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Real Time Servo Motor Control of Single Rotary Inverted Pendulum Using Dspace

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Abstract— The objective of the paper is to carry out real time experiment using state of art hardware dSPACE DS1104 R&D controller board in a laboratory education point of view. The Quanser servo plant module and dSPACE software with the DS1104 R&D controller board are used in the experiment to derive state space equation for the inverted pendulum (ROTPEN-E). The linear and nonlinear analysis of the plant gives both angles (θ and α) control variations. The LQR controller is stabilizing pendulum upright.

Index Terms— Quanser servo plant with Rotary inverted pendulum (SRV02), dSPACE R&D controller board (DS1104), State space equations; LQR control.

I. INTRODUCTION

The Inverted pendulum system consists of a DC motor, internal gear boxes and Pendulum link which makes it suitable for nonlinear systems. Since the pendulum is used for control objective, to balancing it two positions can analyzed. The transfer function of the SRV02 system is derived from frequency response method. In order to find the state space of the inverted pendulum is developed from the mathematical model. The set-up which consists of dSPACE software, DS1104 interface board and UPM power supply module. The continuous input can be providing UPM to the SRV02.

In worldwide Quanser servo plant with the Quanser Q4 or Q8 board and dSPACE software are used to construct laboratory experiment as discussed in [1] and [2] with the DS1104 R&D controller board. Using of dSPACE real time software with inverted pendulum analyzed Dc servo motor for finding parameter in inverted pendulum [3].

The connection of the inverted pendulum with servo plant had been done through the user manual and stated that the inverted pendulum equation based on zero dynamics of cart-pendulum and sliding mode controller for pendulum system [4]. Using this hardware set up and dSPACE software the transfer function of the Quanser servo motor is determined using Frequency domain method with the DS1104 R&D controller board [5].

Euler-Lagrange equations design used on state model with feedback linearization in inverted pendulum model work proposed on the paper [6]. The Swing up control and and LQR based controller of pendulum design process and test method proposed in the paper [7] and [8]. To obtaining real time simulation with matlab development had been done through both methods.

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II. ROTARY INVERTED PENDULUM

A. Rotary inverted pendulum and SRV02 description:

The single rotary inverted pendulum shown in Fig. 1 provided rigid link attached to the pivot arm. The pendulum upright position can done through arm which is moved in the horizontal plane .The pendulum connected with optical shaft encoder used to measure pendulum angle, it offers a quadrature mode resolution of 1024 lines per revolution. Rotary arm connects DC servo motor to inverted pendulum.

The SRV02 is provided with DC motor that is encased in a solid aluminum frame and equipped with a planetary gearbox. It comes with a potentiometer sensor that can be used measure the angular position of the load gear. The SRV02 device can also be fitted with an encoder for digital measurement and a tachometer to measure the speed of the load gear. It has high efficiency and low inductance motor with a small rotor inductance.

Figure 1. View of single Rotary inverted

B. UPM Power supply module:

Figure 2. Front view of UPM 1503

UPM 1503 shown in Fig. 2 is used to provide continuous input to the Quanser servo plant. The UPM amplifies the input signal from the DS1104

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interface board and provides an input of 12v to the Quanser servo plant.

III. INTERFACE INVERTED PENDULUM WITH DSPACE SOFTWARE

The dSPACE is a real time simulation system that consists of a set of hardware and software. The connections are made as Fig 3. An interface board will be provided with the hardware components which have to be placed in the PCI slot of PC. Through this interface board the CP1104 connector panel will be connected for connection between the external hardware which is shown in Fig. 4

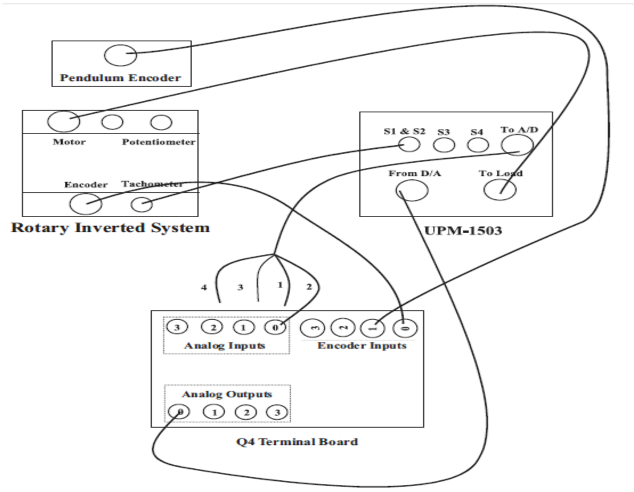

Figure 3. Experimental setup of plant with dSPACE

A. Connecting DC motor to UPM:

- "To Load cable": This connector uses a 6 pin DIN / 4 pin DIN, and goes from the amplifier to the actuator in the plant. One end of the cable has six pins, and the other has four so it is matched appropriately. This cable then transfers power to the plant and the analog control input to the plant.
- S1 & S2: A 6 pin-mini-DIN to 6 pin-mini-DINS is connected between the motor S1& S2 connector and the UPM. This carries the response of the servo motor to UPM. The tachometer connections are not made between the motor and UPM.

Figure 4. Experimental set up of SRV02

B. Connecting UPM and DS1104 Board:

- From D/A: A 5 Pin Din-mono / RCA cable is used to connect one analog output from the dSPACE board to the plant. The cable is called "D/A cable" because of connection made through D/A to UPM. The RCA termination is hooked up to the data acquisition board and the 5 Pin Din-monos is connected to the power module.
- To A/D: A 5 Pin Din-stereo / 4 x RCA cable is used to connect all 4 of the analog inputs to the dSPACE card. The cable is known as "To A/D cable". The RCA termination (like for your stereo) is going to be connected to the data acquisition board and the 5 Pin Din-stereo is going to be connected to the power module.

C. Connecting CP1104 to DS1104 Board:

- The analog input to the SRV02 is given from DACH1 pin in the CP1104 board.
- This signal will be present in the P1A 31 pin of DS1104 board and from the analog output #0 the signal is given to the "From D/A" connector.
- The analog output from the SRV02 is given to UPM through S1 & S2 signals.
- This signal is given to the DS1104 board in analog input port. The analog signal is taken from the pin P1A50 and P1B50 in the interface board and given to the ADCH4 and ADCH5 channels.
- To get the tachometer signal the pin 33 of P1A is connected with ADC6 channel. From this channel the speed of the Quanser servo motor will be recorded which will be useful for deriving the experimental transfer function of the system.
- ENC 1&2: A single ended optical shaft encoder is used both pendulum and srv02 servo plant. The 5 pin-mini-DIN to 5 pin-mini-DINS which measure the pendulum angle and velocity of motor.

IV. MATHEMATICAL MODEL OF ROTARY INVERTED PENDULUM

The total kinetic energy of the system is sum of rotational energy and translational energy.

$$T_L = T_R + T_T \quad (1)$$

The rotational energy is addition of rotation of arm energy and rotation of pendulum energy. The parameters of the system are

J_p : Moment of inertia of pendulum link (kg.m^2),
J_a : Motor arm moment of Inertia (kg.m^2),
Beq : The viscous damping coefficient (N.m.s/rad),
r : Length of horizontal arm (m),
α : Pendulum angle in (rad),
$\dot{\alpha}$: Pendulum velocity (rad/s),
θ : Motor shaft position (rad),
$\dot{\theta}$: Motor rotating velocity (rad/s),
K_t : Motor torque constant (N.m/A).
K_m : Motor back emf constant (V.s/rad),
R_m : Motor armature resistance (Ohm),
η_g : Gearbox efficiency,
η_m : Motor efficiency,
K_g : Total gear ratio,

Then translational energy is finding the velocity obtained from kinetic energy.

$$T_R = \frac{1}{2}\{J_a \ddot{\theta}(t) + J_P \ddot{\alpha}(t)\}$$

$$T_t = \frac{1}{2} m_p [(r\dot{\theta} - l_p \cos\alpha\dot{\alpha})^2 + (-l_p \sin\alpha\dot{\alpha})^2]$$

The potential energy of the rotary inverted pendulum derived from gravitational energy of the object with mass (m), gravitational acceleration (g) and change in the height (dh = h_2-h_1). The potential energy V is

$$V = -m_p g\, l_p \cos\alpha(t) \quad (4)$$

The Lagrangian equation of the system is defined as difference between total kinetic energy of the system and total potential energy of the system. Then Lagrangian L is

$$L = \frac{J_a \dot{\theta}^2}{2} + \frac{m(r^2\dot{\theta}^2 - 2rl\cos\alpha\dot{\theta}\dot{\alpha})}{2} + \frac{2ml^2\dot{\alpha}^2}{3} - mgl\cos\alpha \quad (5)$$

A. Linearized inverted pendulum model:

Euler-Lagrange equation is used to find the equations of motions. The rotary inverted pendulum has two coordinates as Q_1 and Q_2.

$$\frac{d}{dt}(-mrl\cos\alpha\dot{\theta} + \frac{4ml^2\dot{\alpha}}{3} + mgl\sin\alpha) = 0 \quad (6)$$

$$-mrl\cos\alpha\ddot{\theta} + \frac{4ml^2\ddot{\alpha}}{3} + mgl\cos\alpha = 0 \quad (7)$$

There are two sensor motor shaft encoder and pendulum encoder and also two equilibrium points α = π (pendulum down, stable) another one α = 0 (pendulum up, unstable). From nonlinear model the local point linearization technique is used to linearized Q_1 and Q_2.

$$(J_a + mr^2)\ddot{\theta} - mrl\ddot{\alpha} + B_a\dot{\theta} = \tau_m \quad (8)$$

$$\frac{4ml^2\ddot{\alpha}}{3} - mrl\ddot{\theta} - mgl\alpha = 0 \quad (9)$$

The state vector is $x^T = [\theta(t)\ \alpha(t)\ \dot{\theta}(t)\ \dot{\alpha}(t)]$. The noise is neglected while measuring the variables. The output equation of the state vector shows position measurement of the arm and pendulum angle. The state space representation of the rotary inverted pendulum is

$$\begin{bmatrix}\dot{\theta}\\ \dot{\alpha}\\ \ddot{\theta}\\ \ddot{\alpha}\end{bmatrix} = \begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ 0 & \frac{bd}{T} & -\frac{cg}{T} & 0\\ 0 & \frac{ad}{T} & -\frac{bd}{T} & 0\end{bmatrix}\begin{bmatrix}\theta\\ \alpha\\ \dot{\theta}\\ \dot{\alpha}\end{bmatrix} + \begin{bmatrix}0\\ 0\\ \frac{cf}{T}\\ \frac{bf}{T}\end{bmatrix} V_m \quad (10)$$

Where $a = J_a + mr^2 + \eta_g k_g{}^2 J_m$ $\quad b = mlr$ $\quad c = \frac{4ml^2}{3}$

$d = mgl$ $\quad f = \frac{\eta_g \eta_m k_t k_g}{R_m}$ $\quad g = \frac{\eta_g \eta_m k_t k_g{}^2 k_t + B_a R_m}{R_m}$

$T = ac - b^2$

Subsisting the values of the parameters

$$\begin{bmatrix}\dot{\theta}\\ \dot{\alpha}\\ \ddot{\theta}\\ \ddot{\alpha}\end{bmatrix} = \begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ 0 & 34.28 & -14.69 & 0\\ 0 & 55.46 & -12.57 & 0\end{bmatrix}\begin{bmatrix}\theta\\ \alpha\\ \dot{\theta}\\ \dot{\alpha}\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 27.13\\ 22.67\end{bmatrix} V_m \quad (11)$$

The pole of the open loop system is 0, -16.6371, -3.9269 and 5.8740. It shows that system unstable, because of one right hand pole.

A. Verification of linear model against nonlinear model:

In real time hardware system has mostly nonlinear model. Here the linearized model dynamics represents original nonlinear model of the rotary inverted pendulum. To simulate the dynamics of the system using both the linear and non-linear models and then compare their simulation outputs. The simulation results verified linear model as well as range of pendulum angle (α) and motor arm angle (θ).

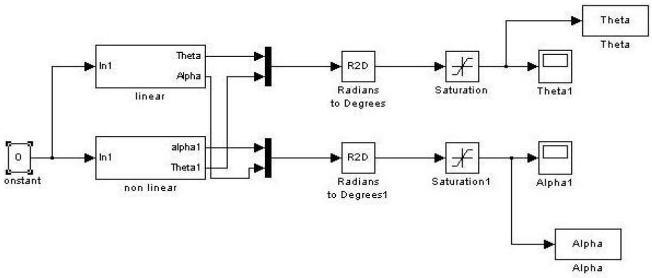

Figure 5. Verifying the linear model

α is given an initial condition (0.001 (rad)) and thus the pendulum is allowed to fall. As one can see from the simulation results shown in Fig. 6, the linear model correctly depicts the motion of the pendulum for the first 20 seconds and then begins to break down. But experimentally the alpha angle can be simulated correctly up to 5 seconds.

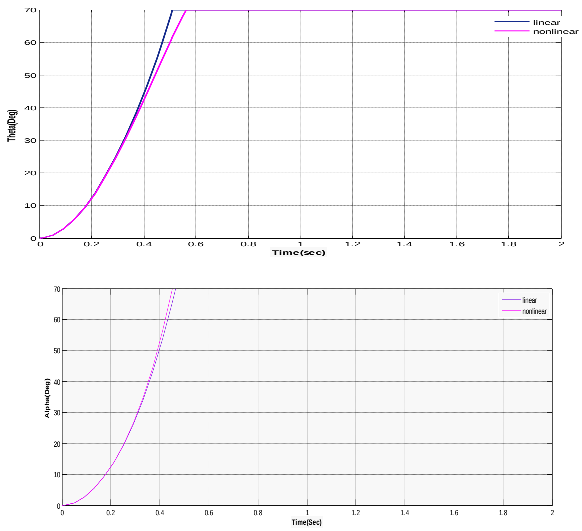

Figure 6. The linear and nonlinear alpha and theta variations

V.CONTROLLER DESIGN OF ROTARY INVERTED PENDULUM

The pendulum in the system has a length of 2L = 0.335 (m) and its center of mass is located at its geometric center. Thus the natural frequency for small oscillations of the pendulum is given by

$$\omega_p = \sqrt{\frac{mgL}{F_a}} = \sqrt{\frac{3g}{L}} = 6.8675 \text{ Rad/sec} \quad (12)$$

A. Design of the position controller:

The closed-loop response of the arm should be considerably faster than the natural frequency of the pendulum. It would then be reasonable to design a closed-loop controller for the

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arm position which has the following specifications.

$\omega_n = 4\omega_p = 27.47$ Rad/sec, %OS =2% and $\varsigma = .7072$ (13)

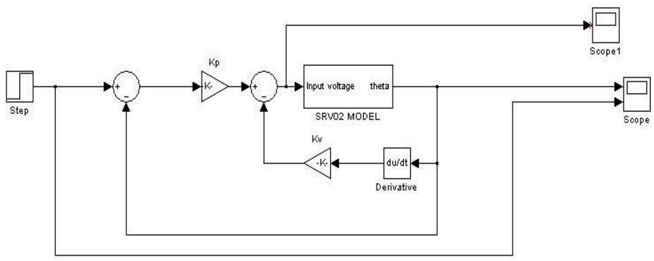

Figure 7. The position controller SRV02 model

For the arm to track the desired position, we design a PD control law

$$V_m = K_p(\theta_d - \theta) - K_v\dot{\theta} \quad (14)$$

This is a position control loop that controls the voltage applied to the motor so that θ tracks θ_d with zero desired velocity. Fig.7 shows that the position control of SRV02 model with inner loop controls velocity error and outer loop minimized position error. We need to determine K_p and K_v according the above defined specifications

$$K_p = \frac{2\omega_n \varsigma J_{eq} R_m - B_{eq} R_m - \eta_g \eta_m K_m K_t K_g}{\eta_g \eta_m K_g K_t} \quad (15)$$

$$Kv = \frac{\omega_n^{\,2} J_{eq} R_m}{\eta_g \eta_m K_g K_t} \quad (16)$$

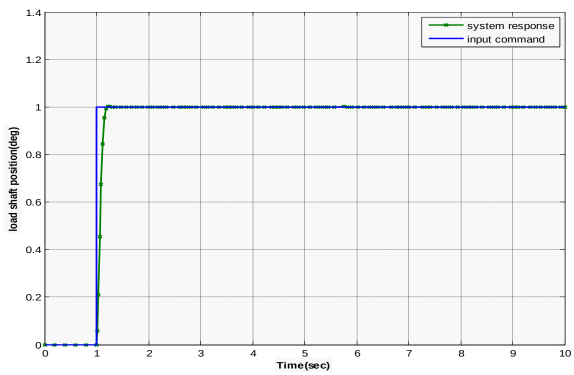

Figure 8. Response of load shaft position with input

The real time plant position control can be obtained based on the system input variation. Encoder in dSPACE is configured such a way that to output would track changes in input. The following Fig. 9 shows that dSPACE position controller output.

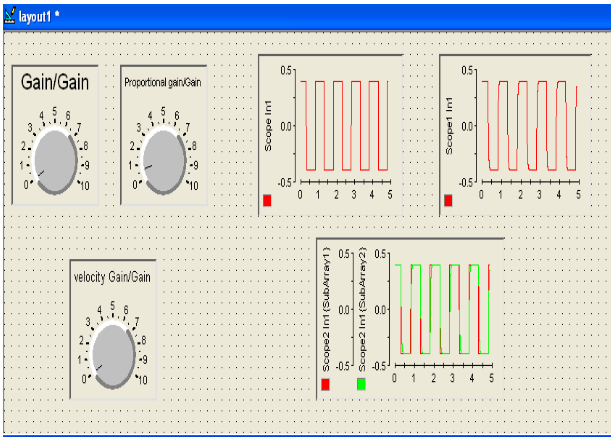

Figure 9. dSPACE response of the position controller

B. Design of the LQR controller:

The stabilization controller can be designed using the Linear Quadratic Regulator (LQR). The object is to determine the optimal controller *u (t) = -Kx (t)* such that a given performance index

$$J = \int_0^\infty (x^T Q x + u^T R u)dt \quad (17)$$

is minimized. The performance index is selected to give the best performance. The choice of the elements of *Q* and *R* allows the relative weighting of individual state variables and individual control inputs. For example, using an identity matrix for Q weights all the states equally. As a starting point you may use a diagonal matrix with values *Q = diag ([100 .1 100 .1]) and* R=1. Then determine the state-feedback gain matrix *K* Fig. 10 shows the LQR design of stabilization controller of α θ $\dot{\alpha}$ and $\dot{\theta}$.

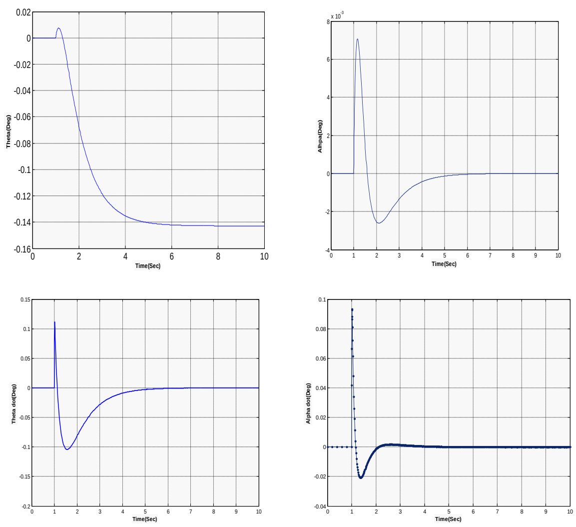

Figure 10. LQR control response of α, θ, $\dot{\alpha}$ and $\dot{\theta}$

VI. CONCLUSION

The interfacing procedure of SRV02 plant with UPM, dSPACE hardware and software is clearly explained in this paper. The modeling of the rotary inverted pendulum using Quanser Servo motor is carried out. Input to the system is given through the DS1104 board and the

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response of the system is obtained using the dSPACE software. Linearized the model and verified experimentally. Controlling of the inverted pendulum can be developed in position control and LQR control in stabilization method.

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REFERENCES

[1] Quanser . "SRV02 MODELING USING QUARC"- User manual.

[2] Quanser. "SRV02-ET ROTARY INVERTED PENDULUM"- User manual.

[3] Muskinja, N. and Tovornik and B, " *Swinging up and stabilization of a real inverted pendulum"*, IEEE Transactions of Innovative Information and Control Vol.3, no 6(B),pp. *631–639*. December 2007.

[4] Park M.S. and Chwa D, "*Swing-up and stabilization control of inverted-pendulum systems via coupled sliding-mode control method",* IEEE Transactions on Industrial Electronics, vol. 56, no. 9, September 2009.

[5] Priya. J, Balamurugan. S and Venkatesh. P, *"Real Time Control of Quanser Module Using dSPACE DS-1104"* Dept. of Electrical Engineering, Thiagarajar college engineering, Madurai. International Conference on Computing and Control Engineering, April 12, 2012.

[6] Shailaja Kurode, Asif chalanga and Bandyopandhyay, "*Swing-Up and Stabilization of Rotary Inverted Pendulum using Sliding Modes",* IFAC world congress 2011 – Italy September 2, 2011.

[7] Sukontanakarn V and Parnichkun M, *" Real-time optimal control for rotary inverted pendulum*", American Journal of Applied Sciences 6, 1106–1115, 2009.

[8] Astrom .K.J. and Furuta, K, " *Swing up a pendulum by energy control"* , Automatica, vol. 36, no. 2, pp. 287–295, February 2000

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