State Variables Estimation of Flexible Link Robot Using Vision Sensor Data

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Abstract: The estimation of state variables plays a significant role in the control of flexible link robots. Flexible robots can have very complex dynamic vibrations during their operations. A vision sensor (i.e. camera) realizing a contactless measurement sensor can be used to measure the deformations. Unfortunately effects like limited accuracy and time delay occur, which are the main inherent problems of vision sensors. The effects and compensation are studied in this work. The dynamic model of the flexible link is derived using the finite element method. Two observers are designed, the first one to estimate the vibrations using strain gauges (fast and complete dynamics), and the second one to estimate the vibrations using vision data (slow dynamical parts). The effects of time delay and noise in states estimation are shown by the comparison of the states from different measured input data. The main goal of the work is to develop an approach to combine suitable measurement devices easy to realize with improved reliability. The contribution describes the combination of the two estimated dynamical parts of the system dynamics. The task to be solved is to combine the estimations of the slow observer (based on vision measurements) with those of the fast observer based on strain gauges.

Keywords: state estimation, camera sensor, flexible robot, delayed measurement, data fusion.

1. INTRODUCTION

The technical progress in processors, digital electronics, and vision sensors (i.e. computer equipment's, cameras) caused an increased use of visual servoing in robotics applications. Compared to rigid robots the end effector position of flexible links cannot be obtained precisely enough based on the kinematics and joint variables, because the position of any point of a flexible link is not only related to the joint angles but also to the link flexural displacements. A vision sensor (camera) represents a contactless virtual movable measurement sensor, or a set of sensors working in the same time (i.e. getting a set of data from the camera), therefore visual servoing can be used effectively to control flexible manipulators. The research on flexible robots with vision based control was initiated in the early 1990s. In Tang et al. (1990) the camera system is used as a deflection measurement sensor of the flexible link. Skaar and vision sensors have been used by several researchers for tip-position measurement of flexible two-link manipulators (Obergfell and Book (1996)). The main inherent problem was the slow processing operation due to the limitations of the camera system in combination with the real time operation of the system. Therefore special techniques are developed in order to reduce the data processing time. An analytical criterion for the selection of suitable sensors for the control of structures with flexible bodies was developed in Stieber et al. (1999). The state estimation of a single link flexible manipulator was studied in Yoshikawat et al. (2001); the vision system was used to estimate the state variables of the virtual joint model of a flexible link. Due to the slow image processing operation in comparison with the real time control several researchers used a two time scale control (Bascetta and Rocco (2006)), Jiang et al. (2007) to overcome these problems. Other researchers developed new approaches of state estimators dealing directly with time delay and noise Zhang et al. (2006), Lu et al. (2008) in detail observers increase the reliability and the realization of practical approaches are designed. In this work the effect of time delay and noise in state estimation process of flexible robot arm are shown through the comparison between the states from different measured input data. The flexible link model used, is related to an elastic ship mounted crane. The seperation of the dynamics is based on the frequencies of the system. The slow dynamics is choosen using assumed camera specifications. Two observers are designed, the first one to estimate the higher modes of the vibration using strain gauges, the second one represents an estimator using the camera as a sensor to estimate a modal set of slow dynamics based on the measurable frequencies of the modes. Below, section 2 describes briefly the dynamic model of a flexible link. The state estimator design follows in section 2. In section 4 the simulation results are shown. Conclusions of the paper are made in section 5.

2. MODELING OF FLEXIBLE LINK

The basis of the model used in this work is related to the elastic ship mounted crane designed by SRS\(^1\) (Fig. 1). The boom in this crane consist of a flexible, and of a rigid part combined together. The flexible part of the boom is

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can be written as

The elastic vibration for a beam consisting of five elements torsion are neglected. The link is assumed to be clamped at primary inertia, transverse shear deformation, axial forces, and using the FE method (Al-Sweiti (2006)), the effects of ro-

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The link is assumed to be clamped at $x = 0$. The elementary dynamic model matrices related to the elastic vibration for a beam consisting of five elements can be written as

$$
M_T \ddot{v}_T + D_T \dot{v}_T + K_T v_T = F_T,
$$

where the $M_T, D_T, and K_T$ matrices represent the $12 \times 12$ mass, damping, and stiffness matrices respectively, $F_T$ represents the $12 \times 1$ force vector, $v_T$ represents nodal translational and rotational displacements variables as

$$
v_T = [\omega_1 \ \theta_1 \ \omega_2 \ \theta_2 \ \cdots \ \omega_5 \ \theta_5]^{T}.
$$

The translational and rotational displacements at $x = 0$ must be zero ($\omega_1 = 0$, $\theta_1 = 0$). The complete system is described by

$$
M \ddot{v} + D \dot{v} + K v = F,
$$

where $M, D, and K$ represent the global $10 \times 10$ mass, damping, and stiffness matrices respectively, $F$ represents the $10 \times 1$ force vector, and $v = [\omega_2 \ \theta_2 \ \omega_3 \ \theta_3 \ \cdots \ \omega_6 \ \theta_6]^{T}$.

The matrix differential equation (3) is represented in a state-space form as

$$
\dot{z} = Az + Bu,
$$

$$
y = Cz + \eta,
$$

with

$$
A = \begin{bmatrix} 0_n & I_n \\ -M^{-1} K & -M^{-1} D \end{bmatrix}, \quad B = \begin{bmatrix} 0_n \\ M^{-1} I_n \end{bmatrix},
$$

$$
C = \begin{bmatrix} C_1 \\ C_2 \end{bmatrix},
$$

here $z$ denotes the $(2 \times n) \times 1$ state vector and $\eta$ represents the measurement noise, with $n = 10$. The values of the elements of matrix $C$ are depending on the sensor gain of the measuring sensor.

In order to separate the state space model (4) to fast and slow subsystem, the state transformation is defined as

$$
z(t) = Tx(t),
$$

with $T$ as nonsingular transformation matrix, the state space model is written by replacing $z$ in (4)

$$
\dot{x} = T^{-1} Ax + T^{-1} Bu,
$$

$$
y = Ctx + \eta.
$$

to obtain

$$
\dot{x} = \hat{A}x + \hat{B}u,
$$

$$
y = \hat{C}x + \eta.
$$

The resulting state matrix from this equation is diagonal/blockdiagonal. By reordering the system states are separated to slow and fast subsystems. The state space equations corresponding to the dynamic separation can be expressed in vector form as

$$
\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \hat{A}_1 & 0 & 0 \\ 0 & \hat{A}_2 & 0 \\ -
\hat{C}_1 & \hat{C}_2 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \eta \end{bmatrix},
$$

In (8) the slow dynamical system can be generated from the overall system according to the frequencies of the modes. The states related to the slow dynamic should be estimated by using the signal from the camera system. An augmented predictor for the delay and noise compensation described in the next section can be used for overall optimal estimation.

3. STATE ESTIMATOR DESIGN

In this work the flexible link model is observed with two types of sensor: strain gauge sensor to observe the overall dynamic states, camera sensor to observe the slow motion of the beam. The vision data, which provide direct measurements of the deflection with respect to inertial coordinate, proves to be a good substitute for
strains. Related to the description (8) two different measurements
\[
y_1(t) = \tilde{C}_1 x_1(t), \\
y_2(t) = \tilde{C}_2 x_2(t - \tau) + \eta(t - \tau),
\] (9)
are used. Here \( \tau \) denote the time delay between the two
sensor types, which is equal to the time of the image frame
transfer and processing.

Practically there will be time delay and noise in the all
types of measurements; here the delay and the noise for the
strain gauge signal are neglected in comparison with the
camera signal. Due to the limitations of the sampling rate,
the vision sensor.

3.1 State Estimator for Non-delayed Measurement

For the non-delayed measurement (based on the strain
gauge signal) the estimated modes are estimated using classical
observer approach as
\[
\dot{x}_1 = (\tilde{A}_1 - K_1 \tilde{C}_1) \tilde{x}_1 + \tilde{B}_1 u + K_1 y_1,
\] (10)
where
\[
K_1 = P_1 C_1^T R_1^{-1}
\]
and \( P_1 \) as the solution of the Riccati
equation described as
\[
\tilde{A}_1 P_1 + P_1 \tilde{A}_1^T - P_1 \tilde{C}_1^T R_1^{-1} \tilde{C}_1 P_1 + Q_1 = 0,
\] (11)
where \( Q_1 \) and \( R_1 \) are positive definite weighting matrices
for the non-delayed states and measurements respectively.

3.2 State Estimator for Noised-delayed Measurement

The advantage of using the camera as a tip sensing device
is the direct inertial measurement. The disadvantage is
a delayed and noisy measurement signal. The delay is
due to the time used in the vision processing and video
signal transmission. In this section the method of defining
states using an augmented predictor for the delay and
noise compensation is described. Here, a Kalman filter
is proposed for the delayed estimation. According to Roberts
(1986), and assuming that the estimated states are delayed
by \( \tau \), the Kalman filter equation can be written as
\[
\dot{x}_2(t - \tau) = (\tilde{A}_2 - K_2 \tilde{C}_2) \tilde{x}_2(t - \tau) + \tilde{B}_2 u + K_2 y_2(t - \tau),
\] (12)
where
\[
K_2 = P_2 \tilde{C}_2^T R_2^{-1}
\]
and \( P_2 \) is the solution of the Riccati
equation described as
\[
\tilde{A}_2 P_2 + P_2 \tilde{A}_2^T - P_2 \tilde{C}_2^T R_2^{-1} \tilde{C}_2 P_2 + Q_2 = 0,
\] (13)
where \( Q_2 \) and \( R_2 \) are positive definite covariance matrices
for the noised-delayed measurement.

To remove the delay effect from the estimated states, a
function \( g \) is defined as
\[
g(t) = \tilde{A}_2 g(t) + \tilde{B}_2 u,
\] (14)
and the non delayed state estimate can now be found as
\[
\hat{x}_2(t) = g(t) + e^{\tilde{A}_2 \tau} \hat{x}_2(t - \tau) - g(t - \tau)
\] (15)
3.3 Combination of the Estimated States

The schematic diagram for the estimation approach is
shown in Fig. 3. Each estimator described before are used
To predict the related modes. The full state estimation can
be found by using (5) as
\[
\dot{\hat{z}} = T \begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \end{bmatrix},
\] (16)
However, in practical implementation the states of the system
can be estimated from different measurements by combining
of all of the corresponding state variable estimates. In
this work for the sake of comparison the full system states
are also estimated based on the strain gauge measurement
and this can be done by changing the variables in (10) by
the complete system dynamics. The states from the second
estimator are combined with the same set of states, which
are estimated using the full observer using the minimum
mean-squared error \( \hat{x} \), with
\[
\dot{\hat{x}}_i = \frac{q_{i,1} \hat{x}_{1,i} + p_{i,1} \hat{x}_{2,i}}{q_{i,1} + p_{i,1}}, \quad i = 1, \ldots, n_1,
\] (17)
here \( n_1 \) denotes the number of slow modes. An optimal
estimation can be achieved, when they are combined properly.
The derivation process of \( q_{i,1}, p_{i,1} \) is explained in detail
in Roberts (1986). Note, that the subscripts ‘1’ and ‘2’
in the states represent cases that the states are estimated
based on measurements ‘1’ and ‘2’, respectively. The transformed
states are used in (17) due to the parameters \( q, p \)
which are related to transformed states.

4. SIMULATION RESULTS

The parameters used in this work for the system illustrated
in section 2 are:
Fig. 4. Simulated measurement of the camera sensor, impulse input

Fig. 5. Simulated measurement of the camera sensor, sweep input (Eq. 18)

Fig. 6. Effects of noise and time delay on the estimated states, impulse input

Fig. 7. Effects of noise and time delay on the estimated states, sweep input (Eq. 18)

Here $a$ denotes the amplitude of the sweep function. The simulation for the measurements of the camera sensor for the 6th node after the applying the input forces is illustrated in Fig’s. 4 and 5. Here node 6 denotes the end effector point of the flexible link. The noise in the signal is generated by adding the random number to the white noise signal and is multiplied the result by a propriate factor related to the measurement signal. The time delay is assumed equal to 0.15 sec. Practically the total delay time can be determined by comparing the camera measurement to the strain gauge measurement for the same node.

4.1 Effect of Noise and Delay on Estimated States

The simulated measurement of the strain gauge for the 3rd node is used to estimate the full states of the system by using a full state observer. The simulated camera measurement is used to estimate the full states of the system. The estimation of the full states using the camera measurement is to show the effect of the noise and the time delay in the estimated state varibles Fig’s 6, and 7. These figures shows the error in the set of estimated states for each type of camera measurement. In these two figures $e$ represent the difference between the two case of estimation $(\hat{z}_c - \hat{z}_s)$, where c, s represent camera and strain gauge respectively, for each type of inputs.

4.2 Compensation of Noise and Delay

It can clearly be seen from the estimated tip point error in Fig’s. 8 and 9 that the slow and fast state estimator dynamics compensates the noise and delay from the estimated states for the each type of input. The observer and estimator which are designed in this work follow the states and remove the effects of noise and time delay very fast. The estimated states of the slow dynamic are combined with the estimated states from the observer to get an optimal augmented state estimation (Fig’s. 10 and 11).

5. CONCLUSIONS AND FUTURE WORK

In this work the estimation of the state variables of the flexible link robot model, which will later be related to an elastic ship mounted crane, is studied. This model is
separated to slow and fast dynamics based on assumed camera specification. Two observers are designed using the fast and slow dynamics, the first one to estimate the higher modes of the vibration using strain gauges, the second one represent an estimator using the camera as a sensor to estimate a modal set of slow dynamics based on the frequency of the system states. The two estimators works well. The states from the noisy delayed measurement are estimated with an acceptable accuracy. The proposed method of states estimation will be used later for the more complicated system, by integrating the flexible link with the overall dynamics of the elastic ship mounted crane.

REFERENCES


