

Virtual and Remote Laboratory with the Ball and Plate System

Ernesto Fabregas* Sebastián Dormido-Canto*
Sebastián Dormido*

* *Universidad Nacional de Educación a Distancia (UNED), Juan del Rosal, 16, 28040, Madrid, Spain. (e-mail: efabregas@bec.uned.es).*

Abstract: This paper presents a virtual and remote laboratory of the ball and plate system with augmented reality. The ball and plate is a non-linear, multi-variable and open-loop unstable system. Due to its inherent complexity, presents challenging problems, such as: 1) *point stabilization control*, to carry the ball to a specific position and hold it there, and 2) *trajectory tracking control*, in which the goal is to make the ball follows a predefined geometric trajectory (*square* and *circle*) minimizing the tracking error. The laboratory is composed by two parts: 1) a virtual laboratory developed in Easy Java Simulations (EJS), which is a 3D interactive simulation of the system; 2) a remote laboratory (developed with EJS and LabVIEW) to connect via Internet to a pilot plant of the system, situated in the laboratory. This laboratory is used in the Systems and Control Engineering Master Program offered by Universidad Nacional de Educación a Distancia and Universidad Complutense de Madrid.

Keywords: Ball and Plate Control System, Virtual Lab, Remote Lab

1. INTRODUCTION

In recent years, with the development of new technologies, technical universities around the world have modified their curricula to adapt them to this environment. In this context, Virtual and Remote Laboratories have experienced a growing integration in higher education in technical engineering areas using the web in the teaching-learning process Dormido (2004). It is due to the huge profits that these experiences provide to distance learning on the acquisition of practical skills through the network using simulations and pilot plants of real experiments (Diwakar et al. (2012); Rico et al. (2012); Raman et al. (2013); Fabregas (2013)).

In this work, a virtual and remote laboratory has been developed based on the ball and plate control system. This system, well-known in the control engineering educational context, consists of a ball that is free to roll without slipping on a rigid plate. The main objective of this system is to control the position of the ball by manipulating the inclination angles of the plate. The ball and plate system is considered as an extension in two dimensions of the ball and beam system (Amjad et al. (2010); Yuanyuan and Yongxin (2015)). This system is also very rich from the dynamics point of view and can be used for various experiments, for example (Nokhbeh and Khashabi (2011)):

- The position control of the ball in a point on the plate.
- Movement of the ball to a particular position via a specific geometric trajectory.
- Traveling of the ball to a certain point under local limitation of rotation in a certain direction.
- Application and research of image processing algorithms.

- Research of PID controller and other classical control methods.
- Research of self-defined control algorithms.

An important point in this laboratory is the design of the controllers (one for each axis of the position of the ball (x,y) - tilt angle of the plate (α, β)). In this case, the provided controllers for the system are the simplest solution (Proportional-Derivative controller). From this feedback loop, student will design the controllers with different strategies as the main objective of the laboratory practice, for example: Robust Control (Rikhtehgar and Jafari (2012)), Fuzzy Logic (Lian-kui et al. (2013)), Genetic Algorithm (Dong et al. (2009)).

This work describes the development of a virtual and remote laboratory of the ball and plate system. The laboratory is composed by two parts: 1) a virtual laboratory developed in Easy Java Simulations (EJS) (Christian et al. (2011)), which is a 3D interactive simulation of the system; 2) a remote laboratory (developed with EJS and LabVIEW) to connect via Internet to a pilot plant of the system, situated in the laboratory. The interface to ensure the communication between EJS and LabVIEW is made using JIL Server (Chacón et al. (2015)). This software tool has been developed in the Departamento de Informática y Automática of the Universidad Nacional de Educación a Distancia of Spain. Besides, to improve the visualization of the results of the experiments, augmented reality has been used in the GUI of the platform.

The remainder of this paper is organized as follows: Section 2 presents the contents related to the ball and plate system and the position control of the ball. Section 3 describes the architecture of the virtual and remote laboratory. Section

4 shows the results of the experiments with the laboratory. Finally, conclusions are summarized in Section 5.

2. THE BALL AND PLATE CASE STUDY

This section describes the mathematical model and control strategy of the ball and plate system.

2.1 Ball and Plate System Model and Features

The ball and plate system is one of the most enduringly popular and important laboratory model for teaching control system engineering Awtar et al. (2002). This is a non-linear, multivariable and open-loop unstable system. Due to its inherent complexity, presents a challenging problem. The main objective of this system is to control the position of the ball on the plate by changing the inclination angles of the plate. The model of this system can be obtained taking into account some considerations:

- The ball is a symmetric and homogeneous sphere.
- The ball is always in contact with the plate.
- The ball can roll on the plate without slip.
- The plate is rigid and homogeneous.
- All frictions are neglected.

Figure 1 shows a representation of the system with the involved variables.

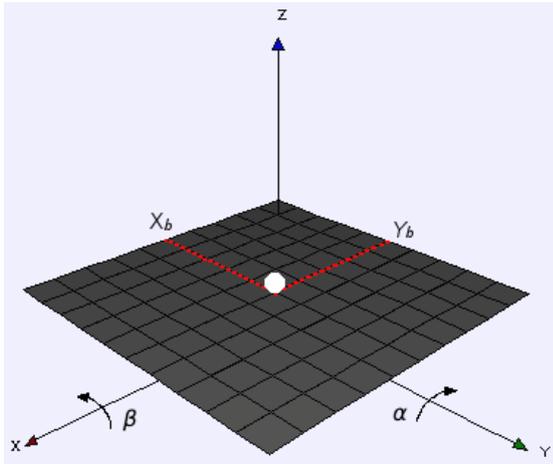


Fig. 1. Ball and Plate System scheme.

The model of the system can be obtained using the variables as generalized coordinates of the *Euler-Lagrange* equations. Equations 1 and 2 describe the dynamic of the system after some transformations Bai et al. (2005); Hongrui et al. (2008).

$$\left(m_b + \frac{I_b}{r_b^2}\right) \ddot{x}_b - m_b (x_b \dot{\alpha}^2 + y_b \dot{\alpha} \dot{\beta}) + m_b g \sin \alpha = 0 \quad (1)$$

$$\left(m_b + \frac{I_b}{r_b^2}\right) \ddot{y}_b - m_b (y_b \dot{\beta}^2 + x_b \dot{\alpha} \dot{\beta}) + m_b g \sin \beta = 0 \quad (2)$$

These equations represent the relation between the ball acceleration and the tilt angular velocity of the plate. The variables that describes the model are the following Yuan and Zhang (2010):

- Mass of ball, m_b .

- Radius of ball, r_b .
- Inertia of the ball about its own center, I_b .
- Position of the ball with respect to the plate (x_b, y_b) .
- Plate inclination angles, α and β .
- The gravity, g .

Some simplifications can be made in the equations of the system in order to implement some experiments (for small angle of inclination of the plate, up to $\pm 5^\circ$): $\alpha \ll 0$, $\beta \ll 0 \implies \sin \alpha \simeq \alpha$ and $\sin \beta \simeq \beta$; $\dot{\alpha} \ll 0$ and $\dot{\beta} \ll 0 \implies \dot{\alpha} \dot{\beta} \simeq 0$, $\dot{\alpha}^2 \simeq 0$, $\dot{\beta}^2 \simeq 0$. After these simplifications the linearized equations of the system can be rewritten as follow Rekdalsbakken (2007); Nokhbeh and Khashabi (2011):

$$\frac{5}{7} \ddot{x}_b + g\alpha = 0 \quad (3)$$

$$\frac{5}{7} \ddot{y}_b + g\beta = 0 \quad (4)$$

The transfer functions of the system can be obtained taking $\alpha(s)$ and $\beta(s)$ as inputs and (x_b, y_b) as outputs. The resulting equations for each axis are the following:

$$U_x(s) = \frac{x_b(s)}{\alpha(s)} = \frac{g}{\frac{5}{7}s^2} \quad (5)$$

$$U_y(s) = \frac{y_b(s)}{\beta(s)} = \frac{g}{\frac{5}{7}s^2} \quad (6)$$

2.2 Position control of the ball

As was mentioned before, the ball and plate system can be considered as a two dimensions extension of the ball and beam system. In the ball and beam system the ball is restricted to one dimensional movement, which is along the beam only and the beam inclination can be manipulated in one direction Chang et al. (2013). While in the ball and plate system, the ball can roll following different paths and the inclination of the plate can be manipulated in two perpendicular directions.

The main goal is to carry the ball by moving on the plate to a desired position. In more precise way, two main tasks can be carried out: a) to carry the ball from a specific position and hold it in the desired position; b) trajectory tracking control in which the goal is to make the ball follows a predefined geometric path with the least error and the minimum time.

From Equations 5 and 6, x_b is dependent on α , while y_b is dependent on β . In this sense, the system can be treated as two different systems operating simultaneously. Hence, similar but independent controllers can be used for controlling each coordinate of the ball motion.

In the literature the design of the controllers can be carried out in different ways. Only a Proportional (P) controller leads to oscillatory behavior that can be compensated with Derivative (D) action. Therefore, a Proportional Derivative (PD) controller is used for each axis. Figure 2 shows the block diagram of the position control of the ball.

As it can be seen, two feedback control loops (one for each coordinate of the position of the ball). Where the parallel PD controllers have the following form:

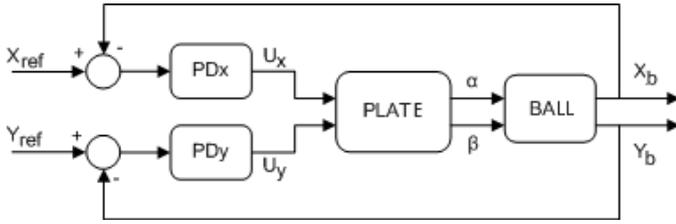


Fig. 2. Position control of the ball strategy block diagram.

$$U_{x,y}(t) = K_p e_{x,y}(t) + K_d \frac{de_{x,y}(t)}{dt} \quad (7)$$

Where the error signal $e(t)$ is the difference between the desired ball position and the real one for each coordinate axis. To adjust the parameters of the PD controllers the Matlab FR-Toolbox (Keyser and Ionescu (2006)) was used. Students will use these parameters as reference to compare their controllers design results Liao et al. (2008).

3. THE VIRTUAL AND REMOTE LABORATORY

The structure of the laboratory is based in a client server architecture (Neamtu et al. (2011); Duro et al. (2008)). Where the client side is a java applet developed in EJS and embedded in a web page. This application allows two main tasks: 1) 3D interactive simulation of the system (Virtual Laboratory); 2) remote access to the real plant situated in the university (Remote Laboratory). Figure 3 shows the architecture of the platform which is based on (Vargas et al. (2008)).

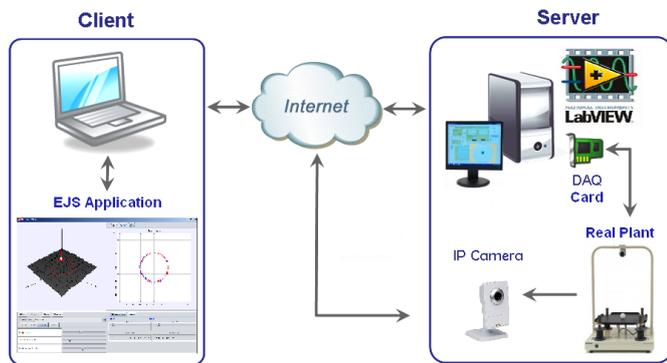


Fig. 3. Platform architecture.

3.1 Virtual Laboratory

The Virtual Laboratory is based on the work presented by the authors in Fabregas et al. (2015). The GUI (Figure 4) of the application has been designed following what has become a *de-facto* standard in author's virtual laboratories: on the left side, a visual representation of the system state with the animated 3D model associated to the system.

The simulation can be controlled with a set of buttons which are located under the animation, to play continuously or run step by step, pause a running simulation, and reset the system to the initial state.

The trajectory can be selected from the drop-down list (square, circle, line), if the selected experiment is a trajectory tracking. The parameters of each trajectory can

be modified in the tabbed panel situated down the drop-down list. The experiments and their parameters are listed below:

- Point: target position of the ball (x and y coordinates).
- Square: size of the side of the square.
- Circular: radius of the circle (x and y axes), an ellipse can be painted.

On the right side, there are three plot views showing different variables of interest. The first one shows the evolution in time of the ball position in the x axis (a controlled variable) and the plate angle θ_x (a manipulated variable). The second one is the same, corresponding to the y coordinate. These views allow to independently study the control loop associated to each axis, and the third plot is the projection of the ball position on the horizontal plane, to see its trajectory.

Under the plots, there are sliders that allow to modify the values of the parameters of each PD controller for both coordinate axes of the plate. Besides, there is a text editor where students can write Matlab code to be executed periodically. In this way, the student can propose a different controller. The values of the plant state are accessible within the code and the control updates input can be assigned again to the plant inputs, thus closing the control loop.

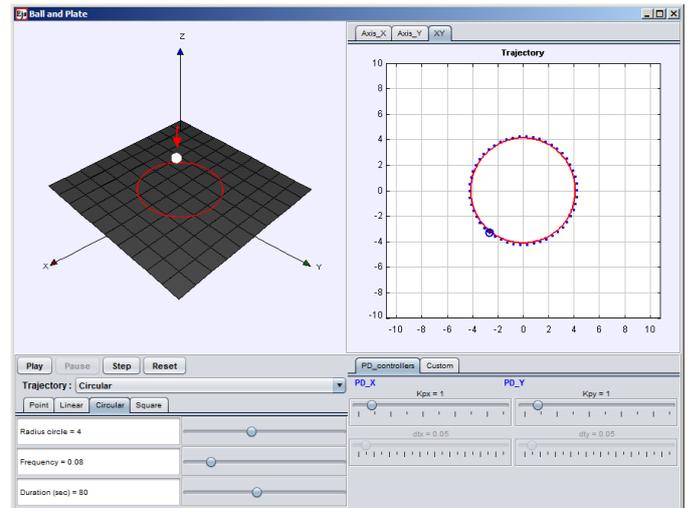


Fig. 4. Graphic User Interface of the virtual application.

3.2 Remote Laboratory

On the server side, a PC is connected to the pilot plant using a DAQ card (from National Instruments) via PCI port. The pilot plant is titled Ball and Plate Control System 33-052 (Feedback Instruments (2016)) from Feedback Instruments and its main components are: (see Figure 5):

- (1) A rigid plastic square plate.
- (2) A plastic solid sphere.
- (3) An USB camera: to obtain the position of the ball by image processing.
- (4) 4 electromagnetic actuators (on each corner of the plate): to manipulate the tilt angle of the plate on both axes.

- (5) 2 potentiometers (situated on the back side of the plate): to measure the tilt angle on each axis.
- (6) A LabVIEW control application: running at the local PC.
- (7) An integrated power supply.

Interactions with the real plant via Internet are carried out by the JIL Server (Chacón et al. (2015); Fabregas et al. (2009)). JIL Server is installed and running at the PC that control the plant, and it is the interface between the Java applet and the LabVIEW control application.

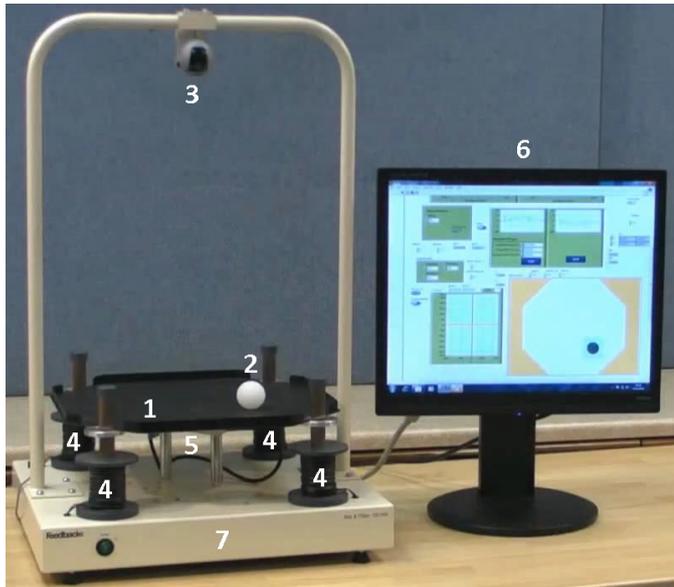


Fig. 5. Ball and plate pilot plant.

The communications are bidirectional to send and receive data of the experiments in remote mode:

- From the client to the server: the values of the controllers, the reference and the current selected experiment.
- From the server to the client: the values of the ball position and the tilt of the plate.

In remote mode, the client application shows the video streaming of an IP camera situated in the laboratory. Through these images the students can see what is happening with the pilot plant during the experiments.

To improve the visualization and help to understand the results of the experiments, at the client side, augmented reality has been used. This has been possible through to an element of EJS developed in our department. This software component is incorporated in EJS and it is in charge to process the images of the IP camera to locate a known sticker in the image. Using this sticker as fixed reference, the data of the experiment (reference and position of the ball) can be painted over the streaming image, as it will be shown in the next section.

4. RESULTS

This section presents the results obtained with the virtual and remote laboratory for the trajectories tracking experiments. This experience consists in dividing a predefined geometric path in points. These points are stored in a

list. The system receives the points in order as references with an established time interval. This time interval has a critical value to be taken into account. Because the system must be able to run the control loop and reach the steady state before receiving the next point. In our case this time interval can be controlled from the client application. It is interesting to modify this parameter and to observe its effect on the experiment. Depending on this value, the ball can easily follow the path or not.

4.1 Trajectory tracking experiment: Square

The square trajectory experiment has been designed as four sequential point stabilization problems, each one around a vertex of the square. The square trajectory is defined by two main elements: 1) the length of the sides of the square; 2) the frequency of the reference for each vertex changes (time interval). Student can change the size of the square using a slider control available for this experiment. The side of the square must take into account the critical time interval of appearance of the points of the trajectory. For large square side, the frequency of the points must increase. Note that the trajectory can be divided into more points for greater accuracy, but in this case the behavior will be slower.

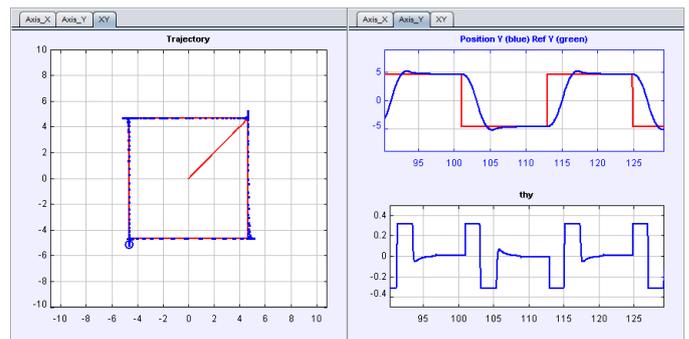


Fig. 6. Square trajectory tracking experiment.

Figure 6 shows the ball tracking the square trajectory in the virtual environment. In the right side the reference and the position of the ball for the Y axe are shown. Also the tilt angle of the plate (control signal) for this axe is depicted. While in the left side, the projection of the ball in the XY plane is shown. In both cases, the reference is depicted in red color and the coordinate of the ball is depicted in blue color. Though there is a small tracking error in the neighborhood of the corners, the overall performance is very good.

Figure 7 shows this experiment in remote mode. As can be seen, from a web browser the student can interact with the real plant situated in the laboratory at the university.

The main panel of the application is the streaming of the IP camera. Using the augmented reality the position of the ball on the plate (green color) and the reference (blue color) are depicted over the video. To do that, the EJS element of augmented reality uses the black sticker that is fixed on the wall of the laboratory.

In the right side of the main panel, at the top the plot shows the reference of the ball (blue color) and its position (green color). Also, the control signal of the tilt angle of

the plate is shown. As can be seen, this signal is very noisy compared to the virtual mode. This is expected, because it is real hardware with corresponding actuators.



Fig. 7. Square trajectory tracking experiment.

Below the main panel the parameters of the controllers and the trajectories can be modified using sliders, like in the virtual mode. Also there are two buttons to start and stop the experiments.

4.2 Trajectory tracking experiment: Circular

Figure 8 shows the results for the case of the circular trajectory experiment in virtual mode. The projection in the XY plane of the position of the ball is shown on the left side panel. On right side panel, the X coordinate of the position of the ball and its corresponding tilt angle of the plate (control signal). As can be seen, the ball follows the trajectory.

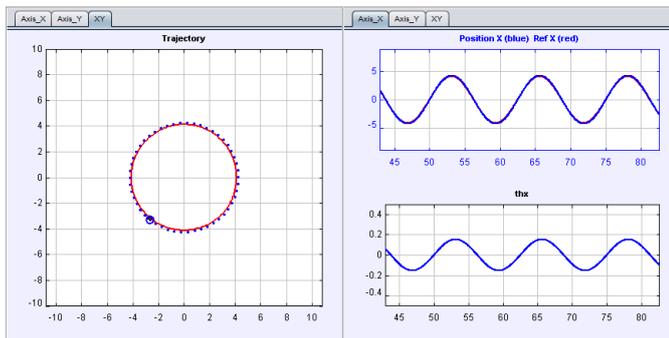


Fig. 8. Circular trajectory tracking experiment.

Like in the previous experiment, the points of the trajectory are dynamically calculated, but in this case, depending of the radius of the circle (which can be changed by the student using a slider control). Like in the previous case, the critical time interval to send the points, must be taken into account. Because the system needs this minimal time to stabilize the ball on each point.

Figure 9 shows this experiment in remote mode. The main panel shows the video streaming of the IP camera with the reference (blue color) and the position of the ball (green color) using the mentioned augmented reality EJS element. On the right side, the plots show the reference (blue color) and the Y coordinate of the position of the ball (green color). Below, the control signal (tilt angle of the plate) in green color. As can be seen, the ball follows the trajectory.



Fig. 9. Circular trajectory tracking experiment.

Below the video streaming there are the controls to manipulate the experiment (buttons start and stop) and the parameters of the trajectory (circle radius, amplitude on each axis, frequency, etc.). Also the parameters of the controllers for each axis can be modified.

5. CONCLUSION

The main contribution of this work is a virtual laboratory and remote laboratory which consist of a 3D simulation and a remote control of the ball and plate system. This system is a popular set-up for teaching control system engineering. Due to its inherent complexity, this lab presents challenging and interesting control problems.

The laboratory may be adjusted for all levels of control engineering education, because it can introduce students to problems of varying levels of complexity. Besides, they can study in deep this kind of systems and understand the objectives of the analyzed process.

The GUI of the platform has a high degree of interactivity and flexibility (due to the properties of EJS), allowing to students perform dynamical experiments in an attractive environment. Furthermore, students get motivated because they can validate the designed controllers and see the results of the experiments on the fly. In this sense the application is considered as a nice tool from a pedagogical point of view.

The results of the experiments presented show the high performance of the application. For the experiments, in

both modes (virtual and remote), with the adequate parameters, the ball follows the reference with high accuracy as expected.

This laboratory is being used in the present, with encouraged results, in the Systems and Control Engineering Master Program offered by the UNED and UCM of Madrid, Spain. Future work will mainly consist of three tasks: a) the implementation of new controllers proposed by students: Robust Control, Fuzzy Logic, Genetic Algorithm; b) let students enter their own trajectories and incorporate these paths to the remote laboratory; and c) to upgrade the Java applet to JavaScript (using EJSs).

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