributions, ways to disseminate results, and recommendations for future research.

Bibliography - includes a part of the titles used in the elaboration of the present thesis.

Annexes - include the developed and processed materials during the elaboration of the thesis. All these materials have been used for the development of the thesis chapters.

1. INTRODUCTION

The concept of mechatronics originates in the activities and researches in Japan of 1970-1973. Research and design activities in multidisciplinary teams have highlighted the need for common concepts, procedures and language for all the working team members. The term was patented by the Yaskawa Electric group and protected until 1982 as a trademark of this company [Mishra, 2011], [Mori, 1969], [***, 1.1].

The concept of mechatronics has generated controversies and different approaches in both definitions and fields of interest for this technology [Harshama, 1996], [Mishra, 2011]. As a way of defining mechatronics, the literature offers various approaches:

- The word „mechatronics" is an abbreviation based on „mecha" (in *mecha*nism) and „tronics" (in electronics). Ko Kikuchi, the president of the Yaskawa group, is considered the author of this concept [Mori, 1969].
- Integration of electronics, control engineering and mechanical engineering [Bolton, 1995].
- Synergetic integration of mechanical engineering with electronics and intelligent control in the design and manufacture of industrial products and processes [Harshama, 1996].

The evolution of the mechatronic systems from the industrial revolution (represented by Watt's regulator) to the revolution of computer science (represented by the microcontroller and microprocessor) is suggested in Figure 1.1 [***, 1.4], [***, 1.5], [***, 1.15].

In 1681 Denis Papin invented a safety valve for a kettle. He called this container the „steam digester", as was being made of cast iron with a tightly sealed cap and an automatic pressure relief valve if the set threshold is exceeded (Figure 1.1) (Figure 1.1) [***, 1.5], [***, 1.6].

In 1799, the inventors R. Delap and M. Murray invented the pressure regulator (Figure 1.1). In 1803 Boulton and Watt combined the two systems invented by D. Papin and the two inventors R. Delap and M. Murray and developed the automatic pressure and level controller.

In the early 1800s, Elias Howe invented the first variant of the sewing machine, highly contributing to the mechanization of the textile industry. In a short time, other variants of the machine were introduced on the market, Wheeler & Wilson sewing machine [***, 1.7]. In 1623 Wilhelm Schickard sets the foundations of modern computers by inventing the first mechanical calculation device (Figure 1.1) [***, 1.9].

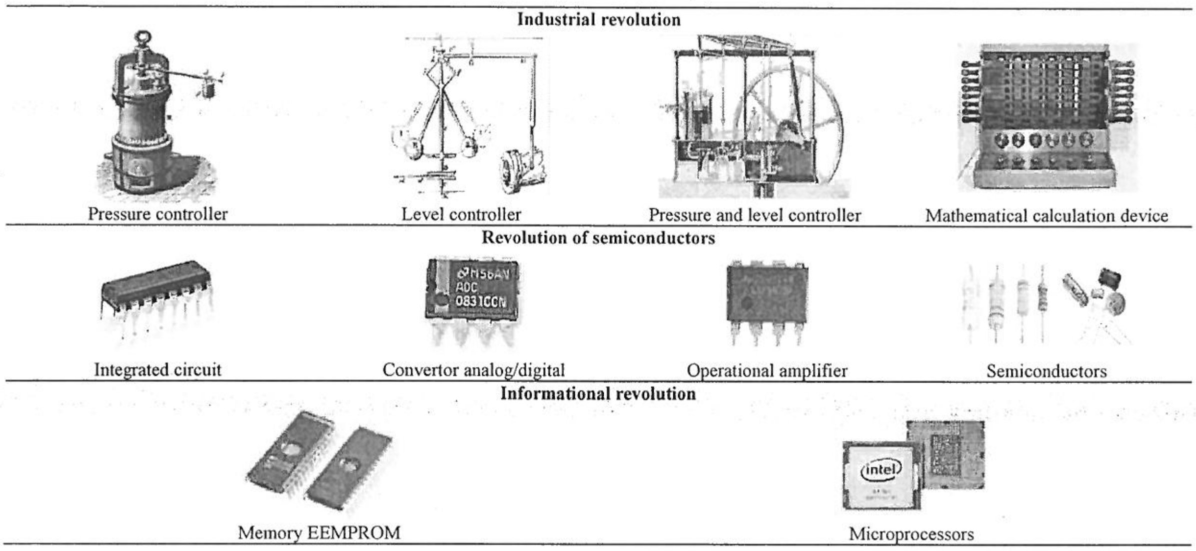


Figura 1.1 Evolution of mechatronic systems

Over time, the evolution of the technique, which resulted in mechanization, automation and robotizing, was mainly determined by the possibility of using the information in a superior way [Dolga, 2007].

The development of mechatronic systems is based on hardware components integration and software component integration. This results from the integration of knowledge from different fields of physics and technical disciplines. This philosophy of designing seeks to achieve a synergistic effect defined by products with quality technical and economical parameters [***, 1.15].

Robotics has been an area of interest for mechatronic technology through its specific products and activities. Over time, a continuous evolution of robotics is noticeable in all areas [***, 1.11]. The number of professional service robots sold in 2015 increased considerably, by 25%, to 41,060 units as compared to 2014, the sales were directed towards: logistics, terrestrial mobility, defense, medicine, cleaning, construction, inspections, public relations, underwater environment, security and rescue, as well as towards other fields of activity [***, 1.12].

In conclusion, the evolution in the sphere of mechatronics has met a remarkable development, starting from the first pioneering steps, when solution for the technical problems of the respective years were being experimented: common language in the development of electromechanical systems, reaching the present time of sophisticated developed robots with complex tasks in unstructured environments.

The automotive and technical domains are generally the industries that benefit most from the development of the mechatronic sphere and of robots. Statistics show that the number of robots used for various activities is steadily increasing.

The field of education uses the mechatronics facilities to train specialists in the multidisciplinary environment.

As technology evolves, the mechatronics contributes with new ideas, solutions and procedures in order to solve current technical problems. [***, 1.13], [Ivanescu, 2002].

2. CURRENT RESEARCHES ON THE INVERTED PENDULUM AND ITS USE IN MECHATRONIC SYSTEMS

The objective of this chapter is to present a synthesis, a specialized bibliography regarding the concept of inverted pendulum, mathematical models and its applications in mechatronics.

In the literature, the notion of pendulum is assigned to a „...solid, heavy body that can oscillate around a fixed point or a fixed axis when it is removed from its stable equilibrium position" [Vâlcovici, 1968], [Silaş, 1968].

Physical pendulum is defined as a solid body (rigid) that can oscillate freely under the action of gravitational force, around a horizontal axis that does not pass through its mass center. In the equilibrium position, the body center C is located on the vertical that passes through the suspension center O (Figure 2.1.a). If we remove the physical pendulum from the equilibrium position and one lets it go, it will perform an oscillatory motion (Figure 2.1.b).

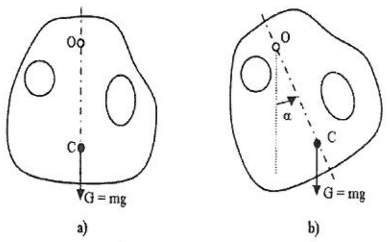


Figura 2.1 Real pendulum in: a) equilibrium; b) oscillating

Similarly, the gravitational pendulum is defined by: a physical system consisting of a mass body m suspended from a fixed point through a thread of the length l, which performs an oscillatory motion under the action of gravitational force. The gravitational pendulum was studied for the first time in depth by the Italian scientist Galileo Galilei and applied in the study of body movement [Vâlcovici, 1968], [Silaş, 1968].

The ideal pendulum represents a mathematical model, where the pendulum thread is considered to be inextensible and does not have its own weight, and the body is punctiform and its entire mass is concentrated in that point. [Vâlcovici, 1968], [Silaş, 1968].

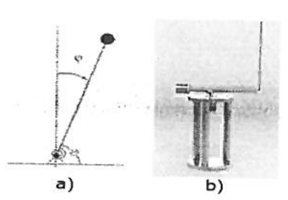
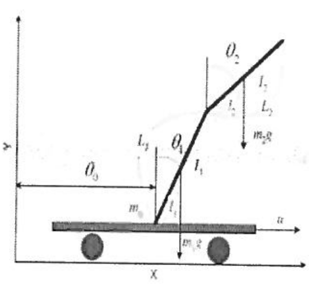
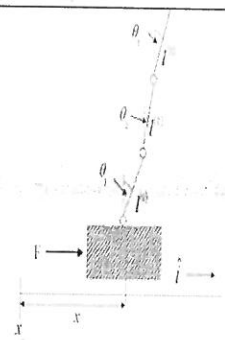
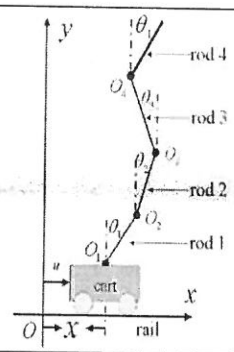
The reverse (inverted) pendulum consists of a pendulum having its center of mass above the pivot point. Inherently, this pendulum is unstable. To stay in the vertical position that defines it, the pendulum must be actively balanced.

Technical reference researches of the technical variants using the balance principle of the inverted pendulum were given by: Acrobot [Spong, 1995], Pendubot [Fantoni, 2000], Furuta Pendulum [Acosta, 2010], Reaction Wheel Pendulum [Block, 2007], Bicycle [Åström, 2005], VTOL aircraft [Martin, 1996], Beam-and-Ball system [Andreev, 2002], [Boubaker, 2013].

An intense development can be seen in the field of steppe robots, especially in the bipedal ones. Honda companies are noted with a biped robot called ASIMO and Sony with the QRIO robot, and also some researches on these robot types [Endo, 2005].

Principal variants for the inverted pendulum are presented in Table 2.1, namely: a classic inverted pendulum system modeled on the basis of an elastic element and a shock absorber, a horizontal rotation module that has a pendulum attached which can oscillate vertically; the double inverted pendulum structure, the mechanism consists of two elements integrated into the structure of a mobile robot in translation movement; triple inverted pendulum system; quadruple inverted pendulum system [Hongxing, 2004].

Table 2.1 Models of the inverted pendulum

			
Inverted pendulum with passive mechanism (bow and shock absorber) [***,2.5]	Double inverted pendulum [Bogdanov, 2004]	Triple inverted pendulum [Su, 2003]	Quadruple inverted pendulum [Hongxing, 2004]

Many researchers attempted to use the inverted pendulum method in order to find the best robotic stabilization solutions, to perform different actions.

In Figure 2.2 there are presented some applications that appeal to the inverted pendulum principle for maintaining the balance.

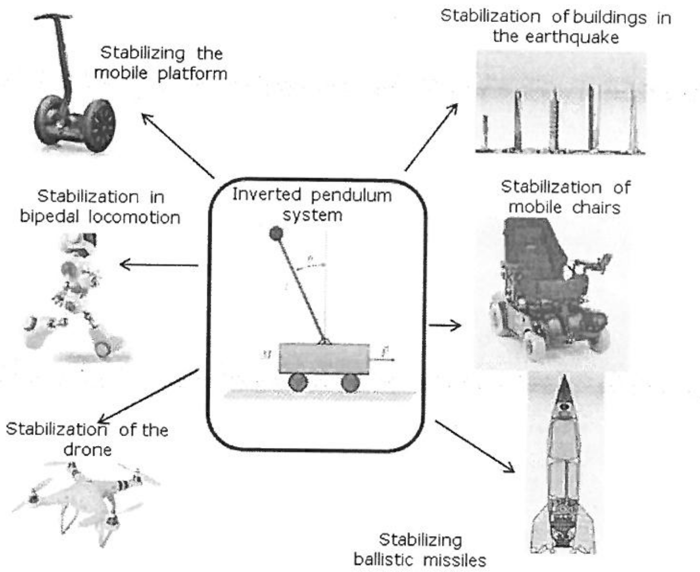


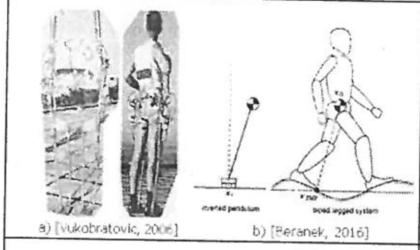
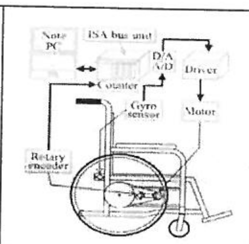
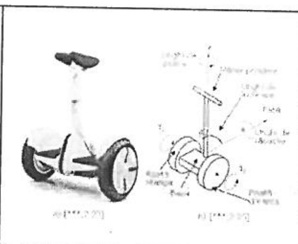
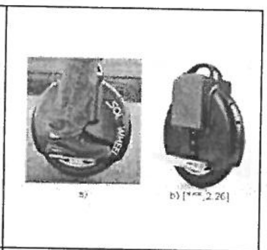
Figura 2.2 Applications using the inverted pendulum concept

The development of mobile humanoid robots coincides with the development of exoskeleton mechatronic systems. The most interesting researches in the field are presented in (Table 2.2):

- Bipedal systems were among the first developed systems. One can consider that the study of an exoskeleton has established the first researches in the field of humanoid robots;
- The wheelchair was designed as a support for people with motor disabilities to facilitate their movement;
- Segway Mobile Platform;

- The mono-cycle transport device is no longer fitted with a handlebar and the user's support is based on the two pedal placed side by side on the drive wheel.

Table 2.2 Locomotion systems

			
a) Pneumatic exoskeleton; b) Inverted pendulum, humanoid robot	Electric wheelchair	a) Segway mobile platform; b) Inverted pendulum system applied to the platform	a) Operator on the mono-cycle device; b) Mono-cycle device

In conclusion:

- the bibliographic synthesis presented highlights the analysis results of a large volume of literature in the field of the thesis;
- the topic of the inverted pendulum is subject of interest thanks to the utility in modeling of applications in the robotics;
- control problems represent a high percentage of the researches of the mechatronic systems and of the subjects allocated in the educational and training area;
- a bibliographic analysis of the principles and the current stage of the mechatronic demonstrators is necessary.

3. MECHATRONIC DEMONSTRATORS AND OPERATING PRINCIPLES

The mechatronic demonstrator is a truly functional system designed to highlight the theoretical and practical aspects of technical research.

The mechatronic demonstrator of a product is built to test all the functional parameters of the product that appear during operation.

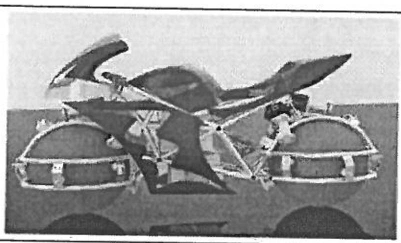
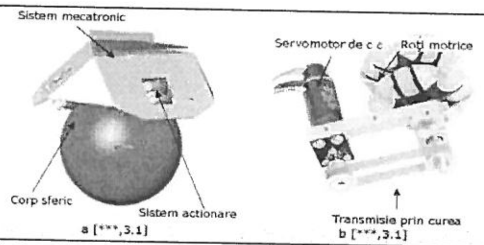
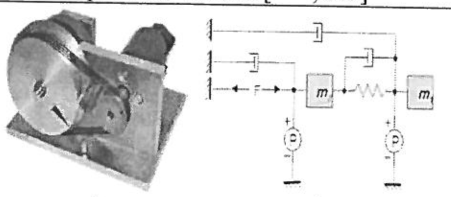
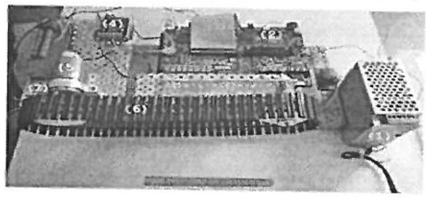
These developed systems represent a result of the interdisciplinary simulation process through which the software part, which controls a combination of precision mechanical and electrical components, is implemented [Isermann, 2005].

The operational objective of the chapter consists of the elaboration of a synthesis of the bibliographic material that highlights applications, constructive solutions and future work directions.

The article nominates the issues to be analyzed by the project (Table 3.1), through various constructive models, namely:

- Spherical wheel version situated under a chassis shaped as a motorcycle, the drive system, the control system, the sensor management system, frame;
- Version of the spherical vehicle in the shape of a ball and the drive system in which there are illustrated constructive aspects of this demonstrator;
- The Linix Demonstrator is a 4th order system, equipped with two inertia wheels, a belt drive, an engine and two sensors;
- Demonstrator for linearization of the oscillatory motion.

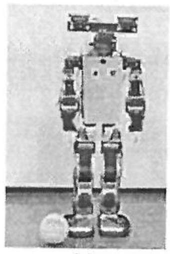
Table 3.1 Constructive models of certain mechatronic demonstrators

	
Spherical vehicle [***, 3.7]	a) Spherical vehicle; b) Drive mode
	
a) Linix demonstrator; b) The model of the demonstrator [Dirne, 2005]	Mechatronic system of linearization and its subsystems

Scientific literature highlights multiple researches on demonstrators dedicated to mobile robots [Matsumoto, 1990].

A humanoid robot named Simon, in interaction with a human operator, is shown in Figure 3.2.a The teacher teaches the robot how to perform new movements by voice command or by manually moving the robotic arm. In Figure 3.2.b there are presented general aspects of an another humanoid robot for the perception of surrounding images.

a)



b)

Figura 3.2 a) Simon in interaction with a human operator ; b) humanoid robot for the perception of surrounding images

In conclusion, all the demonstrators presented in this chapter had the main purpose of translating theoretical ideas into real practical models. The developed demonstrators provide a real opportunity to study at a small-scale physical effects during various processes. Demonstrators for humanoid robots occupy a high percentage in the approaches in the scientific literature.

Some of the requirements of mechatronics demonstrate: the system should fall within the category of mechatronic systems; the variant used must have a complexity degree corresponding to the theoretical and experimental study; the demonstrator's structure must be compact and modular.

4. DESIGNING OF MECHATRONIC SYSTEMS AND REPRESENTATIVE DEMONSTRATORS

The main objective of this chapter is to apply the mechatronic philosophy of designing a system for materializing some mechatronic demonstrators. These demonstrators, according to the operational objectives of the research plan, should allow the modeling of the theoretical aspects and the physical models developed in the elaboration of the thesis.

The design process is a complex activity that needs to take into account of a series of aspects. For the development of a technical system, the designer should consider:

- Solving the problem of initial specifications and requirements, new ideas, qualitative and quantitative assessments;
- Correlating the technological functions, working and shape principles for the synthesis of a technical system;
- Correlating the analyzed product with the requirements of the company, according to the requirements of reliability and quality.

For the same specific problem, which has several possible solutions, methods are being developed for generating ideas, presenting solutions and evaluating them.

The development of technical systems is based on engineering concepts that develop a functional product from the stage of abstract idea to real forms, in the smallest detail of operation.

These demonstrators, according to the operational objectives of the research plan, should allow the modeling of the theoretical aspects and of the physical models developed in the elaboration of the thesis. Figure 4.1 shows the components used in the construction of demonstrators by usage functions.

Functions		Hardware model			
		A	B	C	D
Locomotio n	1	Lego well	Parallax well	Steeping device	Track
Tractions	2	Motor electric Lego	Motor electric Parallax	Electrical drone engine	Hybrid electric-thermic engine
Communicati ons	3	Bluetooth	Wireless	USB Cable	Radio
Energy supply	4	Accumulator	Accumulator	Power supply	Pneumatic supply
Controls	5	Lego CPU controller	Arduino CPU controller	Raspberry pi 2 CPU Controller	Arduino Controller motor
Sensorial	6	Gyroscopic	Optic	Ultrasonic	Acceleration
	7	Infrareds	Gyroscope	Ultrasonic Pralax ping)))	Acceleration - MPU 6050

Figure 4.1 Components used in the construction of demonstrators

The demonstrator's construction started with D-1, a mechatronic humanoid robot demonstrator, Lego NXT-2. Based on the bibliographic synthesis in chapters 2 and 3, we developed a first demonstrator equipped with a gyroscope sensor (1) and an optical sensor (2), specific to humanoid robotics (Figure 4.1).

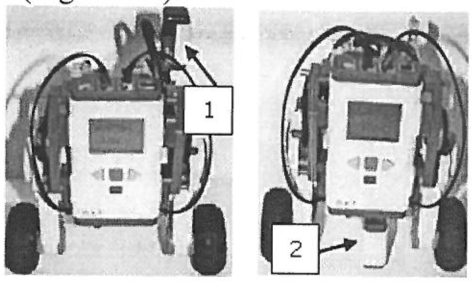


Figure 4.1 Variants of the humanoid demonstrator (D-1) [Sandru, 2016]

The operational objective assigned to the demonstrator aims the modeling of an artificial humanoid system for the analysis of the stability according to the principle of the inverted pendulum.

The following demonstrator (D-2) is designed to analyze the optical sensor feature. This demonstrator aims to confirm the functional parameters of the optical sensor integrated in the D-1 demonstrator and the possibility to correlate the information with the other sensors (Figure 4.2).

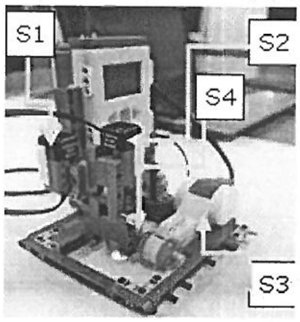


Figure 4.2 Variants of the humanoid demonstrator (D-2) [Sandru, 2016]

The D-3 Demonstrator materializes one of the requirements for the mechatronic demonstrator by combining several mechatronic components. Thus, it offers the possibility of comparing its performances with those of certain demonstrators having the same functions (demonstrator D-1) (Figure 4.3).

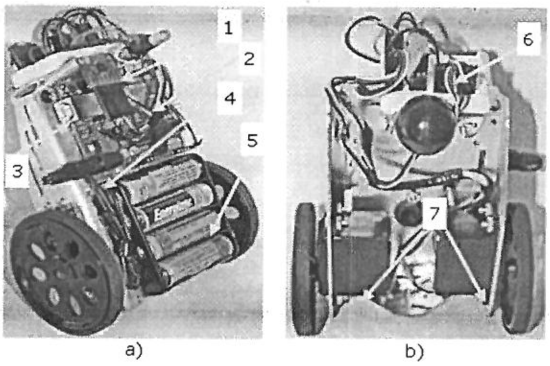


Figure 4.3 Demonstrator D-3: a) Side view; b) Front view [Sandru, 2016]

The hardware component connection scheme used for this mobile humanoid demonstrator is shown in Figure 4.4.

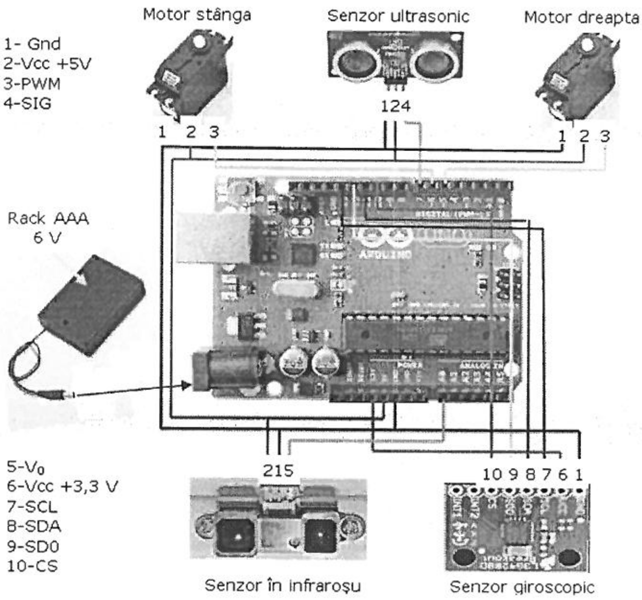


Figure 4.4 Electrical hardware component connection

The D-4 demonstrator develops experiments for writing, drawing or other graphical operations, with an industrial robot Mitsubishi RV-2AJ on different angular surface. This is shown in Figure 4.5.

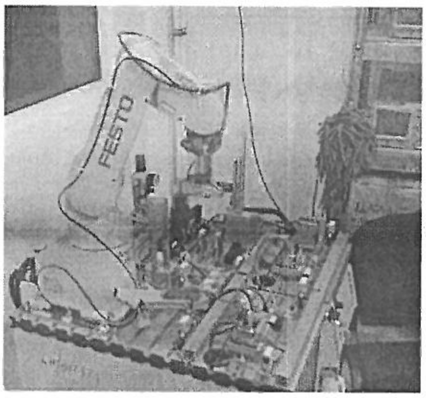


Figure 4.5 Mitsubishi robot RV-2AJ (D4) [Crainic... Sandru, 2016]

The D-5 demonstrator is shown in Figure 4.6 [Sandru, 2015]. The requirements imposed on the demonstrator followed: to highlight the process of the mechatronic demonstrator's materialization and to implement the experimental analysis for an open-loop system.

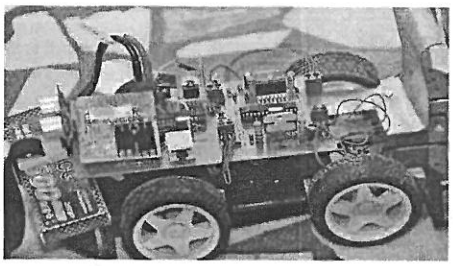


Figure 4.6 Autonomous mechatronic demonstrator (D-5) [Sandru, 2015]

The D-6 demonstrator was designed for the constructive and functional analysis of a mobile robot [Stanescu ..., Sandru, 2015]. The steering mechanism at the mobile robot (Figure 4.7) is able to analyze the ability to perceive information from the outside, has the ability to identify objects in the area of activity. This can be done by using certain sensory systems at the same time or in turn, depending on the information to be obtained.

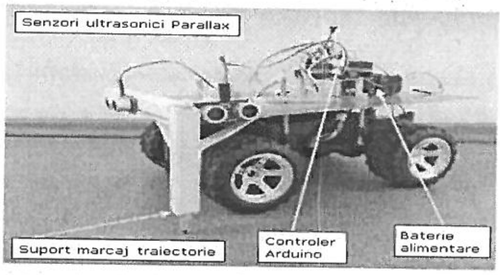


Figure 4.7 Demonstrator designed for the constructive and functional analysis of a mobile robot [Stanescu..., Sandru, 2015]

The D-7 Demonstrator (Figure 4.7) aims to test the features of the ultrasonic sensors as well as the way of how they are influenced by ambient temperature. The results of the analyzes were disseminated through the "Study of the influence of temperature on ultrasonic sensors" [Sandru, 2015].

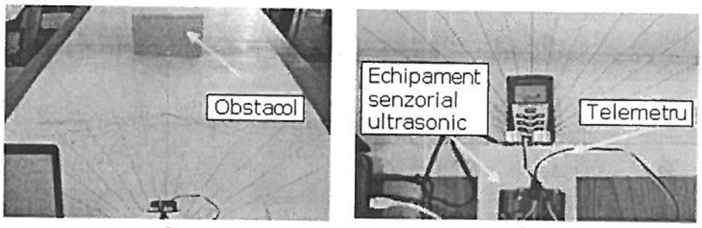


Figure 4.8 a) Experimental stand; b) Telemeter Bosch and ultrasonic sensor

The D-8 Demonstrator has considered the possibility of using the mechatronics technology to design new devices that use the inverted pendulum principle to maintain stability. Based on experiments using the Parrot AR 2 drones [Sandru, 2016] (Figure 4.9), it is intended to develop new command and control methods for flying drones.

Figure 4.9 Parrot AR 2

One of the proposed experiments intend to command and control the drones using a smart glove (Figure 4.10) equipped with a three-axis acceleration sensor that communicates with a control plate Raspberry PI model (Figure 4.11).

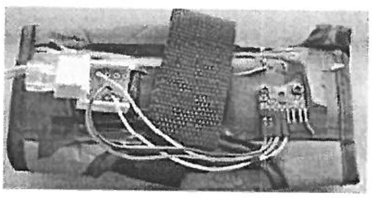


Figure 4.10 Smart glove

The process of reading the movement moments is done with a sensory device that incorporates a gyroscope and a three-axis accelerometer (MPU 6050).

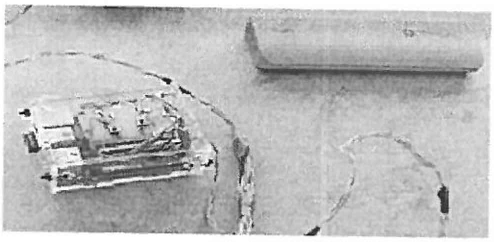


Figure 4.11 Movement moments reading device

In conclusion, the experimental demonstrators open new horizons on the issues to be addressed for different physical phenomena and in the construction of new mechatronic structures.

The presented demonstrators allowed to highlight both the mechatronic structure of the systems and the many possible activities to be performed.

By using demonstrators for didactic purposes, but not only, the actions that take place in the transfer of mathematical models into physical functional systems can be more easily observed.

It was possible to highlight aspects related to mobile robots and the application of the inverted pendulum principle in order to maintain the balance of these while traveling and carrying out certain tasks.

Hardware and software knowledge has been implemented which have led to the materialization of a variety of functional mechatronic systems through integration.

The demonstrators of mobile robots have generated information on which to draw pertinent conclusions about current mechatronic problems and possible solutions for them.

Therefore, following the theoretical and experimental analyzes, the reserach trajectory has been established in order to achieve the operational objectives corresponding to the following chapters.

The results listed within the chapter were disseminated within the published papers (8 papers) and within the patent file filed at OSIM. One can consider the achievement of the operational objective of Chapter 4.

5. EXPERIMENTAL ANALYSIS OF INTEGRATED SENSORS IN THE HUMANOID DEMONSTRATOR STRUCTURE

The operational objective of the chapter aims the designing and building of a demonstrator using the inverted pendulum concept, based on the balance and development of a humanoid mobile robot. The humanoid mobile robot is identified as a mechatronic demonstrator developed according to the mechatronic philosophy, as shown in Figure 5.1.

Regarding the vertical stability of the robot, this is ensured on the basis of information received from sensorial elements integrated within the system.

In order to achieve the operational objective, a set of experiments was designed to analyze the behavior of sensory elements in an environment similar to that of the developed demonstrator and to analyze the possibilities of integration.

The experimental analysis was designed in two phases. In the first phase we conducted the analysis of the behavior of the sensory elements on an experimental stand, developed especially for this purpose. In the second phase, a direct experimental set was conducted on the demonstrator structure in the final phase. A comparison of the results was followed by this approach.

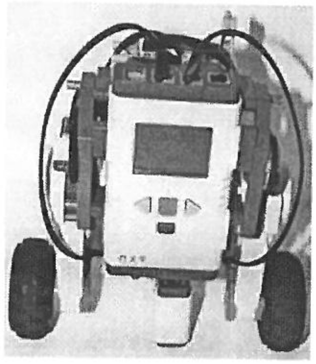


Figure 5.1 Humanoid mobile robot – mechatronic demonstrator equipped with optical sensor

The stand was based on the Lego Mindstorm components. The main concept diagram is shown in Figure 5.2. A mobile element (1) is driven in rotation by an actuator that has integrated the sensing subsystem S3 to acquire the rotation angle φ. The sensors are located on the mobile element: S1 - Acceleration / Tilt Sensor, S2 - Gyro Sensor, S4 - Optical Sensor. The developed structure benefits of the Lego Mindstorm NXT-2 platform advantages in order to acquire data and transfer them for analysis to a computing system.

The objective pursued in the experiments is to retrieve and compare firstly the information from the optical sensor S4 and the rotation sensor S3. One wish to analyze the information of the optical sensor according to the inclination towards the horizontal and the reflection medium. At the same time, the signals from the gyroscopic sensor and the acceleration sensor are acquired for a multiple characterization of the motion parameters. The optical sensorial element was analyzed for different reflection materials, from the working environment.

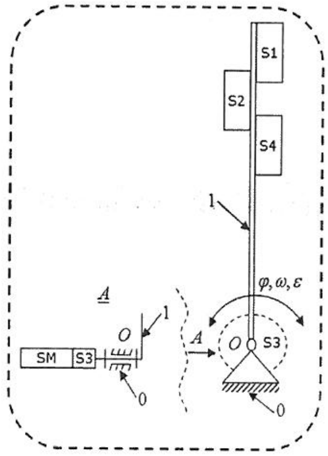
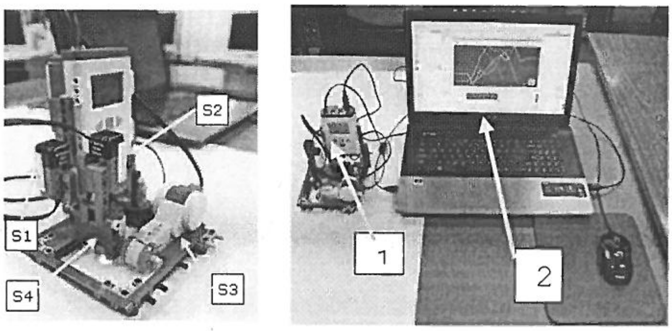


Figure 5.2 The principal diagram of the developed mobile system (SM – electrical servomotor) [Sandru, 2016]

The experiment was conducted in the Sensors and Actuators Laboratory of the Department of Mechatronics of the Polytechnic University of Timisoara.
In Figure 5.3 it is presented the general design of the developed stand for this purpose and the integrated components.

From the data and graph analyzes of each experiment, a general graphical form of the signals of the two sensors S3 and S4 (Figure 5.4) is presented. This representation allows to draw conclusions about the behavior of S3 sensory element in terms of the considered aspects.



a) b)

Figure 5.3 a) Experimental stand: S1- Gyro Sensor; S2- Acceleration sensor; S3 - Rotation sensor, S4- Optical sensor;
b) Experimental stand (1) and the computing system (2) integrated [Sandru, 2016]

thus, the following conclusions can be drawn:

- The reflective surface and the ambient environment have an important influence on the signal acquired from the optical sensor.
- Reference values for results analysis can be defined:
  - The time value t0 allows to specify the limit points a and b (on the two graphs) corresponding to linear variations of the signals;
  - The rotation angle α_0 (relative to the vertical) corresponding to the limit point b.

Relative brightness remains approximately linear between LP1 and LP2 values (corresponding to the time value t0, point a, respectively for an angle rotation α_0).

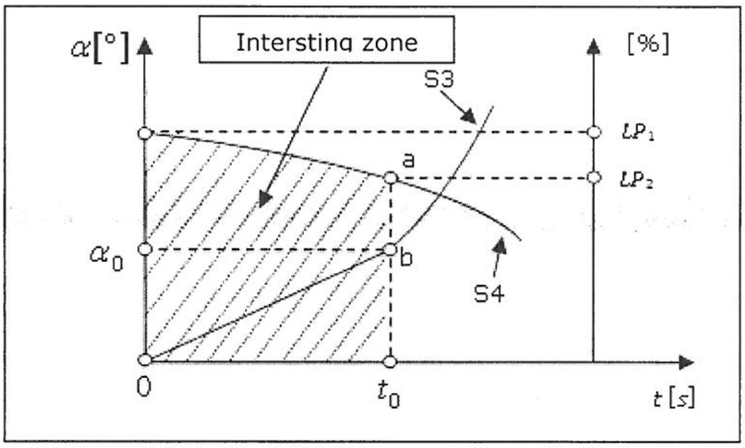


Figure 5.4 General shape of the signals from S4 and S3

- As a result of the carried out experiments, the relative brightness values are in the range [35,3÷66] % for the 10 reflective materials;
- For the experiments in which there were used: matte yellow paper, matte bright green paper, matte white paper, glossy yellow paper, $LP \in [58,5 \div 66]$ %;
- For the experiments in which was used glossy red paper and glossy pale material, $LP \in [55,6 \div 62]$ %;
- For the experiments using glossy purple paper $LP \in$ [59,4 ÷ 53,9] %;
- For the experiments comprising: glossy blue paper and glossy green paper, an interval $LP \in$ [35,4÷46,7]% was measured;
- For experiments comprising: matte black paper, a value of $LP \in$ [35,3÷36,1]% was measured;
- The purchased signals have a very good repeatability in each experiment;

- It is of interest to conduct a numerical analysis of the data correlation from the S1, S2, S3, S4 sensors and the analysis of the information merging;
- It is of interest to reduce the analyzed motion range around the vertical position of the element (1). This results from the pursued objective: the analysis of the stability of a inverted pendulum.

6. HUMANOID DEMONSTRATOR MODELING AND SIMULATION

The operational objective of this chapter is to model and simulate the humanoid demonstrator Lego NXT-2. The operational objective is attached to secondary objectives, oriented towards: developing the physical model of the demonstrator, determining the dimensional and gauge characteristics, classical modeling of some components of the demonstrator structure, real time simulation.

For the first set of record samples, two NXT-2 platforms (Figure 6.1) were used [Savu ..., Sandru, 2016].

The recording method, using the two NXT-2 platforms, complied with the following procedure:

- Interface of system connections was prepared (3 cables with 6 wires each);
- Cables are inserted into YH-55-11 (6-pin) sockets;
- The platform-sensor connections were made taking into account:
    - The signal from port number 1 of the robot platform connects to the gyroscopic sensor;
    - The connection of the wires between the two connection sockets of the LEGO NXT-2 platform is 1 to 1, from pin 3 to pin 6;
    - The pin 1 and pin 2 on the first NXT-2 robot platform are connected in series with pin 1 and pin 2 on the second NXT-2 platform, and the latter must read the same values of the sensor that is connected by the connecting cable to port 1 of the first platform;
- Interfacing the NXT-2 platform (that is receiving data) with a PC via a USB cable. Data viewing and recording is done through the Lego Mindstorms Education NXT-2 Programming, installed on the PC.

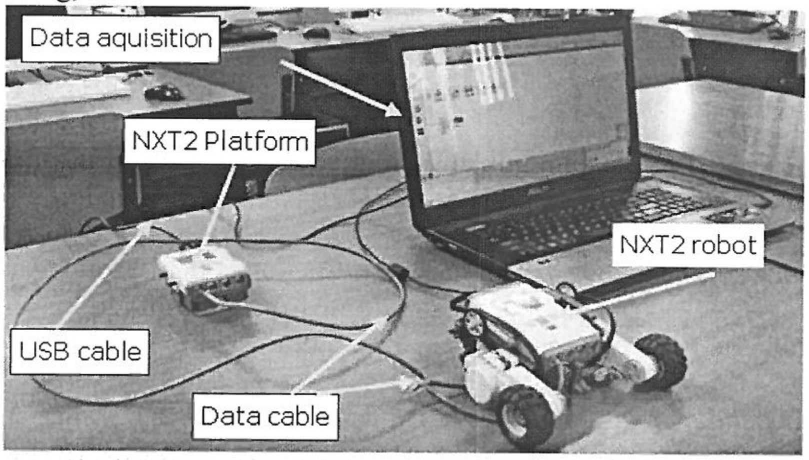


Figure 6.1 Stand using the two NXT-2 platforms

The second method in which the oscilloscope is connected to the sample stand is shown in Figure 6.2.

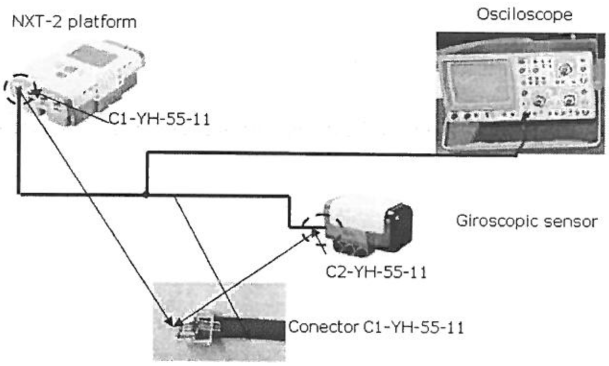


Figure 6.2 Connection scheme

In order to use the oscilloscope to acquire signals from the gyroscope sensor during operation and maintenance of the robot in equilibrium state, the connection cable (YH-55-11 type connector) was stripped between the sensor and port 1 of the NXT-2 robot platform, so we can collect the signal from pin 1 and 2 of the C2-YH-55-11 connector.

Pin number 1 is an analog interface (+9 V) (white wire) and pin number 2 is negative (-), (black wire).

Figure 6.3 shows the information acquired while maintaining the balance of the mobile robot using the gyroscope sensor.

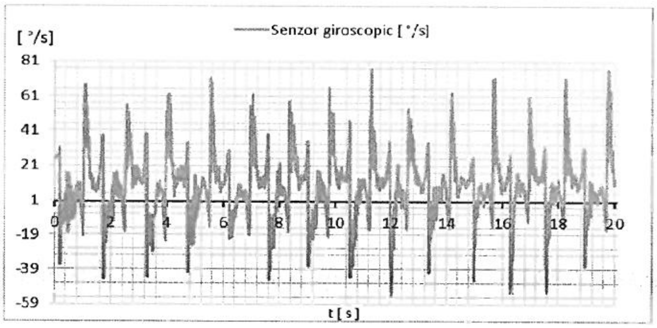


Figure 6.3 Gyroscopic signal of the D-1 demonstrator using the NXT2 platform

Figure 6.4 shows the signal from the gyroscopic sensor during three cycles A, B, C of maintain the stability of the mobile element. In the boxes on the right of the figure there are presented the values of the acquisition parameters.

The parameter on the order (y-axis, [mV]) signifies the oscillation speed of the demonstrator versus the vertical. The duration of a cycle (x-axis, [ms]) is similar for the three cases.

The E detail represents the extreme value of the signal corresponding to the balance loss/maintenance trend. The positive or negative value of this signal indicates the sense of tilting of the mobile element.

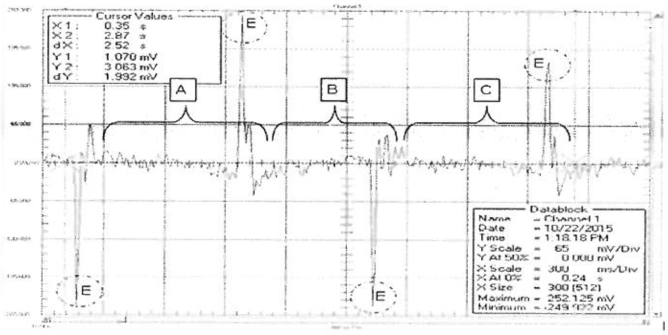


Figure 6.4 Gyroscopic signal of the D-1 demonstrator

Figure 6.5 shows the graphical parameters collected while maintaining the balance of the mobile robot, using the optical sensor, data taken over by the NXT-2 platform, and then presented using the MS-Excel 2010 graphical environment.

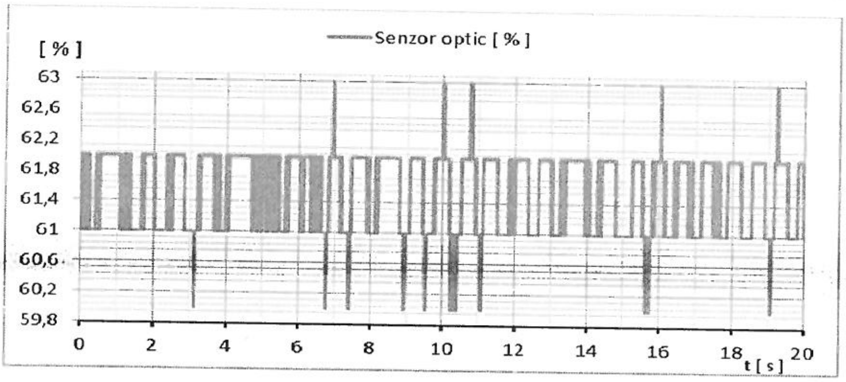


Figure 6.5 Optical signal chart using the NXT-2 platform for 20 s for the D-2 demonstrator

By connecting the oscilloscope to the robot sensor data cable (connections according to Figure 6.3), the signal from S4 was acquired. This signal, corresponding to the maintaining of the D-2 robot balance, is shown in Figure 6.6

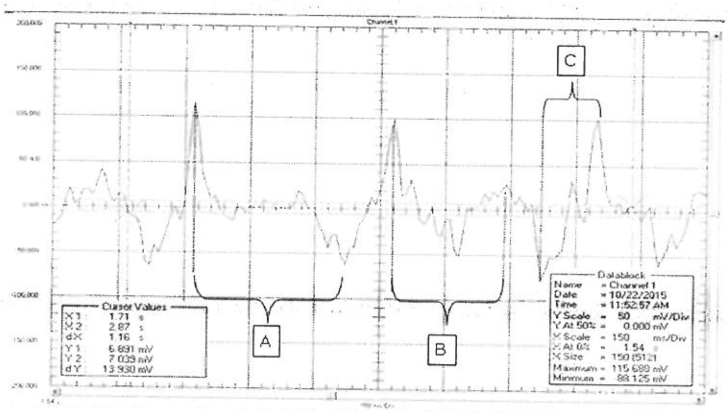


Figure 6.6 Optical signal chart using the oscilloscope for the D-2 demonstrator

Following the data collection and analysis of the above experiments, the following aspects were identified:

- In the case of the optical sensor the signal varies greatly and the duration of stability and return in case of robot destabilization is higher;
- The optical sensor signal is greatly influenced by the reflection environment of the light signal;
- When changing the reflection environment suddenly generates signal thresholds that destabilize the robot by making it unable to return to its equilibrium position;
- The optical sensor signal is influenced by the ambient light that introduces parasitic parameters;
- In the case of the demonstrator that has integrated the gyroscopic sensor, the robot's balance is longer. The process of adjusting and maintaining stability is appropriate;
- The return time for the gyroscopic sensor at the equilibrium state is much lower than that of the optical sensor.

The dynamic analysis of demonstrator operation requires estimating the geometric parameters that define the position of the center of gravity of the second subsystem.

The center of gravity can be determined experimentally in the following way [Gh.

Silos]:

The body is suspended at a point with a binding wire until it is in balance. An indicative extension line is then drawn in the extension of the thread (line A-B in Figure 6.7.a);

The body is suspended in a second position; a line is drawn again; at the intersection of the two drawn lines there is the center of gravity (Figure 6.7.b).

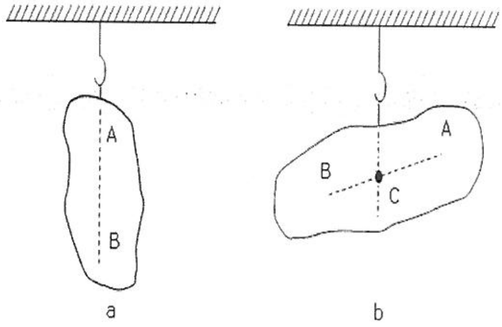


Figure 6.7 Determination of the center of gravity

Figure 6.8.a shows how we try to find the center of mass through the experimental process. Figure 6.8.b shows the center of gravity of the demonstrator equipped with the S5 + S1 sensor.

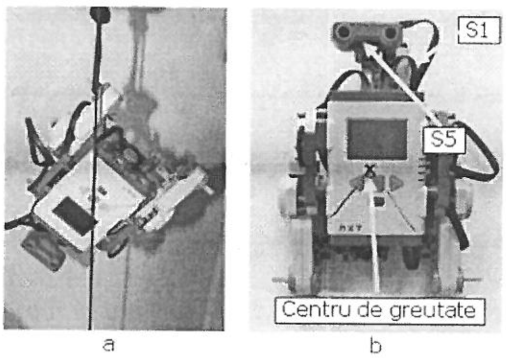


Figure 6.8 a) Finding the center of mass; b) Center of mass with S1 + S5

In order to find the weight of the inverted pendulum equivalent, in each variant tested, its mass was measured using an electronic scale as shown in Figure 6.9.

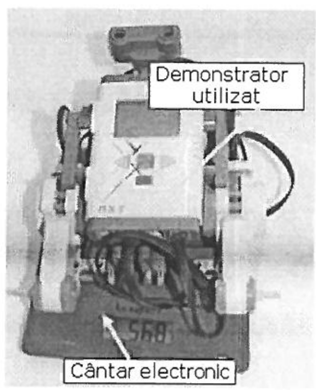


Figure 6.9 Measuring the mass of the demonstrator

Figure 6.10 presents the coordinate systems attached to the three sensory systems integrated into the demonstrator structure for each experiment

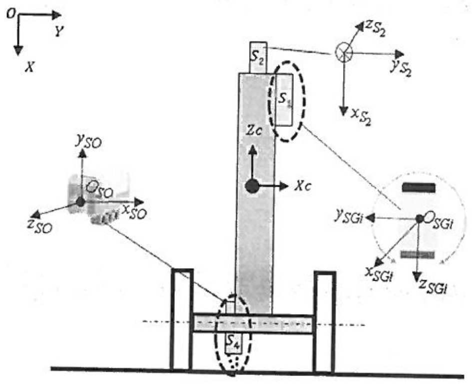


Figure 6.10 Integrated sensors and coordinate systems for S1-gyroscopic, S2-acc, S4-optical

The analyzed demonstrators have integrated electric actuators that provide an essential function of the demonstrator: the movement of an assembly around an axis of rotation (according to the structural diagrams presented in the subchapters and figures of each demonstrator), the actuator is composed of: micro DC motor (with collecting brushes, cylindrical rotor and permanent magnet excitation) Figure 6.11.

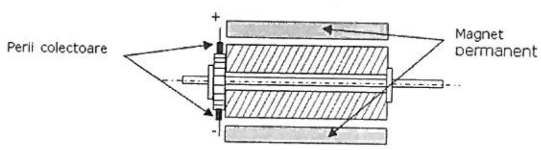


Figure 6.11 Schematic diagram of the electric micro-engine [Dolga, 2009]

The analytical study of the movement of a mobile system (equivalent to a rigid) can be made by choosing a fixed reference system O1x1y1z1 and an Oxyz mobile reference system linked to the mobile system. The movement of the system will be fully described if the Oxyz reference system movement relative to the Ox1y1z1 system is known.
One of the usual methods of expressing the state/position of the mobile system is that dependent on Euler's three rotation angles (Figure 6.12). Leonhard Euler, in order to describe the orientation of a rigid solid and to describe his rotation in space, has defined three angles:

- nutation angle (pitch);
- precession angle (yaw);
- the angle of its own rotation (roll).

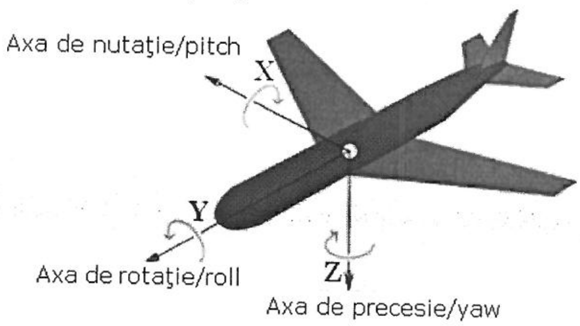


Figure 6.12 Spatial orientation axes

With all input data, data acquired from a real model, signals were modeled using the mathematical model, of maintain the balance of the mobile robot, using the inverted pendulum principle. Output data, following mathematical modeling, are shown in Figure 6.13 and there are shown the sizes expressed in degrees/second.

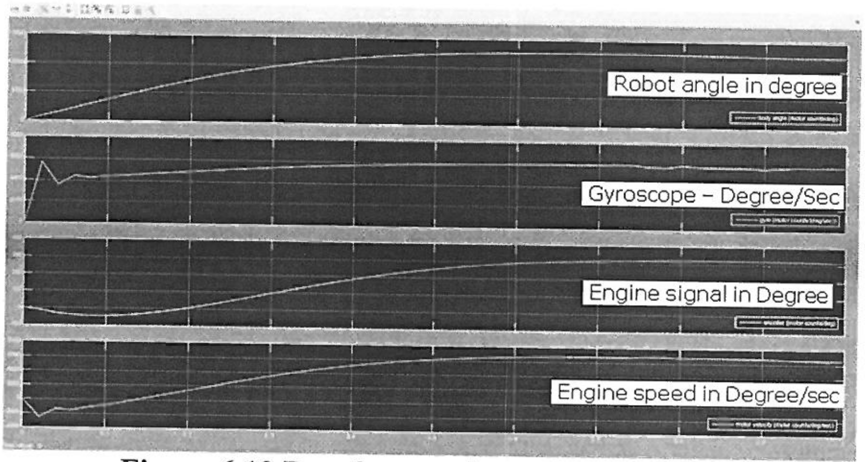


Figure 6.13 Data from mathematical processing

Figure 6.14 provides I/O signals. The output signal from the mathematical modeling for linearization is shown in the bottom box.

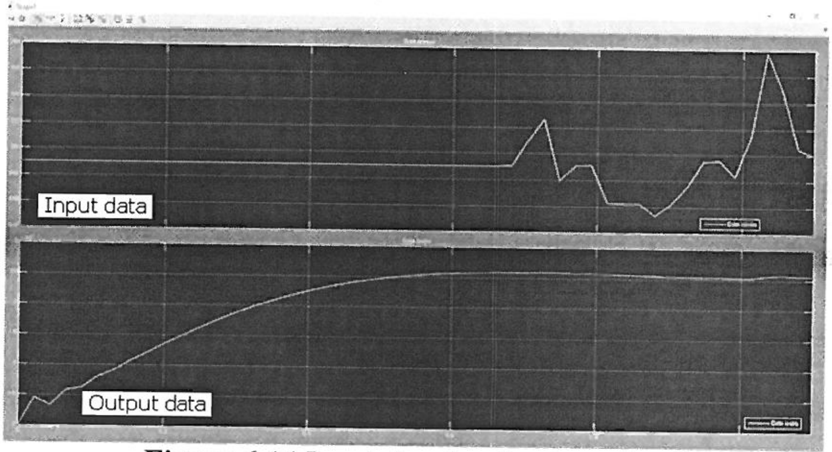


Figure 6.14 Input signal and output signal

In conclusion, as a result of the experiments carried out, the following aspects can be described:

- Two LEGO NXT-2 platforms can be used: one used as a mobile robot and the other one is linked in series to the sensor signals from the first platform for data collection;
- After collecting the signals from the two sensors (optical or gyroscopic), one can notice that there is a large fluctuation in the balance maintaining signal;
- In the experiment where the robot uses signal from the gyro sensor, this has a higher stability and a constant linearity of the signal from the gyroscopic sensor.

By collecting the signal from the sensorial system when the real robotic model was operating, it was possible to create a virtual signal generator, identical to the signal from the working time of the robotic model.

7. FINAL CONCLUSIONS AND PERSONAL CONTRIBUTIONS

7.1. Final conclusions

The accelerated development of the technique has led to the development of various types of mobile robots in various constructive and functional variants, in order to be implemented as best as possible in various fields of activity: military, medicine, industry, agriculture etc.

The mobile robotic systems are a real challenge, using a complex mechanical system, depending on the given application. The mobile robot can be seen as a structure composed of systems and subsystems. Addressing a research theme on the mobile robot or optimal design of such a mechatronic system, requires a thorough analysis of the current state of the mobile robots. Finally, such a system is concretized by a multi-purpose demonstrator.

7.2. Original contributions of the thesis

In relation to the main objective of the PhD thesis and the associated operational objectives, with the developed research plan, the following personal contributions can be highlighted based on the theoretical and experimental content within the volume of the elaborated thesis..

7.2.1. Contributions to fundamental research

- The synthesis of the research program in accordance with the main objective of the thesis and the statement of the associated operational objectives (Chapter 1/1.2);
- The bibliographic synthesis related to the inverted pendulum concept, its applications in demonstrators, robotics, intelligent buildings and the military domain (Chapter 2);
- The bibliographic synthesis of the mechatronic demonstrator concept and its forms of materialization with applications in robotics (Chapter 3);
- Developing the methodology of designing a mechatronic system through the main function method and the secondary functions associated to the system (Chapter 4).

7.2.2. Contributions to theoretical and experimental research

a) Theoretical contributions

- The study of the ambient temperature influence on the ultrasonic sensors' parameters (Chapter 4 / 4.3.7);
- The analysis of the random process concerning the using of the integrated acceleration sensor in the humanoid mobile demonstrator structure (Chapter 5 / 5.2.4);
- The theoretical analysis on the synergistic use of experimental results from gyroscopic, acceleration and rotation sensors in the humanoid demonstrator structure (Chapter 5 / 5.2.5).

b) Applicative contributions

- Elaborate the robotic application with the RJ2 robot for writing text and generating graphic support (Chapter 4 / 4.3.4);
- 3D modeling of the RJ2 robot in the Catia V6 environment.

c) Contributions regarding the physical conducted models

- The construction of two mechatronic demonstrators to concretize a major function specific to a humanoid operator (Chapter 4 / 4.3.1, 4.3.3);
- The construction of the mechatronic demonstrator for the analysis of the optical sensor feature (Chapter 4 / 4.3.2);
- Carrying out the mechatronic demonstrator to concretize a main function specific to a 4-

wheel mobile robot and of the system control board (mini-board) (Chapter 4 / 4.3.5);
- Build the hardware components for the experimental study of a Parrot AR 2 drone (Chapter 4 / 4.3.8).

d) Software contributions
- Development of the software application for the writing/drawing robotic application (Chapter 4 / 4.3.4);
- Development of the software application for the operator-computer interface for the mechatronic demonstrator (mobile system) (Chapter 4 / 4.3.5);
- Development of the control algorithm for the mechatronic demonstrator (mobile system) (Chapter 4 / 4.3.5);
- Development of the software application for the operator interface – Parrot AR 2 drone (Chapter 4 / 4.3.8);
- Model and simulation of the humanoid mobile demonstrator in the Matlab environment (Chapters 6 / 6.4 and 6.5).

e) Contributions regarding the experimental analysis
- Experimental analysis of the transfer of the trajectory information imposed by the operator to a mobile system (robot) and real-time system control via mobile application (Chapter 4 / 4.3.5);
- Development of the material support for the experimental study regarding the movement of a mobile robot in the working scene (Chapter 4 / 4.3.6);
- Development of the experimental structure, working procedures and information acquisition system for the humanoid demonstrator (Chapters 5 / 5.2.1 and 5.2.2);
- Experimental analysis of the integrated sensorial elements into the developed humanoid demonstrator:
    - optical sensor – (Chapter 5/5.2.3);
    - acceleration sensor - (5/5.2.4);
- Development of the experimental structure, work procedures and information acquisition system for the humanoid demonstrator stability analysis using the optical and gyroscopic sensor (Chapters 6 / 6.2.1 - 6.2.3);
- Development of the mathematical model of the humanoid demonstrator (Chapter 6 / 6.3)
- Creating the material support for the experimental research and its integration into a data acquisition system (Chapter 6).

7.3. Dissemination of the researches results

The researches results, carried out in order to elaborate the PhD thesis, were capitalized by publishing 8 works at national, international and specialized journals, as follows:

7.3.1. Scientific papers published within the volumes of ISI indexed manifestations

1. Marius-Florin Crainic, Stefan Preitl, **Lucian Alexandru Şandru**, Valer Dolga, "Secure handwriting using a robot arm for educational purpose" in The 19 International Conference On Methods and Models in Automation and Robotics, MMAR 2014, Polonia
2. **Lucian Alexandru ŞANDRU**, Marius-Florin CRAINIC, Stefan PREITL, Valer DOLGA, "*Path calculation of 4 DOF remote vehicle for educational purpose*" in

IEEE 13th International Symposium on Applied Machine Intelligence and Informatics, SAMI 2015, Slovacia

3. Stanescu T., **Sandru L. A.**, Dolga V., "*Studies Regarding Detection of Obstacles with Different Geometric Shape Using Parallax Ping Sensor*", in IEEE 10th Jubilee International Symposium on Applied Computational Intelligence and Informatics, SACI 2015, 21 - 23 Mai 2015, Timişoara.
4. **L. Sandru** , V. Dolga , C. Moldovan and D. Savu, " Mechatronic demonstrator for testing sensors to be used in mobile robotics functioning on the inverted pendulum concept ", in 7th International Conference on Advanced Concepts in Mechanical Engineering, ACME 2016, Iaşi.

(Published papers, on going to be ISI indexed)

5. **Lucian Alexandru SANDRU**, Marius Florin CRAINIC, Diana SAVU, Cristian MOLDOVAN, Valer DOLGA, Stefan PREITL, "Robotic System Construction with Mechatronic Components. Inverted Pendulum - Humanoid Robot", in The 9th International Conference on Machine Vision, ICMV 2016, Franta
6. **Sandru Lucian Alexandru**, Marius Florin Crainic, Cristian Moldovan, Diana Savu, Valer Dolga and Stefan Preitl, "*Automatic Control of a Quadcopter, AR. Drone, using a Smart Glove*", in The 4th International conference on Control, Mechatronics and Automation, ICCMA 2016, Spania
7. Diana Savu, **Lucian Alexandru Sandru**, Marius Florin Crainic, Cristian Moldovan, Valer Dolga and Stefan Preitl, "*Multiple Methods of Data Acquisition for a LEGO NXT 2 Mobile Robot. The use of a Second NXT 2 Hardware Platform*", in 5th International Conference on Mechatronics and Control Engineering, ICMCE 2016, Italia

7.3.2. Scientific papers published in specialized journals indexed in the database (Google Academic)

1. Stanescu T., Enache B., Savu D., **Sandru L.**, Dolga V., "*Theoretical and Experimental Analysis of Steering Mechanism of a Mobile Robot*", International Journal of Emerging Technology and Advanced Engineering, Volume 5, Issue 4, New Delhy, India, April 2015 (ISSN 2250 – 2459 (Online)) pag. 597 – 600.

7.3.3. Invention patent application

During the PhD work, for personal reasons, while studying certain problems of the reliability of electronic equipment during research on mechatronic demonstrators using electrical energy for operation and displacement. I analyzed a reliable solution for this deficit of energetically autonomy. The idea is pending in order to be patented, it is registered at OSIM under the title of „AUTOMATIC LOADING OF ELECTRIC FLYING DEVICES (DRONES) WHILE FLYING FROM HIGH VOLTAGE LINES", under the registration number A/10040/2016, dated 21st of July, 2016.

7.4. Potential future research directions in the field

Subsequent to the research activity, of the obtained results and of the qualitative and quantitative analysis carried out, I believe that the following research directions are present and interesting for the future:

- Expanding the researches on the capability of working together of several categories of sensors to locate an obstacle and fusion of information;
- Developing a probabilistic model of the mechatronic mobile robot system by evaluating the system's random internal processes and the external ones;
- Analysis of random aspects based on probabilistic theory;
- Research to improve the performance of the two autonomous and mobile robotic structures;
- Approaching ideas that lead to didactic and practical applications on new approaches of the mechatronic system concepts;
- Research on implementing a color sensor along with the optical sensor used in the experiments in order to reduce the errors of determination given by different colors of the reflection environment;
- Research concerning the integration capability of other sensor categories for locating the obstacles, merging information, and building the unstructured environment map.

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