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Research Papers

REAL TIME POLE PLACEMENT CONTROLLER DESIGN AND IMPLEMENTATION OF A ROTARY INVERTED PENDULUM - USING LABVIEW

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Abstract

In this paper, the design and implementation of Pole Placement Controller design for a rotary inverted pendulum is discussed. The Quanser Rotary Inverted Pendulum is highly non-linear, open loop and unstable system. Solving the operation of the Quanser rotary inverted pendulum is one of the classical and fundamental problems in the area of control theory. The practical controller design and implementation for such a system is a challenging task. The main objective is to derive Mathematical modelling for a rotary Inverted Pendulum in a State space form. Secondly, to design a stabilizing controller that balances the inverted pendulum in the up-right position. Real time implementation can be done using NIELVIS trainer kit , Quanser Rotary Inverted Pendulum and LabVIEW software.

KEYWORDS:
Pole Placement Controller, Lab VIEW (Laboratory Virtual Instrumentation Engineering Workbench), NIELVIS (National Instruments Educational Laboratory Virtual Instrumentation Suite), Stabilizing Controller, Quanser Rotary Inverted Pendulum.

INTRODUCTION

Regulatory and servo problems are very common in designing a controller, but feedback can be used in many other useful ways. The name task-based control is used as a common classification of a wide variety of problems [1]. For instance, stabilization of a unstable system is considered as a task based problem. The Segway transporter is a typical example where stabilization is a key task. The other examples are damping of a swinging load on a crane, Stabilization of rocket during take-off and the human posturing systems. There are many examples of task-based control in aerospace such as automatic handling and orbit transfer of satellites. Robotics is a rich field for task-based control strategies with a challenges such as collision avoidance, motion planning and vision based control. Task-based control is more complicated than regulation and servoing but they may contain servo and regulation function as sub-tasks. Here, Quanser rotary inverted pendulum was chosen to illustrate task-based control [2]. The Quanser rotary inverted pendulum is highly nonlinear and open-loop unstable system. The controller design for such a system is a challenging task. Here, state-feedback control system also known as pole placement controller was implemented using NIELVIS trainer kit, LabVIEW software and Quanser Rotary Kit. Figure 1 shows the Physical model of a Quanser rotary inverted pendulum. The rotary inverted pendulum consists of 24 volt DC motor that is coupled with an encoder and is mounted vertically in the metal chamber. The L-shaped arm or hub is connected to motor shaft and it rotates horizontally. At the end of the arm there is suspended pendulum attached so that the pendulum rotates vertically as the arm rotates horizontally. The pendulum angle and arm angle are measured by pendulum encoder and arm encoder respectively. The control variable is the input voltage to the pulse-width modulated amplifier and that drives the motor. The output variables are the pendulum angle and the arm angle [3].

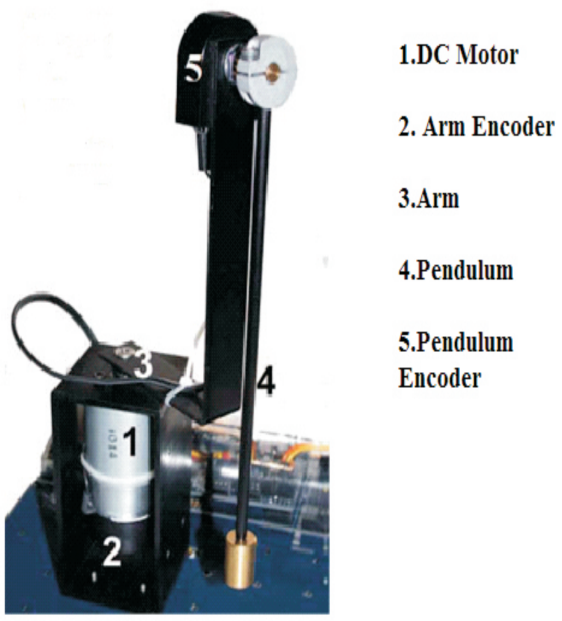

Figure 1: Physical model of a Quanser Rotary Inverted Pendulum

II. MATHEMATICAL MODELLING OF A ROTARY INVERTED PENDULUM

A. Mathematical Modelling

The main objective is to derive mathematical model for a rotary inverted pendulum in state space form. A mathematical model is the set of equations which describe the behavior of the system. A state space representation is a mathematical model of a physical system as a set of input, output and state variables related by first - order differential equations. The state space representation provides a convenient and compact way to model and analyze systems with multiple inputs and outputs.

The following assumptions are important in modelling the system:
1) The system starts in a state of equilibrium meaning that the initial conditions are therefore assumed to be zero.
2) The pendulum does not move more than a few degrees away from the vertical to satisfy a linear model.
3) A small disturbance can be applied on the pendulum.

B. Modelling

Figure 2 depicts the free body diagram of pendulum from which equations of motion can be derived.

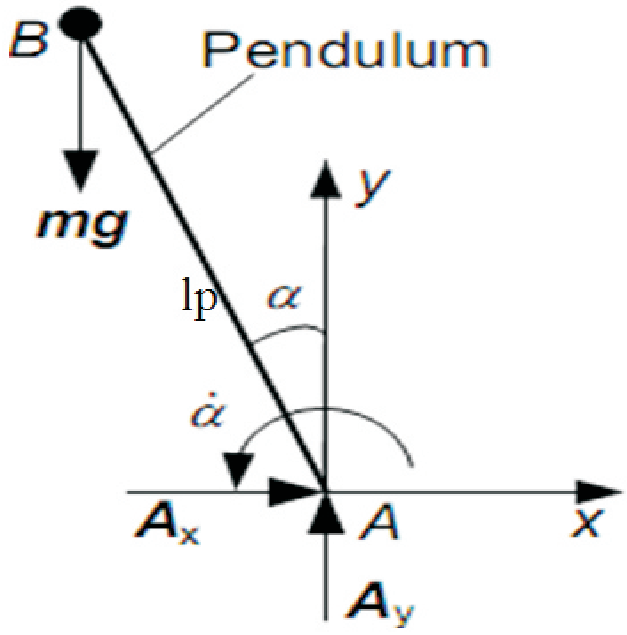

Figure 2: Free body diagram of pendulum

Rotary Inverted pendulum is a rotational system. So modelling is done by using torque balance equations. Derivation of mathematical equation describing dynamics of the rotary inverted pendulum system is based on Euler-Lagrange equations of motion.

Lagrangian of the system is given by equation

$$L \quad T \quad V \qquad (1)$$

where,

T - Total kinetic energy of rotary inverted pendulum system
V - Total potential energy of rotary inverted pendulum system

$$T \quad K.E_{arm} \quad K.E_{pend} \quad K.E_{V_x} \quad K.E_{V_y} \qquad (2)$$

$$V \quad P.E_{pend} \quad M_p g l_p \cos \qquad (3)$$

State variables -

Input variable - V_m

Output variables -

Where,

are arm angle, pendulum angle, arm velocity and pendulum velocity.

By solving the above equation, we would obtain the state space representation of the complete system. The state equation and the output equation are given below

$$\begin{matrix} \cdot \\ \cdot \end{matrix} \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & bd/E & cG/E & 0 \\ 0 & ad/E & bG/E & 0 \end{bmatrix} \begin{matrix} \cdot \\ \cdot \end{matrix} \begin{bmatrix} 0 \\ 0 \\ cK_t/R_mE \\ bK_t/R_mE \end{bmatrix} V_m \tag{4}$$

$$y \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{matrix} \cdot \\ \cdot \end{matrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} V_m \tag{5}$$

The values are then used in the state space model to obtain the numerical representation of the system for the purpose of designing the controller.

III. POLE PLACEMENT CONTROLLER DESIGN

The system of the inverse pendulum is unstable. With the help of pole placement method it is possible to make stable existing system [4]. The Eigen values those are not situated in the unit circle have to be moved to the desired position in the unit circle. Input vector should be designed using the state feedback control law:

$$u(k) = -K.x(k) \tag{6}$$

We can place closed-loop poles by using the following full-state feedback gain matrix given by:

$$K = [k_1\, k_2\, k_3\, k_4] \tag{7}$$

Since the system is fourth order, each pair of closed loop poles is introduced into the left semi plane of the complex plane. The closed loop system matrix (A - BK) has eigen values that coincide with the zeros of the specified desired characteristic polynomial. Poles of the closed loop system are given by:

$$|ZI - (A - BK)| \tag{8}$$

Ackermann's formula is used for inverted pendulum control, with a view to determine full-state feedback gain (8). It is generalized in the sense to direct us in finding desired eigen values instead of characteristic polynomial coefficients [5].Using of state space feedback can affect the internal state of rotary inverted pendulum system. Figure 3 illustrates the block diagram of the Full State Feedback (FSF) or Pole Placement Controller.

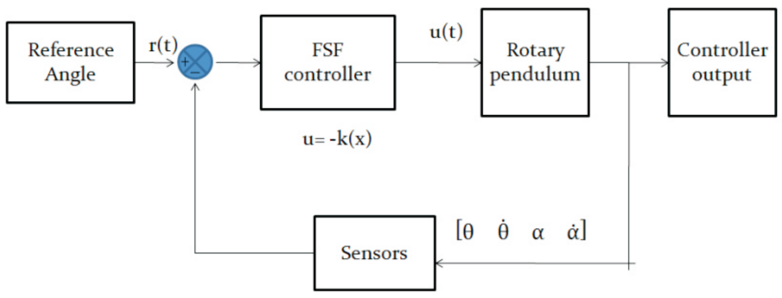

Figure 3: Block diagram of FSF controller

STEPS INVOLVED IN DESIGNING A CONTROLLER

The following process have to be done in designing the controller which is given below
1.Obtain a state - space representation of a open -loop system
2.Design and tune a Pole Placement Controller based state - feedback controller satisfying the closed-loop system's desired design specifications.
3.Implement state feedback controller in real-time and then evaluate its actual performance.
4.Finally, desired pole location, arm response of the system, Pendulum response of the system and controller gain value are obtained.
5.Using the Controller gain value Balance Controller block diagram is designed, which stabilizes the pendulum in an upright position.

SIMULATION

Simulation and experimental results are discussed in this section. Controllability and Observability are main issues in the analysis of a system before deciding best control strategy to be applied. The symbolic model representation of the matrices for the state - space model of a rotary inverted pendulum system was designed using mathscript node. Here, Controllability, Observability, Stability conditions was checked and the following results were achieved after the simulation of the block diagram.

$$\begin{pmatrix} 0.00 & 13.65 & -6.20 & 132.59 \\ 0.00 & 3.50 & -1.59 & 140.44 \\ 13.65 & -6.20 & 132.59 & -119.22 \\ 3.50 & -1.59 & 140.44 & -78.96 \end{pmatrix}$$

Figure 4: Controllability Matrix

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Figure 5: Observability Matrix

From Figure 4 & 5 we can conclude that the system is completely state controllable because it doesn't have non - zero row and rank of the matrix is 4x4 and it has unique solution. Similarly Observability matrix proves that the system is completely state observable because it doesn't have any non - zero column and it also has unique solution. So the primary condition for pole placement controller was verified and the system is suitable for controller implementation. Figure 6 Pole - Zero map to determine actual poles of the system.

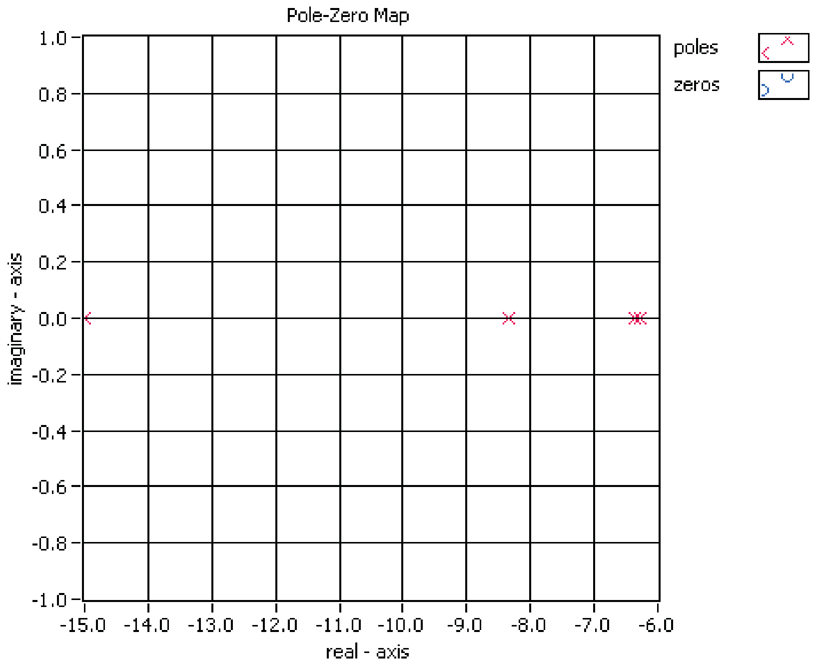

Figure 6: Pole - Zero map location

We can conclude that the present system is unstable because out of four poles, two poles (-6.3742 & -0.3457) are present on left half of the complex plane and one pole (0.0000) on the margin and the other (6.2655) on the right half of the plane. Hence we conclude that the system is unstable.

Figure 7 shows the Simulation results after pole placement depicts the response of the pendulum with tuned poles (-6.2655, 6.3742, 8.45, -15). The pendulum response looks faster, i.e. peak time decreases mainly due to increased arm proportional gain. so arm proportional gain is to increased to make faster settling time of arm response. Obtained gain value from the tuned poles are predicted below:

k_1 = -6.32
k_2 = 81.17
k_3 = -2.76
k_4 = 10.87

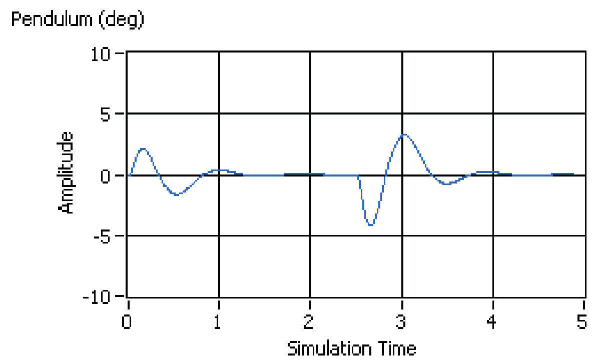

Figure 7: Response of the pendulum

EXPERIMENTAL RESULTS

By experiments better results were found. The problem of balancing inverted pendulum is like balancing a vertical stick with our hand by moving it back and forth. By applying appropriate linear force the stick can be kept more or less vertical. In this case the pendulum is being balanced by applying torque to the arm. The balance controller supplies a motor voltage that applies a torque to the pendulum pivot and the amount of voltage supplied depends on the angular position and speed of both the arm and the pendulum.

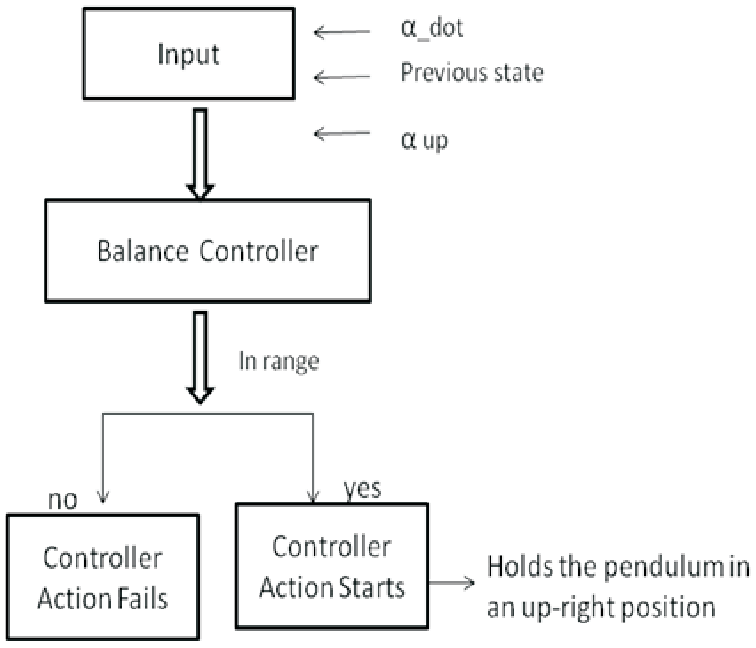

Figure 8: Balance Controller Flow Chart

Figure 8 represents the flow chart for balance controller design. It shows that the activation of the Balance controller was based on the following conditions. The pendulum is in range if all these are true:

(i) Angular speed is within ± 720 deg/s.
(ii) Pendulum is within ± 30 deg of vertical
(iii) Pendulum is within ± 2 deg of vertical or within ± 2 deg of vertical in the previous sample.

Manually rotate the pendulum about certain range of it up-right vertical angle. If balance controller range matches, then it kicks in and balances the pendulum. Figure 9 depicts the speed and output voltage of a DC motor during real time Interface. Figure 10 depicts real - time implementation of a rotary inverted pendulum after simulation.

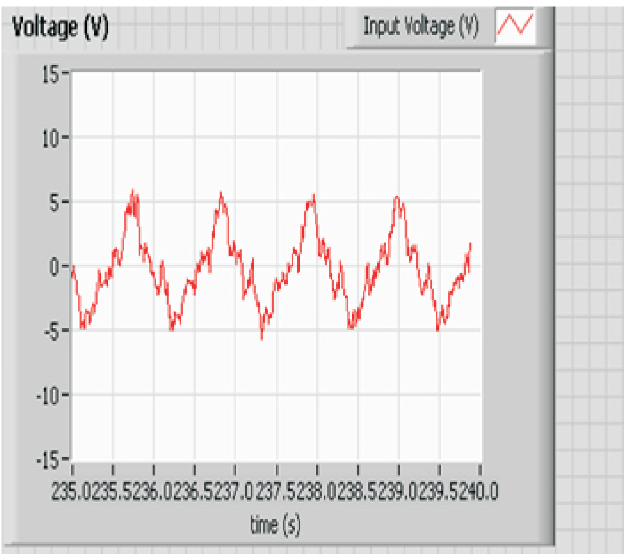

Figure 9: Angular position and speed of arm and pendulum

Figure 10: Real-Time Implementation after designing the Controller

CONCLUSION

In this investigation, the application of state feedback control for regulation & stabilization of inverted pendulum was presented. Here, pole - placement method is used to put desired poles in our target position. So following system is stabilized and controllable by using full state - feedback method. Pole placement technique is insensitive to system parameter variations and external disturbances. It remains stable even in the case of model approximation errors. The simulation results demonstrated that the system can successfully be handled by using Pole-placement controller and real-time implementation was also discussed. Thus it can be concluded that the pole-placement controller design for a rotary inverted pendulum is efficient and it holds the pendulum to the upright position and it is suitable for disturbance. Further study on this system would bring significant benefits to robotics and control professionals.

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