Application of LEGO Mindstorms Kits for Teaching Mechatronics Engineering

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Abstract

One of the major educators' challenges is to teach the theoretical lessons with practical examples that can be taught in the classroom or teaching laboratories. The application of these examples will face a major problem for students in engineering: the difficulty of understanding and seeing how a mechatronic device works in everyday life. This requires the use of tools that enable the construction of different low cost prototypes to assist in student learning. Another challenge to educators is the need to motivate students during the lessons and to present models that students can make and develop on their own. Within this context this paper presents a pedagogic proposition based on the use of LEGO Mindstorms kits to teach practical lab activities in a mechatronics engineering course. The objective is to develop teaching methodologies with the use of these LEGO kits in order to motivate the students and also to promote a higher interdisciplinarity, by proposing projects that unify different disciplines. Thus, the paper is divided into three parts according to the educational experiences implemented in the course of mechatronics engineering at the Federal University of Uberlândia, Brazil. The first part presents the use of the kits in robotics discipline. The second part presents the use of the virtual kits in the Computer Aided Design discipline with zero-cost. The third part presents a multi-disciplinary project EDROM in mechatronics using LEGO kits.

Keywords: Mechatronics; Robotics; CAD; EDROM; LEGO

1. Introduction

The use of new technologies in teaching and learning processes is currently increasing. Educational robotics has made remarkable progress in several educational environments [1-3]. In spite of the usefulness and the versatility of such an educational tool, it is not widely used in Brazil, mainly due to the high costs of the equipment. In [4] was affirmed that the popularity of robotics kits in education is significantly higher in the developed countries (typically Western Europe and North America), while the kits are still on the edge of breaking into the market of developing countries (South Asia and Africa). In function of initiative of RoboCup Brazil Federation that promote robotics competition (http://www.cbrobotica.org/?page_id=6&lang=en) I include the Brazil in the edge, i. e., is in the accelerated progress of incorporation of robotics kits in undergraduate curses of Mechatronics Engineering. A current problem has motivated the development of this research comprising a low cost solution to implement in

the Mechatronics Engineering course at the Federal University of Uberlândia (UFU).
Today, in the market, there are several kits specially designed for education, in which students are required to have fun at the same time as they learn the bases of Mechatronics [4-7].
One of the major educator's challenges is to teach the theoretical lessons with practical examples that can be taught in the classroom or teaching laboratories. The application of these examples will face a major problem for students in engineering: the difficulty of understanding and seeing how a mechatronic device works in everyday life. This requires the use of tools that enable the construction of different low cost prototypes to assist in students' learning [8]. Another challenge to educators is the need to motivate students during the lessons and to present models that students can make and develop on their own [9-10].
Aiming to satisfy these needs, the Massachusetts Institute of Technology [11] developed a programmable bricks used by LEGO in the Mindstorms kits.
LEGO® kits are used directly on three fronts of the UFU Mechatronics Engineering course: robotics discipline (professional 9th term), in the Computer Aided Design (initial discipline of the 3rd term) and EDROM (Development Team in Mobile Robotics) multi-disciplinary extension activity.
Thus, this paper reports about development of activities to build physical and virtual mechatronics prototypes using the LEGO® kits.
Firstly, LEGO Mindstorms NXT kit and its relationship with the mechatronics and robotics are presented. After, examples of parallel robotics structures are presented focusing in the singularity analysis.
Section III presents the methodology and some projects developed using LEGO kits for the construction of virtual models in Computer Aided Design.
Section IV presents some projects developed by a team of students, competition-based program, also using LEGO kits.
Finally the discussion and conclusions are presented.

2. Robotics and LEGO

Mechatronics can be defined as the synergistic integration of precision mechanical engineering, electronics, intelligent control, and systems thinking about the design of smarts products and processes [8].
According to Rosario [12], the graduation in mechatronics should be based on: i) solid fundaments and as extensive as possible, ii) systemic and multidisciplinary approach involving mechanics, electronics and computing, and iii) learning based on experimentation, in order to eliminate the gap between purely academic project and the real world, with its limitations and compromises. It is understood, therefore, that in a mechatronics engineering course, students should be offered the opportunity of doing activities that develop their design skills in the real world, their multidisciplinary teamwork ability, communication and time management skills [13].
LEGO Mindstorms NXT kit used in this work is formed by: a PLC (Programmable Logic Controller) with 32-bit processor; three interactive geared servo motors that feature built-in rotation sensors (sensitive to one degree out of 360°) for precise control; ultrasonic sensor; sound sensor; light sensor; touch sensor and a set of pieces LEGO TECHNIC. The NXT microprocessor can be programmed to exhibit autonomous behavior using either a PC or a MAC. After building a robot, users can create a program with feature

LabVIEW software from National Instruments which works with a graphical language or using software based in language C. The communication with the computer is made using Bluetooth or a USB cable. The ultrasonic sensor enables a robot to "see" obstacles, to measure distances and to respond to movement. A sound sensor enables robots to respond to sound commands with sound patterns and tone recognition. A light sensor permits color differentiation and a touch sensor reacts to contact or release allowing robots to "feel" their surroundings.
In this way, the Fig. 1 shows the relationship between LEGO Mindstorms and Mechatronics. Students can apply concepts of mechatronics to robotic structure, with the construction of mechanical part using a set of LEGO pieces technique, sensors allowing interaction with the environment, programming the robot to give it intelligence and finally a processing unit, PLC, to connect the parts.

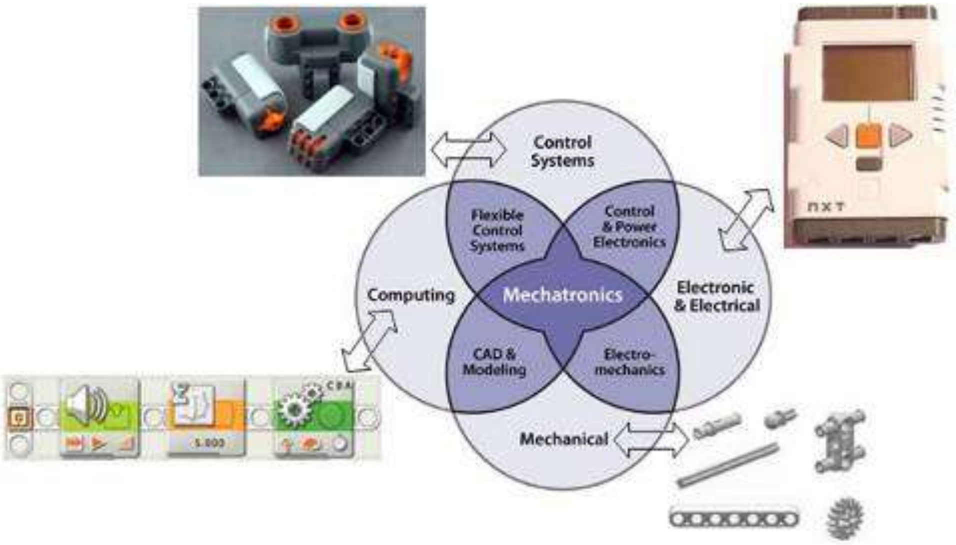


Figure 1. Relation with Mechatronics and LEGO Mindstorms.

These LEGO Mindstorms kits are used at the graduation course of Mechatronic Engineering at UFU and allow the construction of the multibody system like parallel robot structures in the discipline of Robotics. The multibody system consists on a structure composed by segments that can be rigid or flexible, connected together by joints. A multibody system that has been widely studied in recent years is the so-called parallel manipulator. A parallel manipulator typically consists of a moving platform that is connected to a fixed base by several serial chains, called limbs [14].
Parallel robot structure prototypes have been conceived and built together with the development of theoretical investigations on kinematics and dynamics, but the cost and time to develop these prototypes is high. The attention is focused on a number of possible industrial applications such as manipulation, packing and assembly/disassembly machines, motion simulation, milling machines, toys and sensors.
A few papers report the undergraduate LEGO applications [10, 13-14]. Ebert-Uphoff [10] used LEGO and other inexpensive prototypes of parallel manipulators as an efficient educational tool to teach undergraduate students not only the basics of parallel manipulators but also reinforce another disciplines.
For undergraduate teaching, one of the difficulties is to view the function and to understand the parallel

structures in a robotics course, its workspace, singularities and collisions between the segments. The use of LEGO kits allows the easy view of these problems, as detailed in our works [13-14].

Therefore, one of the important limitations of parallel mechanisms is that they may lead to singular configurations in which the stiffness of the mechanism is lost. The physical meaning of a singularity in kinematics refers to those configurations in which the number of degree of freedom (dof) of the mechanism changes instantaneously. The kit LEGO permits visualize this problem.

Other important characteristic of manipulators is the workspace. The workspace is the set of position and orientation configurations in which the end-effector is controllable and the workspace determines geometrical limits on the task that can be performed. The workspace of parallel kinematic mechanisms has in general a complex volume shape. Again the use of LEGO kits allows the visualization the workspace and its different configurations with the change of the parameters of the structure under study.

Thus, this paper uses LEGO Mindstorm Kits to facilitate the teaching of robotics and the visualization of singularities, workspace and understanding the functioning of robotic three-dimensional structures described in the next items.

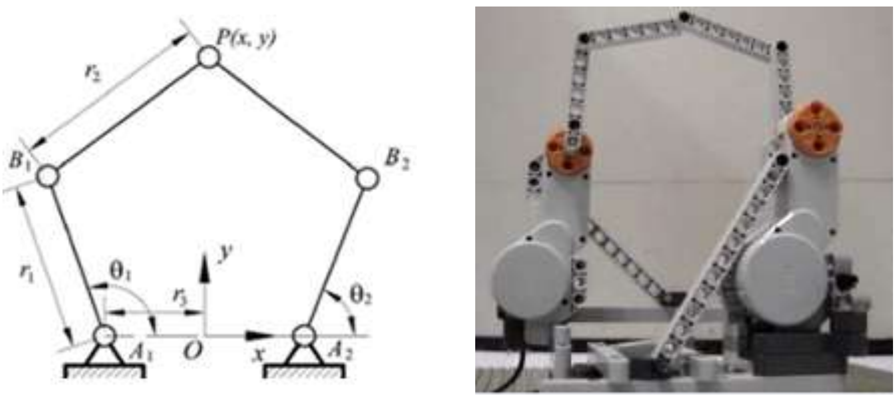
2.1 Example – Parallel Structure 5R and the Singularities.

Close to or in singular configurations, the parallel manipulator becomes uncontrollable. In these configurations, the mechanism tends to lose its stiffness while gaining extra degrees of freedom. Physically, when the mechanism is in a singular configuration, the structure cannot resist an external wrench applied to the end-effectors (mobile platform), therefore it may collapse [15].

The five-bar manipulator is a typical parallel manipulator with the minimal degrees of freedom, which can be used for positioning a point in a region of a plane. A 5R parallel manipulator consists on five bars that are connected end to end by five revolute joints, two of which are connected to the base and actuated, as shown in Fig. 2(a).

In this structure, the direct singularities occur when A_1B_1P or A_2B_2P, Fig. 2(a), are completely extended or folded [16]. These singular configurations are complex configurations where the actuators cannot resist to applied forces and/or moments on the moving platform and this loci singularities are inside the workspace. The singularities due to inverse kinematic model correspond to the configurations in which the moving platform loses one or more degrees of freedom. These singularities occur when A_1B_1 is parallel to B_1P or when A_2B_2 is parallel to B_2P. These singularities determine the boundary of the workspace.

The singularity positions illustrated in Fig. 3 were obtained from the initial positioning of the 5R mechanism free of singularity, Fig. 2(b), and the movement of the servomotors to the loci of singularity. In these configurations or close to them, the structure locks or loses control and the students can visualize these problems.



(a) (b)

Figure 2. (a) Parameters of the 5R Mechanism; (b) Prototype assembled with LEGO.

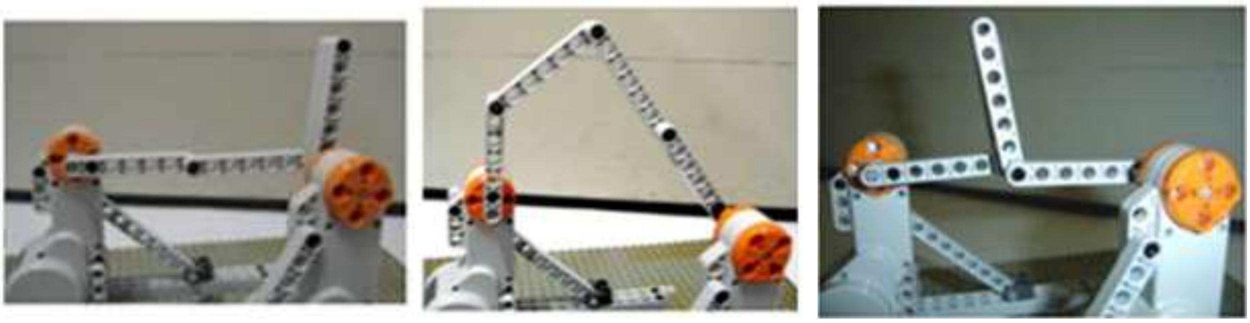


Figure 3. Some singularity configurations of 5R mechanism built with LEGO.

2.2 Construction of three-dimensional Parallel Structures.

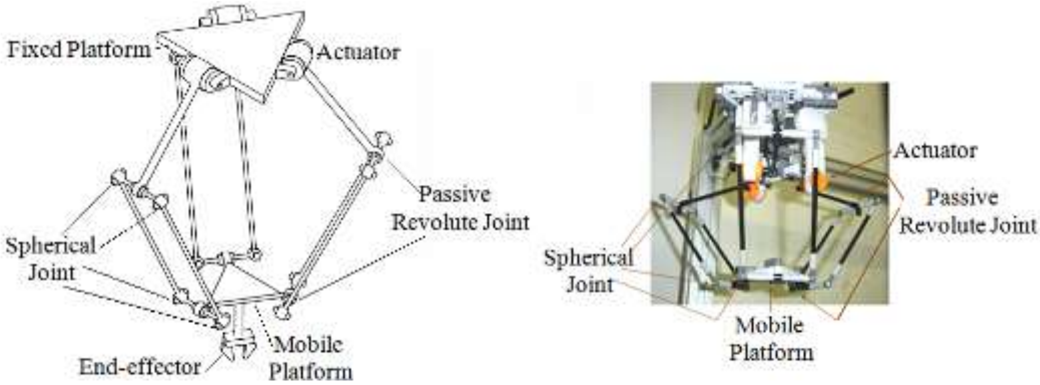
This section describes some three-dimensional robotic structures developed with LEGO Mindstorm kits. The purpose of these assemblies with LEGO is to show the functioning of these structures facilitating students' understanding of the applications of these structures in the discipline of robotics.

As shown in Fig. 4(a), the kinematic chain of the Delta parallel manipulator is composed of three identical serial kinematic chains that share the base or fixed platform and the mobile platform [17]. For each serial chain (from the base to the end-effector), the links are coupled by an actuated revolute joint and the passive revolute joints. Fig. 4(b) shows the LEGO Delta manipulator built. During the experimental tests of the Delta structure built with LEGO the mobile platform always remained parallel to the base, Fig 4(c-f). Figure 4(f) represents a singularity configuration in which the segments are aligned.

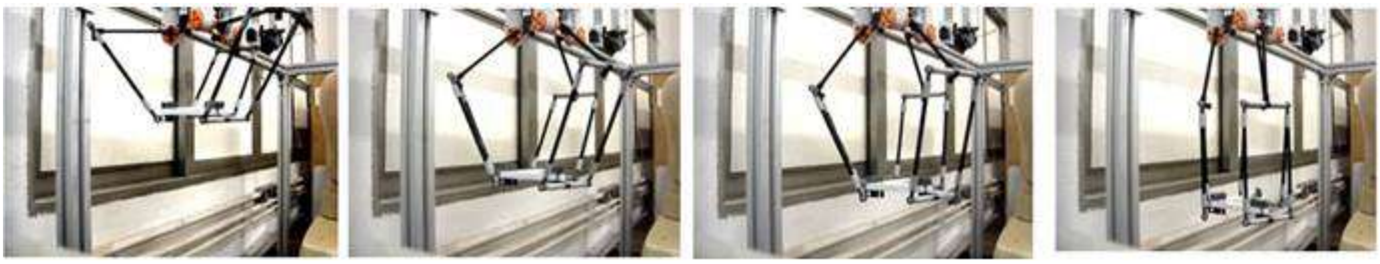
Another built parallel structure is CaPaMan (Cassino Parallel Manipulator). CaPaMan is a 3 degree of freedom spatial parallel manipulator that has been designed at the Laboratory of Robotics and Mechatronics, in Cassino. It is composed by a fixed platform that is connected to a mobile platform by means of three leg mechanisms [18]. Each of these mechanisms is composed by an articulated parallelogram, a prismatic joint and a connecting bar, Fig. 5(a). The centers of the bases of these mechanisms are arranged at the vertices of an equilateral triangle in the fixed platform, so that the planes containing them, form angles of 120°, thus giving the symmetry properties of the manipulator, Fig. 5(a).

In order to construct CaPaMan using LEGO Mindstorms NXT kit, Fig. 5(b), it was necessary to construct a passive prismatic joint, Fig. 5(c).

Other examples LEGO parallel structures that are built and used in the Robotics course at UFU are presented in [14].

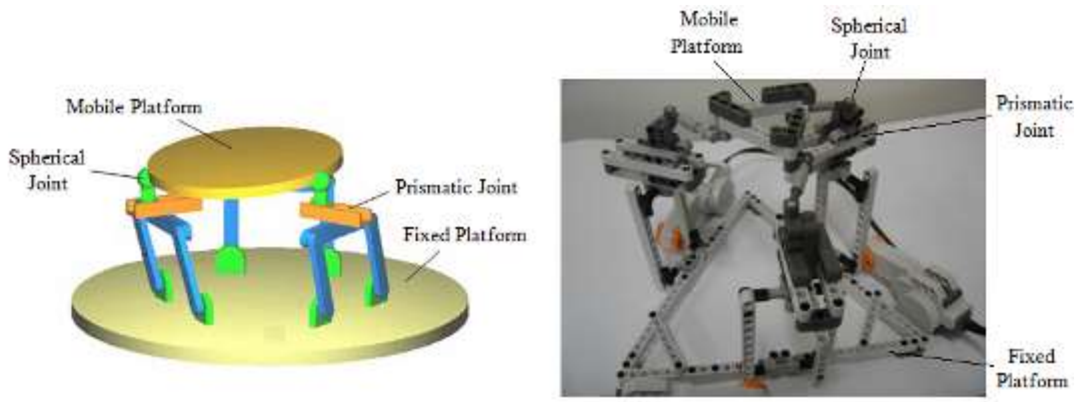


(a) (b)

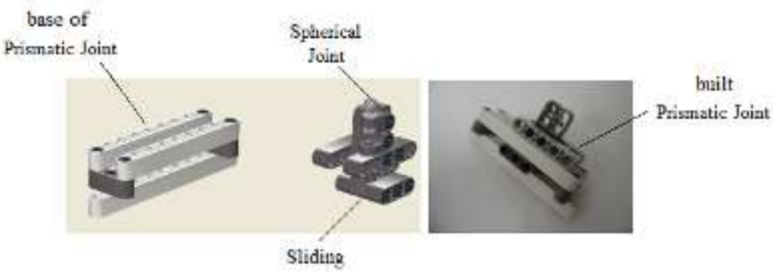


(c) (d) (e) (f)

Figure 4. (a) Delta manipulator sketch; (b) Delta manipulator built with LEGO; (c-e) Sequence of moving the Delta manipulator; (f) Singularity configuration.



(a) (b)



(c)

Figure 5. (a) CaPaMan sketch; (b) CaPaMan built with LEGO; (c) Prismatic joint built with LEGO.

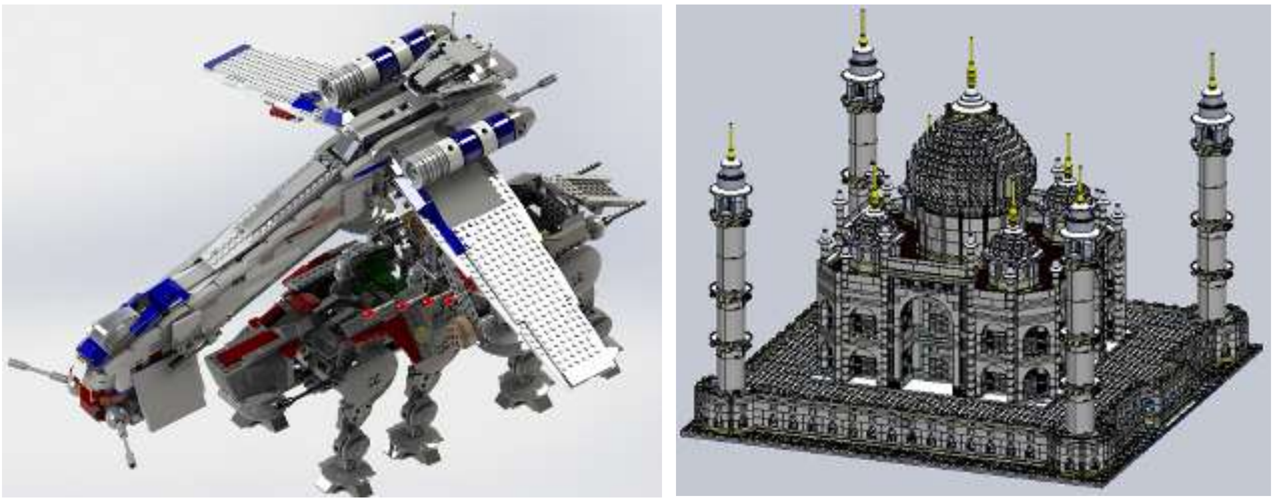
3. CAD and LEGO

LEGO kits are also used in the discipline of Computer Aided Design (CAD). This course is mandatory for students and is offered in the third term. The purpose of this course is to enable students in the 3D modeling elements of machines and assemblies with simulation of movements. This course is offered with a workload of 45 semester hours. Currently, the CAD software used is the SolidWorks.

For students to learn a three-dimensional modeling tool and memorize the knowledge/features taught during the classes, they are divided into groups of up to 5 students and have to choose a LEGO kit for their virtual construction. The chosen kits often have more than 1,000 pieces, Fig. 6(a), which leads students to work in teams and manage large projects. As LEGO kits include all machine elements such as pins, gears, springs, bars, pulleys, etc. students end up implementing the software features for the construction of mechanical elements. Figure 6(b) shows the Taj Mahal virtual project with over 5,900 pieces.

After the construction of the pieces, students must assemble the kits using subassemblies make up the complete assembly, Fig. 7. Finally students must use the concepts that were taught in class to perform kinematics and dynamics motion simulations, for example, simulating the motion of the moving parts of an engine, Fig. 6(c).

The use of LEGO kits in the CAD discipline motivates students to get the final result converted into 40% of the total grade of the course. As students must draw several pieces of different shapes and complexities, they are familiar with the basic CAD software for practicing the profession of engineering. Statically around 40% of the groups fail to complete the project in a timely manner due to lack of planning and to postponing the development of the project to the end of the semester.



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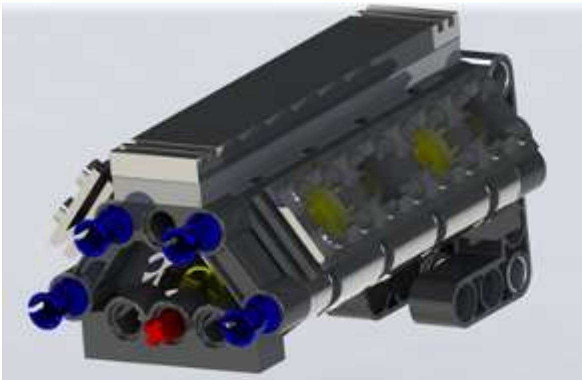
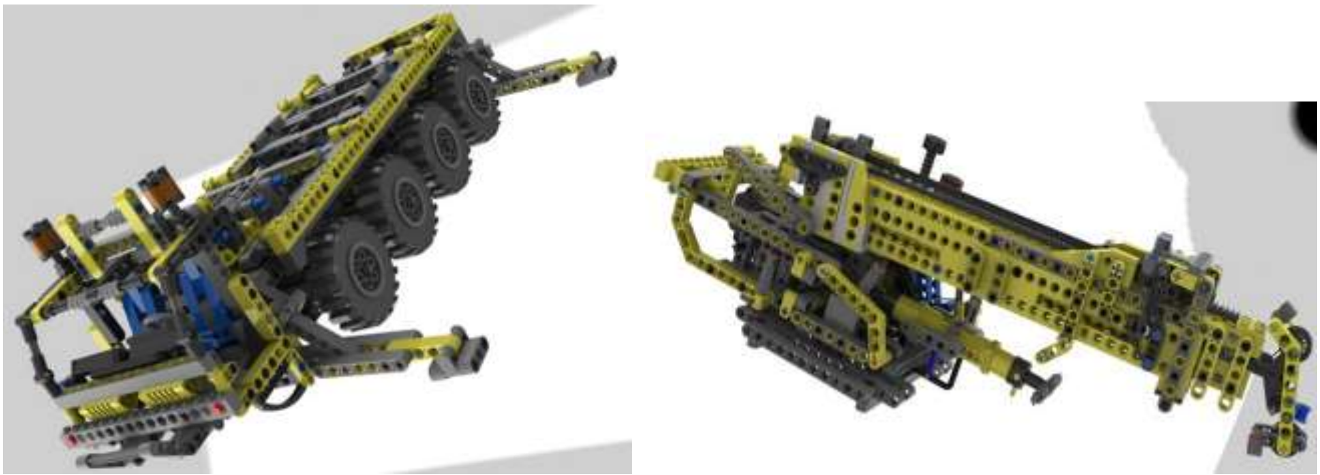


(c)

Figure 6. (a) Built virtual model LEGO; (b) LEGO Taj Mahal; (c) Engine.



(a) (b)

(c)

Figure 7. Virtual LEGO Assembly.

4. EDROM and LEGO

EDROM (Team Development in Mobile Robotics) is an extension activity at the Federal University of

Uberlândia. EDROM aims to: participate in competitions involving the development of mechatronic systems; promoting technical and academic development of its members; encourage the entrepreneurial spirit of team members; promote contact of students with the job market and perform outreach activities inherent in undergraduate courses. This team works in technology development, as it becomes more popular because of competitions such as humanoid robot soccer competitions and robots built with LEGO parts, etc., making it a showcase for the dissemination of technological development. The EDROM has taken part in competitions since 2010.

The EDROM uses the LEGO Mindstorm NXT and EV3 kits in competition modality IEEE Standard Educational Kit (SEK) and IEEE Open. These competition modalities are an initiative of the IEEE Robotics & Automation Society in Latin America.

The IEEE SEK modality aims to present a challenge for graduation students, so it generally changes every two years. Students need to build autonomous robots using education kits approved for competition. Students work with up to two robots cooperative with embedded programming. External commands are not allowed, the robots must be autonomous.

In the IEEE Open modality, students can use any material for the development of robots. The challenging task usually tries to reproduce the real challenges of robotics in a smaller scale.

In the literature have few papers that work with LEGO in the undergraduate engineering but focusing in specific disciplines. In [6, 19-21] the LEGO was used to teach programming. In [22-24] the LEGO kits were used to teach control and in [25] to teach industrial automation.

The development of robots by EDROM students enables the integration and practical application in several disciplines that are part of the UFU Mechatronics course curriculum with emphasis on: Introduction to Mechatronics engineering; Technical drawing; Algorithms and computer programs; Differential and Integral Calculus 1; Analytic Geometry; Machine Drawing; Programming Applied to Engineering; Differential and Integral Calculus 2; Linear Algebra; General Physics I; Experimental Physics I; Differential and Integral Calculus 3; Kinematics; Computer Aided Design; Metrology; Mathematical Methods Applied to Engineering; Dynamics; Basic Electronic for Mechatronics; Optics; Optics Laboratory; Electric Circuits for Mechatronics; Computer Organization and Architecture I; Digital Electronics; Linear System Control; Dynamics of Machines; Elements of mechanics; Operating Systems; Instrumentation; Digital Control of Systems; Digital Signal Processing; Industrial Networks; Digital Systems for Mechatronics; Power electronics for Mechatronics; Database; Simulation of Automated Systems; Industrial Automation and Robotics. Almost 60% of the obligatory disciplines are used directly in the development of robots.

Figure 8 shows some of the robots that were developed and the year when they were used. A curiosity about the robots developed by EDROM is that they always have female names. This happens due to the predominance of male students in the course of mechatronics engineering at UFU.

In 2010 the IEEE modality OPEN aimed to develop an autonomous robot named FIONA, Fig. 8(a), that should manipulate products sent by producers and organize them in packages that would be sent to sales points later on. The full video can be accessed at: http://www.youtube.com/watch?v=Rehs2V00V-Y

In 2010 the goal of IEEE SEK was to develop two cooperative robots that must repair the pipeline, besides the construction of an alternative pipeline in order to reduce the time of interruption in the oil flow. EDROM's project consisted in 2 robots of same aspects, named Vera and Lucia, built with 2 wheels and a sphere system that gives an appearance of a tricycle, Fig. 8(b). Each robot is capable of lift up the pipes using a claw and a system that just needs 1 servomotor. A count-lines system was created, improving the precision of the engines that rotate the robot wheels and give a best precision to make curves. It uses a color sensor to recognize the pipes. The full video can be accessed at: http://www.youtube.com/watch?v=CGhRhgTRfb0.

The challenge posed in IEEE SEK 2011 was to construct containment barriers, dikes, for population protection of a city situated near a river about to overflow. In an arena, an overflow that can occur in one or even in both sides of the river was simulated. So, the two robots that were built, named Vânia and Cristina, Fig. 8(c), must work cooperatively and autonomously to construct the barriers to contain the overflow. The programming was made using the language Not eXactly C [15]. It was chosen because the members of the team have knowledge about programming in C during the mechatronics engineering curse.

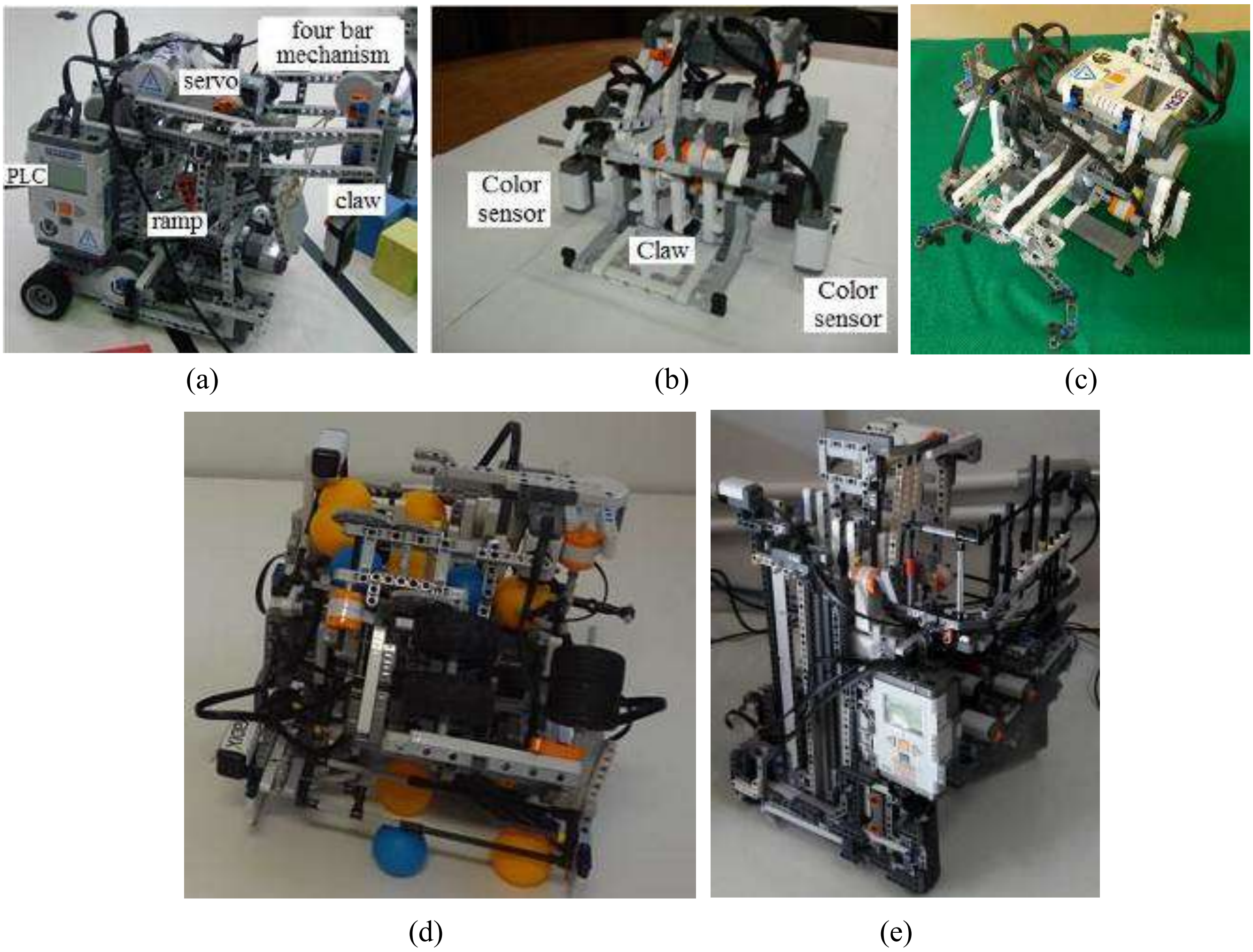


Figure 8. (a) Robot FIONA, 2010; (b) Robot Vera, 2010; (c) Robot Vânia, 2011; (d) Robot Sansa, 2012; (e) Robot Rey 2016.

From 2012 to 2014, the challenge presented to the teams was the THBall, that is a game in which the group who acquires more points in 5 minutes wins the match. This game is played with two robots of each team. Robots have limited size, and they must fit in a cube of 250 mm. In the beginning of the match, the arena is organized with a Table-Tennis ball in orange and blue colors. Orange balls imply negative points to the team, and blue balls imply positive points. So, orange balls must be launched to the opponent side and blue balls must be maintained on the team's side. At the end of 5 minutes of game, the score is calculated and the one who has more points wins.

The full video of EDROM participation can be accessed at: https://www.youtube.com/watch?v=nRMW5DHxtUE.

In 2015 and 2016, the challenge presented was build a robot to explore the environment of a CLOCLON and rescue the inhabitants of a nation as the rescue color designated to the robot. The robot competed against another robot, created by another team, in the arena (CLOCLON). The robots should rescue SIMUs (humanoid polystyrene black) or ESITUs (humanoid polystyrene white), leaving the KIEFAs (humanoid polystyrene red) within the circular caves. As time is short, two robots, each from different teams, must enter the CLOCLON simultaneously, each seeking to rescue a specific nation (ESITU or SIMU). The ESITU nation should be taken to blue rescue area and the SIMU to green rescue area. The full video of 2016 EDROM participation can be accessed at: https://www.youtube.com/watch?v=_2Ii875ajnw.

The EDROM has participated in competitions since 2010 and has had excellent results, Tab. 1.

Mobile robots designed besides being applied to competitions allow: integration of several disciplines similar to the way that students will use them in the job market; managing deadlines to meet targets; development of teamwork; learning to deal with stress and unpredictable problems. These qualities are sought by companies and we have EDROM graduation students working or worked in multinationals as: HONDA; EMBRAER; Volkswagen and Mitsubishi.

Table 1. Team EDROM achievements.

Year	Competition	Modality SEK Classification
2010	Latin American Robotics Competition (LARC 2010)	2nd Place
2011	Latin American Robotics Competition (LARC 2011)	2nd Place
2011	Brazilian Robotics Competition (CBR 2011)	1st Place
2012	Latin American Robotics Competition (LARC 2012)	1st Place
2013	Brazilian Robotics Competition (CBR 2013)	2nd Place
2016	Latin American Robotics Competition (LARC 2016)	3th Place

5. Discussion and Conclusions

This paper presented a proposal for a multidisciplinary educational course in mechatronics focused on the use of Lego Mindstorms kits.

Takács et al. [4] compared different educational kits and the LEGO Mindstorms is the cheaper modular robotic kit in the market and had good reviews in the adopted criteria cost, modularity level, design, extension possibilities, compatibility, availability and portability.

The use of Lego Mindstorms kits made it possible to offer the students a systemic view of mechatronics engineering, including information technology (through programming), mechanical (through experience with the use of different types of transmissions, gears, bars) and electrical (through experimentation and activation of sensor and control). Other highlights are: reduced cost of deployment compared to traditional robotics labs, a paradigm shift in teaching methodology, with learning based on trial and encouraging the use of creativity in the solutions.

The undergraduate teaching of mechatronics engineering at Federal University of Uberlândia includes formal laboratory work for robotics teaching and final year projects. These activities utilize the fast development capabilities of the LEGO technical framework coupled with imagination and fun to provide the desired pedagogical outcomes.

Students find it difficult to see some existing problems in robotics such as the presence of singularities. Thus, the uses of kits from LEGO provided the illustration of these issues in a quick, easy and low cost way.

The use of LEGO kits in the CAD discipline motivates students to get the final result converted into 40% of the total grade of the course. As students must draw several pieces of different shapes and complexity they are familiar with the basic CAD software for practicing the profession of engineering. Statically around 40% of the groups fail to complete the project in a timely manner due to lack of planning and to postponing the development of the project to the end of the semester. In addition, this methodology is zero-cost.

In Machine Drawing/CAD discipline usually are used books [26-29] that present mechanical parts with geometry more simple than LEGO parts. Another point to be taken into consideration is that traditional books [26-29] present assemblies with much smaller parts than fifty. In the methodology presented in this paper students are encouraged to selecting kits from LEGO with over a thousand parts.

The development of LEGO robots by EDROM students enables the integration and practical application in several disciplines that are part of the UFU Mechatronics course curriculum. Almost 60% of the obligatory disciplines are used directly in the development of robots.

Another problem is to motivate the beginning undergraduate students that desire to learn about robotics and program these and the EDROM is one opportunity. Bower [20] considered strategies for teaching beginning students how to program mobile robots using the software LabVIEW applying one example in a DaNI Robot. But this strategies not add some skills desired by the companies. The EDROM mobile robots designed besides being applied to competitions allow: integration of several disciplines similar to the way that students will use them in the job market; managing deadlines to meet targets; development of teamwork; learning to deal with stress and unpredictable problems. These qualities are sought by companies.

To be part of EDROM, students must participate in a selection process. Students from the first to the sixth terms are selected. Students in the last semesters of the graduation are not selected because we intend to keep students in the team for at least one or two years. The team usually has 14 members. The mechatronics engineering course offers 20 vacancies per semester. In this way, they would be skillful to make the selection process out of 120 students. Usually 25 students participate in the selection process, which represents only 21% of possible candidates.

According to [30 and 31] engineering courses have few women. In [31] the following question is asked: "Can Robots in Classrooms Attract More Women to Engineering?". I can not answer yes, but I can evaluate the presence of women in the Mechatronics Engineering course of UFU and its direct involvement in activities involving robots. In general, every six months there are between 3 and 4 women per class out of 20 students of mechatronics engineering. Between the years 2010 and 2012 there was one woman in the team. Currently, there are 5 women in the team, which represents 36% of the team members and it shows women's interest and involvement with robots.

Thus, the use of LEGO Mindstorm kits provides complete learning solutions which cover important mechatronics engineering curriculum areas while stimulating creativity, problem-solving and team-working skills.

6. Acknowledgement

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