Automatic grading of student-specific exercises in large groups of the subject Theory of Machines and Mechanisms

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Abstract This study establishes an already defined and tested method to grade exercises of kinematics and dynamics within the course entitled "Theory of Machines and Mechanisms" of the Industrial Technologies Engineering Degree at the Seville School of Engineering (Spain). Particular emphasis is made on the automation of grading and personalization of the exercises, due to the large number of students enrolled in this course. The former is made through a teaching platform available at the University of Seville and called Doctus, whilst the latter is achieved by defining the input data of the exercises and the requested results as a function of the digits of the student's ID. The students must face and solve a personalized problem by their own with the knowledge and competences acquired during the academic course. This paper describes the exercises and the tools used to grade them and shows the satisfactory results obtained with these exercises after three academic courses.

1 Introduction

The course on "Theory of Machines and Mechanisms" is basic in the formation of a Mechanical Engineer. In the Seville School of Engineering this subject is taught during the second course in the Industrial Technologies Engineering Degree ("Grado en Ingeniería de las Tecnologías Industriales"). The course covers 6 ECTS and its syllabus was designed to provide the basic knowledge about kinematics and dynamics of planar mechanisms, some concepts of synthesis of mechanisms and some basic aspects of calculation and design of several machine elements (cams, belts and gears). The text book followed has been written by professors of the department [1]

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and covers all topics treated during the course. Moreover, the syllabus was designed to comply with the Bologna Process for the European Higher Education Area.

Concerning kinematics and dynamics of mechanisms, which spans about 40% of the course, the objective is that students acquire the basic concepts to analyse and design planar mechanisms and understand how the movements and forces are transmitted within the mechanism to perform the task it was designed for. The particular objective pursued by the kinematic analysis is understanding the constraints imposed by the joints and visualize the movements of the different links of the mechanism. The objective of the dynamic analysis is to provide the students with the tools needed to associate movements with the forces that cause it or viceversa.

It was detected that, in general, the students have difficulties when facing up to kinematic and dynamic analysis of mechanisms, due to the complex mathematical and physics concepts involved as well as to a likely deficient background. This issue was also observed before the Bologna Process, when this course was offered under a different name, "Machines Theory". After the Bologna process came into effect, the contents of the course were extended and the time devoted to kinematics and dynamics of mechanisms shortened, which increased the difficulties encountered by the students in this part of the subject.

Aware of the problem, the faculty designed an innovative teaching activity to improve the results and, overall, to force the students to learn the contents of the course in a steady and continuous way. The activity proposed a couple of exercises, respectively, a kinematic and a dynamic analysis of the corresponding mechanisms, as a way of self-assessment of their knowledge before the final exam. Due to the fact that the student could solve the exercises at home, these exercises needed to be personalized in order to minimize cheating. It was a real challenge to design personalized exercises for all the students enrolled on this course (around 500) and, more importantly, to grade them quickly. An automated process was clearly required. Another advantage of personalized exercises is that it tries to force the students to solve the problem on their own.

The finally designed activity is presented in this paper, which intends to present an example of personalized problems and automated grading within the Mechanical Engineering curriculum. Automation was achieved with the help of Doctus (http://doctus.us.es/sdocencia/public/index.php), a teaching app developed by the Department of Systems and Automatic Engineering of the University of Seville. Personalization was made by defining the input data of the exercises and the requested results as a function of the digits of the student's ID.

Personalized and automatically graded exercises generated the following benefits:

- The exercises can be more complete and complex.
- They can replace the traditional system of evaluation.
- It is recommended that students use a mathematical software to program the resolution of the exercise, therefore improving their ability in programming engineering like codes.
- They can be used by the student as a self-assessment technique.

- They can help the students to follow the subject up-to-date, guiding and enabling them to learn through practice, which is crucial for students of mechanical engineering.

The next sections are organized as follows: Section 2 explains the general methodology used in the design of the exercises to minimize some problems that might occur, such as singular configurations, non-existence of solutions, etc. Section 3 shows two examples: a kinematic and a dynamic exercise, respectively. Section 4 is devoted to results and conclusions obtained from the study of the correlation between the grades obtained in the exercises and those obtained in the final exam.

2 Material and methods

This section describes the procedure followed to pose personalized, or student-specific, problems to a group of the subject dealt with in this paper. In principle, it is based in two important parts that will be briefly described next. The first one is the web application Doctus that facilitates the management of the personalized problems and the grades generated after the automatic correction of the results submitted by the students. The second important part is the problem itself that has to be well parameterized in order to make it dependent on each student personal data.

2.1 The teaching assistive application Doctus

The web application Doctus was developed in the department "Ingeniería de Sistemas y Automática" of the University of Seville as a platform intended to assist teaching activities in large groups of students. It has been the subject of some papers and a Doctoral Thesis [3]. The application is offered free to any interested university and is continuously maintained by personnel of the department.

The application Doctus is built up with two different interfaces: the teacher interface and the student interface. Both interfaces are accessed by using a web browser and relay on a big data base that stores the information of the students, the exercise the do, the grade they achieve, etc. Among many other utilities, the teacher interface allows the following actions that are useful for the purpose of the evaluation process reported in this paper:

1. To load a list of students pertaining to a group, no matter how large the group is. It is possible to have different groups of students associated to different subjects.
2. To create exercises that can be assigned to a group. Each exercise is composed of a problem statement and a code that will be lately used to correct the results provided by students. In this particular case, the code is programmed using Matlab [2]. This is the key point of Doctus for the purpose of this paper. Since the code can easily account for variables that are dependent on the personal data of

a student, the problem statement can be parameterized so that each student will have to solve a different problem.
3. To automatically order the evaluation of the numerical results submitted by the students. For the evaluation MATLAB is called in batch mode to run the same solution code for the data of each stundent. Since the evaluation is done over numerical results, a tolerance of 5 % is typically allowed.
4. To automatically collect the results of all students on a csv file. It is possible to include in the same file the results of all exercises posed to a group.

The student interface need no detailed description. It is enough to say that this interface allows the student to access an exercise and send his numerical results to the data base that is accessed for evaluation. Of course, all students were aware of being evaluated by the application.

2.2 Design of exercises

The design of the exercise is not a simple task since it should guarantee that each student has to solve a different problem, meaning different known numerical data leading to different numerical results. The rules to design an exercise are summarized here. The exercises referred in this paper focus on different topics, one concentrates on Kinematics and the other in Dynamics. Nevertheless, both exercises have a common feature: a mechanism on which questions can be posed. The next is a list of considerations taken into account to design a useful exercise:

1. The mechanism object of the exercise must include at least one of each type of the kinematic pairs (joints) studied during the course.
2. The configuration of the mechanism, position of solids, must be different for each student. This is usually achieved by parametrization of lengths and distances in terms of the ID number of the student. In order to minimize the possibility of two students having the same configuration, an irrational number in the range $(0,1)$ is defined as follows:

$$\xi = \frac{\sqrt[8]{\prod_{i=1}^{8} A_i}}{2 + \frac{1}{8}\sum_{i=1}^{8} A_i} \tag{1}$$

where A_i are the eight digits of the student ID number assuming that a 0 means 10 to avoid singularities.
3. Singular configurations (null Jacobian) must be avoided since the solution code would give NaN results which can not be compared with those of the student. This may be difficult to achieve in all cases and is highly dependent on the experience of the teacher. The experience of the authors reveals that the use of the number ξ helps to avoid singular configurations when it is used in the following way. The mechanism topology is divided in angular sectors that contains the geometric vectors involved in the calculus of velocities and accelerations. Then, the orientation of these vectors is taken as a weighted mean between the limits of the

angular sectors. As an example, the radius vector of a point A could be calculated as

$$r^A = r^{C_5} + R_6 \begin{pmatrix} \cos\gamma \\ \sin\gamma \end{pmatrix} \qquad (2)$$

where r^{C_5} is known, R_6 is parameterized in terms of the ID digits and $\gamma = \frac{2\pi}{3} + \xi \cdot \frac{\pi}{6}$ rad. Note that in this case the limits of the angular sector are $\frac{2\pi}{3}$ and $\frac{5\pi}{6}$. Controlling the orientation of vectors in this way it is possible to avoid singular configuration in almost any case.

4. Several inputs and outputs must be available in order to generate combinations of inputs and an output that increase the number of different exercises. In general, the mechanisms used in this kind of exercises would be single d.o.f. mechanisms. Therefore it is useful to parameterize also which are the inputs and which is the output.

5. Finally, it is necessary to pose questions that can be answered numerically. The numerical solution of this kind of exercise involve many computations and therefore it is recommended that the student codes the resolution of the process. In despite of this recommendation many students take the risk of solving the problem manually, which is an excellent training for the written exam.

After grading all students, Doctus application allows the teacher to make visible the results corresponding to each students. This way, even if the grade got by a student was not good he/she still can learn from repeating the exercise until the exact solution is achieved, a process that may point to possible sources of mistakes.

3 Exercises proposed during course 2015-2016

Figures 1 and 2 shows the two mechanisms that where object of kinematic and dynamic analysis during the course 2015-2016[1]. In the figures, one can find all the parameters that define the configuration of the mechanism. For instance, parameter R_6 in Figure 1 is defined as A_2 meters, being A_2 the second digit of the ID number.

To show how the input data can be parameterized, in the kinematic analyses of the mechanism in Figure 1 the value of the independent velocity was given according to

- $v_{32} = 1\,\mathrm{m/s}$ if A_7 is 1, 2 or 3.
- $\omega_{31} = 1\,\mathrm{rad/s}$ if A_7 is 4, 5 or 6.
- $\omega_{41} = 1\,\mathrm{rad/s}$ if A_7 is 7, 8, 9 or 10.

being A_7 the seventh digit of the ID number.

The mechanism in Figure 2 was subject to the dynamic analysis. Again, the problem is completely parameterized including forces or moment applied to different

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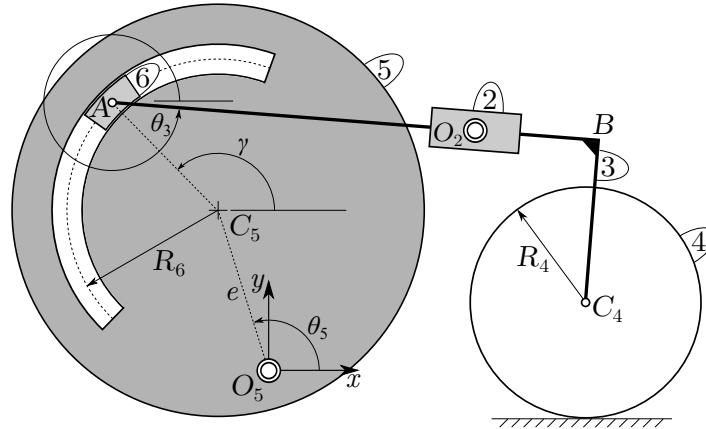[1] The complete exercise is available on request to dgvallejo@us.es

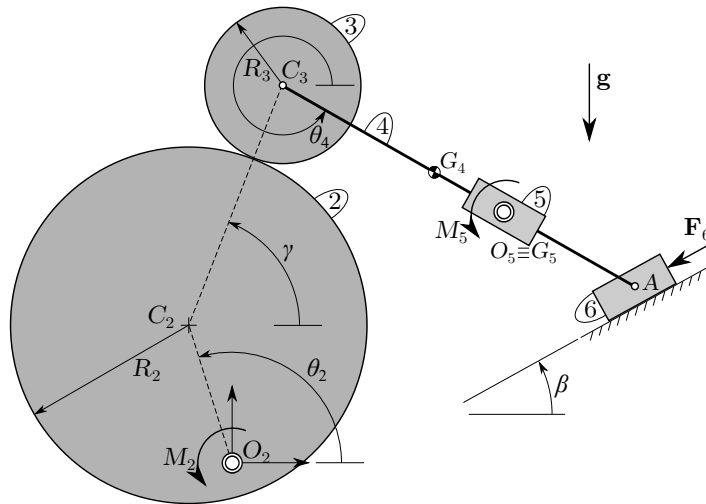**Fig. 1** Draft of the mechanism whose kinematics has to be analyzed.

Fig. 2 Draft of the mechanism whose dynamics has to be analyzed.

bodies. In this case, the following types of analysis were requested on the same configuration (position) of the mechanism: a static equilibrium scenario, an inverse dynamic analysis with the mechanism in repose (null velocities), a direct dynamic analysis with the mechanism in repose, an inverse dynamic analysis with the mechanism in movement and a direct dynamic analysis with the mechanism in movement. The method suggested to solve the problem is the application of the Virtual Power Principle. This five previous cases helps at clarifying which situations require null inertial forces or when virtual velocities need to be different to real ones, for example.

The kinematic analysis was carried out by 393 out of 462 students. Among them 123 obtained the highest grade while 77 obtained the lowest. The mean grade was 6.23 over 10. On the other hand, the dynamic analysis exercise was done by 344 students. Only one student got the highest grade while 171 student got the lowest grade. The mean grade in this exercise was 1.81 over 10.

4 Correlation between exercises and exam grades

It is also important to analyze whether the exercises had any effect in the students' learning achievements. To do so the grades obtained by the students in final exam was correlated with those obtained in the exercises during the academic year 2015-16. That year 462 students were enrolled in the course, though only the 96 students attending the exam in June were considered for the study. Their grades in the part of the exam devoted to Kinematics and Dynamics of Mechanisms (named EXAM) were correlated with the corresponding grades obtained in the two exercises proposed during the year and explained in section 3. These grades are named, respectively, KIN and DYN.

It must be noted that EXAM was graded in the range $[0, 10]$ and using quarters of point as the grading unit. Meanwhile, KIN and DYN were graded, respectively, in the ranges $[0,6]$ and $[0,9]$, being 1 the grading unit. In other words, KIN and DYN had, respectively, 6 and 9 questions and only true or false (1 or 0) were accepted as grades in each question.

Pairwise comparisons of the three grades can be seen in figure 3.

First, a Kolmogorov-Smirnov test using the Lilliefors significance correction was performed to check the normality of the samples. The test was significant in all cases ($p < .001$ for KIN and DYN and $p = .007$ for EXAM) and, thus, the correlation performed between the grades was based on the ranks.

The grade EXAM was significantly correlated with DYN (Spearman $R = .217$ and $p = .034$) but not with KIN (Spearman $R = .152$ and $p = .138$). In the first case $R^2 = .047$ is not very high, but it is obvious that the students' grades in a certain exam may depend on multiple variables. That year the grade obtained in the Dynamics exercise explained almost 5% of the grade in the final exam and that is not negligible. On the contrary, it is revealing that a continuous study of the course helped the students to achieve good results.

One of those multiple effects that may affect the grades of an exam is the difficulty of the exercises, which did not seem high in case KIN. This could explain the low correlation between KIN and EXAM. However, it is noteworthy the strong correlation found between KIN and DYN (Spearman $= .508$ and $p < .001$). Here, the similar conditions upon which the exercises were completed by the students: at home, with time enough to solve the problems, with the help of their textbooks, etc. may be behind that stronger correlation.

Another factor that is surely biasing the comparisons is the fact that the grades KIN and DYN were calculated using a true/false scheme, based on the results and
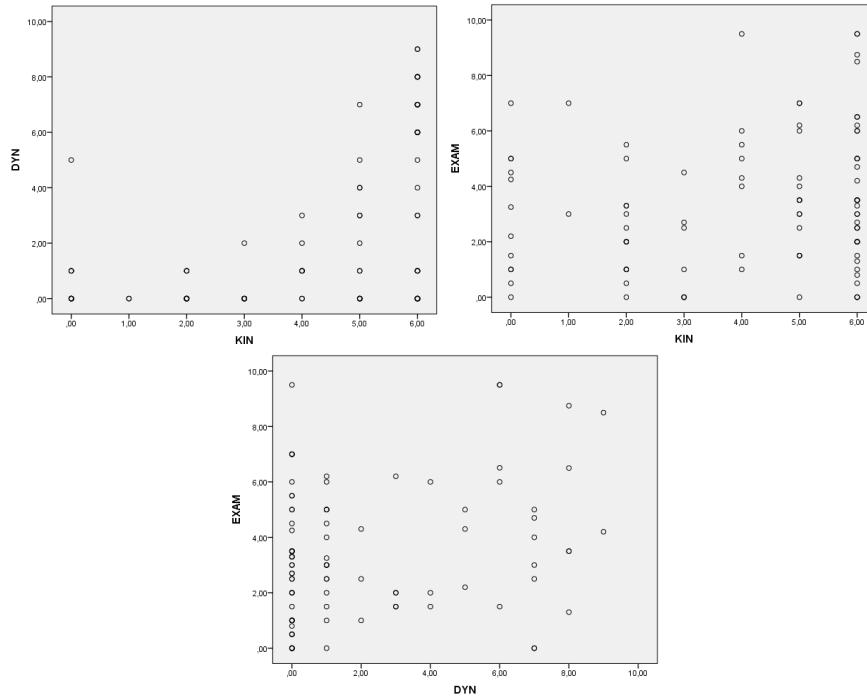
Fig. 3 Pairwise comparisons of the grades EXAM, KIN and DYN.

an acceptable tolerance, in contrast to EXAM in which the process followed to solve the problem was taken into account to calculate the grade.

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