TEACHING EXPERIENCE ON MECHANISM DESIGN AT THE POLYTECHNIC SCHOOL OF SÃO PAULO UNIVERSITY

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Abstract. *We present some ideas on the implementation of practical activities to accompany undergraduate courses. All steps we followed(preparation of tutorials, choice of software, synthesis and analysis, logistics, etc.) are detailed in this article. Initially, a historical background is provided in order to clarify some aspects of the courses evolution. We cover the period from 1970 to the year 2010. In addition, we focused not only on the employed text-books, but also on the problem-solving techniques, from the graphical methods to the utilization of sophisticated computer packages. In another section, we will treat the undergraduate courses on mechanism design currently offered at our Polytechnic School, enumerating the objectives, explaining the topics and the approaches that are taught, defining the students profile etc. As we shall explain in the paper, the course main directive is to employ a unified approach during the classes. As a consequence, the student will be capable of analyzing either a single-actuated mechanism or even a 6-dof robot manipulator. In the following section, the activities developed by our students are described in detail. Essentially, we intend that the students go through the fundamental phases of the design: specifications definition, type synthesis, simulation and prototyping. Finally, the conclusions are outlined. In this way, we expect to provide a useful discussion on how to implement an undergraduate course that is strong on theoretical concepts and that at the same time provides a vibrant hands-on activity.*

Keywords: *mechanisms, teaching experience, linkages, engineering education*

1. INTRODUCTION

During the last ten years, thanks to the efforts of companies, universities and research institutes, we have witnessed a great number of technological innovations. In fact, we can mention, for instance, the Big Dog (2008), the robotic mule; the Adept Quattro (2010), the fattest pick-and-place robot ever made; the Da Vinci surgical system (Intuitive Surgical, 2011); the humanoid Asimo (Honda, 2011). Moreover, by admiring the kinetic sculptures from Theo Jansen (Jansen, 2011) that walk on the wind, we can also recognize the presence of the mechanisms in Art.

Certainly, most of those achievements were made possible for two reasons. First, the qualification of the engineers involved in the product development process (Cavacece *et al.*, 2005; Fraczek and Wojtyra, 2005) and second, the recent advances on the field of mechanisms and robotics.

Basically, a mechanism is composed by links and joints, which works as a motion transformer, capable of converting the available motions – provided by either linear or even rotary actuators - to the desired ones. Consequently, it is the mechanical subsystem of any machine or robotic device.

In this context, this paper deals with the teaching experience on mechanism design at University of Sao Paulo. Initially, a historical background is provided in order to clarify some aspects of the courses evolution. We cover the period from 1970 to the year 2010. In addition, we focused not only on the employed text-books, but also on the problem-solving techniques, from the graphical methods to the utilization of sophisticated computer packages.

The Polytechnic School of Sao Paulo University (Escola Politécnica da Universidade de São Paulo, in Brazilian Portuguese) is in charge of all engineering courses at Sao Paulo campus. In all, there are 17 undergraduate courses comprising four major engineering fields: civil, electrical, mechanical, and chemistry. It takes at least 5 years for a student to major. All programs comprise mandatory and elective courses. In addition, there are graduate programs for both Master and Doctor of Engineering Degrees comprising most modern research fields.

"Design of Mechanisms" is a mandatory course for both Mechanical Engineering and Mechatronics Engineering students. It is usually taught at the 5th or 7th semester, and covers such topics as analysis and synthesis of planar linkages, gear trains, cams, and introductory 3D mechanisms (robotics). There are two lectures of 100min each every week, comprising a total of 28 lectures during the semester. In addition, students must take two examinations and must prepare a final work (design, modeling, construction of a mechanism, and the related report).

Most students of our engineering programs often complains that there are few practical activities during their five years long course. In fact, this is true and very counterproductive. We believe students may develop their skills immensely by applying the theoretical concepts they learn in practical "design and build" activities.

With this issues in mind, it was relatively easy to find interesting and useful mechanisms (both planar and spacial) to propose as a practical activity, aiming at raising the students motivation and, consequently, their grades. On the other hand, the logistics behind that was a more complicated issue, since it involves some critical decisions such as choice of modeling techniques, choice of software for computational simulations, choice of materials and components, use of machine shop, actuation systems (motors and drivers), etc. In addition, the number of students in each class varies from 70 (Mechatronics Engineering) to 80 (Mechanical Engineering).

This text describes the implementation of a practical activity to accompany the course on Design of Mechanisms. It includes the following stages: design (analytical modeling, and computational simulations), construction, and tests. It is the hope of the authors that this work can be used as a model for a low budget yet inspiring course on Mechanisms.

The following section treats of the undergraduate courses on mechanism design currently offered at our university, enumerating the objectives, explaining the topics and the approaches that are taught, defining the students profile etc. As we shall explain in the paper, the course main directive is to employ a unified approach during the classes. As a consequence, the student will be capable of analyzing either a single-actuated mechanism or even a 6-dof robot manipulator.

In another section, the activities developed by our students are described in detail. Essentially, we intend that the students go through the fundamental phases of the design: specifications definition, type synthesis, simulation and prototyping. Finally, the conclusions are outlined.

1.1 Historical Background

The historical evolution of the courses on mechanism design at Polytechnic School, (EPUSP) covers a period of 40 years (1970-2010). Prof. Omar Moore de Madureira1 was the course idealizer and the first professor. He became a professor of Mechanical Engineering at Polytechnic School in 1961. With his enthusiastic spirit, this outstanding engineer and consulter on Automotive Engineering and Product Design always motivated his students, demonstrating the small distance between theory and practice.

Figure 1 shows a chronological diagram of the evolution of the courses. From this figure, one can find significant information, namely, the courses contents, number of students and textbooks (Erdman and Sandor, 1997; Norton, 2002; Shigley, 1970; Shigley and Uicker, 1995; Tsai, 1999; Sclater and Chironis, 2007; Artobolevsky, 1975). During 40 years, it is possible to notice that the number of students almost duplicated. In addition, at present, there are two courses, one for students with major in Mechanical Engineering and another for students with major in Mechatronics Engineering. Despite the aggregation of upgraded topics, the courses contents remained nearly the same. Regarding the solving approaches, they changed from graphical to analytical and numerical methods.

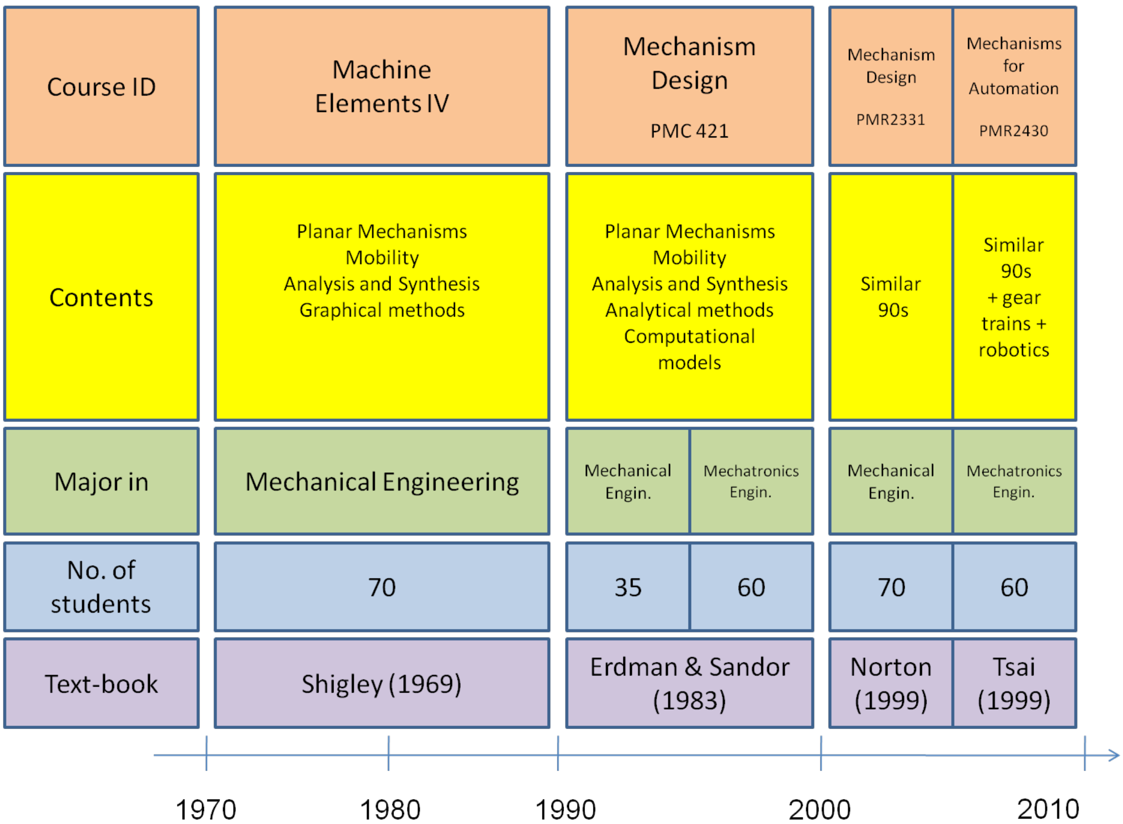


Figure 1. Chronological diagram of the evolution of the mechanism design courses at Polytechnic School (EPUSP)

1.2. Undergraduate courses on Mechanism Design at Polytechnic School of Sao Paulo University

As mentioned in previous section, there are two undergraduate courses in Polytechnic School, "PMR2331 Mechanism Design" (major in Mechanical Engineering) and "PMR2430 Mechanisms for Automation" (Major in Mechatronics Engineering). In both courses, we have a great concern about teaching a unified approach and methods for formulation and solution. Hence, the students will apply the same methodology to analyze and synthesize either mechanisms or robots.

In this paper, we focus on the characteristics of the course "PMR 2331 Mechanism Design". Table 1 shows the topics list, the employed methods (Hess-Coelho, 2008; Ibrahim, 2008) and the correspondent number of classes. Each class lasts 100 min in a typical four-month course. Among the taught methods, some constitute a generalization of the fundamental principles of Mechanics to multibody systems (systems that contain several rigid bodies, actuators, damping and elastic elements). Others deal with the mobility analysis and dimensional synthesis, based on the relevant contribution of German kinematicians – Reuleaux, Burmester, Kutzbach and Gruebler. Moreover, type synthesis of closed and open loop kinematic chains is also a topic of growing interest due to the applications on the design of serial and parallel robots.

Regarding the available resources, we can mention the licensed softwares MatLab, Mathematica, MSC-Adams and a demonstration version of Working Model 2D. In addition, to develop the assigned activities, the students can use the school workshop, which has drillers, lathes and milling machines.

Table 1. Topics of the Mechanism Design course (PMR2331)

Topics	Methods	Number of classes
Introduction, Degrees of freedom, Mobility	Kutzbach-Gruebler, Group Theory	3
Kinematic analysis in 2 and 3 dimensions	Graphical, polar-complex notation, matricial, Newton-Raphson	10
Dynamic analysis in 2D	Graphical, Newton-Euler, Kane	4
Type synthesis	Kutzbach-Gruebler, enumeration of active limbs, addition of passive limb	1
Dimensional synthesis	Graphical, analytical	4
Cams, Gear trains	Analytical	5
Softwares: Working Model 2D, Adams	Demonstration class	1

2. METHODOLOGY TO IMPLEMENT PRACTICAL ACTIVITIES

As mentioned in the introductory section, our aim is to report some experiences on the implementation of practical activities to enhance the students learning process. The following sections will focus on the practical activities requested to the students of Mechanical Engineering during the 5th semester of the program.

In the last two years, we have successfully proposed the construction of a toy mechanism that can imitate the walking movement of some animals based exclusively on a four bar planar linkage. Students have constructed toys that imitate frog, elephant, horse connected to a cart, a dancing toy, etc. It can be labeled as the "four bar planar walking mechanism project". Therefore, this part of the work is related to planar linkages, and includes some details of the design techniques students must employ in order to accomplish their tasks.

It is important to note that we divide the class into 8 groups of around 10 students each, since the total number of students varies from 70 to 80. In this way, due to the relatively large number of students in each group, complex tasks can be requested, and the amount of money spent by each student is low. In addition to build and present their toy mechanism, each group must prepare a full printed report showing all calculations and graphics in detail.

Basic concepts of Analysis of Mechanisms is introduced in the beginning of the course. Although we spend some time on "graphical methods", our curse is predominantly based on "analytical methods". Software useful for design of mechanisms is also introduced. We have been using 3 types: Matlab, Working Model 2D, and MSC-Adams. Since students are introduced to this software for the first time, it was necessary to prepare a basic tutorial on Matlab.

Working Model is very easy to learn and just a simple demonstration is enough. Adams is a more complex software and a tutorial would be better, although we have not finished one yet.

Working Model and Adams are software customized for modeling and simulation of moving parts (dynamics) of mechanical systems, particularly mechanisms. Adams can be used for both 2D and 3D mechanisms, while Working Model is suitable only for planar mechanisms.

Matlab is a programming environment with some very handy set of functions. In this way, Matlab is useful as a computational tool for students to write the complete set of equations for analysis and synthesis. In addition, it includes resources for plotting graphics and for animations.

All three mentioned applications are commercial software, and the school has to pay a license fee. However, there are some free alternatives for those short in budget. There is a free demo version of Working Model 2D, with full functionality except that projects cannot be saved. Octave is a freeware that can substitute for Matlab, although with limited capabilities. Adams is a very powerful software, capable of modeling 3D mechanisms as well as generating impressive animations, and is worth its educational license fee.

2.1. Kinematic analysis

Analysis of four bar planar mechanisms is taught based on the contents of several excellent textbooks, in particular Norton (2002), Shigley and Uicker (1995), Erdman and Sandor (1997). Initially, several types of common planar mechanisms and machines are presented: crane, reciprocating saw, backhoe, internal combustion engine (crankshaft, connecting rod, piston), the quick-return mechanism of a shaper, windshield wiper, etc. Showing movies and animations make a whole difference in motivating the students.

Concerning the "four bar planar walking mechanism project", it is commonly assembled as a RRRR (four revolute joints) linkage. Usually, dimensions of the bars (more precisely, distance between consecutive joints), and position of the two fixed pivots are known in advance. In addition, input angle, angular velocity and angular acceleration of the crank link must be specified in advance. Then, position, velocity and acceleration of any point in the four bar linkage can be calculated analytically. For example, the following bar length set, given in arbitrary units, is very suitable: 2; 4.5; 5.5; 6. Also, in case of a Grashof mechanism (one in which at least one of the links can rotate 360°), it is usual to assume a uniform angular velocity for the crank link and a null angular acceleration for the crank link.

The walking mechanism project has the following requirements:

- mobility=1;
- must be assembled as a planar four bar RRRR linkage;
- must be a crank-rocker Grashof mechanism;
- must have at least two legs moving in synchrony;
- materials: wood, acrylic glass, metal plate, gears and shafts from old toys, etc.;
- analytical modeling must be made using Matlab (or Octave); simulations in Matlab or WorkingModel or Adams;
- the project must be completed within about a 10 weeks period.

Before starting the main calculations, it is important to test for Grashof condition; to estimate the two limit positions of the rocker link; and to test for toggle positions. As for the numerical example mentioned in this section, it is a Grashof mechanism with the two limit positions shown in figure 2.

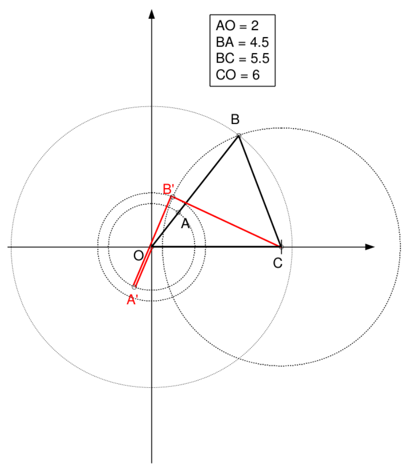


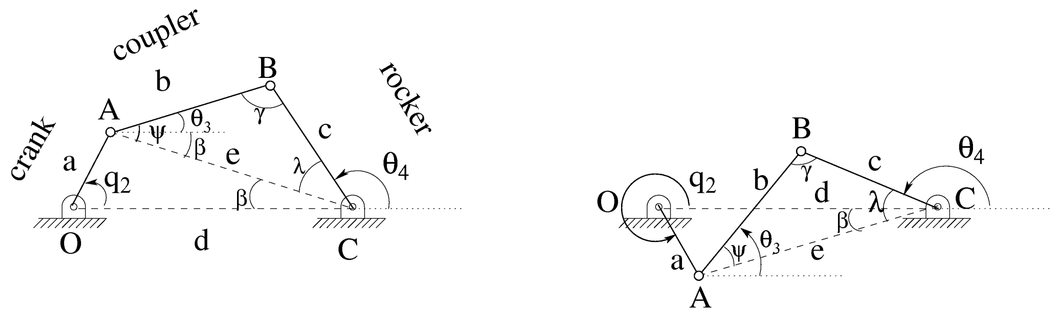
Figure 2. Limit positions of the rocker link for the crank-rocker linkage example.

Students are requested to calculate the two limit angles of the rocker link as an exercise. One possible way to solve it is by using the cosine law in the triangles.

Then, the position analysis can start by writing the vector loop equation. A set of two scalar equations can be obtained by using the polar form or by using vector decomposition. However, it involves a set of two of nonlinear scalar equations, with the two unknowns being the angular positions of the coupler (θ_3) and of the rocker (θ_4) links. In addition, it must be reminded that this problem may have two possible solutions: the so called open configuration, and the so called crossed configuration. We introduce three classical methods to solve the "position problem". Students can choose freely.

Freundenstein's Method is described on most textbooks (Norton, 2002) and is based on manipulation of trigonometric functions in order to isolate a desired variable. The only major concern is the use of the arc tangent function for the calculation of the rocker link angle. Most pocket calculators and computer software (Matlab included) solves the arc tangent only for the first or fourth quadrant. Therefore, it is very important to calculate the limit positions of the rocker link previously.

Another interesting method is also described in many textbooks, in particular in Shigley and Uicker (1995). Although not given much emphasis, this is a very creative geometrical method based on the use the cosine law: the quadrilateral representing the RRRR linkage is divided in two triangles, and the cosine law is applied several times, figure 3. A Matlab script can be prepared to solve for θ_3 and for θ_4. One must be careful to consider two cases: when the input angle q_2 is in the range from 0 rad to π rad, and when it is in the range from π rad to 2π rad.



$0 < q_2 < \pi$ $\pi < q_2 < 2\pi$

Figure 3. Configuration for the use of the geometrical method.

The third approach we teach sometimes is the numeric method based on the "multidimensional Newton-Raphson technique". That method gives approximate solutions and must be used with great care. In particular, stop criteria based on angle error is very troublesome. Students seldom choose this method.

Lecture notes (Hess-Coelho, 2008; Ibrahim, 2008) include some script templates for Matlab regarding those methods. However, such templates are not fully functional: we believe students must practice by completing parts of the scripts as exercise.

Velocity analysis is based on the time derivative of the vector loop equation used in the position analysis. Again, a set of two scalar equations can be obtained. Nevertheless, this time one obtains a set of linear equations that can be easily solved in Matlab (or Octave). The unknowns are the angular velocity of the coupler link (ω_3), and the angular velocity of the rocker link (ω_4).

Acceleration analysis is based on the time derivative of the velocity vector equation. Once again, a set of two linear scalar equations can be obtained, and the unknowns are the angular acceleration of the coupler link (α_3) and the angular acceleration of the rocker link (α_4).

Once the positions, velocities and accelerations of every link is known, it is possible to calculate these kinematic properties for any selected points in the linkage. In particular, it is requested to calculate the accelerations of the center of gravity of each link, since it will be used in the kinetic analysis later.

At this stage, students must have complete and fully functional scripts for kinematic analysis of RRRR linkages using Matlab. Results of the kinematic analysis obtained with Matlab can be compared with the ones obtained with WorkingModel or MSC-Adams.

2.2 Kinetic analysis

Force and torque in selected points of the linkage can be calculated by several methods, particularly Euler or Lagrange. Euler method, which follows a Newtonian approach, was chosen since it is easier to understand and it is described in most textbooks on mechanisms (Norton, 2002; Erdman and Sandor, 1997; Shigley and Uicker, 1995). First, the student must prepare free-body diagrams for each link, showing the torques and forces involved. Then, it must be obtained a set of three equations for each link: force components in X and in Y directions, and torque equations (in Z direction). Finally, all equations are arranged in matrix form and solved as a linear system.

Students must calculate (or measure) the mass and the mass moment of inertia with respect to the center of gravity of each component of the real linkage they are constructing in order to use in the equations.

An iterative script can be easily prepared in Matlab to deal with a full range of input angle q_2. Such script can be inserted in the kinematic analysis script in a way that a complete analysis can be performed. Then, again, results can be compared with the ones obtained with WorkingModel or Adams.

Sometimes, a simple static analysis may also be very helpful in order to have an initial idea of the forces and torques involved. Therefore, we also teach the static analysis method (Norton, 2002; Shigley and Uicker, 1995).

2.3. Synthesis of planar linkages

Synthesis is based on the method originally described in the textbook by Edman & Sandor (1997), which is also explained in the textbook by Norton (2002). The synthesis method is much more complicated to understand than the kinematic and kinetic analyzes. Students have some difficulty in understanding the idea in the beginning. Therefore, an elaborated tutorial needs to be prepared, including some examples of scripts in Matlab.

Since the technique involves the arbitrary choice of positions and rotation angles for some links, it is very useful to test such arbitrary points using WorkingModel, or Adams, or Matlab simulations in advance. A combination of computer simulations with Erdman and Sandor's method proved to be very effective among students.

In this way, students are advised to initially choose four suitable positions (precision points) that represent a possible leg trajectory as a good way to start the synthesis process. Since there are infinite eligible arbitrary points, most students prefer to test some possible four bar linkage configurations using WorkingModel. Although this is a trial and error method, it can be made more effective using the Grashof condition as a preliminary test. The crank link must be allowed to have a complete turn. In this way, most students achieved reasonable configurations after a few trials.

3. RESULTS AND CONCLUSIONS

We dedicated some 15 minutes in the end of several classes for meetings with the students to discuss the progress of their work. In addition, partial assessments are carried out every 3 weeks in order to assure that students will complete their duties in the scheduled time.

They were allowed to use any inexpensive material available to them. Most chose wood or metallic plate as the structural material for the mechanisms. One group chose LEGO (the educative toy) parts, which made the construction very simple and robust. However, we intend to forbid the use of LEGO parts in order to force the students to experience the difficulties involved in the fabrication of mechanism parts. Acrylic glass might also be a good choice, although no one has chosen yet.

In order to transmit power from the electric motors, plastic toy gears were used to form a reduction gear train, although some students used electric motors with gear trains already assembled. Round nylon or polyurethane billets can also be machined by the students using a simple lathe to produce pulleys and simple shaft couplings. Students also had to show all their creativity to build functional revolute joints to connect the links.

As for the power supply, most students chose batteries. Inexpensive switching power supplies, the type used in desktop computers, would also have been a good choice to power the electric motors (12 V output). So far, students are not required to build electric circuits to control the motors, although we may change that in future.

Figure 4 shows some pictures taken from the walking mechanisms students constructed. They were very creative. However, some mechanisms were not robust enough, failing after few minutes working. This was mostly due to problems with the joints. We intend to be more demanding on the quality of the mechanical constructions in future.

Students enrolled in the Mechanisms Design Course successfully fulfilled all the assigned tasks in the last two years. In spite of having to spend extra time to finish the work in time, students showed full engagement and were very satisfied with the results they achieved. However, it must be emphasized that hands-on activities only work if well planned in advance; otherwise, it may depress engineering students even more. Simple goals must be proposed first; complexities must be gradually added.

The safety of all students must be assured. In this way, work at the machine shop must be restricted to usual day time hours, when students can be accompanied by an experienced technician. In addition, since there is only one machine shop for the whole department, working time must be fairly scheduled.

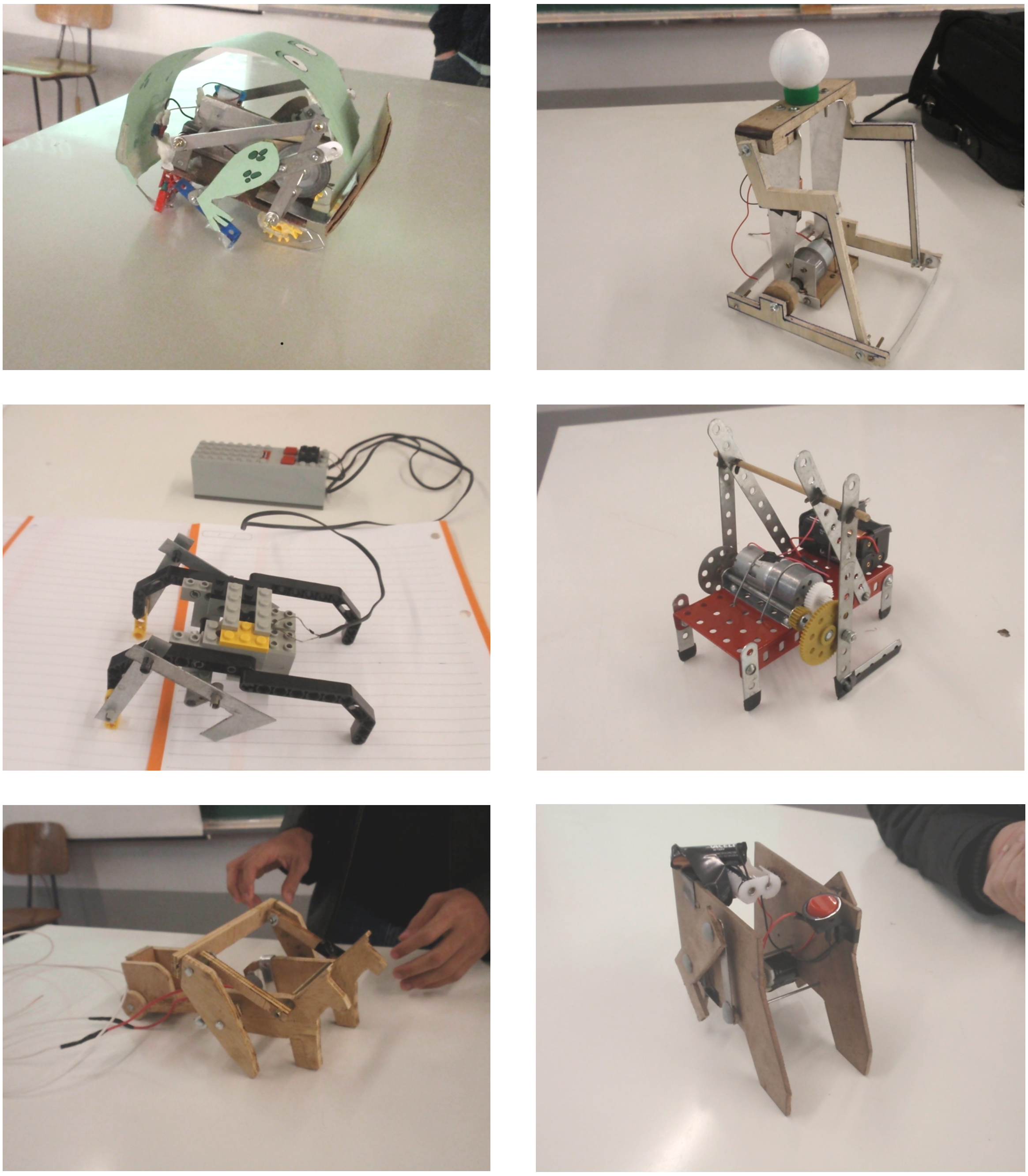


Figure 4. Some samples of walking mechanisms constructed by the students.

This work dealt with the teaching experience on mechanism design at Polytechnic School, University of Sao Paulo. The characteristics of the undergraduate courses on mechanism design, currently offered at our university, were described. In addition, the activities developed by our students were illustrated by examples.

The sequence of courses topics follows a didactic order. This means that it starts with planar and ends with three dimensional mechanisms. Moreover, the courses begin with the mobility evaluation, then, kinematic and dynamic analysis and finally, type and dimensional synthesis. On the other hand, during the development of their activities, students have the opportunity to apply the taught methodology in the reverse order. First, they generate the mechanism type and dimensions (synthesis) suitable for the task. Second, they build kinematic and dynamic models (analysis) to evaluate the goal accomplishment (effectiveness) and performance (efficiency).

Despite the courses have received very good evaluations by the students, we have to manage some conflicts that arise from the variety of methods and computational tools that are taught. When developing either their design activities or even the homework assignments, students are not enough mature to prefer the utilization of general and structured methods (Newton-Raphson, Matricial, Lagrange, Kane) instead of more specific and intuitive approaches (graphic, polar-complex, vector, Newton-Euler). Moreover, in a four-months period, students also have to dedicate their time to other five-six courses which certainly contributes to this choice.

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