Implementation and Assessment of a Virtual Laboratory of Parallel Robots Developed for Engineering Students

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***Abstract*—This paper presents a tool, LABEL, oriented to the teaching of parallel robotics. The application, organized as a set of tools developed using Easy Java Simulations, enables the study of the kinematics of parallel robotics. A set of classical parallel structures was implemented such that LABEL can solve the inverse and direct kinematic problem of 5R, 3RRR, and Delta robots. An intuitive graphical user interface lets the student change the joint coordinates or Cartesian coordinates of the end effector while observing a graphical representation of the robot. In addition, a set of five practical sessions based upon this tool was developed. During the practical sessions, the student analyzes the inverse kinematics of parallel structures and the direct kinematic problem. Moreover, LABEL makes it easy to analyze the singularities that appear in the solution of the inverse and direct kinematic problem. These singularities are analyzed through the use of a path planning application, which allows the user to plan a trajectory in the robot's workspace. This helps the student to analyze the position and velocity of the end effector while observing the joint trajectories and speeds of the actuators. LABEL was implemented during the academic year 2011–2012 and has been well accepted. Finally, an assessment of LABEL is presented.**

***Index Terms*—Education, parallel robots, robot kinematics, simulation, software tools, virtual laboratories.**

I. INTRODUCTION

THIS paper presents an educational tool, LABoratory for parallEL robots (LABEL), focused on the field of parallel robotics. This application provides a visualization of three classical parallel structures and enables a user to carry out a series of experiments with them. LABEL was developed to facilitate comprehension of the basic concepts in parallel robotics, most importantly the direct and inverse kinematic problems. In addition to formal lectures on parallel robotics that introduce students to the theoretical knowledge, experimentation has a very positive effect during learning, as has been widely recognized [1], [2]. Being able to test and clearly visualize solutions encourages the student to have more interest in learning the theoretical concepts. Also, it is generally accepted that using a variety of educational approaches enhances student learning, and that laboratory practical classes play a major role in the education of engineers. Some authors claim that practical sessions not only provide additional stimulus, but also promote additional skills and a deep comprehension of the concepts involved [3].

Parallel robots are known for their ability to bear high loads while achieving high accuracy. However, they are relatively difficult to teach [4]. Robot manufacturers have created their own industrial models for special applications. Thus, parallel robots are an important educational topic that requires tailored and effective educational approaches. The teaching of parallel robotics cannot be treated as a mere continuation of serial robotics because there are significant conceptual differences between these two types of manipulators. For example, knowledge of the kinematics of a serial manipulator cannot be directly applied to a parallel structure. Students generally find it easier to understand the direct kinematics of a serial manipulator than they do a numerical solution to the direct kinematics of a parallel robot. Thus, it is of paramount importance to provide students with a tool that allows them to visualize the concepts of parallel robotics; this need motivated the development of LABEL. This tool clearly presents the state of the robot and its various features. It requires no installation since it can be downloaded and executed online,[1] embedded in a Web browser; this feature allows students to carry out their practical sessions at home and with no time limitations. LABEL is the first educational tool that facilitates a fast comprehension of the most classical parallel structures.

LABEL was used at the Miguel Hernández University, Elche, Spain, during the academic year 2011–3012, in the Bachelor's degree programs in Electronic Engineering and Industrial Automation and in Industrial Engineering, and in the Master's program in Industrial and Communication Technology Research[1]. In particular, LABEL covers the kinematic problems of parallel robots of type 3RRR, 5R, and Delta, integrated within a common intuitive graphical interface, and presents the results graphically. The geometric parameters of each robot can be easily modified, and the feasibility of each solution and the values of each joint can be checked. The student can observe the various solutions and results as the robot mechanisms are moved. LABEL presents a visualization of the singularities in the solution of the direct and inverse kinematic problems. A path planner lets the student evaluate the effects of the existing singularities in the robot's workspace. A set of LABEL-based

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[1] From http://arvc.umh.es/label

[2] Please see http://en.umh.es for more information.

TABLE I
ROBOTICS COURSES ACROSS PROGRAMS, WITH LABEL USED TO TEACH PARALLEL ROBOTICS

Program	**Course**	**Total number of hours**	**Theoretical Lectures (hours)**		**Practical sessions (hours)**		**Topics covered**	**Sessions carried out**	**#students**
Bachelor's degree in Electronic Engineering and industrial automation	1770 ROBOTICS	140	Serial robotics	30	Serial robotics	18			
			Parallel robotics	**30**	**Parallel robotics**	**20**	Motion analysis. Inverse kinematics. Forward kinematics. Singularity analysis. Path planning.	**1, 2, 3, 4, 5**	45
			Mobile robotics	30	Mobile robotics	12			
			Sub-Total	90	Sub-total	50			
Master in Industrial and Communication Technology Research	541 SENSOR CONTROL OF ROBOT SYSTEMS	80	Serial robotics	30	Serial robotics	18			16
			Parallel robotics	**20**	**Parallel robotics**	**12**	Motion analysis. Inverse kinematics. Forward kinematics	**1, 2, 3**	
			Sub-total:	50	Sub-total:	30			
Bachelor's Master in Industrial Engineering	4747 ROBOT CONTROL AND SENSORIAL SYSTEMS	120	Serial robotics	30	Serial robotics	18			63
			Parallel robotics	**20**	**Parallel robotics**	**12**	Motion analysis. Inverse kinematics. Forward kinematics	**1, 2, 3**	
			Computer vision	20	Computer vision	20			
			Sub-total	70	Sub-total	50			

practical sessions was designed to cover the fundamentals of the field of parallel robotics.

New educational technologies have changed how students carry out their practical sessions. Virtual laboratories emulate the behavior of the real equipment [5], and remote laboratories give remote access to real equipment [6], [7]. For example, in [6], a remote laboratory gives a student access to a dc motor. The control parameters of the physical remote installation can be varied by means of a remote MATLAB/Simulink environment.

In the field of robotic manipulators, one work of note simulated a serial robotic manipulator, [8], as well as allowing the teleoperation of a real robotic arm while the student observed the results via a webcam. Another application, based on Easy Java Simulations (EJS), presents a virtual laboratory and a remote laboratory, both of which use the same EJS library software framework [9]; this tool only deals with serial link mechanisms.

In the field of parallel robotics, [7] presents a remote laboratory that enables students and researchers to experiment upon and to control thermal systems, dc motors, and a 3-DOF parallel robot.

The rest of the paper is organized as follows. Section II presents the course sequence and discusses students' educational backgrounds. Next, Section III summarizes the objectives for LABEL. Its use is presented in Section IV, and each of the parallel structures is described. The activity set is summarized in Section V. The main results obtained since LABEL has been in use are presented in Section VI. Finally, conclusions are presented in Section VII.

II. COURSE SEQUENCE AND STUDENT BACKGROUND

LABEL, designed as an introduction to parallel robotics, is used in robotics-related courses at Miguel Hernandez University. Robotics is taught by the System Engineering and Automation Department in three courses in three areas of study (Table I):

- 1770 Robotics, in the Bachelor's program in Electronic Engineering and Industrial Automation;
- 4747 Robot Control and Sensorial Systems, in the Bachelor's program in and in Industrial Engineering;
- 541 Sensor Control of Robot Systems, in the Master's program in Automation and Telecommunication.

These courses have no prerequisites and are taught in the fourth or fifth year of study. They require only the basic mathematical background and the basic formation in physics that students acquire during the first and second year of their engineering degrees. In each of the three courses, students receive an initial training in serial robotics that covers direct and inverse kinematics for serial manipulators, dynamics, and path planning. An introduction to parallel robotics follows, which in each case uses the LABEL tool.

Table I summarizes the use of LABEL in the three courses. The first two columns give the name of the program and course. The third column gives the total number of contact hours for each course. These are divided between theory lectures and practical sessions, covering a range of topics. The fourth column gives the theoretical topics covered in each course, along with the expected duration in hours. The fifth column gives the topics covered by practical sessions for each of the different topics. The theoretical lectures and practical sessions dedicated to parallel robotics are shown in bold text.

As can be seen in Table I, the number of practical sessions in parallel robotics differs between courses, meaning that the use of LABEL had to be adapted in each case. The 1770 Robotics Bachelor's course had 20 h available, so students were able to carry out all five practical sessions. The other two courses only allocated 12 h, so students just carried out practical sessions 1–3.

The theory lectures, allocated the same number of hours in each course, include an introduction to the analysis of serial robotics since it is advisable for students to learn the basic concepts of serial robotics before embarking on parallel robotics. The authors have noticed that students with prior knowledge of serial robotics find it easier to understand the concepts of parallel robotics.

III. OBJECTIVES OF THE LABEL TOOL

The introduction to parallel robotics featuring LABEL has the educational goals of familiarizing students with the following:

- inverse kinematics;
- direct kinematics;
- workspace and singularities.

These concepts are fundamental for an introduction to parallel robotics. Other concepts, such as dynamics, are also very important, but are not introduced here because of time limitations.

Some educators follow a hands-on-experiments approach and encourage the students to build low-cost systems and try them in the laboratory [10]. Although this trend in education has many advantages, a robotic structure built in this way is difficult to modify. LABEL, on the other hand, allows easy modification of all system parameters, such as the range of the actuators, the link lengths, and the relative position of the bases. Experimenting with these parameters and obtaining their own results helps students comprehend the concepts involved. Some topics, such as the workspace and singularities analysis, are easier to understand when the various parameters involved can be modified.

IV. USE OF LABEL

LABEL addresses the educational issues stated above. The instructional approach followed in each course is to begin with the kinematic analysis of the 5R robot, as described in Section IV-A.

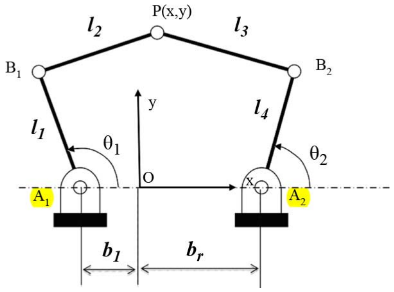


Fig. 1. 5R parallel robot.

A. 5R Robot

The 5R parallel robot is a simple mechanism with two degrees of freedom and a planar movement. The mechanism consists of four moving links and five joints, two of them active. Fig. 1 shows the mechanism, where joints A_1 and A_2 are active, and joints B_1, B_2 and P are passive. The end effector is considered as the point P, as shown in the figure. The kinematics of this mechanism have been widely studied by other authors [11]. This mechanism presents, as usual for parallel robots, an easy solution to the inverse kinematic problem: Given $P = (x, y)$, four different solutions exist for joints θ_1 and θ_2. The direct kinematic analysis considers the computation of $P = (x, y)$ as a function of the active joints θ_1 and θ_2. In this case, two different solutions exist as proved in [11].

The simulator of the 5R parallel robot helps students to understand the concept of direct and inverse kinematics and apply it to the case of the 5R mechanism. This is done by having LABEL show the Cartesian coordinates of the end effector and the joint coordinates in the same frame. The student can easily change the Cartesian coordinates of the point $P = (x, y)$ by dragging it with the mouse while simultaneously observing the joint coordinates. This feature helps the student to relate the inverse and direct kinematic problems. The various solutions to the inverse and direct kinematic problems can be easily chosen from the right-hand panel (four different solutions for inverse kinematics and two for direct kinematics).

B. 3RRR Robot

The 3RRR robot consists of a moving platform linked to a fixed base by means of three kinematic chains. Each of the three kinematic chains contains three revolute joints. The mechanism is governed by three active joints (O, Q, R) and possesses a total of six passive joints. As shown in Fig. 2, this configuration attains three degrees of freedom, thus the position of point $A = (x_A, y_A)$ and orientation ϕ of the end effector can be changed independently.

Because the 3RRR structure is harder to analyze than that of the 5R robot, this is explained in theory lessons that cover the straightforward analysis of the inverse kinematic solution of the 3RRR robot, and then go on to explain a direct kinematic solution [12], [13].

C. Delta Robot

The delta robot is illustrated in Fig. 3, where the three kinematic chains that connect the end effector with the static base are shown. Each kinematic chain is formed by two links that connect the base and end effector through three rotational joints.

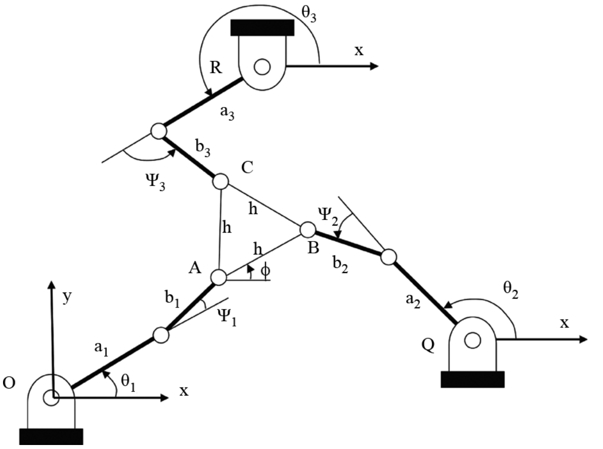


Fig. 2. Geometric analysis of the 3RRR parallel robot.

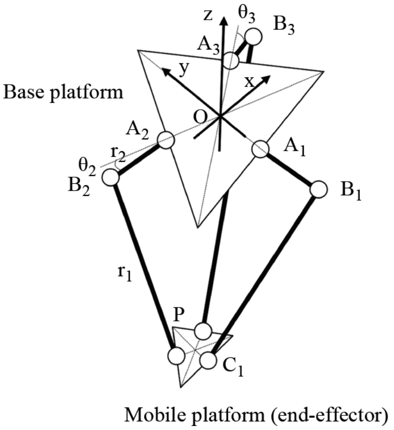


Fig. 3. Delta robot.

The joints restrict the movement of the end effector so that the orientation is kept constant with respect to the base. Fig. 3 presents the three active joints θ_1, θ_2, and θ_3 that can be modified. These joints are moved by three motors, installed on the joints indicated as A_1, A_2, and A_3. The inverse kinematic of the delta robot can be solved in different ways; for example in [14], a closed-form solution was developed. The solution of the direct kinematic problem is more complex, as described in [15].

V. LABEL'S ACTIVITY SET AND IMPLEMENTATION

This section describes the set of activities designed to use LABEL to introduce the topics gradually, as the necessary theory is provided in lectures. In total, the five activity sessions are the following:

- *Session 1*: Introduction to LABEL and to motion analysis of parallel structures (2 h);
- *Session 2*: Inverse kinematics (4 h);
- *Session 3*: Forward kinematics (6 h);
- *Session 4*: Singularity and workspace analysis (4 h);
- *Session 5*: Path planning (4 h).

These practical sessions, described more fully in the following, can be divided into: motion analysis, which involves direct and inverse kinematics; singularity analysis; and path planning. As described above, LABEL is used in various contexts to adapt to the particular needs of each of the three courses.

A. Session 1: Introduction to LABEL and to Motion Analysis of Parallel Structures

This 2-h laboratory session is designed as a "start-up" in the understanding of parallel robotics and is carried out in the on-campus laboratory. The student is encouraged to analyze the movement of a set of parallel structures in terms of the restrictions imposed by each link. The degrees of freedom of a mechanism are computed using the Grübler criterion [16]. The student is required to compute the degrees of freedom of each of the mechanisms analyzed in the tool. Next, the student has to observe the possible movements of each of the mechanisms by means of the graphical representation in LABEL, thus consolidating their knowledge.

B. Session 2: Inverse Kinematics

The inverse kinematic solution in parallel robotics is usually easier to understand than the forward kinematic problem. This 4-h practical session is also carried out in the laboratory. First, the inverse kinematics of the 5R robot are analyzed; the student should be able to derive the equations herself/himself. Next, the student checks and visualizes all the feasible solutions using the software tool provided. The 3RRR robot and the Delta robot are analyzed in the same way.

This session is particularly interesting for students since they can observe the different configurations of the robot in rapid succession to achieve the same position and orientation of the end effector. In the case of the 5R robot, there are four different solutions for the inverse kinematic problem (Fig. 4).

C. Session 3: Forward Kinematics

This 6-h laboratory session focuses on the forward kinematic problem. Four of the session hours are spent in the laboratory, and the remaining two at the student's home. The students are asked to solve the geometric constraints of the 5R, 3RRR, and Delta robots in terms of the joint coordinates. The students should come to understand the complexity of the forward kinematic problem, in contrast to the inverse kinematic problem, for parallel robots.

LABEL allows students to find the relationship between the direct and inverse kinematic problems by asking them to compare the inverse and direct kinematic solutions of the 5R robot.

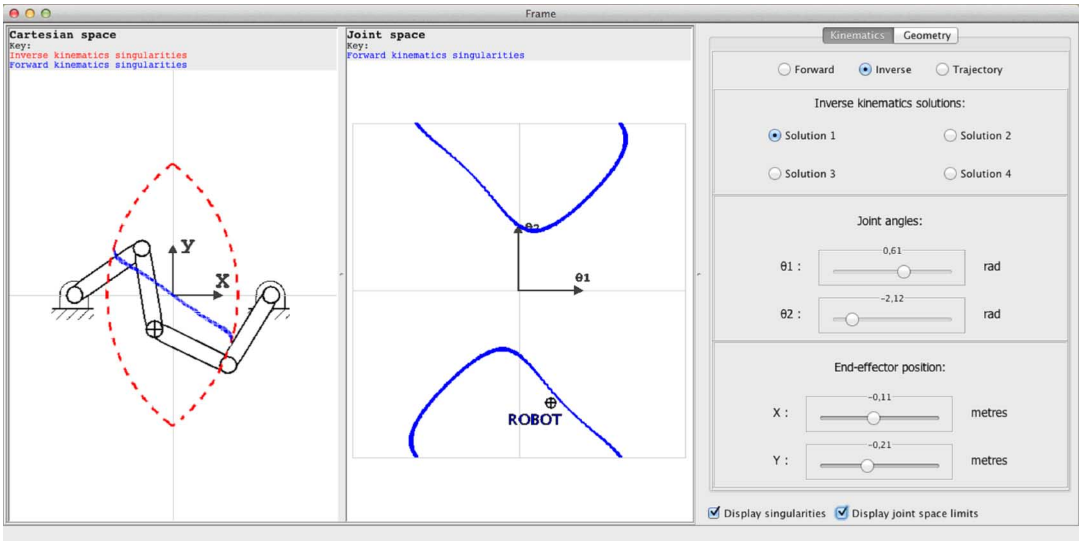
D. Session 4: Singularity and Workspace Analysis

In this 4-h session, the student should come to understand the concept of singular point, in both direct and inverse kinematics. Two hours are spent in the laboratory, and two at the student's home.

As an example of the work done in this session, Fig. 4 shows the inverse singularities of the mechanism in a continuous line on the x-y plot. In the case of 5R mechanisms, these singularities correspond to the limits in the robot workspace. The singularities in forward kinematics, harder for students to visualize and understand, are clearly shown in LABEL, greatly helping student comprehension.

E. Session 5: Path Planning

In this final 4-h session, carried out entirely at home, students explore the trajectory analysis for the Delta and 5R robots. First, the importance of the problem of path planning is underlined,



Cartesian space
Key:
Inverse kinematics singularities
Forward kinematics singularities

Joint space
Key:
Forward kinematics singularities

○ Forward ● Inverse ○ Trajectory

Inverse kinematics solutions:
● Solution 1 ○ Solution 2
○ Solution 3 ○ Solution 4

Joint angles:
θ1 : 0,61 rad
θ2 : -2,12 rad

End-effector position:
X : -0,11 metres
Y : -0,21 metres

☑ Display singularities ☑ Display joint space limits

Fig. 4. 5R robot. The reachable workspace is represented with a dashed line; the forward kinematic singularities are represented with a continuous line. Forward kinematic singularities can be viewed in *(left)* the Cartesian space and *(right)* the Joint space.

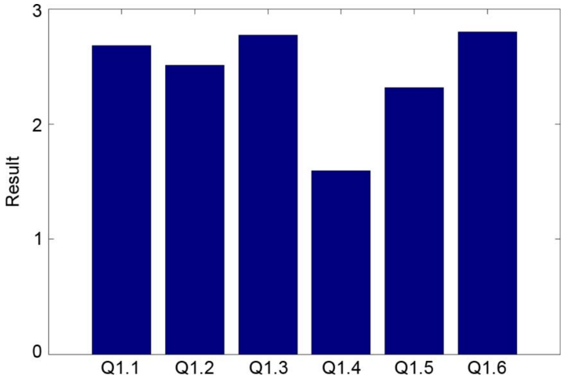


Fig. 5. Mean results obtained for S1 section questions, on the usefulness of LABEL in teaching parallel robotics.

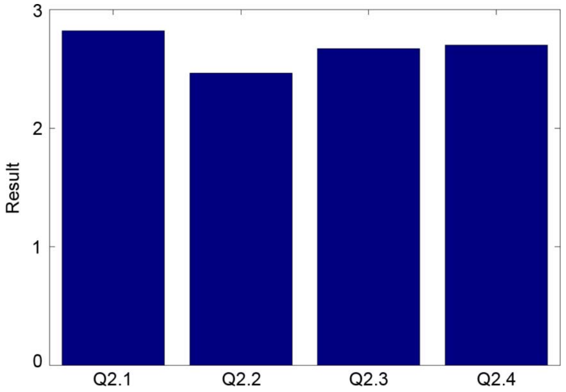


Fig. 6. Mean results for the SI section questions, on the design of LABEL.

and some approaches are mentioned. The students are then told to simulate some trajectories for the Delta robot in LABEL. Since singularities are not considered in the path-planning algorithm used in the Delta simulator, the students may have problems with some simulated trajectories; this leads them to discover the necessity of designing singularity-free trajectories.

TABLE II
EVALUATION OF THE TOOL: TIME SPENT BY STUDENTS

Session	Mean time (hours)	Standard deviation (hours)
Session 1	1.85	0.89
Session 2	3.85	0.98
Session 3	5.42	0.78
Session 4	4.71	0.75
Session 5	4.57	1.51

VI. EVALUATION OF LABEL'S EFFECTIVENESS

To evaluate LABEL's contribution to the teaching–learning process, a student survey was conducted at the end of the course, and student grades in the laboratory sessions were analyzed.

The anonymous survey, whose questions followed the guidelines in [17] and deployed in [18], was completed by students from all three courses. The number of registered students in each subject is found in Table I, as well as the number of sessions carried out by each and the hours this took. The survey was in three sections, each addressing a particular evaluation research item. The final item (M1) is taken from the material handed in by students after the laboratory sessions. These four research items were as follows:

- S1) Usefulness of LABEL in teaching parallel robotics;
- S2) The design of LABEL;
- S3) Time required by students to complete the laboratory sessions;
- M1) Marks obtained by students.

For each section, students responded on a scale from 0 (fully disagree), 1 (disagree), 2 (agree), to 3 (fully agree).

The first section addressed the usefulness of LABEL in helping students understand the concepts met in theory lessons and posed these questions.

- Q1.1) Do you think that LABEL helped you understand the Grüebler analysis of mechanisms?
- Q1.2) Did LABEL help you understand the movement types of the 5R, 3RRR, and Delta parallel mechanisms?
- Q1.3) Do you consider that LABELwas useful in the inverse kinematic analysis of the 3RRR, 5R, and Delta mechanisms?

TABLE III
EVALUATION OF THE TOOL (M1): CORRECTNESS OF THE ANSWERS

Session	Mean qualification (0-10)	Standard deviation	Questions for each session
1	9.1	0.69	a) Analyze the 3RRR and 5R robots. How many degrees of freedom do the mechanisms possess? b) Describe two actions that would increase the workspace of those robots.
2	9.0	0.77	a) Derive the equations that constrain the motion of the 5R robot. b) Present a solution for the inverse kinematic problem for this robot. How many solutions can you find? c) Describe the singularities that appear in these mechanisms and identify them using LABEL.
3	7.5	1.41	a) Write the equations that restrict the movement of the 3RRR robot. b) How many different solutions can you find in the direct kinematic problem of the 3RRR robot? c) Describe the singularities in the direct kinematic problem and use LABEL to identify them.
4	7.2	1.86	a) Describe, using a mathematical notation, what happens when the robot is placed at a singular point. b) Is it possible to place the 5R robot at a singular point? c) Use LABEL to place the 3RRR robot at a singular point.
5	8.6	0.95	a) Propose an algorithm that is able to plan a path across three consecutive poses. b) Describe a path-planning algorithm that could choose between the different solutions to the direct and inverse kinematic problem in parallel robots.

- Q1.4) Was LABEL helpful when analyzing the forward kinematic problem of the 3RRR, 5R, and Delta mechanisms?
- Q1.5) Did LABEL's path-planning capabilities help you to understand the singularities of the robots?
- Q1.6) Were the explanations given clear?

The mean of the responses is given in Fig. 5. In general, all the items received an acceptable result, so LABEL can be said to have been found useful by students. It can be observed that question Q1.4 received a low mark, which is probably due to the high complexity of the forward kinematic problem.

The next section addressed LABEL's design from the student point of view.

- Q2.1) Do you find LABEL easy to use?
- Q2.2) Is the representation of the variables involved in the kinematic analysis of parallel structures clear?
- Q2.3) Does the graphical representation help you to understand parallel structures?
- Q2.4) Did you find LABEL to be well organized?

Fig. 6 gives the means of the responses; these indicate that students consider, in general, that LABEL presents information clearly.

Finally, students were asked the time they spent with LABEL. For each of the five laboratory sessions, the following questions were asked.

- Q3.1) How much time did you spend using the LABEL?
- Q3.2) How much time did you spend reading the LABEL instructions?
- Q3.3) How much time did you spend studying the theory lectures associated with the practical sessions?
- Q3.4) Was the time you spent using LABEL all in a single day, or spread over several days?

Table II presents the mean time spent by the students on each of the practical sessions, as well as the total time spent by students, both in the laboratory and at home. The mean time can be seen to be very close to the time planned for each laboratory session. Table II, which applies to the results of sessions 1–3, presents the combined results for the three courses in which LABEL was used. This is valid because when the practical sessions are carried out, all the students had received the same background training in parallel robotics, whichever program they were in.

Sessions 5 and 6 lasted slightly longer than the time allowed and will be shortened in the future. The timing is of paramount importance since the European Credit Transfer and Accumulation System (ECTS) credits relate directly (1:1) to the hours spent in study.

Finally, an evaluation was carried out of the knowledge students acquired (M1). Once the students finish all the practical sessions, they must hand in a report answering a list of questions and problems. Table III presents the marks obtained, as well as a mean value and standard deviation. It is also interesting to assess whether students have correctly acquired the concepts of parallel mechanisms. To this end, each session has at least five questions, which are marked out of 10. The last column of Table III includes a subset of these knowledge evaluation questions. Sessions 1, 2, and 5 were easier for students to understand, and so, understandably, these show higher marks. However, sessions 3 and 4 yielded lower marks since the concepts involved are significantly harder. The difference in difficulty level of the practical sessions is due to the differing mathematical background required to understand the problems. For example, in session 3, the students are asked to write the equations that define the forward kinematic problem for the 3RRR robot; this implies writing an eight-degree polynomial in terms the variables involved. Session 4 is also hard to understand by students since it includes a Jacobian analysis of the robots, for which students must analyze the Jacobian matrices that relate the direct and inverse kinematic problem and find the configurations where their determinants become null.

VII. CONCLUSION

A new educational tool, LABEL, focused on the kinematic analysis of parallel robotic mechanisms, has been implemented for three classical parallel structures: the 5R, 3RRR, and Delta robots. To the best of the authors' knowledge, no other virtual laboratories possess the same features offered by LABEL. An intuitive graphical user interface enables the student to change the joint coordinates or the Cartesian coordinates of the end effector, as well as the geometric parameters of the robot. A set of five LABEL-based practical sessions guides students through the inverse and direct kinematic problems in parallel structures.

In general terms, the authors have found LABEL to a useful resource to help students rapidly acquire knowledge of the operation of the included classical parallel robotics structures. The tool's graphical capabilities are of great help in understanding the kinematic models of these structures.

The student survey elicited positive response, particularly in terms of the tool's design and its usefulness in the teaching–learning process. The time needed by students to complete the practical sessions was about that expected. In addition, the results indicate a significant knowledge gain by students.

Future work might compare the level of student understanding acquired via a virtual laboratory to that achieved via hands-on experiments. In addition, a dynamic analysis of the three mechanisms will be integrated in the tool.

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