Network Based Control of 2-DOF Serial Flexible Link Manipulator

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Abstract—As a new generation of robot, lightweight flexible manipulator presents various applications in the field of advanced medical, modern industry, space and defense application, etc. Nowadays, these applications need control of flexible-link manipulator (FLM) from a distance, so the use of the network is essential for receiving the sensor signal and transmitting actuator signal. In this work, a new concept of network based control of 2-DOF Serial Flexible Link Manipulator (NC-2DSFLM) is introduced. The issue of communication delay and packet dropout is considered in the modeling of 2DSFLM. It is essential to use delay compensation technique to deal with the network induced issues actively. Here, digital smith predictor (DSP) based delay compensation technique has been developed with the objective of mitigating the detrimental effects of the network induced delays that are distributed between the sensor, controller, and actuator within a control loop of NC-2DSFLM. The performance of the framework of NC-2DSFLM is investigated by modeling and simulation of dynamics of NC-2DSFLM in MATLAB and SIMULINK environment.

Keywords: 2-DOF Serial Flexible Link Manipulator, Delay Compensation, Digital Smith Predictor, Network Control System.

I. INTRODUCTION

Flexible link manipulator (FLM) is a lightweight new generation robot. FLMs are more maneuverable and more transportable compared to the rigid manipulator. The Dynamics of FLMs possess mechanical flexibilities in the links, unlike rigid manipulator. FLM experience rigid and flexible types of motion. The resulting dynamic equations of FLM are highly complex, because of the rigid and flexible motions. So, the control task becomes more complicated compared to that for the rigid manipulator [1].

A Networked Control System (NCS) is a control system wherein, the traditional feedback control system is closed via a communication network. The functionality of a typical NCS is established by the use of four basic elements sensors, controllers, actuators, and communication network. The applications of network control system (NCS) are paradigms that are growing faster in an area like medical, space and industries. There are two type of network, dedicated and non-dedicated used for communication in NCS. The non-dedicated networks are advantageous due to lesser cost, ready availability. However, delays and packet losses are encountered in such systems due to the time taken in transporting information from one node to another. In this work, implementation of NCS to manipulate a flexible manipulator is presented. NC-2DSFLM realizes from techniques of robotics and computer science. A 2DSFLM is teleoperated through NCS, in which multiple nodes have been used to acquire and exchange sensor/actuator signal and to compute robotic algorithm. It will allow the interface between controller node and 2DSFLM by using the network. In NC-2DSFLM, the presence of communication network causes many issues like signal sampling, data quantization, communication delay, packet dropout, medium access constraints, channel fading, power constraints. Network delay and packet dropout are major issues in NC-2DSFLM. That deteriorate the tip tracking performance of 2DSFLM. In [2], Implementation of a network control system has been implemented for a robotic manipulator as cloud service.

The objective of this work is, to build a network controlled 2-DOF Serial Flexible Link Manipulator, so that one can apply it in the remote and hazardous area. To achieve this objective, it is necessary to model time delay and packet dropout in the modeling of 2DSFLM, which can simplify the controller design for NC-2DSFLM. Finally, delay compensation technique needed to be developed to improve the tip tracking performance by dealing with network induced issues. In this work, a communication delay is modeled as random transport delay, packet dropout has been modeled as a two-state switch, and assumed mode method (AMM) [3] considered for dynamic modeling of the flexible manipulator. Also, digital smith predictor based delay compensation technique has been implemented for moderating the effects of the network induced delays.

In this article, new concept of network based control of 2DSFLM is presented. This paper has been organized as follows: Section-I includes a brief description plans, motivation, the necessity of NC-2DSFLM and purpose of this work. Mathematical modeling of NC-2DSFLM using AMM has been shown in the Section-II. Delay estimation techniques are discussed in Section-III. Implementation, results and discussions are presented in the Section-IV, and conclusions of the work and suggestions for the future research has been provided in the Section-V.
II. MODELLING OF THE NC-2DSFLM

The structure of NC-2DSFLM:

The structure of NC-2DSFLM comprises of the controller and a remote system containing a 2DSFLM, sensor, and actuator. The sensor is used to acquire information, to provide commands and decision controller is used, the actuator is used to perform control command, and the network is used to enable the exchange of information. Fig. 1 shows the structure of NC-2DSFLM.

Model Description:

In FLM, due to flexure nature of the link, the positioning and tracking of tip are very difficult. In this study, it is assumed that link is moving in a horizontal plane, have constant cross-sectional area and have uniform material properties [4]. The tip of the 2DSFLM is attached with a payload of mass \( m \).

The dynamics of 2DSFLM is given in [3] is

\[
M(\theta_i, \delta_i) \begin{bmatrix} \dot{\theta}_i \\ \dot{\delta}_i \end{bmatrix} + \begin{bmatrix} c_1(\theta_i, \delta_i, \dot{\theta}_i, \dot{\delta}_i) \\ c_2(\theta_i, \delta_i, \dot{\theta}_i, \dot{\delta}_i) \end{bmatrix} + \begin{bmatrix} 0 \\ \delta_i \end{bmatrix} + \begin{bmatrix} \tau_i \\ \dot{\delta}_i \end{bmatrix} + \begin{bmatrix} 0 \\ \delta_i \end{bmatrix} = \begin{bmatrix} 0 \\ \delta_i \end{bmatrix} \]

(1)

where \( M \) is the positive definite symmetric inertia matrix, \( c_1 \) and \( c_2 \) are the Coriolis and Centrifugal forces vectors, respectively, \( K \) is the stiffness matrix, and \( D \) is the Damping Matrix. The complete system behaves as a non-minimum phase system, when tip position is taken as output. Hence the elastic displacement is redefined as

\[
y_{pi} = \theta_i + \left[ \frac{d_i(l_i, t)}{l_i} \right]
\]

(2)

where \( l_i \) is the \( i^{th} \) link length. The dynamics of 2DSFLM (1) can be rewritten in state space form as

\[
\dot{x} = Ax + Bu
\]

\[
y = Cx
\]

where

\[
A = \begin{bmatrix} 0_m & I_m \\ -M^{-1}K & -M^{-1}D \end{bmatrix}, B = \begin{bmatrix} 0_{m \times 1} \\ M^{-1}e_1 \end{bmatrix},
\]

\[
c = \begin{bmatrix} 0_m & I_m \end{bmatrix}, \quad u_i = \begin{bmatrix} \tau_i \\ 0 \end{bmatrix}^T, \quad x_i = \begin{bmatrix} \theta_i \\ \dot{\theta}_i \\ \delta_i \\ \dot{\delta}_i \end{bmatrix}^T.
\]

Time Delay and Packet Dropout:

In NC-2DSFLM, there are three nodes i.e. sensor node, controller node and actuator node. The sampling method assumed for the sensor to controller communication is a time-driven sampling. The control computation and nodes are assumed to be synchronized at sampling interval \( h \) with the \( k^{th} \) sampling instant is denoted as [5]. Computation delay (\( n_{ck}^c \)), controller-to-actuator delay (\( n_{ca}^c \)) and sensor-to-controller delay (\( n_{sc}^c \)) are types of delay occurs in NC-2DSFLM, that is shown and explained in Fig. 3.

![Fig. 3: Delay in NC-2DSFLM](image)

The network induced delay in the feedback channel is defined as \( n_{dc}^a(k) \) regarding multiples of \( h \). Since the number of packet losses is integer multiples of \( h \), these can be appended to the delay in the feedback channel as shown in Fig. 4. Let \( n_{dc}^p(k) \) be the number of packet losses. The appending the packet losses to the delay i.e. \( n_{dc}^p = n_{dc}^a(k) + n_{dc}^p(k) \) with the condition \( n_{dc}^c \leq n_{dc}^p \leq \bar{n}_{dc} \).

On the other hand, the controller to actuator communication is assumed to be event-driven one. For this, the normalized controller to actuator delay, i.e. \( h^{-1} \) (actual delay value) is denoted as \( n_{ca}^a \). It is assumed to be bounded as

\[
n_{ca}^d \leq n_{ca}^a(k) \leq \bar{n}_{ca}^d
\]

(4)
Fig. 4: Time delay diagram of NC-2DSFLM

where \( n_{ca} \) and \( \bar{n}_{ca} \) are integers. Since the packet loss is integer multiple of the sampling interval due to the time-driven sending node at the controller end, the packet loss is considered as

\[
0 \leq n_{ca}^{pa}(k) \leq \bar{n}_{ca}^{pa}
\]  

(5)

For feedback system with periodic sampling and ideal data transmission channel, the closed loop system (3) is equidistantly updated by

\[
h = t_{k+1} - t_k
\]  

(6)

The values of the state vector \( x(t_k) \) arrive at the controller side with a feedback time delay \( n_{sc}^{ex} \) consisting of time delay and packet dropout. At the controller side, the holding interval between two consecutive updates at time instants \( t_k + n_{k}^{sc} \) and \( t_{k+1} + n_{k+1}^{sc} \) is denoted by \( h_k \).

\[
h_k = \left( t_{k+1} + n_{k+1}^{sc} \right) - \left( t_k - n_{k}^{sc} \right)
\]  

(7)

As a result (3) becomes a sampled data system with the feedback delay \( n_{k}^{sc} \).

\[
x(t) = Ax(t) + BKx(t_k)
y(t) = Cx(t)
t \in \left[ t_k + n_{k}^{sc}, t_{k+1} + n_{k+1}^{sc} \right]
\]  

(8)

The discrete time approximation of (8) using forward difference approximation is expressed as

\[
x_m(k+1) = A_dx_m(k) + B_du(k)
y_m(k) = Cx_m(k)
\]  

(9)

where \( x_m(k) \), \( u(k) \) and \( y_m(k) \) are a discrete state, input, and output respectively. The control problem to be addressed is formulated as follows.

**Control Problem:**

Given a system with random feedback time delay, so the objective is to find a control input \( u(k) \) such that when \( k \to \infty \), the system output sampled data \( y(k) \) at \( t = h \) with \( k^{th} \) sampling instance will track desired output trajectory.

That means that developed control scheme for closed-loop system (9) should guarantee: (i) trajectory of output \( y(k) \) should asymptotic track reference signal and, (ii) bounded in exponentially mean-square sense.

**III. DELAY COMPENSATION**

Communication delay is unpredictable events along the communication path. If this delay is not compensated, may destabilize the system. Thus it is essential to address delay compensation method for variable communication delay. Various delay compensation techniques have been formulated based on some specific assumption, types of network behavior and configurations [6].

Delay Compensation techniques can be categorized into three groups: predictive, tele-programming and direct delay compensation. Predictive delay compensation method is depending on prior knowledge of controller and remote system. Tele-programming delay compensation method uses a complicated model to produce a high level command, but it is not accurate and requires backtracking. Direct delay compensation uses passivity theory to guarantee stability, but system performance is affected [7].

In this work, digital smith predictor (DSP) based delay compensator for communication delay and packet losses have been proposed. NC-2DSFLM with Digital smith predictor based delay compensator is shown in Fig.5.

**Fig. 5: NC-2DSFLM with DSP**

The input to the controller block can be written as

\[
v(k) = y_m(k - n_d) - y_m(k) - y(k - n_{k}^{sc})
\]  

(10)

In (10), predictor delay \( n_d \) is selected by the designer. The first term compensates the delayed output signal and the...
The second term is predicted plant output. Delay compensation is achieved only when \( n_d = n_{k_c}^{sc} \).

In this model, a static feedback controller is considered as

\[
  u(k) = Kv(k)
\]  

(11)

**Discretization of the NC-2DSFLM:**

The discretized plant dynamics of (8) with (11) can be re-written as

\[
x(k + 1) = Ax(k) + BKv(k) \\
  = Ax(k) + BK(y_m(k - n_d) - y_m(k)) \\
  - v(k - n_{k_c}^{sc}) \\
  = x(k) + BKx_m(k - n_{k_c}^{sc}) \\
  + BKx_m(k - n_d - n_{k_c}^{sc}) \\
  - BKx_s(k - n_{k_c}^{sc} - n_{k_a}^{ca})
\]  

(12)

Both the channel delay \( n_{k_c}^{sc} \) and \( n_{k_a}^{ca} \) appears independent and combine in (12). The effect of the term \( BKx_s(k - n_{k_c}^{sc} - n_{k_a}^{ca}) \) compensated by \( BKx_m(k - n_d - n_{k_c}^{sc}) \) in (12). Then (9) can be re-written using (11) as

\[
x_m(k + 1) = A_dx_m(k) + B_dKv(k) \\
  = B_dKx_m(k - n_d) - B_dKCx_s(k - n_{k_c}^{sc}) \\
  + (A_d - B_dKC)x_m(k)
\]  

(13)

In (13), term \( x_m(k - n_d) \) helps to compensate the network delay \( n_{k_c}^{sc} \).

**IV. IMPLEMENTATION, RESULT, AND DISCUSSION**

In this section, simulation of NC-2DSFLM model have been performed which is derived in Section-II and analyze the performance of proposed DSP based delay compensator in Section-III. Network time delay is modeled as transport delay, and packet dropout is modeled as a two-state switch, where \( \theta \in \{0, 1\} \) is called receiving sequence that indicates reception (\( \theta = 1 \)) or loss (\( \theta = 0 \)). Table I shows the physical parameter of link-1 and link-2. In this simulation, considered torque input for link 1 and 2 of 2DSFLM is symmetric bang-bang torque input of 0.3 Nm and 0.2 Nm amplitude respectively.

Fig. 6 and Fig. 9 show the control input of stage 1 and 2 respectively. Fig. 7 and Fig. 10 show hub angular response of link-1 and 2.

**TABLE I: Physical Parameter of Link-1 and 2.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Link-1</th>
<th>Link-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link length</td>
<td>( L_1 = 0.201m )</td>
<td>( L_2 = 0.2m )</td>
</tr>
<tr>
<td>Elasticity</td>
<td>( E_1 = 2.0684 \times 10^{11} N/m^2 )</td>
<td>( E_2 = 2.0684 \times 10^{11} N/m^2 )</td>
</tr>
<tr>
<td>Rotor Moment of Inertia</td>
<td>( J_{m1} = 6.28 \times 10^{-6} kg/m^2 )</td>
<td>( J_{m2} = 1.03 \times 10^{-6} kg/m^2 )</td>
</tr>
<tr>
<td>Drive moment of Inertia</td>
<td>( J_1 = 7.361 \times 10^{-6} kg/m^2 )</td>
<td>( J_2 = 44.55 \times 10^{-6} kg/m^2 )</td>
</tr>
<tr>
<td>Link Moment of Inertia</td>
<td>( l_1 = 0.17043 kg/m^2 )</td>
<td>( l_2 = 0.00643872 kg/m^2 )</td>
</tr>
</tbody>
</table>

Fig. 8 and Fig. 11 shows tip acceleration performance of link-1 and 2 of 2DSFLM considering only time delay (TD). It is also observed, large amount of undershoot occurs in tip acceleration response due to network induced delay that deteriorate the tip tracking performance of 2DSFLM.
Now, performance of DSP based delay compensator is analyzed. It is observed from Fig. 12 and Fig. 13 undershoot occurs in tip acceleration response due to network induced delay is minimized, and also improves the stability performance. Different network control system technique can be used in development of NC-2DSFLM, and also applied in various emerging applications.

V. CONCLUSION

A new concept of network controlled 2-DOF serial flexible link manipulator (NC-2DSFLM) is introduced in this work. In which, NCS has been implanted for 2DSFLM. This NC-2DSFLM is generating applications that are useful in several areas such as flexible manufacturing, disaster management, health care, space exploration, education, etc. In this work, the issue of communication delay and packet dropout is considered in the modeling of 2DSFLM. Communication delay is modeled as random transport delay, and packet dropout has been modeled as a two-state switch. Also, digital smith predictor (DSP) based delay compensation technique has been developed with the objective of mitigating the detrimental effects of the network induced delays. The performance of developed theory has been investigated by modeling and simulation of NC-2DSFLM in MATLAB and SIMULINK environment. In future, adaptive smith predictor based delay compensator for estimating the predictor delay ($n_d$) can be applied for delay compensation of NC-2DSFLM.
REFERENCES


