DIGITAL TWINS OF ROTARY MOTION AND CART-PENDULUM PLATFORMS FOR EDUCATION IN AUTOMATIC CONTROL

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Abstract

Modern educational systems, similarly to Industry 4.0, are focusing their efforts to the development of new digital resources that allow to understand, simulate, predict, and optimize real systems through virtual replicas. In this sense, digital twins (DTs), which are high-fidelity virtual or digital representations of a physical product or process, are turning into a disruptive trend in the education sector and its influence is expected to be significant on future of many degrees, especially in engineering. This paper presents the DTs of three educational platforms which are widely used in automatic control for educative purposes: rotary motion equipment developed by Quanser, and a cart-pendulum platform developed by Feedback Instruments. The DTs have been built in the MATLAB®/Simulink© environment thanks to the physical modeling toolbox Simscape™ through blocks contained in its libraries rather than using mathematical models. A set of possible control exercises that can be performed by students of automatic control courses are proposed, which are supported by the use of these educative resources.

Keywords: Digital twin, simulator, laboratory, automatic control, Simulink.

1   INTRODUCTION

Nowadays, engineering education is focusing in the search for attractive ways of acquiring practical skills using technological resources, connecting theoretical and practical concepts in a simple way. In this sense, the virtualization of teaching, mainly in the laboratory, is currently a reality thanks to virtual laboratories (VLs) [4], since they allow cost savings as well as a better use of time in the laboratory. Particularly, a new digital resource to be applied in education is digital twins (DTs), which are commonly described as high-fidelity virtual or digital representations of a physical product or process to understand, simulate, predict, and optimize such a reality [5, 8]. As opposed to traditional VLs, DTs allow much more realistic and accurate simulations of the real system through real-time 3D models that mimic the system behavior, including the connection with the physical reality and interchange of data with it.

In respect with the types of DTs that can be found, different classifications have been proposed (refer to [5, 8] and references therein). Highlighting the classification in terms of the level of development, three types of DTs are distinguised: 1) digital models at the first level, with no automated data exchange between the physical entity and its digital counterpart; 2) digital shadows secondly, with one-way data flow; and 3) DTs at the highest level, with full and bidirectional data exchange between both entities [5].

Despite of their benefits at industry as an essential technology within digital transformation in the era of Industry 4.0, the use of this type of resource in education is relatively new. Among its advantages are: personalized learning support (each student can use his/her own DT); reduction of maintenance and investment costs; display of system performance and state in real time and at each student's computer; increase of safety (for both the students and the real system); and inspection and/or prediction of potential changes in system operation, which will allow to design preventive strategies to reduce costs and protect the system.

Given this background, the final objective of this work is to develop DTs of real equipment to support teaching in automatic control in the laboratory in engineering degrees. The DTs are built through the toolbox Simscape™ from the MATLAB®/Simulink© software package. In this regard, this paper introduces the first steps to build the DTs of both a rotary motion platform (integrating functionalities of two equipment manufactured by Quanser, namely the Qube-Servo and the Rotary Flexible Link) and a cart-pendulum platform, the model 33-935 Digital Pendulum by Feedback Instruments. Also, some examples of activities that can be performed by students using the DTs are proposed, ranging from system modeling to velocity and position control.
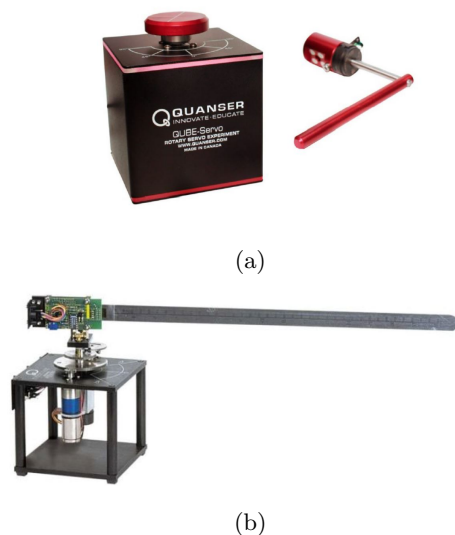
(a)

(b)

Figure 1: Rotary motion platforms manufactured by Quanser: (a) Qube-Servo (b) Rotary Flexible Link.

The remainder of the paper is organized as follows. Sections 2 and 3 contain the description of the real platforms and their DTs, respectively. Section 4 offers possible control problems to be solved by students using the DTs of the rotary motion platform and the cart-pendulum. Finally, conclusions of this work are drawn in Section 5.

2 REAL PLATFORMS

This section devotes to the description of the real platforms in which the DTs developed in this work are based. Firstly, the rotary motion platform is described, followed by the cart-pendulum one.

2.1 ROTARY MOTION PLATFORM: QUBE-SERVO AND ROTARY FLEXIBLE LINK

The rotary motion platform includes the functionalities of two equipment manufactured by Quanser, namely the Qube-Servo and the Rotary Flexible Link [2].

The Qube-Servo (see Fig. 1(a)) is composed of a base and two interchangeable modules, i.e. an inertial disk and a pendulum with an encoder. The base includes a high-quality direct-drive brushed DC motor and the electronics for its control: two encoders, an internal data acquisition system, pulse-width modulation (PWM) amplifier, and led indicators. The platform is provided with a USB port to be connected to a computer. The Rotary Flexible Link (see Fig. 1(b)) consists of a rotary servomotor (at the platform base) and a stainless steel flexible link, coupled to
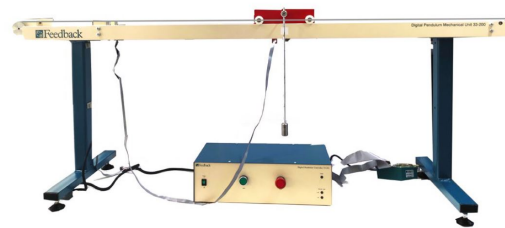

Figure 2: Picture of the laboratory platform of the 33-935 Digital Pendulum by Feedback Instruments Ltd.

its shaft to rotate in a horizontal plane, with a strain gage that detects the deflection of the link tip. This platform is ideal for studying concepts related to control of vibration and resonance of lightweight flexible structures.

2.2 CART-PENDULUM PLATFORM

The inverted pendulum system is a common example found in control system textbooks and research literature. Its popularity derives, in part, from the fact that it is unstable without control. Furthermore, the system has nonlinear dynamics. The appearance of the laboratory platform is shown in Fig. 2, which is constituted by the beam-cart system, incremental encoders, and a digital box (which interfaces the system and the computer) [3]. The beam-cart system, which is based on the Digital Pendulum (model 33-935) by Feedback Instruments, is formed by an aluminum beam mounted on a cart, which can swing in the vertical plane due to the rotary joint attached to the cart. The latter is driven by a DC motor along a rail of limited length. At the ends of the rails there are two limit switches that turn off the DC motor when the cart overruns the limit points to prevent the car from leaving the rail. The incremental encoders measure both the position of the cart and the pendulum angle. The digital box, which interfaces the system and the computer, contains the power amplifier, the main power switch and the DC motor power switch. This box is connected to a computer by means of an Advantech PCI1711 data acquisition board.

3 DIGITAL TWINS

The DTs have been developed in Simulink$^{©}$ through the physical modelling toolbox named Simscape$^{™}$. It uses a physical network approach to model building. Components corresponding to physical elements of the system are joined by lines that refer to the physical connections. Thus, this tool allows for system modeling from its physical composition, rather than using mathematical
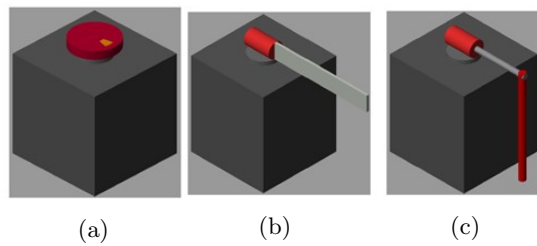
Figure 3: Appearance of the DT of Quanser rotary motion platforms with different modules: (a) inertial disk (b) rigid/flexible arm (c) pendulum.

Figure 4: Appearance of the DT of the 33-935 Digital Pendulum by Feedback Instruments Ltd.

expressions, by connecting blocks of different domains, such as mechanical, electrical, thermal, and hydraulic. It also provides a 3D visualization of the system as long as a computer-aided design (CAD) model is assigned to each of the system components. More details of Simscape™ can be found in [9].

It is important to remark that MATLAB®/Simulink© is widely used in automatic control courses for simulation purposes, and the students are already familiar with it. Consequently, building the DT under MATLAB®/Simulink© is beneficial for two main reasons: firstly, the students can design controllers in a known simulation environment, Simulink© in this case; and secondly, they can apply the designed controllers to both the DT and the real platform with no changes in the implementation of the controllers.

The appearance of the DTs can be seen in Fig. 3 and 4. Note that, in the case of the rotary motion platform, it has been given the appearance of the Qube-Servo regardless of which module is chosen.

In the following subsections, a brief explanation of the construction of the DTs is included, although the complete description can be found in [6, 10].
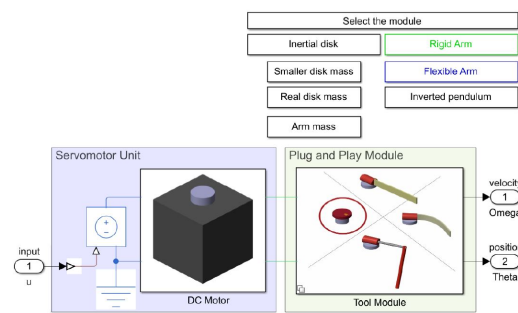

Figure 5: Block diagram of the DT of the rotary motion platform, developed in Simscape™.

3.1 DIGITAL TWIN OF THE ROTARY MOTION PLATFORM

The DT of the rotary motion platform includes the same elements as the real platform, i.e. the DC motor and the modules (inertial disk, rigid arm, flexible arm, and inverted pendulum), as shown in the block diagram of Fig. 5. As can be seen at the top right of this figure, the DT has a graphical interface that allows to select between the different modules. Likewise, its input is the voltage to be applied to the servomotor unit, whereas its outputs are the angular velocity and position of the selected module. The system will need a controller block to generate the motor voltage required for the desired movement; this controller will be designed by the students depending on the problem to be solved and will be connected to the other two blocks by means of a classical unity feedback loop.

The DC motor in the "Servomotor Unit" block from Fig. 5 is modeled based on its electrical circuit. The electrical part includes the resistance and the inductance of the motor, as well as a controlled voltage source. A rotational electromechanical converter transforms the voltage generated by the electrical circuit into mechanical energy. The mechanical part also includes an inertial block that represents an ideal mechanical rotation inertia, and a rotational viscous friction.

As for the "Plug and Play Module", different modules can be selected:

- Inertial disk: it is coupled to the motor shaft by means of a revolute joint, and its mass can be selected within a range of three options: small, medium and high. The output of this module is the rotational speed of the disk, $\omega(t)$, in rad/s.

- Rigid and flexible arms: they are composed of a bar and a revolute joint, distinguishing two ways of modelling the bar depending on the

type of the arm: the bar is a rigid solid in the case of a rigid arm, and the flexible arm contains a group of small rigid solids connected in series with spring-damper elements. An encoder is included in both cases to measure the rotation angle of the bar, $\theta(t)$ in rad, and the angular velocity, $\omega(t)$ in rad/s. Likewise, the model incorporates another sensor so as to be able to measure the deflection of the arm end.

- Pendulum arm: it consists of a rigid arm coupled to the motor shaft through a revolute joint and a bar that can rotate (the pendulum). Two encoders are included in this module to measure the rotation angle of the arm, $\theta(t)$, and the angle of the pendulum, $\alpha(t)$, both in rad. Also, the angular velocities are measured, i.e. $\omega(t) = \dot{\theta}(t)$ and $\dot{\alpha}(t)$, in rad/s.

3.2   DIGITAL TWIN OF THE CART-PENDULUM PLATFORM

The DT contains all the elements of the cart-pendulum system described, namely the cart motor, the base, the cart, and the pendulum, with the exception of the digital box. The block diagram of the DT is shown in Fig. 6. As can be observed, it consists of a block that models the cart motor connected to the cart-pendulum itself (i.e. the base, the cart, and the pendulum); each of these blocks are built from elements of the electromechanical and mechanical domains of Simscape™. The system input is the voltage to be applied to the motor, whereas the outputs are the angle of the pendulum and the position of the cart. As in the previous DT, the system will need a controller block to generate the motor voltage required; this controller will be designed by the students depending on the problem to be solved, as will be shown later on.

The cart motor block from Fig. 6 is modeled in the same way as for the DT of the rotary motion platform. An electromechanical converter transforms the energy of the electrical circuit, composed of the resistance and inductance of the motor, to mechanical energy. The mechanical part also has an
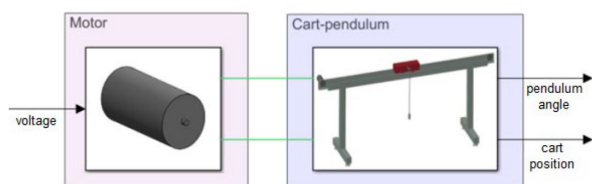
inertial block and a rotational viscous friction.

The cart-pendulum block includes purely mechanical blocks: it contains the motion transmission from the motor to the cart and the models of the cart, base and pendulum. The motion transmission is modeled as a pulley that transforms the rotational output of the motor into a linear movement and conveys it to the cart. The electrical signals from the motor block are converted to multibody signals, in order to carry out the connection of the rest of the elements. The platform base, the cart and the pendulum are modeled from Simscape™ Multibody library as rigid solids with joints between them to enable their movement in the 3D animation.

4   CONTROL COURSEWARE USING DIGITAL RESOURCES

A wide variety of control theory problems can be carried out by both the rotary motion and the cart-pendulum platforms, including modeling and control problems.

With regard to the rotary motion platform, possible control problems and their details can be found in the student workbooks from Quanser [7]. Here, the main topics have been depicted:

- Modeling of system dynamics.

- Design of several kinds of control applied to the inertial disk (velocity and position control in the context of both classical and modern control theory, optimal control, friction identification, and robust control by after adding load disturbances).

- Balance control, swing-up control, and optimal control of the pendulum.

- Modeling of flexible link stiffness and control of the position of the servo while minimizing the deflection of the link end.

Concerning the pendulum-cart platform, it also offers a wide variety of problems of control theory, ranging from modeling to control. Its purpose is to apply a sequence of forces of constrained magnitude to the cart, such that the beam starts to swing. Within the course Automatic Control, the most appropriate problems are:

- System modeling, through ordinary differential equations, transfer functions and/or state space.

- Position control of the cart, with or without the pendulum (considered as a disturbance).

Figure 6: Block diagram of the DT of the cart-pendulum platform, developed in Simscape™.

- Crane control, meaning the cart steering from point to point with minimum oscillation of the pendulum.

- Stabilization control of the pendulum at upright position starting from positions close to it.

- Inverted pendulum control, starting from the downright position (stable equilibrium position) and swinging up the pendulum by acting the cart to the vicinity of the upright position, stabilizing it at that position.

In the following subsections, several activities which can be carried out by the students using the DTs are introduced and solved. Only some of the above-mentioned experiments are carried out, specifically the first two problems of the rotary motion platform and the position control of the cart in the cart-pendulum platform. Also, the results of the identified models and those of the DTs are compared. The purpose of the following subsections is not to design the best control strategy, but showing an example on how to use the DTs.

4.1 IDENTIFICATION OF THE MODULES DYNAMICS OF THE ROTARY MOTION PLATFORM

Firstly, the identification of the selected module dynamics is addressed, in order to determine a mathematical model in the form of a transfer function and later design a controller for the desired motion. Particularly, the identification of the inertial disk and the rigid arm modules are carried out.

4.1.1 Inertial disk

The inertial disk rotates at the same time as the servomotor at the base of the platform, so the objective of this activity is to identify the transfer function that characterizes the servomotor for velocity in order to control its velocity of rotation, considering different masses of the disk.

Activity 1: The Quanser platform is a direct-drive rotary servo system with different modules. Its motor armature circuit schematic is shown in Fig. 7. For this exercise, an inertial disk, with a mass m, is connected to the DC motor shaft as motor load. The modeling of the DC motor should be addressed applying Kirchhoff's voltage law to the motor circuit, considering the motor shaft equation and the applied torque to be proportional to the current of the motor (the complete mathematical development is not included here, it can be found in [10]).
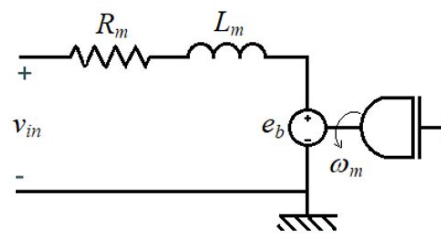

Figure 7: Schematic of the motor armature circuit of the Quanser rotary motion platform with the load (inertial disk).

Given the previous context, the objective of this activity is to determine a model, in the form of transfer function, that describes the system dynamics for velocity.

Solution: By the application of the Laplace transform for zero initial conditions, one can obtain the following:

$$V_{in}(s) = \left(R_m \frac{J_m}{k_t} s + k_m \right) \Omega_m(s) \qquad (1)$$

where $V_{in}(s)$ is the voltage applied to the motor, R_m is the resistance of the motor, J_m the total moment of inertia acting on the motor shaft, k_t the torque constant, k_m the back-emf constant of the motor, and $\Omega(s)$ is the speed of the motor shaft.

The model of a velocity servomotor is given by the following first order transfer function:

$$G_v(s) = \frac{\Omega_m(s)}{V_{in}(s)} = \frac{K}{\tau s + 1} \qquad (2)$$

where K and τ are the gain and the time constant of the system, to be determined, which depend on the motor parameters.

For identification purposes, the unit step response in open-loop of the system is obtained and shown in Fig. 8(a), from which the identification can be carried out measuring the value that the output of the system takes at steady state (y_{ss}) and time at which the output reaches 63% of y_{ss}. Thus, the system parameters are determined as follows: $K = y_{ss}/V_{in} = 23.5$ and $\tau = t(0.63y_{ss}) \approx 0.07$. Note that this procedure can be repeated for each value of the inertial disk mass.

4.1.2 Rigid arm

Activity 2: Taking into account the background given in *Activity 1*, the objective of this activity is to determine a model, in the form of transfer function, that describes the system dynamics for position.

Solution: The system voltage-to-position transfer function can be deduced from (2) since velocity is

the first order derivative of position, i.e. $\omega_m(t) = \dot{\theta}_m(t)$, so the transfer function is given by:

$$G_p(s) = \frac{\Theta_m(s)}{V_{in}(s)} = \frac{K}{s(\tau s + 1)} \quad (3)$$

where K and τ are the gain and the time constant of the system, to be determined, which depend on the motor parameters (notice that these values have to be similar to those obtained for velocity). In this case, identification must be carried out by means of a scheme in closed-loop, since system (3) has a pole at origin. Then, the transfer function of the system in closed-loop can be written as:

$$F_{cl}(s) = \frac{G_p(s)}{1 + G_p(s)} = \frac{K/\tau}{s^2 + s/\tau + K/\tau} \quad (4)$$

Once the unit step response is obtained (plotted in Fig. 8(b)), overshoot (M_p) and peak time (t_p) can be measured, resulting $M_p = 25\%$ and $t_p = 0.18$ s, which correspond to a classical second order system with damping ratio of $\delta = 0.404$ and a natural frequency of $\omega_n = 19.077$ rad/s. These parameters are compared with those of (4), so the system parameters can be calculated as follows: $\tau = 1/(2\delta\omega_n) = 0.065$ and $K = \omega_n/(2\delta) = 23.627$. As it can be seen, these results are similar to the obtained in *Activity 1*.
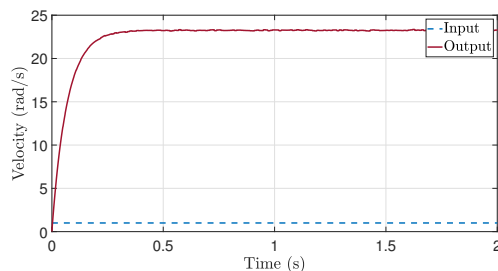
(a)
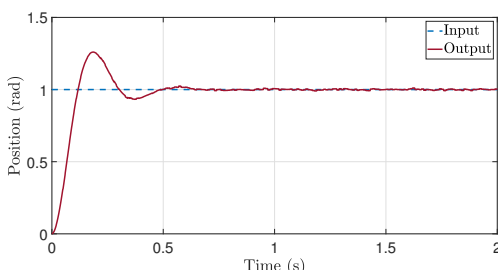
(b)

Figure 8: Unit step response for the identification of: (a) velocity servomotor dynamics (b) position servomotor dynamics.

4.2 VELOCITY CONTROL OF THE INERTIAL DISK MODULE

Activity 3: Taking into account the model obtained in *Activity 1* for the inertial disk module, design a control strategy that maintains the rotation velocity of the disk to a desired value with the following design specifications: null steady state error ($e_{ss} = 0$), overshoot $M_p = 12.5\%$ and settling time $t_s = 0.4$ s.

Solution: The controller should have an integral term in order to remove the steady state error, as the dynamics of the system is of first order. Then, the simplest controller to fulfill this specification is a proportional-integral (PI), whose transfer function, in parallel form, is given by:

$$C(s) = K_p + \frac{K_i}{s} \quad (5)$$

where K_p and K_i are the proportional and integral gains, respectively. A possible tuning method is by pole placement, which will be applied in this case. By this method, the characteristic equation of the controlled system has to be equal to the desired dynamics, being of second order due to the specifications, i.e. $1 + C(s)G_v(s) = s^2 + 2\delta\omega_n s + \omega_n^2$. By equating coefficients of the polynomials of each side of the equation, the controller parameters can be obtained by the following expressions: $K_p = (2\delta\omega_n\tau - 1)/K$ and $K_i = (\tau\omega_n^2)/K$.

The desired dynamics can be deduced from the specifications, obtaining a damping ratio of $\delta = 0.552$ and a natural frequency of $\omega_n = 18.118$ rad/s. Thus, the controller parameters are $K_p = 0.017$ and $K_i = 0.978$. The results obtained for the controlled system considering a step input are plotted in Fig. 9(a), where it can be observed that the motor reaches the velocity reference at about 0.4 s and the overshoot is about 12.5%, so the design specifications are fulfilled.

4.3 POSITION CONTROL OF THE RIGID ARM MODULE

Activity 4: Considering the model obtained in *Activity 2* for the rigid arm module, design a control strategy that maintains the angle of the arm to a desired value with the following design specifications: overdamped response ($M_p = 0$) with $t_s \leq 1.5$ s.

Solution: In this case, a proportional-derivative (PD) controller is enough to meet the specifications, being its transfer function in standard form:

$$C(s) = K_p(T_d s + 1) \quad (6)$$

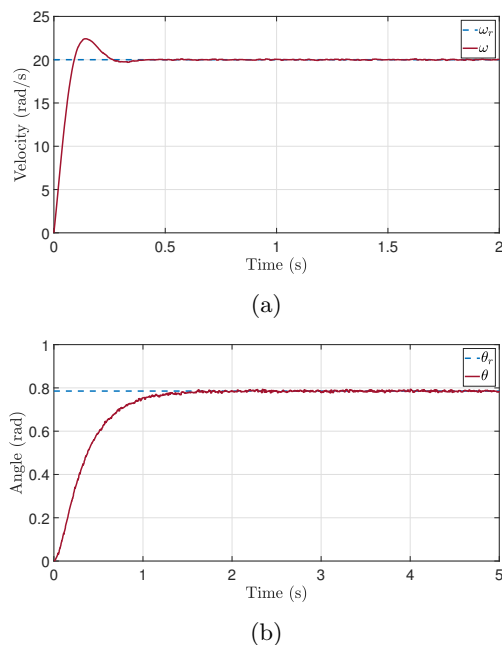where K_p and T_d are the proportional gain and the derivative time constant, respectively. The

(a)

(b)

Figure 9: Controlled system response: (a) velocity control (inertial disk module) (b) position control (rigid arm module).

(a)

(b)

Figure 10: Results of the experiments of the cart: (a) identification (b) position control.

tuning method selected in this activity is lambda tuning, a simple method to obtain an overdamped response [1]. It is based on the cancellation of the system pole by means of the zero of the PD controller. Hence, the derivative time constant can be calculated as $T_d = \tau = 0.065$ while K_p is obtained by comparing the resulting characteristic equation with one of first order with response time equal to the parameter λ as follows: $K_p = 1/(\lambda K) = 0.141$ for $\lambda = 0.3$ (it was chosen to fulfill the design specification of t_s).

The response of the controlled system for a desired position of $\theta_r = \pi/4$ rad is shown in Fig. 9(b). It can be seen that the arm reaches the desired position without exceeding the reference before 1.5 seconds, so the design specifications are also met.

4.4 POSITION CONTROL OF THE CART

This exercise deals with controlling the position of the cart neglecting the pendulum dynamics.

Activity 6: Design a proportional-derivative (PD) controller for the cart position to obtain an overdamped response with a settling time (t_s) less than 10 s.

Solution: At first, the transfer function describing the system dynamics must be identifed, considering the position of the cart as the output and the force applied to the cart as the input. Hence, the transfer function takes the form of a position
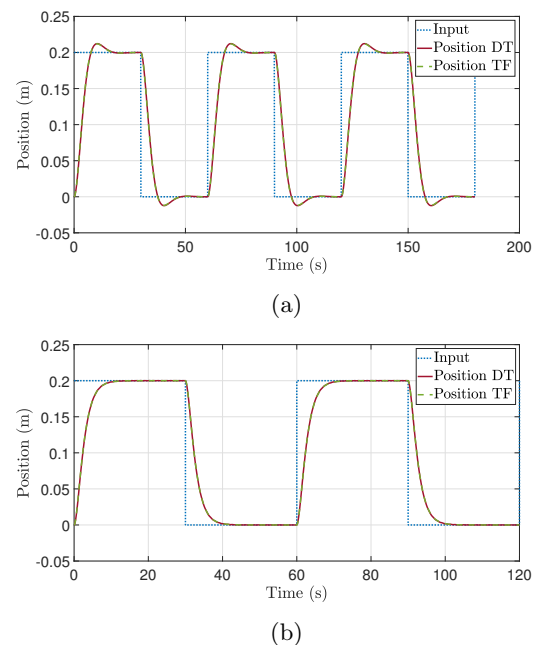
servomotor as:

$$P_{cart}(s) = \frac{X(s)}{F(s)} = \frac{k}{s(\tau s + 1)} \tag{7}$$

where τ and k are the time constant and system gain, respectively, to be determined. For identification, the system has to be excited in a closed-loop, so the transfer function turns out to be similar to (4).

As already seen in *Activity 2*, overshoot (M_p) and peak time (t_p) can be measured from the step response, resulting in $M_p = 6\%$ and $t_p = 10.29$ s, which correspond to a classical second order system with damping ratio of $\delta = 0.667$ and a natural frequency of $\omega_n = 0.41$ rad/s. Comparing the coefficients of the transfer function of a second order system with those of the transfer function in closed-loop, the system parameters are obtained as follows: $\tau = 1/(2\delta\omega_n) = 1.829$ and $k = \omega_n/(2\delta) = 0.307$. The responses of the DT and the identified model (named as TF) to a square input are shown in Fig. 10(a), observing that both responses match, which validates the model.

In order to meet the specifications, a PD controller can be designed, which is described by:

$$C(s) = K_p(T_d s + 1) \tag{8}$$

being K_p and T_d the proportional gain and the derivative time constant, respectively. As seen in *Activity 4*, lambda tuning is a simple method to

obtain overdamped response, which is also the objective in this case. Applying this method, the parameters of the controller are: $T_d = \tau = 1.829$ and $K_p = 1/(\lambda k) = 3.26$ for $\lambda = 1$ (it was chosen to fulfill the design specification of t_s). The response of the controlled system of both the DT and the model is plotted in Fig. 10(b). As of the results, the design specifications for the controlled system are met (response with no overshoot and $t_s = 9.5$ s) and, again, there are no differences between the response of the DT and the model.

5 CONCLUSIONS

This paper has presented two digital twins (DTs) of both a rotary motion platform (integrating functionalities of two equipment manufactured by Quanser, namely the Qube-Servo and the Rotary Flexible Link) and a cart-pendulum platform, the model 33-935 Digital Pendulum by Feedback Instruments. DTs are digital replicas of a physical entity that are able to mimic the system behavior, and allow to perform several kinds of problems within the context of control theory for engineering degrees. The DTs were developed in MATLAB®/Simulink© environment by means of the toolbox Simscape™. The descriptions of both platforms together with their DTs were given, including some examples of activities that can be performed by students using the DTs, which range from system modeling to velocity and position control.

Acknowledgement

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