Revealing the Hidden Technology by Means of an Overhead Crane

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Abstract: In this paper we show that an industrial-like overhead crane can be effectively employed to show the role of control in industrial automation systems and in everyday life. The devised experiments are particularly indicated for secondary school students who are in general not aware of the presence of control in engineering. The related educational activity consists of explaining the integration of mechanics, electronics, computer science and control in an automation system and then of making the student understand that the presence of an automatic controller can increase the performance with respect to a manual one. The approach has been tested with some classrooms and the results obtained with an assessment questionnaire have shown the effectiveness of the approach.

Keywords: Control education, control systems, automation systems, overhead crane.

1. INTRODUCTION

According to a well known definition coined by K. J. Åström (Åström, 1999), automatic control is considered as a hidden technology because, even if feedback controllers are present almost everywhere in our lives (from home appliances to very complex industrial systems), their importance is often not perceived by those who are not expert in the engineering field. This is maybe because it is easier to explain how a device works rather than how an algorithm works. For this reason, it is difficult to attract high school students to this discipline and a significant effort has been provided in recent years to increase the general awareness of the role of control technology and its cross-disciplinary nature (see, for example, the workshops for middle and high school teachers and students organized within the American Control Conference and the IEEE International Conference on Decision and Control each year).

In a more general framework, it has to be recognized that industrial automation is also a topic that is not very well known to the general public as the integration of mechanics, electronics, computer science and automatic control is quite complex and the role of each discipline is often not clear. In this context, it is useful to have simple experimental setups that can be used to show the different components of an automation system and, in particular, the role of the control system. Actually, the most important issue is to make the students aware of the presence and of the usefulness of a control system, without requiring any complex (possibly mathematical) explanation, but by stimulating their intuition. In other words, it is important that students see the role of a control system with their own eyes.

For this purpose, in this paper we propose to use a laboratory scale overhead crane, made by industrial components. Cranes have been already widely used for education activity in the control field (see, for example, (Horacek, 2000; Lawrence et al., 2006; Lawrence, 2006; Singhose et al., 2008)), however they have been mainly exploited to teach automatic control and mechatronics concepts rather than making the usefulness of a control systems clear in a transparent way to the user. In fact, the purpose of the control system is to reduce the residual oscillation of the load by minimizing the travelling time at the same time and this makes the device suitable for undergraduate and graduate students to understand the dynamics of oscillatory systems and to evaluate many kinds of control design methodologies. Further, issues related to the motion control of mechanical systems (for example, friction) can be also highlighted. According to the previously done considerations, in this paper we propose a different use of the setup, by making the algorithm transparent to the high-school student. In particular, the student has to compare the motion of the crane made manually and by means of a control algorithm that automatically reduce the residual oscillation. In this way, the advantages of the use of a control system are evident. The employed control algorithm is the well-known input shaping one (Singhose et al., 1994, 1997; Vaughan et al., 2008; Singhose and Vaughan, 2011; Potter and Singhose, 2013), which is actually a motion planning strategy that is particularly suitable to be implemented in a practical industrial environment.

The paper is organized as follows. The experimental setup is presented in Section 2, while the input shaping approach is briefly reviewed in Section 3. The activity to be performed with the high-school students is described in Section 4. The evaluation of its application to a group of students performed at the University of Brescia, Italy, is given in Section 5. Concluding remarks are in Section 6.

2. EXPERIMENTAL SETUP

A laboratory-scale overhead crane, made of industrial components, has been built for educational and research purposes (see Figure 1). The machine has a dimension of approximatively a cube of edge length equal to 3 [m]. It is worth stressing again that all the employed components are off-the-shelf components and therefore they are particularly suitable to explain to the students the devices that are actually employed in a mechatronic system. The cart is actuated with a brushless servomotor through a pulley and toothed belt system. The maximum motor continuous torque is $T_{max} = 3$ [Nm], while the peak one is $T_{peak} = 6$ [Nm]. The pulley radius is $r = 0.0233$ [m]. The motor is connected to the pulley through an epicycloidal speed reducer whose reduction ratio is $i = 10$ and whose mechanical efficiency is $\eta = 0.95$ (note that epicycloidal speed reducers have a very symmetrical behavior between direct and reverse motion). The cart mass is $M = 38$ [kg]. The load mass is $m = 20$ [kg], while the nominal rope length is $l = 1.61$ [m]. The load angle is measured through a servopotentiometer mounted coaxially to the load pivoting axis. Note that this sensor is never used for control purposes, but it is used to evaluate the performance of the input shaping motion planning approach.

Denoting the force acting on the cart as u, the cart and the load frictions as c_1 and c_2, respectively, the cart position as x, and the load angle as θ, a dynamic model of the system can be written as:

$$\begin{cases} (M+m)\ddot{x} + ml\cos\theta\ddot{\theta} + ml\sin\theta\dot{\theta}^2 + c_1\dot{x} = u \\ ml\ddot{\theta} + mg\sin\theta + m\ddot{x}\cos\theta + \frac{c_2\dot{\theta}}{l} = 0. \end{cases} \quad (1)$$

Considering the state vector $\mathbf{x} = [x\ \dot{x}\ \theta\ \dot{\theta}]^T$, the model (1) can be linearized around the origin of the state space, leading to

$$\dot{\mathbf{x}}(t) = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{c_1}{M} & \frac{mg}{M} & \frac{c_2}{Ml} \\ 0 & 0 & 0 & 1 \\ 0 & \frac{c_1}{Ml} & \frac{-g(m+M)}{Ml} & -\frac{(M+m)c_2}{Mml^2} \end{bmatrix} \mathbf{x}(t) + \begin{bmatrix} 0 \\ \frac{1}{M} \\ 0 \\ -\frac{1}{Ml} \end{bmatrix} u(t). \quad (2)$$

The horizontal position of the suspended load is $x_p = x + l\sin(\theta)$ which, by considering $\sin(\theta) \approx \theta$, can be written as

$$x_p = x + l\theta. \quad (3)$$

Using the previous equation, together with the state-space model (2), the following transfer function is obtained:

$$\frac{X_p(s)}{U(s)} = \frac{\frac{c_2}{mMl^2}s + \frac{g}{Ml}}{s\ \left[s^3 + \left((m+M)\frac{c_2}{Mml^2} + \frac{c_1}{M}\right)s^2 + \left((m+M)\frac{g}{Ml} + \frac{c_1c_2}{Mml^2}\right)s + \frac{c_1g}{Ml}\right]}. \quad (4)$$

The previous transfer function describes the input-output dynamic model between the force applied to the cart u and the horizontal position of the suspended load. However, as industrial components are used, the position/speed feedback is only available from the motor axes, *i.e.*, from the cart position/speed.

Therefore, it is meaningful to represent the systems as the product of two different transfer functions and an integrator, namely

Fig. 1. A picture of the experimental setup.

$$\frac{X_p(s)}{U(s)} = P(s)\frac{1}{s}G(s), \quad (5)$$

where

$$P(s) = \frac{V(s)}{U(s)} = \frac{s^2 + s\frac{c_2}{ml^2} + \frac{g}{l}}{\left[s^3 + \left((m+M)\frac{c_2}{Mml^2} + \frac{c_1}{M}\right)s^2 + \left((m+M)\frac{g}{Ml} + \frac{c_1c_2}{Mml^2}\right)s + \frac{c_1g}{Ml}\right]} \quad (6)$$

is the transfer function between the force $u(t)$ and the cart speed $v(t)$, and

$$G(s) = \frac{X_p(s)}{X(s)} = \frac{V_p(s)}{V(s)} = \frac{\frac{c_2}{ml^2}s + \frac{g}{l}}{s^2 + s\frac{c_2}{ml^2} + \frac{g}{l}}. \quad (7)$$

is the transfer function from the cart position/speed to the load position/speed (this transfer function does not change).

The general control system that has been implemented is based on a standard cascade position/speed control architecture such as the one represented in Figure 2 (top), with two Proportional-Integral (PI) controllers. The control loops are embedded into the servomotor drives, they receive the reference signals via the real time Ethernet bus Powerlink (see B&R Automation (2016) for details) from the Programmable Logic Controller (PLC). The control algorithm is implemented in the real-time operating system Automation Runtime (see B&R Automation (2016) for details) that runs on the PLC accordingly to the PLCopen standard (PLCopen, 2016) and the control program cycle is of 0.8 [ms], so that the reference signals are refreshed with this frequency.

For the educational purpose presented in this paper, however, only the speed control has been used (see Figure 2 (bottom)) as the position is controlled manually. The input shaping strategy has been used to provide an oscillations-free motion of the load.

3. INPUT SHAPING

The well-known input shaping technique, which is briefly reviewed here for the sake of readability, is used in order to provide an oscillations-free motion of the payload. The general technique (Singer and Seering, 1990) is derived from the linear system theory. Considering a vibratory system with one oscillatory mode, where $x(t)$ is the output function, the impulse response can be expressed as that of a second-order system with the following decaying sinusoidal response:

$$x(t) = \left[A\frac{\omega_0}{\sqrt{1-\xi^2}}e^{-\xi\omega_0(t-t_0)}\right]\sin(\omega_0\sqrt{1.0-\xi^2}(t-t_0)),$$

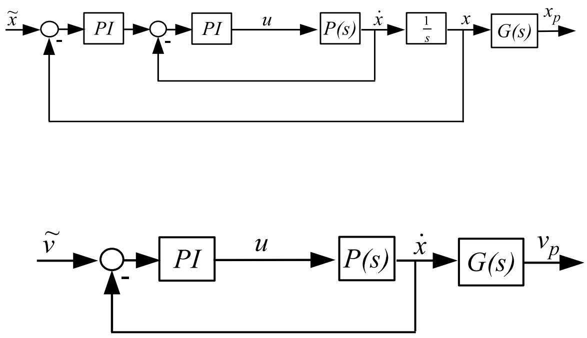

Fig. 2. The general cascade position control architecture (top) and the speed control architecture used for educational purpose (bottom).

where A is the amplitude of the impulse, ω_0 is the undamped natural frequency of the plant, ξ is the damping ratio, t is the time and t_0 is the time of the impulse input. It turns out that two impulse responses can be superposed so that the system output vibration is suppressed after the second impulse, as shown in Figure 3. The mathematical derivation of the time ΔT between the impulses and of their amplitudes is quite simple (Singer, 1988). It results that at time $t = t_0$ an impulse of amplitude $1/(1 + K)$ has to be applied at the input, followed by an impulse of amplitude $K/(1+K)$ at time $t_0+\Delta T$ (see Figure 4), where it is

$$K = e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}}$$

and

$$\Delta T = \frac{\pi}{\omega_0\sqrt{1-\xi^1}}.$$

It is worth noting that, in order to cope with system uncertainties and/or multi vibration modes, more complex input shapers can be applied. However, they are not necessary in the case of the system considered in this paper as the nominal model is known with a sufficient accuracy.

In practical cases, a reference signal has to be defined in order to obtain a desired load motion, considering the system as rigid. Then, this signal has to be convolved with the input shaper to obtain a new input function which has to be applied to the actual control system in order to set to zero the residual vibration.

In the case of the overhead crane, a ramp velocity signal is considered as the reference signal. In particular, when the user presses a button available on the user interface (see Section 4) and the input shaping is not applied, a positive ramp signal with a selected slope is generated by the controller and used as a reference value for the control scheme of Figure 2 (bottom) until a predefined steady-state velocity value of the crane is achieved. Similarly, when the button is released, a negative ramp is generated until the velocity is set to zero. The technique is illustrated in Figure 5. When the input shaping strategy is applied, these signals are convolved with the input shaper, providing the signal shown in Figure 6.

Illustrative examples of the application of the ramp velocity signals with and without the input shaping are shown in Figures 7-10 where the obtained velocities of the cart and

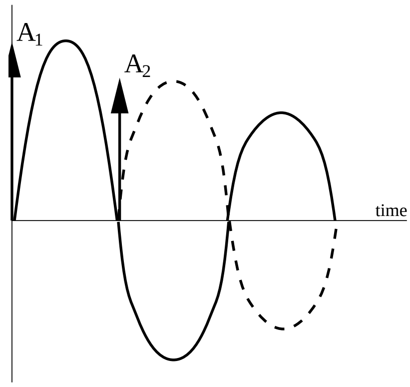

Fig. 3. The basic idea of the input shaping technique.

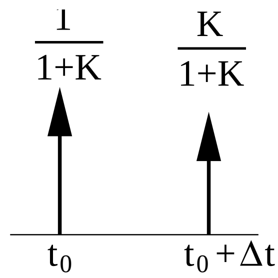

Fig. 4. The two-impulse input shaper.

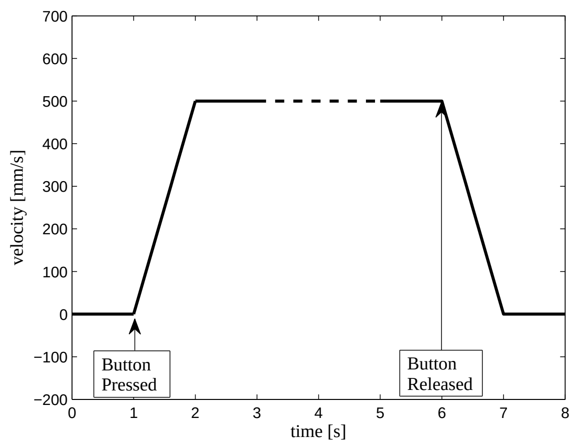

Fig. 5. Velocity reference signal without input shaping.

the corresponding load angles with and without the input shaping are shown. It can be observed that the method is very effective in providing an evident visual intuition of the role of the control system.

4. STUDENT EXERCISE

Having the experimental setup described in the previous sections, the following educational activity can be proposed to high school students. First, an explanation of the setup is given. Without giving technical details that cannot be understood without a significant mathematical background, it is important in this phase to describe the mechanical structure (the crane), the electrical and electronic devices (the motor, the drive system, the cables, the microprocessor) and the graphical user interface. In this way, it should be clear that even a simple automation

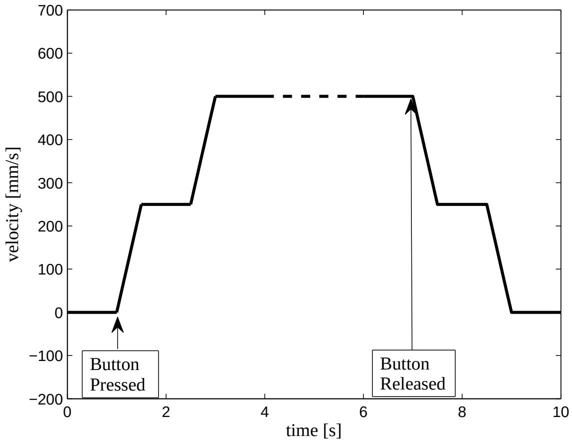

Fig. 6. Velocity reference signal with input shaping.

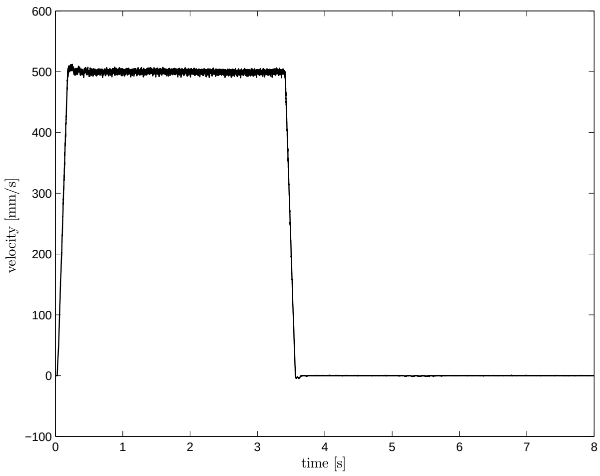

Fig. 7. Obtained velocity of the trolley without input shaping.

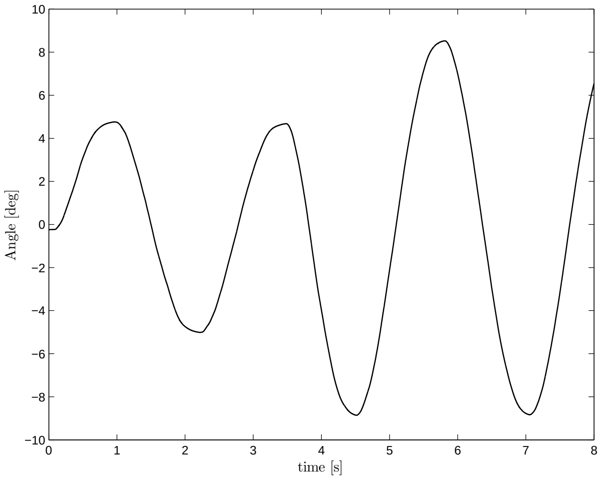

Fig. 8. Obtained load angle without input shaping.

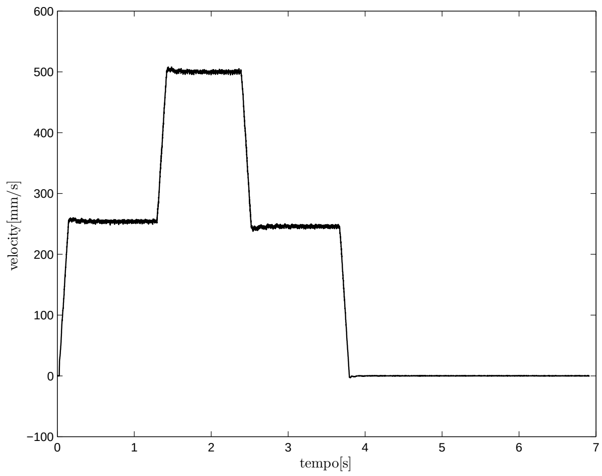

Fig. 9. Obtained velocity of the trolley with input shaping.

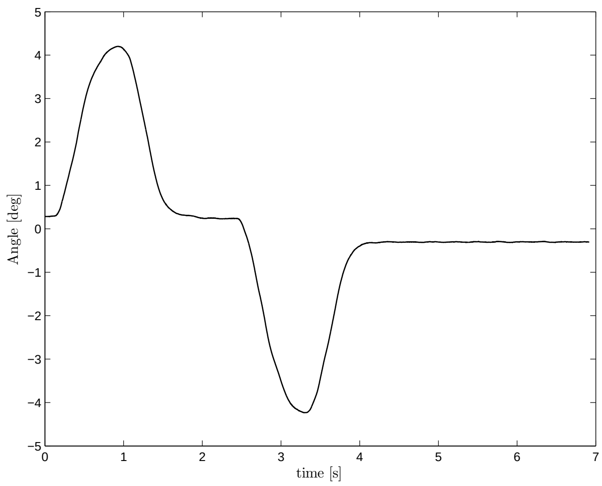

Fig. 10. Obtained load angle with input shaping.

system is the result of the integration of different engineering disciplines. At this point, the student should be aware that an automation engineer should have an expertise in different topics and the main concepts that have to be studied at a university level span many fields. It is believed that the overhead crane can tangibly make the student aware of this issue.
Then, the student should be made aware of the usefulness of a control system and of its presence in automation systems even if they are often "hidden". For this purpose, each student has to be invited to try to move manually the crane from a position to another one by achieving the final position without a residual oscillation. A graphical user interface has been built for this task and it is shown in Figure 11. It can be observed that there is a button that corresponds to the velocity command described in Section 3 (actually, there is one button for each direction of the crane). Thus, the student can press and release the button in order to perform the task, but it is unlikely he/she will succeed as the task is quite difficult also for skilled crane operators. The input shaping technique is subsequently inserted into the control system and a new graphical user interface is given to the student who is asked again to perform the motion control task (see Figure 12). In this way, it will be clearly visible that there is no more

Fig. 11. Graphical user interface for manual control without input shaping.

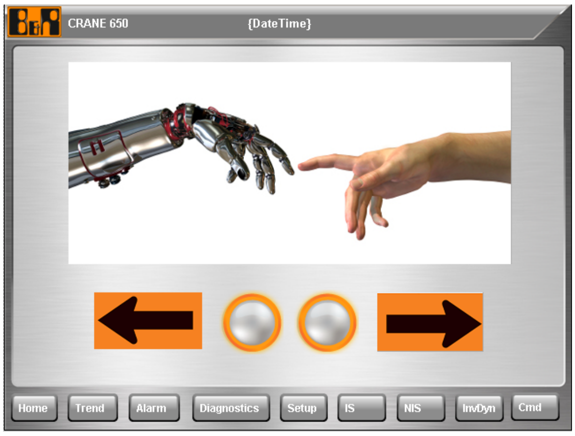

Fig. 12. Graphical user interface for control with input shaping.

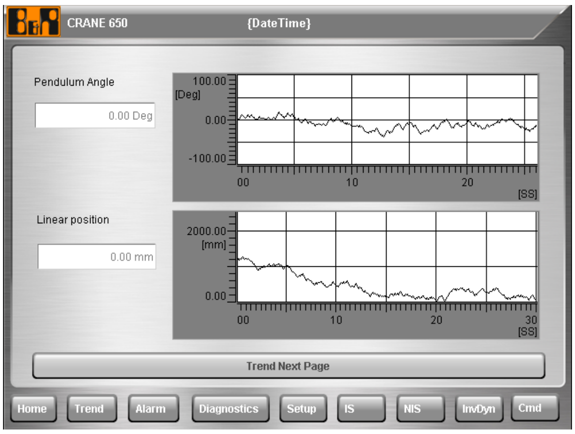

Fig. 13. An illustrative example of the plots of the signals obtained in an experiment.

a residual oscillation and the effect of having a control system will be clearly perceived. To further persuade the user, the most relevant signals of the experiment can be plotted (see Figure 13).

5. EVALUATION

In order to evaluate the effectiveness of the educational strategy, 42 high-school students from Brescia have been invited to the laboratory of the University of Brescia. Almost half of them (19 people) were from a technical school, while the rest were from a secondary school focusing on sciences. After the exercise in which, after the general explanation, each student has tried to control the crane without and with the input shaping, a simple questionnaire has been given to the class. In particular, five statements have been proposed (followed by the possible answers):

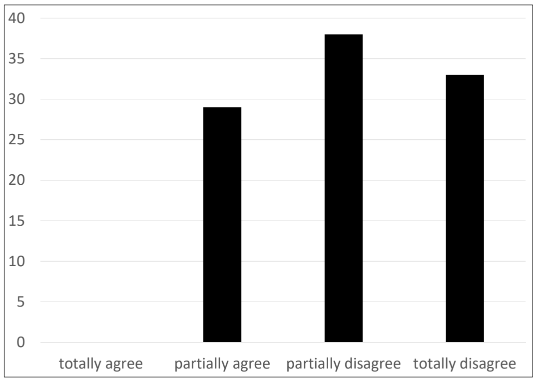

Fig. 14. Answers to the first question.

(1) I already had an idea of what an automation system is before the experience with the crane (totally agree / partially agree / partially disagree / totally disagree)
(2) I have now an idea of what an automation system is (agree / disagree)
(3) I already had an idea of what a control system is before the experience with the crane (totally agree / partially agree / partially disagree / totally disagree)
(4) I have now (after the experience) an idea of what a control system is (agree / disagree)
(5) I am able now (after the experience) to recognize the presence of automatic control in other systems in your everyday life (agree / disagree)

Regarding the first question (see Figure 14), none (0%) answered 'totally agree', 12 students (29%) answered 'partially agree', 16 (38%) students answered 'partially disagree' and 14 students (33%) answered 'totally disagree'. Then, the answer 'disagree' to the second question were given by only 2 (5%) students, while the other 40 (95%) answered 'agree' (see Figure 15).
Regarding the last three questions, in the third one (see Figure 16) none (0%) answered 'totally agree', 10 students (24%) answered 'partially agree', 22 (52%) students answered 'partially disagree' and 10 students (24%) answered 'totally disagree', indicating that, in general, the awareness of the role of automatic control is not high, as expected. Then, as shown in Figures 17 and 18, only 2 (5%) answered 'disagree' to the fourth question and 8 (19%) answered 'disagree' to the fifth question. This indicates that the experience is very effective even if, after the experience, it is obviously worth stimulating a discussion related to other cases where control systems are relevant.

6. CONCLUSIONS

In this paper we have presented an educational activity devised for high school students in order to make them aware of the role of control systems and, in addition, of the need to integrate mechanics, electronics, computer

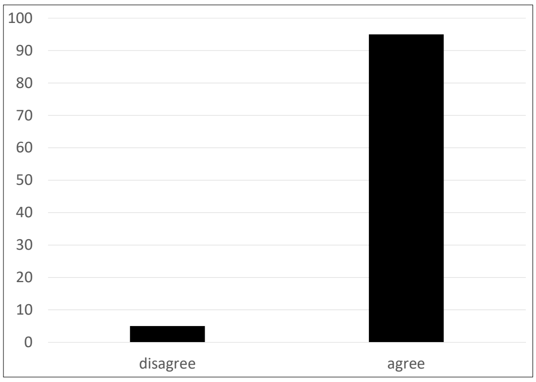

Fig. 15. Answers to the second question.

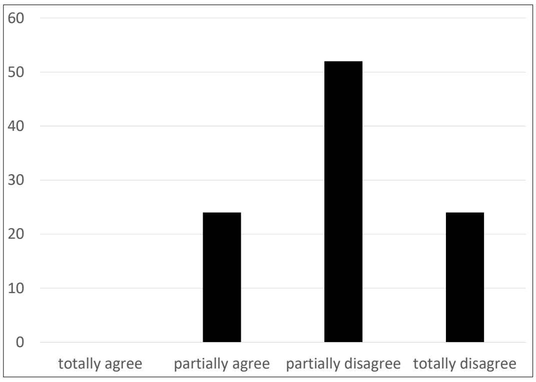

Fig. 16. Answers to the third question.

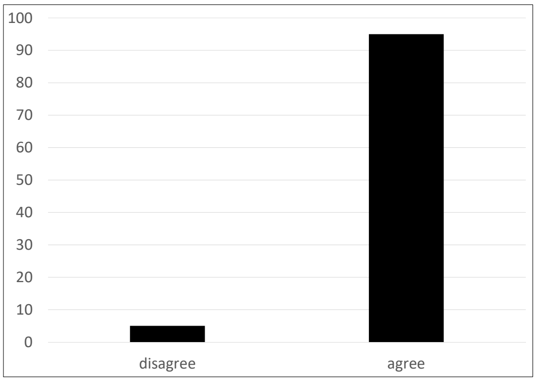

Fig. 17. Answers to the fourth question.

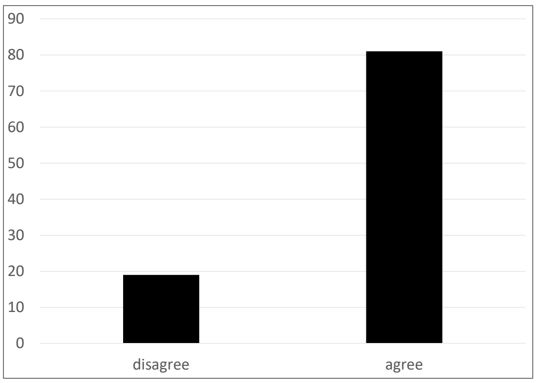

Fig. 18. Answers to the fifth question.

science and automatic control in an automation system. An overhead crane has been employed and a practical experience in trying to control it manually and with a suitable control system has been proposed. In this way students, by means of a hands-on exercise, can get at least a rough idea of the so-called hidden technology and can be attracted to this discipline and to automation engineering in general.

ACKNOWLEDGEMENTS

Authors thank Domenico Facchinetti and Alberto Saleri for their help with the experimental setup. The contribution of B&R Automation in providing the drive system is also acknowledged.

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