

GLOBAL ACADEMIC RESEARCH INSTITUTE

COLOMBO, SRI LANKA



GARI International Journal of Multidisciplinary Research

ISSN 2659-2193

Volume: 07 | Issue: 01

On 28th February 2021

<http://www.research.lk>

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GARI Publisher | Online Teaching | Volume: 07 | Issue: 01

Article ID: IN/GARI/ICET/2020/101 | Pages: 10-25 (16)

ISSN 2659-2193 | Edit: GARI Editorial Team

Received: 24.11.2020 | Publish: 28.02.2021

DEVELOPMENT OF A VIRTUAL INVERTED PENDULUM CONTROLLING SYSTEM FOR ONLINE TEACHING

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ABSTRACT

Many established practices of modern society require rapid changes to accommodate challenges introduced by the Covid-19 pandemic. Education is one such important aspect of modern society, which demands changes, and online teaching became an attractive alternative method. Engineering profession demands hands-on experience to practice engineering. Therefore lab-practicals are one of the major requirements in Engineering studies. This paper presents a simulation platform, which allows the students to get hands-on experience in inverted pendulum control. balancing system. The PID and LQR controllers were used with the developed simulator and the results are presented. The simulation environment was developed using commonly available software in control systems laboratories, as well as with students, as the interface. The inverted pendulum system was modelled using CAD software and was imported into the modelling software to build a nonlinear system dynamics simulation. The mathematical model for the proposed system was established using systems theory. Furthermore, a prototype was fabricated according to the CAD model. Therefore virtual-system is based on a real system which allows the students to compare system performance in linear,

nonlinear and real aspects. This simulation platform has been developed to conduct practicals on controller designing for the inverted pendulum system, performance comparison among different control laws, and for the development of a nonlinear model from an existing system. This approach in control engineering could be further extended, to produce a commercialized virtual-lab. The presented system can be used to develop advanced control systems including robust and optimal control as well as nonlinear control systems.

Keywords: Virtual Practical, Inverted Pendulum, Online teaching, PID, LQR

INTRODUCTION

Online teaching has gained more popularity around the world, during the past few months. Though the popularity was gained recently, there were higher educational institutes, who offered their courses online since a considerable period. With the Covid-19 pandemic, which affected the public life immensely, most of the educational institutions including higher educational institutes have been focusing on continuing studies online. It is said by the experts that the Covid-19 pandemic will affect the normal life for another two or more years, which was

predicted based on experience on pandemics like Spanish flu (Owen, 2020). Therefore, for almost all of the higher educational institutes, the only method to continue their study programs is using online technology. Due to these concerns, it is predicted that the online teaching market would grow by another 8% by the year 2026 (Anon., 2020). Online teaching provides various advantages over the traditional method to both the teacher and the student. Flexibility in conducting and attending lectures, despite their location is the main advantage, which is a significant factor in considering this method for higher educational institutions. In the perspective of institutions, with the online teaching, cost on infrastructure that was spent during traditional teaching is saved. In terms of students, they can follow the program at their speed and with the availability of the recorded sources, the students have got the opportunity to use back up resources if they were unable to participate in some of the teaching programs. A study on evaluating the distance learning from the student's perspective reveals that the most of the students are in favour of the distance learning as they mention that, it guides them towards autonomous learning (Gonzalez, et al., 2019). The main disadvantage followed by distance learning or online learning is that lack of the ability of a student to manage time may negatively affect the progress of a student. In terms of teaching, though it is possible to teach thousands of students at the same time, active participation of students in evaluating the effectiveness is quite difficult. Also, for engineering studies, it is very much important for the student to obtain hands-on experience related to the modules, which may be acquired through pieces of training and laboratory classes. But with the Covid-19 pandemic, the ability to access such resources is limited and most of the laboratory classes are conducted as video sessions, where

student interaction is minimum. A simulation platform for students to participate in practical work would do great support to overcome the above-mentioned problem. When analysing the available platforms, the studies conducted in china reveals that for almost all the platforms, internet stability is a key factor that would affect both teaching and learning processes (Cao, et al., 2020). Therefore, the ability to continue the learning process, despite the internet stability and quality was considered as one of the main areas of focus for this research. In this study main focus is on the development of a simulation platform for the students, to involve in practicals related to control systems engineering.

In studying control systems engineering, as in other engineering subjects, it is important to have a thorough understanding of the practical applications of the theories learned. In most of the higher educational institutes, this knowledge is given during traditional teaching process by involving students in the lab classes, which has been a limited option during this time. Most of the lab classes related to control systems engineering include balancing of an inverted pendulum, due to its importance in teaching fundamental theories in control system engineering. Discussions and studies to use an inverted pendulum balancing system as a laboratory equipment haven been under considerations from early 90 s. In a study conducted during early 90 s, use of a rotary pendulum have been analysed, which have comparatively a smaller number of uncertainties than the linear inverted pendulum, as the belts drives, wires and other methods used in generating motion affect the linearity of the model. In the study, the main focus has been on using the apparatus for lab experiment in studying model uncertainties and evaluating controllers (Furuta, et al., 1991). But in this setup, it is required for

the physical model to be available for control, and real-time controlling is done, which would not be much advantageous for distance learning. Even, for now, controlling of the inverted pendulum is the most commonly used laboratory experiment to teach the fundamentals related to control systems engineering, where the controller designing is done using the real-time simulation. Controlling a linearized nonlinear model of an inverted pendulum is a difficult task due to model uncertainties. Therefore, it is a must to have precise instrumentation for sensors and actuators to avoid the model uncertainties as much as possible. This will cause the cost of instrumentation to rise, and use of a single instrument within several institutions will not be a satisfactory solution. These problems have been addressed by a study conducted in 2004, where the concept of the virtual laboratory has been considered for allowing students to get exposure to the practical application of control engineering theories. There, the simulations are based on a single physical system and experiments could be done remotely to observe the performance. There are several visualization options were available for the students, and a standard web-browser (or VRML Plug-In and Java Media Framework) was required to run the virtual laboratory. Another main requirement was a steady internet connection to connect with the virtual lab (Hoyer, et al., 2004). Though this virtual laboratory platform has been successful in providing multiple access to institutions with a single instrument, connection to the virtual laboratory requires a steady internet connection. And addition to that, the users are required to have special add-ins to use the virtual laboratory from a remote location. Another issue with the above platform is that it allows the student to explore different algorithms, but some fundamental areas like mathematical modelling of the inverted pendulum

system had not been addressed. Another approach in addressing these issues is the virtual control laboratory by Lima and the group. In this virtual laboratory, a state-space model has been developed, and the simulations consist of a 3D representation of the linear inverted pendulum movement, along with its cart. The system has been simulated with the use of a PID controller and state-space feedback controller. Further, the system has been simulated with the addition of noise. This platform allows the student to involve in PID tuning as well as to monitor the system parameters under different controllers (Lima, et al., 2006). But this virtual laboratory platform focuses only on the SSM and hence the range of the deviation of the pendulum angle is confined to a small region, where the system can be approximated to a linear system. Also, the system does not allow the user to change the parameters and study the effect of variation of parameters of the system such as the height of the beam, weight of the beam on the system performance. Open-source inverted pendulum system invented for feedback control laboratory courses in 2015 is another approach to address this issue. There the system is modelled based on an existing physical system, unlike in the previous study. In this platform, students are allowed to change the parameters to investigate the effect. For controlling the system, a PID controller have been utilised. With this laboratory platform, students can understand and develop fully original control functions, while understanding the fundamentals behind automatic feedback control (Turner & Cooley, 2015). Though the system was able to provide solutions to some of the issues associated with the previous studies, only a PID controller has been used here for controlling the system. Thus, investigating the effect of different controllers on the system had not been addressed. Also, the concept of distance

learning has not been considered here as the main focus has been set only on real-time controlling of the existing physical system remotely. This issue has been addressed by virtual instrumentation, where applications are created as per the user requirement using customizable software and modular measurements. A study conducted to model an inverted pendulum system by using Labview is an instance where virtual instrumentation has been utilized. In this case, the system has been simulated with an LQR (Linear Quadratic Regulator) and pole placement to investigate the behaviour of the system (Rawat, et al., 2018). In this system, users are provided with a platform, which does not require a continuous internet connection, it is useful only in monitoring the effect of applying different controllers to the system. The platform does not provide the opportunity to compare the LTI (Linear Time-Invariant) system with the nonlinear model, and this system provides only conventional graphs as results. Also, a real system related to the system does not exist, and therefore it is not possible to compare the simulation results with the real model, to study the uncertainties associated with the real system.

There are many studies conducted on this aspect, considering its theoretical value along with the practical application. It has been proven that the inverted pendulum can be used as a system to investigate the performance and efficiency of different controllers (Kafetzis & Moysis, 2017). Therefore, the development of a simulation platform for controlling an inverted pendulum system may allow the users to explore various fundamentals related to control systems engineering. An existing platform similar to this is the rotary inverted pendulum platform developed by Quanser. There they have provided a simulation platform, where the students are allowed to gain the exposure to control systems by tuning the

control system (Oksuz, et al., 2018). The platform is capable of being used as a teaching platform to teach intermediate control concept. The platform run in Matlab Simulink environment and different controllers such as fractional order PID have been tested on the platform, when the pendulum angle is very close to the equilibrium point (Wang, et al., 2018). Though this product satisfies most of the practical requirements of a platform used for control systems, it is required to buy the rotary motion platform at a considerably higher cost. And also, though this rotary motion platform by Quanser provides the ability to use various controllers on the inverted pendulum, the platform does not provide the facilities change the parameters of the model, to observe the effect of changing parameters on the system performance. Another drawback of the system is that the system does not provide the platform to study the state-space model of a system, which is a fundamental area to be covered in control systems engineering.

By investigating the existing studies related to the development of a virtual platform for practices related to controlling an inverted pendulum, two types of inverted pendulum systems could be identified. Namely, rotary inverted pendulum and linear inverted pendulum. And for the task of developing a virtual platform, the linear-rotary pendulum was selected. By developing a virtual platform for controlling a linear inverted pendulum, the following objectives are to be fulfilled.

- Development of a physical model for linear inverted pendulum
- Developing the SSM for the fabricated system to design controllers
- Designing a controller to control the nonlinear model, imported from the CAD model
- Investigating the system performance of the SSM model and the

nonlinear model for the designed controllers

- Investigating the system uncertainties associated with the physical model and nonlinear model, compared to the SSM
- Designing a controller for real-time controlling of the physical model

In addition to the objectives mentioned above, the designed platform would be advantageous over the existing platforms, in several aspects. The designed system would be based on Matlab Simulink and Matlab Mechanics Explorer Add-ins and they are readily available in almost all the control engineering laboratories and with almost every student studying control systems engineering. Also, the results of the system would be provided via graphs, while for the nonlinear model, a graphical representation would be generated. Also, the designed system must be able to be operated even without internet connections, which would provide the students with the flexibility to engage in the laboratory work at any time, at any location. The system must allow the students to vary the parameters and to observe the effect on the performance of the system to themselves. This virtual platform must be designed to support the aiming of two types of students. The first group to be addressed is the students, who are freshers to the control system engineering. The platform must allow them to get familiar with the controller designing for the existing SSM and the nonlinear model while getting familiar with the system uncertainties associated when it comes to the real physical model. The second group to be addressed is the students who have fundamental knowledge, to develop the SSM and nonlinear model from scratch, which is then compared with the existing model for evaluation. With this model, the interaction of the students with the practical aspects of the control systems engineering theories can be improved,

thus giving students more understanding about the fundamental theories. When the parameters like the height of the beam, mass of the cart system can be changed as per the choice of the user, along with the initial conditions, the platform would be more interesting for the students to work with. To work with the platform, basic knowledge relevant to the Matlab platform would be required. Despite the Covid-19 issue, the platform would be advantageous over the currently available practical methods. This is because when working with the real system in a laboratory, in most of the cases, the students are not allowed to apply controller values of their choice, as the unstable controller gains can damage the physical system. But the virtual platform can be used to investigate the system by applying any controller value. Even if the system is highly unstable, there will be no physical damage, and the effect of applying an unstable controller can be viewed graphically.

METHODOLOGY

For the development of a simulation platform for inverted pendulum balancing, the main requirement is the presence of a physical system for reference, where almost all the parameters required for state-space modelling are known. To fulfil this requirement, firstly, designing of a physical model was done using low-cost material. Then the CAD model was developed for the design to re-assess the design before fabrication. A direct implementation of the model is to be used for the nonlinear model. The CAD model of the complete system is shown in Figure 1.

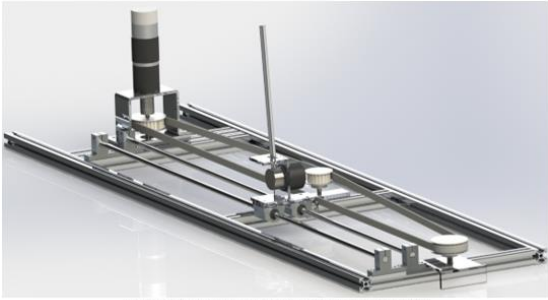


Figure 1: 3D Model Developed for the Complete System

The fabrication of the inverted pendulum balancing system was done, where the height of the pendulum was 0.2 m and the maximum deviation of the beam from the vertical axis was 10°. The system has been scaled down to reduce the power requirement of the system. A detailed image of the fabricated model is shown in Figure 2.

Motor	GP36 DC Planetary Gear Motor
Microcontroller	C2000 - F28379D
Motor Driver Board	HiLetgo VNH5019 2-Channel
Sensor	Incremental Rotary Encoder – 600 CPR

Other than this equipment included in the model, a power supply is required for the system to supply a voltage of 12 V to the motor through the motor driver board. Limit switches have been utilized at either end of the structure to prevent the cart from colliding with the structure ends.

After completing the model fabrication, mathematical modelling of the fabricated model was done. For that, the State Space Model (SSM) of the inverted pendulum balancing system was done using the parameters of the actual system. Force analysis was done to obtain the system equations. Sketch of the force body diagram of the system is indicated using in Figure 3.

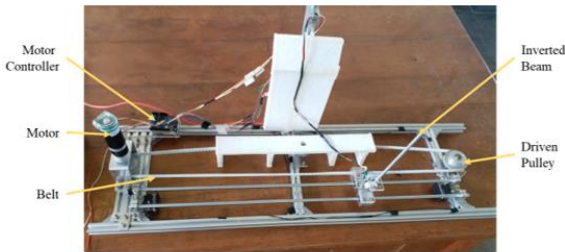


Figure 2: Top view of the Fabricated Model

Here the base of the model was fabricated using aluminium T-slots for reducing the vibrations of the system while in operation, and the mounting brackets of the cart were made of Perspex to reduce the weight of the system, and to improve system controllability. The cart consists of an encoder, linear bearings (8 mm) and mounting brackets. Details of the motor and the other equipment are listed below.

Table 1: Details of the Main Equipment Used

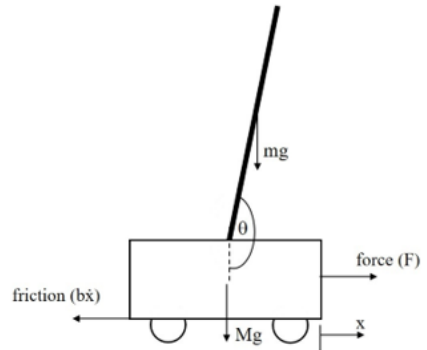


Figure 3: Forces Applied on the inverted Pendulum and the Cart

The force diagram is further simplified to indicate individual forces acting on the cart and the pendulum separately. Forces acting on the cart is depicted in Figure 4.

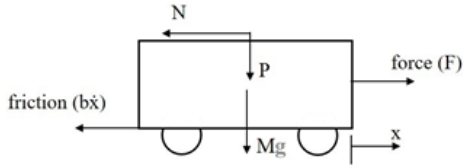


Figure 4: Forces Acting on the Cart

In Figure 4, the arrows N and P indicate the horizontal and vertical force components of the reaction force acting on the cart due to the pendulum. Displacement of the cart is denoted by x . By balancing the forces acting on the cart, the following equation could be obtained.

$$F = M\ddot{x} + b\dot{x} + N \quad (1)$$

In equation (1), \dot{x} and \ddot{x} represent the first and the second derivative of the position of the cart, respectively. Then the forces acting on the inverted pendulum are

$$N = m\ddot{x} + ml\ddot{\theta} \cos \theta - ml\dot{\theta}^2 \sin \theta \quad (2)$$

By substituting N from the equation (2) in the equation (1), the following relationship could be obtained for the force acting on the cart.

$$F = (M + m)\ddot{x} + b\dot{x} + ml\ddot{\theta} \cos \theta - ml\dot{\theta}^2 \sin \theta \quad (3)$$

Following relationships could be derived by resolving the forces acting in the perpendicular direction to the inverted pendulum and by considering the moments around the centroid of the beam.

$$P \sin \theta + N \cos \theta - mg \sin \theta = ml\ddot{\theta} + m\ddot{x} \cos \theta \quad (4)$$

$$-Pl \sin \theta - Nl \cos \theta = I\ddot{\theta} \quad (5)$$

By equating the equations (4) and (5), terms P and N were eliminated to derive the following relationship.

$$(I + ml^2)\ddot{\theta} + mgl \sin \theta = -ml\ddot{x} \cos \theta \quad (6)$$

After obtaining the governing equations (equation (3) and equation (6)), the system was linearized to derive the state-space model of the inverted pendulum balancing system. There the deviation of the inverted pendulum from the vertical axis was considered to be very small. Therefore θ was rewritten as follows.

analysed and the corresponding sketch is indicated in Figure 5.

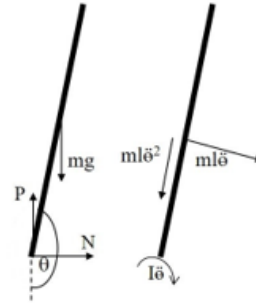


Figure 5: Forces Acting on the Inverted Pendulum

Angle made by the inverted pendulum to the vertical axis, angular velocity and the angular acceleration is denoted by θ , $\dot{\theta}$ and $\ddot{\theta}$ respectively. Resolving of the forces in the horizontal direction resulted in the derivation of the following equation.

$$\theta = \pi + \phi \quad (6)$$

With the assumption of ϕ being very small, the following approximations can be done.

$$\cos \theta = \cos \pi + \phi \approx -1 \quad (7)$$

$$\sin \theta = \sin \pi + \phi \approx -\phi \quad (8)$$

$$\dot{\theta}^2 = \dot{\phi}^2 \approx 0 \quad (9)$$

By replacing the terms with the above approximations, the equation (3) and the equation (6) can be rewritten as follows.

$$(M + m)\ddot{x} + b\dot{x} - ml\ddot{\phi} = u \quad (10)$$

$$(I + ml^2)\ddot{\phi} - mgl\phi = ml\ddot{x} \quad (11)$$

Above equations can be re-organized to obtain expressions for $\ddot{\phi}$ and \ddot{x} .

$$\ddot{\phi} = \frac{ml}{I(M + m) + Mml^2} F + \frac{mgl(M + m)}{I(M + m) + Mml^2} \phi - \frac{bml}{I(M + m) + Mml^2} \dot{x} \quad (12)$$

$$\ddot{x} = \frac{(I + ml^2)}{I(M + m) + Mml^2} F + \frac{m^2 l^2 g}{I(M + m) + Mml^2} \phi - \frac{b(I + ml^2)}{I(M + m) + Mml^2} \dot{x} \quad (13)$$

Using the above relationships for the system, the state-space model for the system was derived. States of the system and the derivative of the states are denoted by X and \dot{X} matrices respectively. Four states considered for the model are x , \dot{x} , ϕ and $\dot{\phi}$ respectively. Thus the state-space model was obtained for the system, which is also known as the Linear Time-Invariant (LTI) system. Relationship between the states and the inputs can be expressed in the following general form.

$$\dot{X} = AX + Bu \quad (14)$$

$$Y = CX + Du \quad (15)$$

In the above equations, the matrix u represent the input matrix, which is the force F in this case. When the system is expressed as in the equation (14) and the equation (15), matrices A , B , C and D are as follows.

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & \frac{-b(I + ml^2)}{I(M + m) + Mml^2} & \frac{m^2 l^2 g}{I(M + m) + Mml^2} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{bml}{I(M + m) + Mml^2} & \frac{mgl(M + m)}{I(M + m) + Mml^2} & 0 \end{bmatrix} \quad (16)$$

$$B = \begin{bmatrix} 0 \\ \frac{I + ml^2}{I(M + m) + Mml^2} \\ 0 \\ \frac{ml}{I(M + m) + Mml^2} \end{bmatrix} \quad (17)$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (18)$$

$$D = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (19)$$

Above matrices derived using symbols were substituted with the parameters related to the real physical model. Parameters of the physical model are given in Table 2.

Table 2: Parameters of the Inverted Pendulum Balancing System

Symbol	Description	Measured Value
M	Mass of the cart	0.2138 kg
m	Mass of the beam	0.01527 kg
b	Coefficient of friction for cart	0.01 N/m.s
l	Length to beam's centre of mass	0.1 m
I	Mass moment of inertia of the beam	0.00020 kg.m ²
F	Force applied to the cart	-
x	Cart position coordinate	-
θ	Beam angle from vertical	-

After the substitution of the above values in the matrices, A and B matrices were as follows.

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -0.0450 & 0.2912 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -0.1946 & 43.6896 & 0 \end{bmatrix} \quad (20)$$

$$B = \begin{bmatrix} 0 \\ 4.4952 \\ 0 \\ 19.4618 \end{bmatrix} \quad (21)$$

The simplified 3D model used for the nonlinear model development is shown in Figure 7.

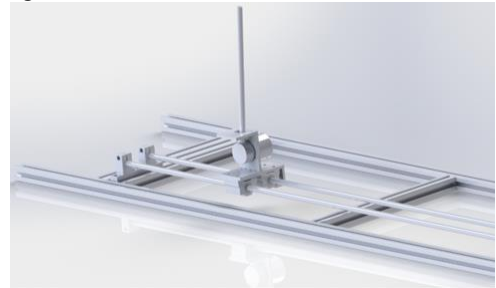


Figure 7: Simplified CAD Model of the System

Then the non-linear modelling of the inverted pendulum was done. For this, a simplified 3D model of the system was created and was imported to Matlab Simulink Environment. The modified Matlab Simscape Multibody diagram is shown in Figure 6.

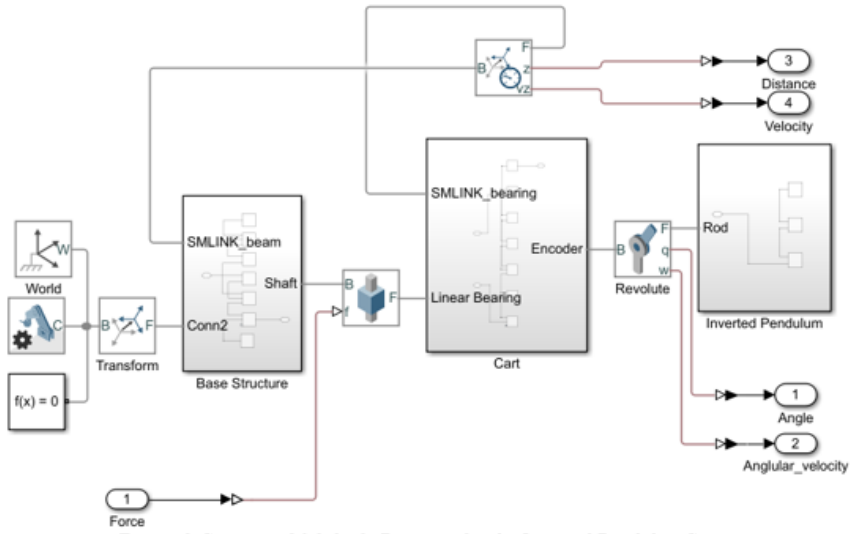


Figure 6: Simscape Multibody Diagram for the Inverted Pendulum System

After the completion of importing of the non-linear model, controller designing phase was done. For the controlling process, two controller types were

considered for the comparison of results. For PID controller designing, two separate PID controllers were installed for angle and distance control. The LTI model with the PID controller is shown in Figure 8.

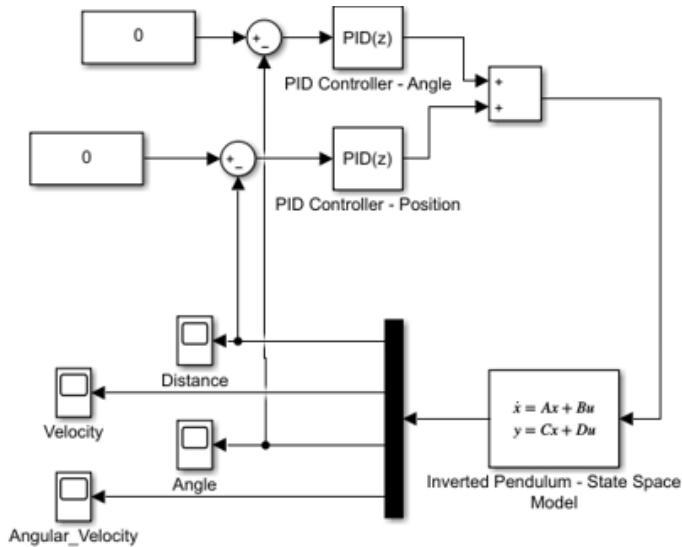


Figure 8: PID Controlled LTI System of the Inverted Pendulum System

PID tuning was done using the inbuilt PID tuner based on the transfer function, and the alterations were done manually using trial and error method. For the same

LTI model, a Linear Quadratic Regulator (LQR) was designed using Matlab inbuilt functions, and the Simulink model of the closed-loop system for the inverted

pendulum balancing system with LQR controller is depicted in Figure 9.

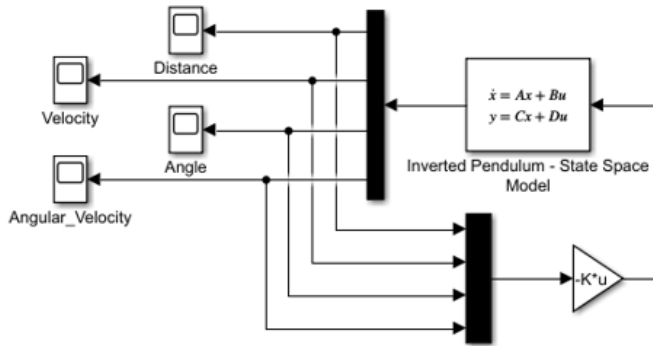


Figure 9: LQR Controlled LTI System of the Inverted Pendulum System

To obtain the LQR gains, only distance and angular measurement were considered as outputs and in the weighted matrix, the outputs were weighed equally. Parameters such as weight of the cart, the weight of the pendulum, height of the pendulum etc. can be changed in the script, and the corresponding matrices could be obtained for the state-space model. Application of the PID controller to the non-linear model was done by applying two PID controllers for each angular and displacement control. And the corresponding Simulink diagram is shown in Figure 10.

For controlling the non-linear model, PID tuning was done in the same process as in controlling the LTI model. In both cases, angle controlling was done at first and then the position controlling was done. Application of the LQR to the non-linear model was the next task in the list and the LQR gains obtained were from the LTI model, but the gains of the weighted matrix were changed to weigh more on angular stability. Simulink model of the non-linear model, controlled using LQR is shown in Figure 11.

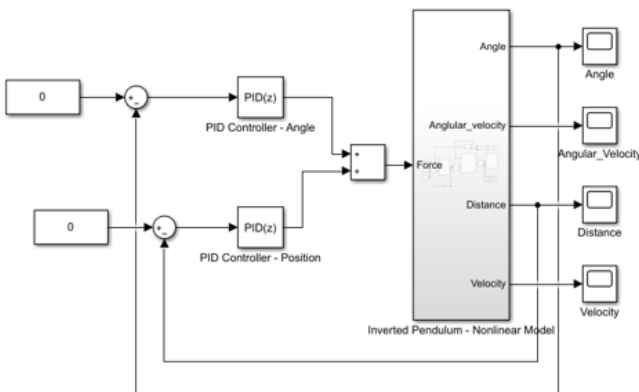


Figure 10: Non-linear Model Controlled using PID Controller

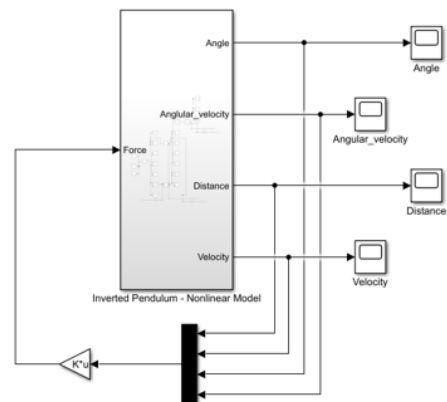


Figure 11: Nonlinear Model of the Inverted Pendulum System Controlled using LQR

RESULTS ANALYSIS

With the State Space Model derived, the behaviour of the inverted pendulum system with the application of a PID controller was observed. As mentioned in the methodology, for angular and position controlling two different PID controllers were implemented. PID gains obtained for the angular and position controlling of the SSM were as in following Table 4.

Table 4: PID Gains for the two Controllers of the SSM

	Gain	Value
Angular Controlling	Proportional (P)	7.1151
	Integral (I)	0
	Derivative (D)	1.0704
	Filter Coefficient (N)	70
Position Controlling	Proportional (P)	-1
	Integral (I)	0
	Derivative (D)	-1.007
	Filter Coefficient (N)	106.55

For the values denoted in the previous table, the system was stabilized within the first few seconds of the motion. Angular movement of the inverted pendulum with the change in time and the behaviour of the cart in terms of displacement are depicted in Figure 13.

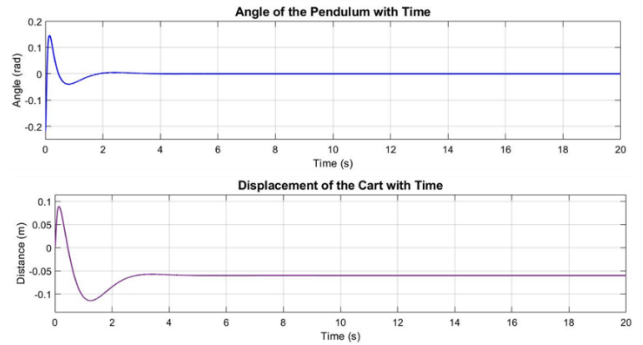


Figure 13: Behaviour of the System after Implementation of PID Controllers

For the SSM the initial angle was - 0.2182 radians and the initial location of the cart was at the zero position. Intended angle for the inverted pendulum was zero radians while for the cart, the desired location was 0.06 m away from the zero position. The system was capable of stabilizing within 4 s of time.

The SSM of the system was also controlled using the LQR. For the LQR controlled system also, the initial conditions were similar to that of the PID controlled model, where the initial angle was -0.2182 and the initial location was at the zero position. LQR gains for the system were as follows.

$$K = [-1 \quad -1.0070 \quad 7.1151 \quad 1.0714] \quad (21)$$

Following Figure 14 depicts the behaviour of the system with the implementation of the LQR controller.

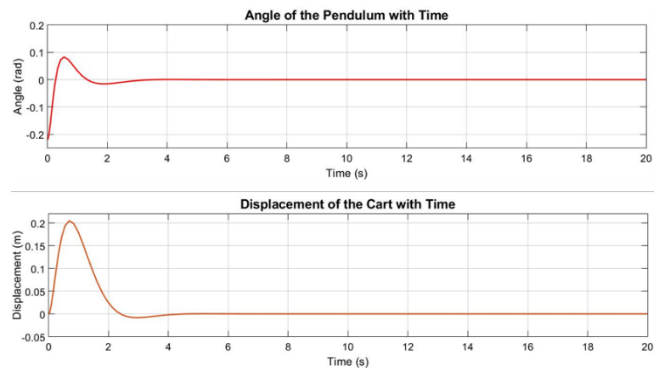


Figure 14: Behaviour of the System after Implementation of the LQR Controller

When comparing the system with the PID controlled system, the settling time has been increased slightly. But when considering the pendulum angle, the amplitude of the initial response have decreased delivering a smoother output. For the LQR implantation, the desired location for the cart was the zero position. Though the results for the PID implemented system was slightly better, when considering the controller designing, the LQR controller was very easy to be designed using Matlab mathematical modelling software. To investigate the behavioural changes of the LTI model and the nonlinear model, the same gains obtained for the PID controllers of the LTI model was applied to the nonlinear model. Initial conditions of the nonlinear model further reduced to be closer to the zero position. Results obtained were as follows.

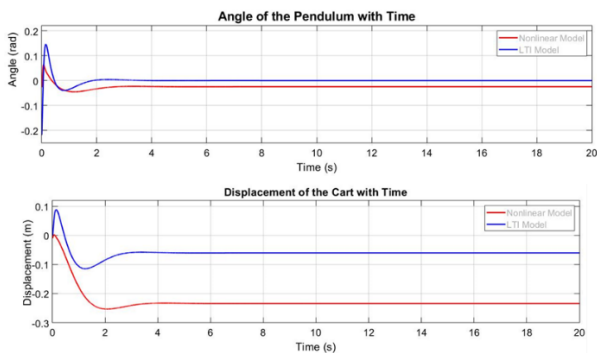


Figure 15: Comparison of Results from LTI Model with Nonlinear Model

When the PID gains from the LTI model was applied to control the non-linear model, both the angle of the pendulum and the displacement of the cart with time, failed to reach the desired values. Initial conditions of the nonlinear model were, beam at -0.024 radian inclination and the cart at the zero position. Though the desired values for both models were the

same, the nonlinear model was not able to reach the desired values. Hence from the results, it is clear that though linearizing a non-linear model is applicable for instances where the initial conditions are very close to the required conditions, it cannot be applied for every initial condition. Therefore this setup can be used in understanding the behavioural changes of the linear and non-linear models when the same apparatus are used as the reference. For the task of PID tuning for the existing model, the inbuilt PID tuner of the PID block was utilized. And thus following results could be obtained.

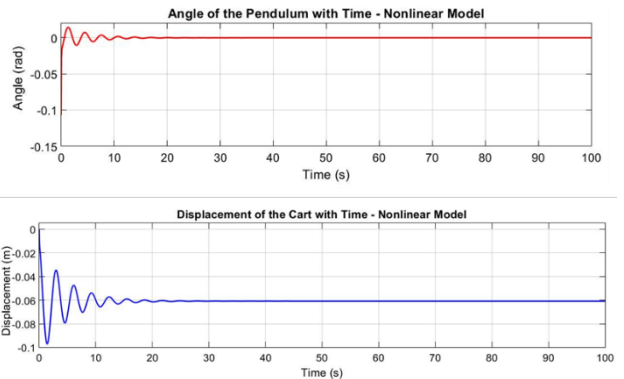


Figure 16: Behaviour of the Nonlinear Model with PID Controller

With the inbuilt PID tuner, which is based on transfer functions, the system is capable of balancing the beam at the vertical position after 20 s of time. And the time taken for the cart to reach the desired position is around 30 s. For the system, the initial angle was -0.1 rad and the cart was positioned at the zero position. The desired position for the cart was 0.6 m away from the zero position. From the results, it further confirms that the nonlinear model is more difficult to be controlled over the LTI system. With Mechanic Explorer Add-in in Matlab, the movement of the beam and the cart can be visualized as in Figure 17.

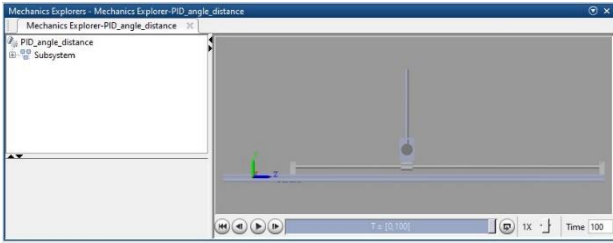


Figure 17: Visualization of the Behaviour of the Nonlinear Model

After successful importing of the CAD model to Matlab Simulink, the nonlinear model can be visualized as above, thus allowing the user to involve in the practicals with visual guidance on the model.

From the platform created, the practical aspect of model linearization can be studied. By changing the parameters of the physical model virtually, changes resulting in the LTI model can be visualized. As the initial conditions can be varied for the LTI model, the effect on the performance, when the initial conditions have deviated from the zero locations at a considerable amount, can be observed. Thus the concept of linearization of the nonlinear systems can be viewed practically. Practical application of controllers such as PID and LQR can be done with this platform. With the guidance and materials provided in the platform along with the script file, the procedure to apply an LQR for a linearized nonlinear model can be explored. As for the application of a PID controller, the system is allowed to be tested while the gains proportional, integral and derivative are changed individually. This leads to a clear understanding of the effect of the PID controller on an LTI and nonlinear system. As in the case of the nonlinear model, the effect of these gains on the actual system can be approximately viewed as in Figure 17. To change the parameters related to the nonlinear model, such as initial conditions, the CAD model is to be revised

and the importing process has to be repeated. With this platform, in addition to studying the LTI, nonlinear and real models, the process of controlling a real system by creating simulations can be studied.

CONCLUSION

In this paper, the main focus was on the development of a virtual inverted pendulum controlling system for online teaching which is the main requirement during Covid 19 pandemic. The system has been developed using Matlab Simulink interface, which is a tool commonly available with the students and lecturers. The developed platform is consisting of three main system types including linear model (LTI model), the nonlinear model and the real physical model. Though the system depends on a single physical system, many users can involve with controlling the respective linear and nonlinear models of the system. Another advantage offered by this virtual platform is that there will be no limitations in implementing PID and LQR controllers to observe the stability of the system, unlike for the practical classes involving a real physical model. This is because the damage that can occur to a physical system through unstable controller implementations is high, therefore in practical classes controller implementation is done only to observe the stable response. For the use of the platform, uninterrupted internet service is not necessary, allowing students to engage in studies with minimum facilities. This virtual platform can be used for students of various levels of knowledge on control systems engineering, as the platform includes an already balanced LTI and nonlinear model, a background for controller designing as well as facilities to develop a nonlinear model from the respective CAD model. Another advanced feature of this platform is that it allows the

students to vary the parameters of the models and to observe the effect, which would be a difficult task in the lab. Therefore this virtual platform can be used as a perfect solution to conduct practicals involving inverted pendulum balancing system, which would be a great option during this pandemic period.

FUTURE WORK

This virtual inverted pendulum controlling system can be improved further to be used with a variety of linear and nonlinear controllers. Also, the platform can be further developed to improve the user interface. The system can also be developed to be controlled when noise is given to the system. Development of the system to withstand any weight applied at the top end of the pendulum will allow the students to improve their knowledge as well as interest in control systems engineering.

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