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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

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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:

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

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

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

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

$$x_p = x + l\theta. \tag{3}$$

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

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

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.

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

where

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

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

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

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:

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