Development of Nonlinear Dynamics Simulator for 2-DOF Ball Balancing Platform to Assist Distance Learning of Control Systems

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***Abstract*—In a wide range of control applications, balance control systems are known to be one of the most crucial and challenging applications. 2-DOF ball balancing platform is an experimental platform which can perform various kinds of balance control experiments. Hence, this laboratory experiment is widely used in many control engineering courses. But with COVID-19, travel restrictions and social distancing, performing laboratory experiments have become much more challenging. Hence, this research explores the feasibility of performing control engineering experiments on Ball on plate system in a simulation environment for distance learning purposes. This paper represents the control design theory, system modelling & simulations of ball balancing platform and proposes a method of performing lab experiments for remote-learning. All the system modelling and simulations of this research were done using MATLAB Simulink based on the Simscape model developed using SolidWorks.**

***Index Terms*—ball on plate; PID; nonlinear control; MATLAB simulink; simscape simulations; FIR; filtering; distance learning**

I. Introduction

Laboratory experiments can be identified as a key activity during the academic studies as it helps to gain interactive experience in fundamental theories and to understand the implications of extreme parameters. This hands-on laboratory experiments can be a great challenge during these times with remote learning, social distancing and the pandemic. Ball balancing platform on a simulation environment with accurate dynamics and 3D visuals can aid as a media to perform control engineering laboratory tests on a different computer setting. This experimental setup can be accessed by using common remote access software. Thus, allowing students/ researchers to gain an extensive hypothesis about the system prior to the physical implementation. Also, this allows the user to experience the effects and behavior of the system while changing parameters of the system.

In controls engineering, balancing systems are well-known as challenging compared to other systems. Ball balancing platform a.k.a the ball on plate (BOP) system is an improved version of the ball and beam system. This ball balancing platform consists of 2-degrees of freedom and controls in two perpendicular directions, X and Y. This balancing system caused a recognition in classic, modern and nonlinear control studies due to its nonlinear characteristics. This system can be identified as extremely unstable because, a small inclination in the plate in open loop can cause an indefinite movement of the ball.

One of the main objectives of the ball on plate system is to develop a system which is capable of balancing a ball at a pre-desired location on the plate and returning to its stable position when an outside force is applied. By examine the effects of proportional integral derivative (PID) controller parameters of the BOP system, this can be achieved with the least possible error and the smallest settling time. The physical ball on plate system mainly consists components of a touch panel, a ball joint, a ball and actuators driven by servo motors. Though this study was carried out using simulations, all the components were decided prior to increase the accuracy of the study. Hence, TI C2000 Launchpad was selected as the micro-controller due to its performance on nonlinear real-time control. HiTec carbonite gear servo motors were selected to use as the actuators due to its operating speed and torque.

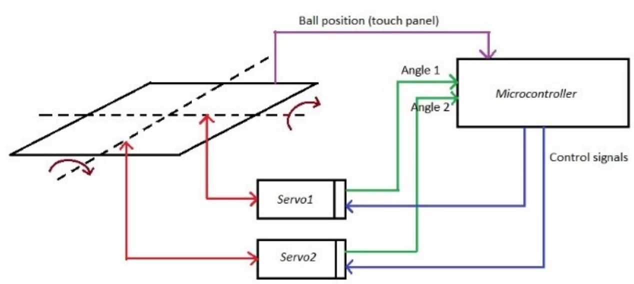

Fig. 1: Physical representation of the BOP system

Deriving the equations of motion of the BOP system helps to identify the behavior of the system. In most previous studies, the second kind Lagrange equations or Euler-Lagrange equations were used when deriving the dynamic motion of equations of the BOP system. These methods are known to be much complicated methods. But derivation of motion equations using the Newtonian second law of motion [1], is much simpler than the above-mentioned methods but very reliable. It only considers the relationship between the inclination angle of plate and the position of the ball while neglecting the friction.

In some studies [2] [3] [4], the position of the ball is obtained using a camera through optical detection. This position of the ball also can be acquired either by laser technology, basic sonar rangefinders, or by using a resistive touch panel [1] [5] [6] [7]. Nonetheless the accuracy is much higher in optical detection, heavy processing is needed for position elimination. Also, using the laser technology for position tracking is much more complex and advance when compared with other methods. Therefore, the position of the ball was tracked using the resistive touch panel method [1] in this study for its positive features.

In previous work, several control techniques have proposed to stabilize the ball and plate system. [8] proposed a cascade control strategy with low order ADRC, while [6] [9] [10] proposed model predictive controller and [11] proposed a fuzzy logic controller. But due to the complexity of these controlling techniques PID control was proposed as it is more accurate and more robust considered to its simplicity.

II. METHODOLOGY

A. Mathematical Model

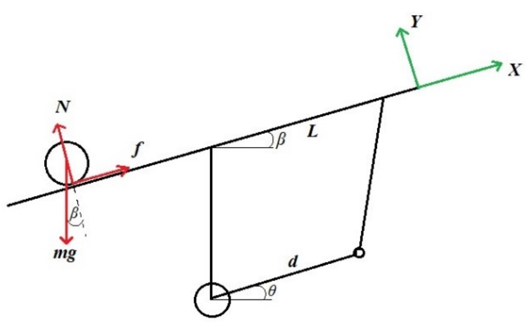

Fig. 2: Free body diagram of the dynamic system

In order to observe the behaviour of the system, mathematical model was developed using Newtonian second law equations. To achieve this, several assumptions were made such as; the ball is perfectly spherical and homogeneous, the ball only rolls and does not slip on the platform, the ball does not have any relative upward translation with the plate, and the friction between the ball and the plate is negligible. In order to simplify the 3-dimensional BOP system, it was separated into two, 2-dimensional ball on beam systems.

Forces that are acting on different parts of the BOP system can be recognized from the free body diagram in Fig. 2.

From system equations;

$$\begin{Bmatrix} F_X = m\ddot{x_G} \\ F_Y = m\ddot{y_G} \\ M_2 = I_G\ddot{\theta} \end{Bmatrix} \tag{1}$$

From above assumptions made,

$$F_Y = 0 \tag{2}$$

By obtaining the system equations separately in each dimension, the forces acting in each direction can be obtained [12]

$$F_x = m\ddot{x_G} \rightarrow -mg\sin\beta + f = m\ddot{x_G} \tag{3}$$

$$F_Y = m\ddot{y_G} \rightarrow N - mg\cos\beta = m\ddot{y_G} \tag{4}$$

$$M_2 = I_G\ddot{\theta} \rightarrow f_r = I_G\ddot{\theta} \tag{5}$$

As there is no acceleration along y axis, eq. (3) in above set of equations can be neglected. From the assumption made earlier, there will be an acceleration along x axis as the ball rolls on the plate.

$$\ddot{X_G} = r\ddot{\theta} \tag{6}$$

Describing the friction force f using $\ddot{X_G}$

$$f = I_G\ddot{X_G}/r^2 \tag{7}$$

By substituting eq. (6) in eq. (2) of system equations,

$$\ddot{X_G} = mr^2 g\sin\beta/(I_G + mr^2) \tag{8}$$

B. Development of the CAD model

The computer aided design (CAD) models can be designed to represent a part or a system in both 2-dimension (2D) and 3-dimension (3D). These models are defined by their geometrical parameters and they can easily be modified by altering relevant parameters. These CAD models allow the system to be viewed under an extensive range of representations and be used to perform experiments under real-world conditions in a simulated environment [4].

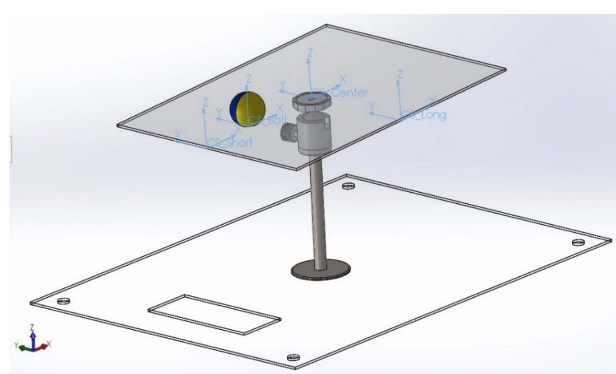

Fig. 3: Simplified CAD model for nonlinear 3D Simulations

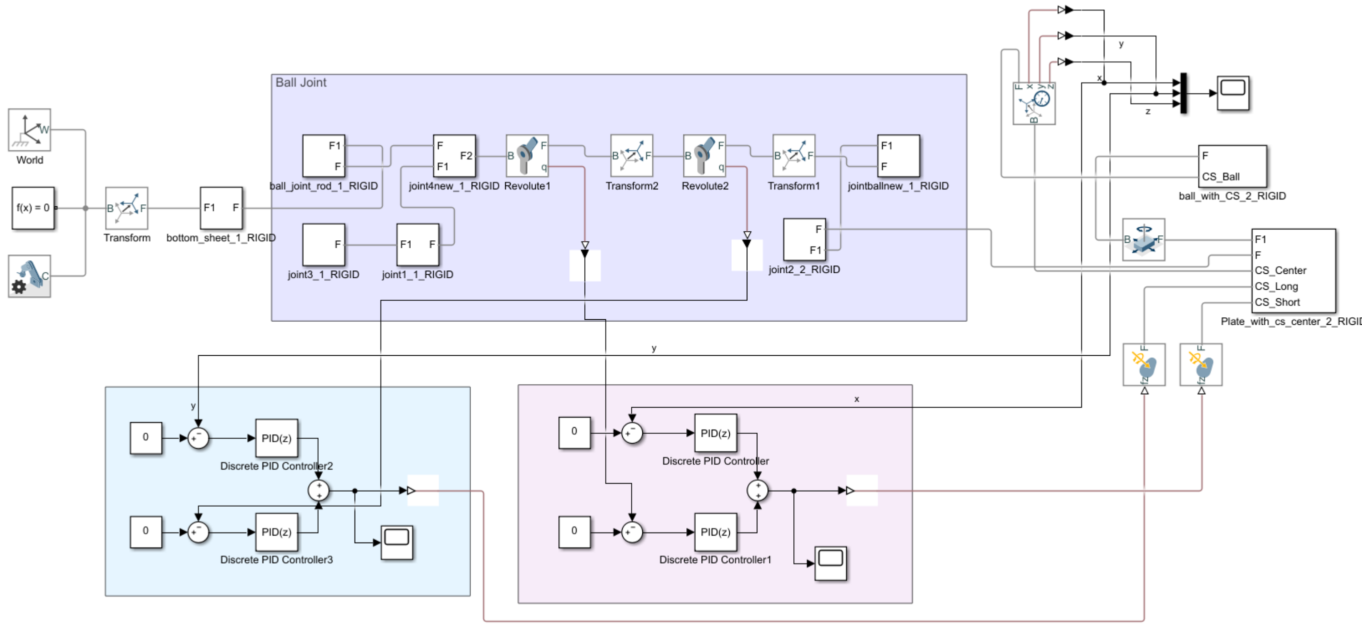

Fig. 4: Simulink block diagram of the BOP system

In this study, initially a sample 3D model of the full BOP system using SolidWorks software was drawn to get an impression about the overall design, parameters, and the movement of the system. This CAD model design consisted of all the main prototype components including the plate, the ball, servo arms etc.

Complex models with advance mates fail to function in the Simscape environment. It complicates the Simulink model and becomes difficult to perform simulations. Therefore, simple CAD model as Fig, 3, was designed using only major components; the ball, plate, ball-joint and the base. Then, four external coordinate systems were added; three on the plate and one on the ball. Here of, the ball's displacement from the working point along x, y and z axes can be determined using the coordinate systems added to the middle of the ball and the platform. Other two external forces were given to the middle of two perpendicular borders of the plate which allows in applying forces along the z axis to stabilize the system by tilting the plate accordingly.

C. 3D Simulations and Controller Design

To perform nonlinear 3D simulations, the CAD models of the system should be exported into MATLAB Simulink workspace through Simscape multibody link. Simscape multibody is an add-on application of the Simulink software. This allows the CAD models developed using SolidWorks to simulate in the MATLAB Simulink simulation environment. Simscape is capable of creating bodies of the exported CAD models using the geometry files and joints using mate definitions. Simscape allows to perform an accurate real-time simulation of the system as it automatically transfers all the data of the CAD model from dimensions to the location of each part's center of gravity.

The Simulink model that generates from the system only contains the solid parts of the prototype and the geometry of the system. All other external forces and joint mates should be added separately to the system block in order to perform simulations. Thus, the BOP Simulink model was also modified by adding 2 external forces to 2 external coordinates frames in the platform along x and y axes. A transform senser was also added to observe the ball's displacement from the center along x, y and z axes.

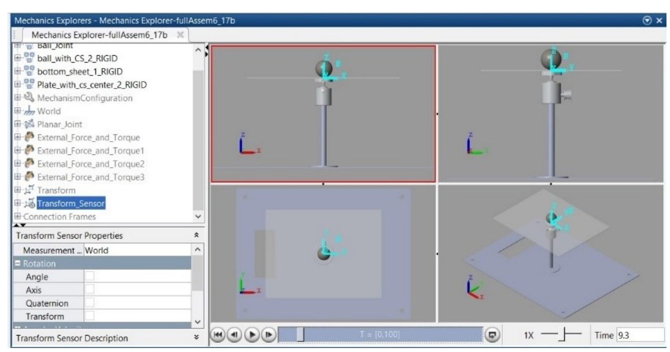

Fig. 5: Nonlinear 3D Simulations

When designing a feedback controller for the BOP system, the errors should be identified to use as feedback for the controller; which are the ball displacement from the operating point and the angle of the platform inclination in this system. Thus, the ball's displacement from the working point along x axis and the plate angle with respect to z-x plane were used to feed into 2 discrete PID controllers, then the summation of the O/P signal was fed back to the system as an external force. Similarly, this was performed in the other perpendicular direction in order to control the plate in y-z plane to stabilize the system.

D. Disturbance Rejection

Disturbance is a signal represent unwanted input or change in input signal which affects the output of the control system which increases the error of the system. The controller of closed loop system, with its feedback is able to shape the input of the system by using the output. Hence, many disturbances do not affect the system much and do not generate large deviations from the desired output. In this ball balancing system, PID controller feedback help the system to reject disturbances that occur during the system running time. In order to check disturbance rejection capability of this system, two external forces of 0.5 N at 20S and -0.6 N at 30S were given to the added coordinate systems at the edge of the platform separately along Z.

E. Introduction of FIR filter

Finally, a FIR filter was introduced to the experiments of BOP system in the presence of external noise as in Fig. 6, to identify its impact and benefits on the controller.

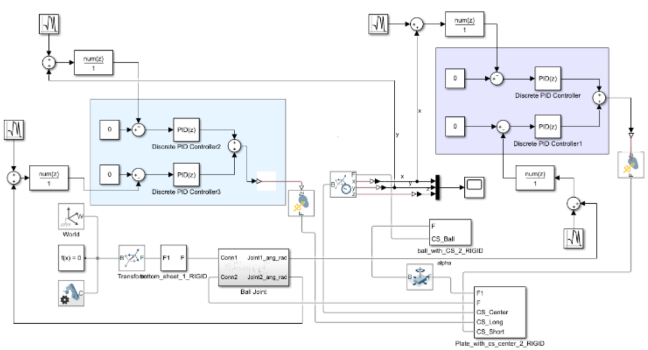

Fig. 6: FIR filter implementation

F. Remote-control access for distance learning experiments

To identify the feasibility in performing the simulation experiments in a different computer/ laptop, free-licensed video conferencing and remote-control access software Zoom and Anydesk were used. By sharing the Simulink model through above software, remote-control access was given to the user from the other end to conduct experiments on the BOP system. This was tested on 4 different computers and frames per second (FPS) rate was recorded to determine the quality of the experiment when performing it remotely.

III. RESULTS

To balance the unstable system, PID controllers were proposed in this study and it was carried out in a real-time simulation environment. Above Fig. 4 demonstrates the Simulink model of the system and how the PID controllers are connected in order to balance the system in the stable position. The PID controllers were manually tuned for a better step response. As two PID controllers, control the system in each axis, they were tuned separately in order to get the lowest error and fastest settling time.

Following table 1 shows the values of the gains; K_P, K_I and K_D after manually tuning the PID controllers.

TABLE I: PID controller gains

Gain	K_P	K_I	K_D
Controller 1	5	0.3	0.15
Controller 2	-20	-30	-0.4
Controller 3	2	0.105	3
Controller 4	-50	-22	-24

After tuning the PID controllers, the ball and plate system was able to stabilize with a minimum settling time of approx. 5 seconds and with a minor overshoot. Fig. 7 & Fig. 8 demonstrate the displacement of the ball from the center and angular displacement of the system along x and y axis respectively.

As deliberated in the previous section, disturbance signals were given in order to verify the stability of the system. Following Fig. 9 & Fig. 10 demonstrates the behaviour of the system when such disturbances are occurred. Which concludes that the PID controllers are capable of handling small disturbances and reject them in order to keep the system stabilized.

Using the system model, an FIR filter was presented for the PID control simulation experiments. The FIR filter added was successfully capable of producing a filtered output of the ball displacement from the working point and the angular displacement of the system under external noise. Thus, the BOP system reached the stability and settled approximately within 4S. Fig. 11-Fig.13 demonstrate the successful balance operation with FIR filtering. This system experiment in a simulated environment delivered positive perception to the implementation of filters for nonlinear systems, especially for balance systems which can later be used in future experiments on a physical prototype.

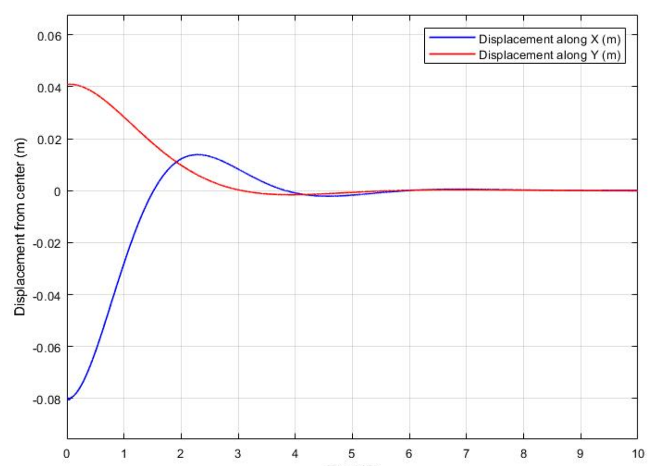

Fig. 7: Ball's displacement from the working point

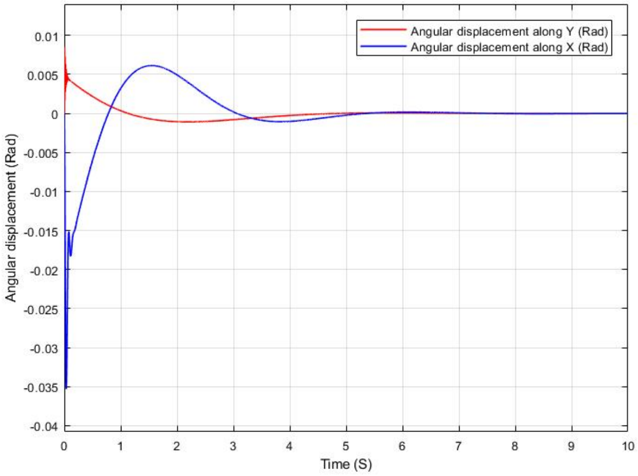

Fig. 8: Angular displacement of the system

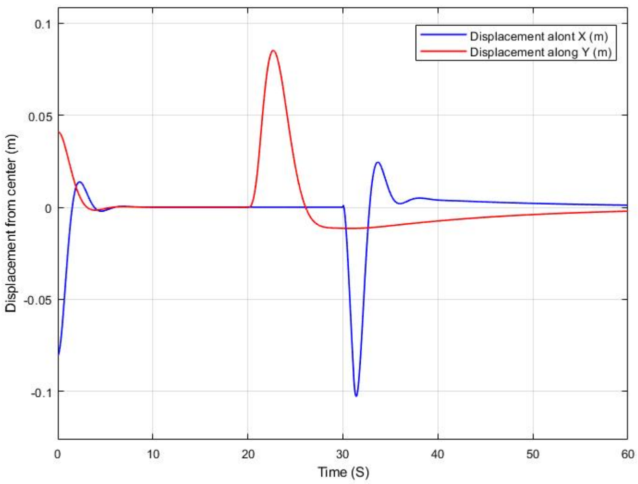

Fig. 9: Displacement of the ball from the center of the plate with external disturbances

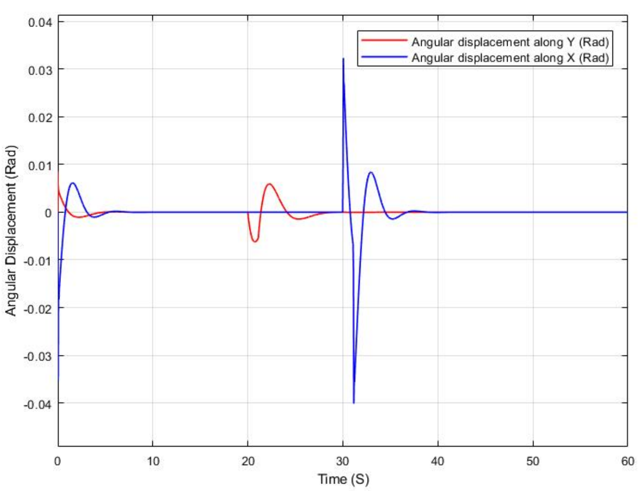

Fig. 10: Angular displacement of the system with external disturbance

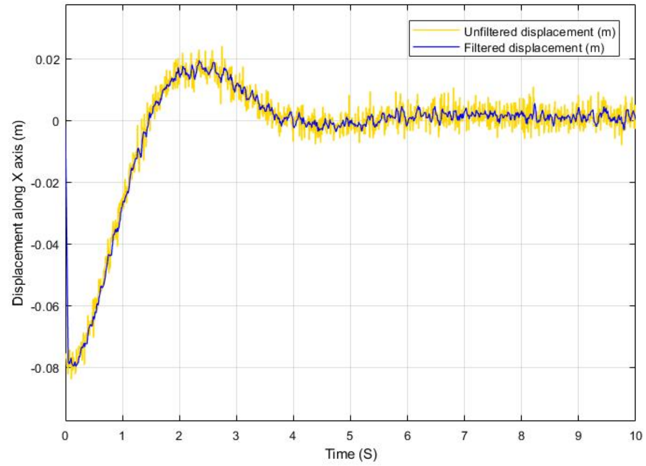

Fig. 11: Ball's displacement from working point along X axis on FIR filter

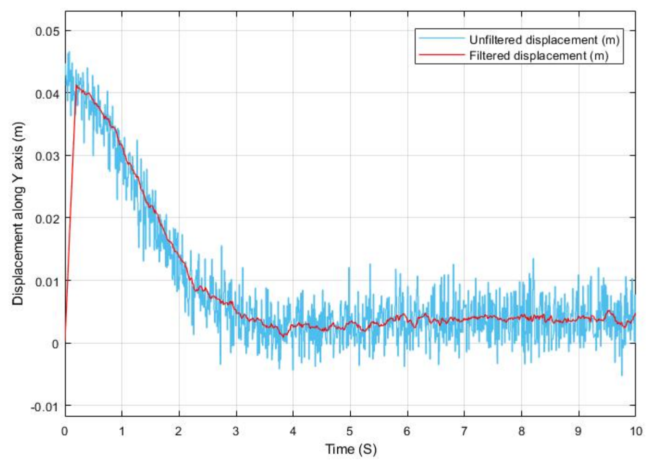

Fig. 12: Ball's displacement from working point along Y axis on FIR filter

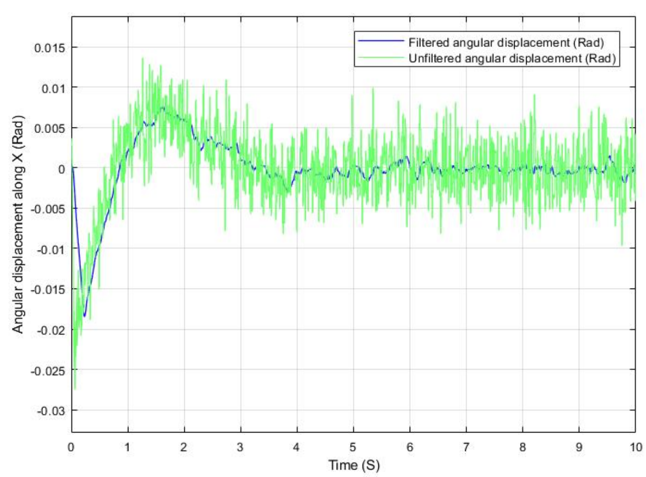

Fig. 13: Angular displacement of the system on FIR filter

Last of all, performing the simulations in a remote desktop/ laptop using Zoom and Anydesk was satisfying. Not only all the experiments were successfully conducted using remote-access, but also was capable of editing the model & parameters and perform experiments by the remote user.

TABLE II: Remote sharing FPS on different computers

Computer & Model	FPS in Zoom	FPS in Anydesk
Asus Vivobook	27	38
HP Probook 450 G4	24	35
Asus TUF dash F15	28	41
Samsung Tab A7 Lite	26	29

From above table, it can be seen that the FPS rate in Anydesk software is relatively higher than in Zoom software which makes it more advantageous in conducting remote simulation experiments.

IV. Conclusion

This research study was carried out in a simulation environment. The results of this study are presented for an ideal model. The same results of a real physical system can deviate from the results of this ideal system due to external factors. The performance of the PID controllers was satisfying. After tuning, both the rise time and the overshoot became low which means the controllers are fast and stale and the system is robust. This meets the demands that the system needs to fulfill. It is possible to make the system even faster by decreasing the rise time, but at cost of increased overshoot. This results to an increased settling time which considered as unacceptable as the system needs to be fast whilst being stable. The rise time is below 3S and the settling time is achieved approximately at 5S. Though the settling time is quite larger for a fast system like this, it is acceptable as the controllers were manually tuned. The overshoot of the system is below 5% which slightly affected the settling time specially when rejecting disturbance. To decrease the overshoot more than the results obtained, the speed of the system must be reduced. Which affects the usage of the controller as it should be able to manage outer disturbances as fast as possible. Although the systems that use PID controllers are known as SISO systems, based on the application of this study, this system can be identified as a coupled MIMO system.

Performing simulation experiments in a remote computer using 3rd party software was a success. Though the FPS in both Zoom and Anydesk was over 20, the FPS rates in Anydesk were relatively higher than in Zoom. Therefore, Anydesk software can be identified as a better fit for distance learning purposes. Another plus point is that both software let the users to communicate via texting & voice making the lab session more interactive.

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