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Reduced Order Observer Based State Feedback Design of a Practical Excavator Arm attached to a Crane (2 DOF)

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Abstract:
A nonlinear robot plant that incorporates robot manipulator dynamics as well as implementation of observer to estimate unmeasured states is proposed in this paper. The robot manipulator operates in the robot task space in lifting the object at a defined place and at a specified angle. Computer simulations are performed to verify feasibility of robot manipulator along with the implemented observer. The experiments show that the proposed work produces good tracking performances in estimating the states yielding conspicuously improved performance. Computationally this method is very elegant.

Keywords: ***Robotic Arm, Manipulator, State Feedback Control, Multiple Integrator, Forward Kinematics, Lagrangian, Reduced-order Observer, Generalized Matrix Inverse, Luenberger Observer, Das & Ghosal Observer.***

1. Introduction:

This paper focuses on robotic manipulators covering current practical methodologies for kinematics, dynamics, modeling and computations. The kinematics model represents the motion of the robot considering the forces that cause the motion. The dynamic model establishes the relationships between force and the torque taking into account the masses and moment of inertia. The kinematic model is a prerequisite for motion planning and workspace analysis. Different authors proposed different design procedures using observers for linear systems/non linear systems, time variant/time invariant systems, discrete/ continuous systems. But to the best of my knowledge no design procedure is proposed using Das & Ghosal observer for a robotic plant. In case of a full order observer all the states can be estimated whereas in case of reduced order observer the states which are not measurable can be estimated. Das & Ghosal observer is a reduced order observer. In the paper it is described about the immeasurable states which are estimated using Das & Ghosal observer with state feedback and PI controller.

2. Brief Theory on Robotics:

A robot system consists of

- Manipulator
- Sensory Devices
- Controller
- Power Conversion Unit

A. Manipulator:

The Manipulator consists of a series of rigid members called Links connected by joints. Motion of a particular joint causes subsequent Links attached to it to move. The motion of a joint is accomplished by an actuator mechanism. The actuator can be connected directly to the next Link or through some mechanical transmission. The Manipulator ends with a Link on which a tool can be mounted. The interface between the last Link and the tool or the end effectors is called Tool Mounting Plate or Tool Flange.

The Manipulator itself may be thought of as being composed of three divisions:

- The major Linkages
- The minor Linkages
- The end Effectors

The manipulator is a collection of mechanical linkages connected by joints. The manipulator is capable of movement in various directions and is said to do “the work” of the robot. Generally the joints of the manipulator fall into two classes. The first, *revolute* joint produces pure rotary motion. Consequently the term rotary joint is often used to describe it. The second *prismatic* produces pure linear or translational motion and as a result it is often referred to as linear joint. Each joint of the robot defines a joint axis about or along which the particular link either rotates or slides (translates). Every joint axis defines a degree of freedom (DOF) so that the total number of DOF’s is equal to the number of joints. The manipulator defined by joint-link structure generally contains three main structural elements: the arm, the wrist end the end effectors. Besides mechanical components most manipulators contain devices for producing the movement of various mechanical members. These devices are referred to as actuators and may be pneumatic, hydraulic or electrical in nature. They are invariably coupled to various to various mechanical links or joints (axes) of the arm either directly or indirectly.

B. Sensory Devices:

These devices monitor position, speed, acceleration and torque. The sensor is connected to actuator shaft. However it could be coupled to the output of transmission

C. Controller:

The controller provides intelligence to cause the Manipulator to perform in a manner described by its user.

Each controller consists of:

- A memory to store data defining the position
- A sequencer to interpret the data stored in memory
- A computational unit
- An interface to obtain the sensory data into the sequencer
- An interface to transfer sequencer information to the power conversion unit
- An interface to ancillary equipment

D. Power conversion Unit:

This unit contains components required to take a signal from sequencer and convert it to the meaningful power level so that actuators can move.

3. Dynamic Model of Robot Manipulators:

We describe here robot manipulators and its dynamics. The manipulator is attached to a cart. The cart is moving in a particular direction and the manipulator is rotating with respect to a particular axis. The manipulator here is working as an excavating arm. The problem defined here is that the cart in which the arm (manipulator) is attached will move in a specific direction and will lift the object at a predefined place.

The mechanism is shown in the adjacent figure. The main body is propelled by a traction force F. The body is attached with a rotating arm of mass m and moment of inertia J about the axis of rotation. It is driven by an actuator located on the crane of the body. At the end of the arm, the end effecter is attached for picking up the object. In this model x_1 and x_3 are measurable. Now a days optical encoders are available. Optical encoders are of two types: linear and rotary. With the linear one we can measure linear displacement(x_1) and with the rotary we can measure angular displacement(x_3). The other two parameters viz x_2 and x_4 are estimated using Das & Ghosal observer for measuring velocity of the cart and rate of change of angular momentum respectively.

Let x_1 = Linear displacement of the cart
x_2 = Velocity of the cart
x_3 = Displacement of the link with vertical (θ)
x_4 = Rate of change of angular momentum ($\dot{\theta}$)
u_1 = Force applied
u_2 = Torque applied
M = Mass of the cart
m = Mass of the manipulator

For Mass M:

$M\ddot{x}_1 = F_x + F$ …… (1)

$M\ddot{y}_1 = R_1 + R_2 - F_y - M_y$ …… (2)

For mass m:

$m\ddot{x}_2 = -F_x$ …… (3)

$m\ddot{y}_2 = F_y - mg$ …… (4)

Torque equation :

$J\ddot{\theta} = aF_x\cos\theta - aF_y\sin\theta + T$ …… (5)

Eliminating F_x in Eqn (1) and (3) we get :

$M\ddot{x}_1 = -m\ddot{x}_2 + F$

$M\ddot{x}_1 + m\ddot{x}_2 = F$ ……. (6)

Eliminating F_y in Eqn (4) and (5) we get :

$J\ddot{\theta} + m\ddot{x}\, a\cos\theta + m(\ddot{y}_2 + g)a\sin\theta = T$ ……. (7)

From geometry, displacements are related to θ

$x_2 = x_1 + a\sin\theta$

$y_2 = -a\cos\theta$

$\ddot{x}_2 = \ddot{x}_1 - a\dot{\theta}^2\sin\theta + a\cos\theta\ddot{\theta}$ ……. (8)

$\ddot{y}_2 = a\sin\theta\,\ddot{\theta} + a\cos\theta\dot{\theta}^2$ …….. (9)

Putting the values of $\ddot{x}_2$ and $\ddot{y}_2$ in (7)

$(J + ma^2)\ddot{\theta} + ma\cos\theta\ddot{x}_1 + mag\sin\theta = T$ …….. (10)

Putting (8) in (6) :

$(M + m)\ddot{x}_1 + ma\ddot{\theta}\cos\theta - ma\sin\theta\dot{\theta}^2 = F$ ……… (11)

After doing Linearization,

We get
$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0\\ 0 & 0 & \frac{mag}{M(J+ma^2)+mJ} & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & -\frac{(M+m)mag}{M(J+ma^2)+mJ} & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix} + \begin{bmatrix}0 & 0\\ \frac{J+ma^2}{M(J+ma^2)+mJ} & \frac{-ma}{M(J+ma^2)+mJ}\\ 0 & 0\\ \frac{-ma}{M(J+ma^2)+mJ} & \frac{M+m}{M(J+ma^2)+mJ}\end{bmatrix}\begin{bmatrix}u_1\\ u_2\end{bmatrix}$$

And
$$y = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix}$$

Taking the standard values: J = 0.004 oz-s2., m = 0.75 lb., M= 1.0 lb., a = 0.8 m

$$\begin{bmatrix}\dot{x_1}\\ \dot{x_2}\\ \dot{x_3}\\ \dot{x_4}\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0\\ 0 & 0 & 39.44 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & -68.99 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix} +$$

$$\begin{bmatrix}0 & 0\\ 099 & -1.23\\ 0 & 0\\ -1.23 & 3.59\end{bmatrix}\begin{bmatrix}u_1\\ u_2\end{bmatrix}$$

$$y = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix}$$

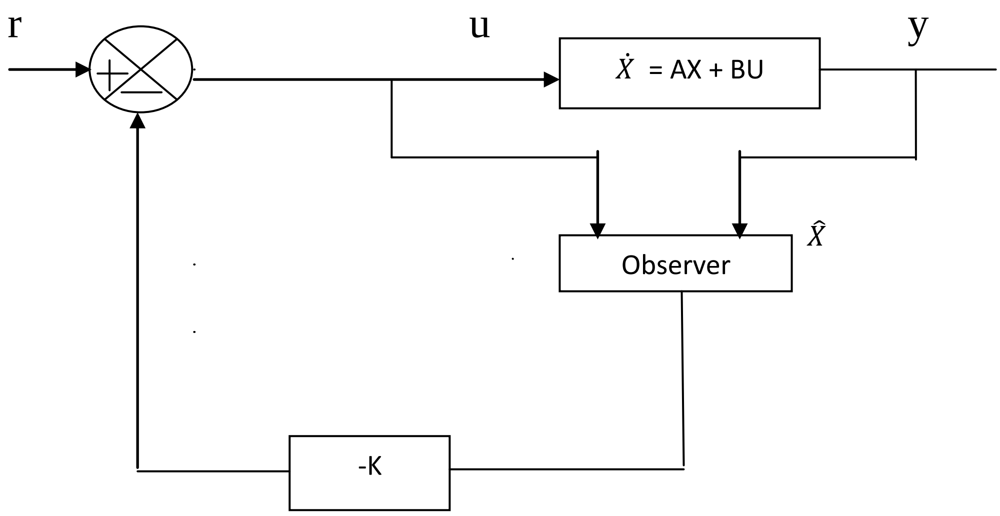
4. Observers

The input and output of a system are always physical quantities and are usually measurable. We therefore need a subsystem need a subsystem that performs the estimation of state variables based on the information received from the input u (t) and the output y (t). This subsystem is called an Observer whose design is based on the Observability property of the controlled system.

A plant is said to be completely observable if all the state variables in x (t) can be observed from measurements of the output y (t) and the input u (t). The block diagram is shown in the above figure. The two inputs to the system are Force (u1) and the torque (u_2). The system equation is described by $\dot{X}$ =AX + BU and the output as Y = CX. There is PI Controller which has two reference inputs designated as REF INPUT1 and REF INPUT2. The former represents the Position Reference whereas the later indicates Angle Reference. As we know that the inputs to the system are fed into observer so Force and Torque (as inputs to the system) are fed into the observer .Since a reduced order observer is used we know $\widehat{X_1} = X_1$ and $\widehat{X_3} = X_3$ But $\widehat{X_2} \neq X_2$ and $\widehat{X_4} \neq X_4$. The outputs are fed back into REF INPUT1 and REF INPUT2.

NB: r = u - K $\hat{X}$ = u - $K_{ij}\begin{bmatrix}\widehat{X_1}\\ \widehat{X_2}\\ \widehat{X_3}\\ \widehat{X_4}\end{bmatrix}$

Fig. 1



5. Plant Simulation along with Reduced Order Observer & State Feedback & Multiple Integrator

A. Governing Equations:

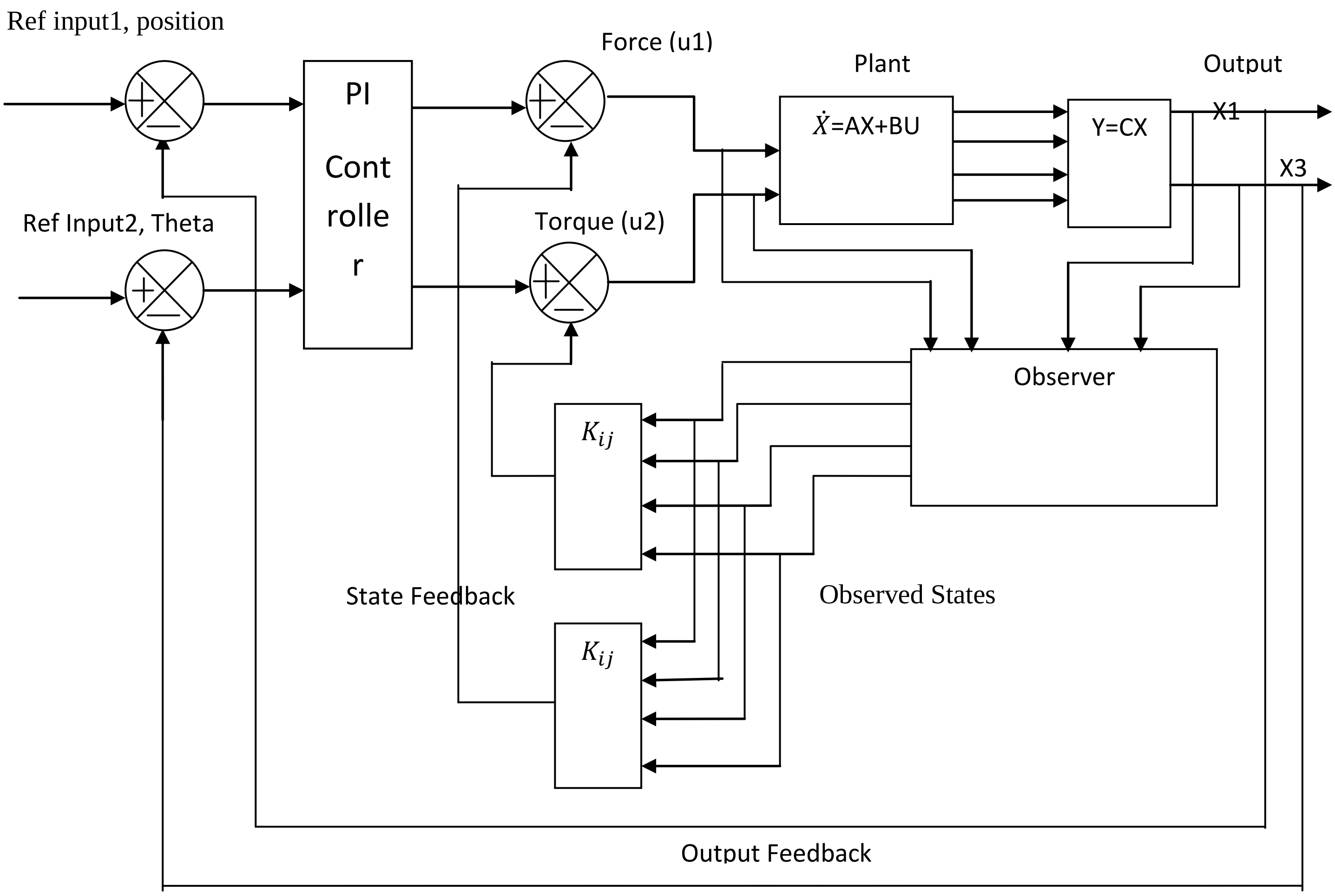
1) $\dot{X}$ =AX + BU
2) Y = CX
3) u = $K_i\, x_i$ - K $\hat{x}$
4) $\dot{X_\iota}$ = r – Y = r- CX
5) $\dot{\hat{q}} = \hat{A}\,\hat{q} + \hat{B}u + \hat{J}y$ (Dynamic Equation for Reduced Order Observer)
6) $\hat{X} = \hat{C}\,\hat{q} + \hat{D}y$ (Output / Mapping)
7) $\hat{A} = A_{22} - M A_{12}$
8) $\hat{B} = B_2 - MB_1$
9) $\hat{J} = (A_{22} - M A_{12}) *M + (A_{21} - M A_{11})$

The block diagram is shown in the figure. The two inputs to the system are Force (u_1) and the torque (u_2). The system equation is described by $\dot{X}$ =AX + BU and the output as Y = CX. There is PI Controller which has two reference inputs designated as REF INPUT1 and REF INPUT2. The former represents the Position Reference whereas the later indicates Angle Reference. As we know that the inputs to the system are fed into observer so Force and Torque (as inputs to the system) are fed into the observer .Since a reduced order observer is used we know $\widehat{X_1} = X_1$ and $\widehat{X_3} = X_3$ But $\widehat{X_2} \neq X_2$ and $\widehat{X_4} \neq X_4$. The outputs are fed back into REF INPUT1 and REF INPUT2.

$$\text{NB: } r = u - K\hat{X} = u - K_{ij}\begin{bmatrix}\widehat{X_1}\\ \widehat{X_2}\\ \widehat{X_3}\\ \widehat{X_4}\end{bmatrix}$$

6. Block Diagram:

Fig. 2



7. MATLAB Simulation Results:

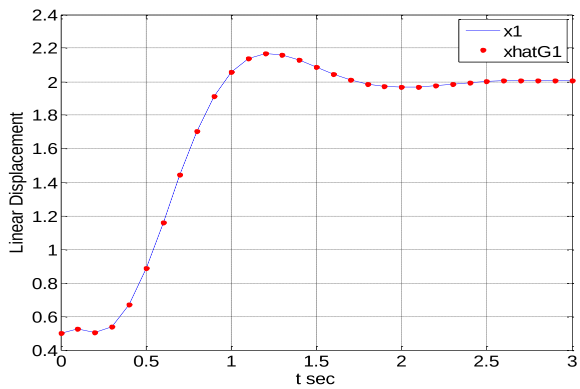


Figure 3: x4 is plant state and xhatG4 is estimated state

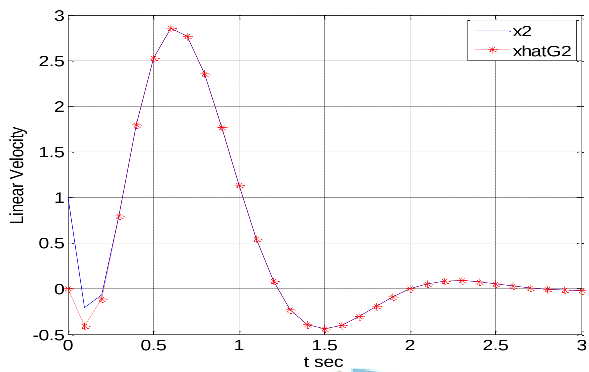


Figure 4: x2 is plant state and xhatG2 is estimated state

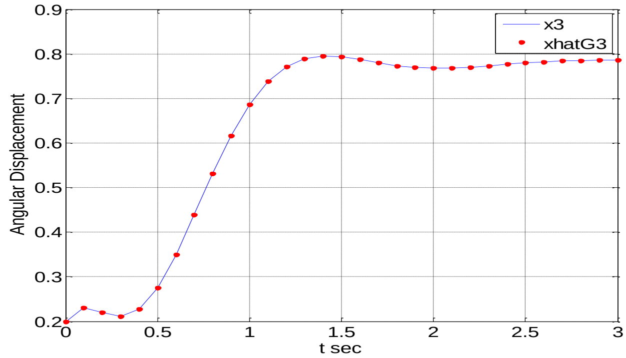


Figure 5: **x3 is plant state and xhatG3 is estimated state**

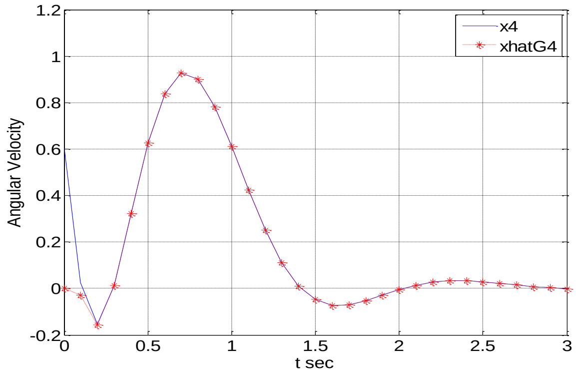


Figure 6: **x4 is plant state and xhatG4 is estimated state**

8. Discussion and Conclusion:

In this paper a robotic excavator arm, attached to a Crain, has been used to lift an object from ground to a certain height and at a specified distance towards a particular direction. Reduced order Das & Ghosal observer has also been implemented in this application to estimate two states – linear velocity and angular velocity. Though these two states can be measured but these are being estimated because to measure angular velocity gyroscope along with gimbals system is required which are very difficult to set up. That's why observer has been used and other two states i.e. linear displacement and angular displacement can be easily measured by using linear and rotary optical encoder or proximity sensors which are much simple to be set up. From the responses it is seen that the estimated states i.e. xhatG2 and xhatG4 catch the original plant states within a very short period of time (in this case within less than 0.4 second). So performance wise it is working very well. From the responses of x1 and x3 i.e. linear displacement and angular displacement respectively, it can be readily inferred that the excavator arm has reached the specified goal (in this simulation 2meter distance is taken to be covered and the object has to be raised to 45 degree angle from ground) very smoothly within only 3 seconds.

To realize state feedback control all states are required to be fedback. So in practical robotic system also reduced order observer can be implemented successfully to estimate the states which are not accessible for direct measurement or very difficult to be measured. If all the eigen values of the observer system are properly chosen in the left half of 's' plane then it does not impair the stability of the overall system, it simply add it's own eigen values to the closed loop system's eigen values. Also the observer system does not degrade the performance of the original plant.

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