Delay Handling for an Adaptive Control of a Remotely Operated Robotic Manipulator

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Abstract*—This paper presents a time delay analysis of an adaptively controlled two link rigid Revolute-Revolute joint type manipulator when the device is remotely triggered or controlled. Such a manipulator could be connected to the internet and is controlled by a remote user through an internet server. However a delay is produced when the feedback signals reach the controller at the user's end. This delay is often found to severely pull down the accuracy of the manipulator in terms of its ability to execute a trajectory. The deviation from the desired to the drawn trajectory in this paper is calculated using the Hausdorff metric. Analysis with several values of delay clearly depicts an increase in inaccuracy of the output with increasing delay. The variation of the Hausdorff error with changes in control parameters of the system is also described. It is found that there exists a critical delay value above which the system practically fails to complete the objective. The dynamic equations of motion of the system have been formulated using the Lagrange-Euler method. A PD feedback controller is used for control. This analysis and determination of the critical delay is crucial for remotely triggered devices and will find application in the control of tele-robots.

Keywords—time delay, adaptive control, robotic manipulator, error analysis

I. INTRODUCTION

The study of time delay on an adaptively controlled two-link rigid Revolute-Revolute joint type manipulator (Fig. 1) is the focus of this paper. The robot is connected to the user via the internet or any other internal network. Fig. 2 shows the block diagram of the robotic system. If the controller and the robot are separated in space, then due to the time delay involved in transmission of the control signal and receiving of the feedback signal, there would be a time difference between the application of control command and the sensing of the state of the robot. Generally the user inputs the robot end effector states to the controller and so when the end effector states are time varying, due to the time-delay in feedback, there will be errors.

Remotely controlled robots have been the focus of several researchers. Work in real time remote manipulation [1] and applications in minimally invasive surgery [2] has received much attention in recent years. Teleoperation using haptic interfaces is also being carried out by many researchers [3]. Various control schemes and methods in this direction have been described in [4-6]. Monitoring of such systems along with active camera control has been described in [7].

Internet based control has received focus in recent time. The design of virtual instruments for real time experimentation has been discussed in [8]. The various issues with internet based control and the development of internet models has been described in [9]. In [10] the difficulty of time delay is dealt with compensators. An overview of control methods in tele-operation with time delays is discussed in [11].

The remote internet control of a robotic arm involves the process of encoding, transfer and decoding of data in the form of control and feedback signals over the internet. These processes cause the aforementioned time delay. During experiments with a remotely triggered robotic arm, it is observed that time delays play an important role in the accuracy of the robotic arm pertaining to the execution of a desired trajectory.

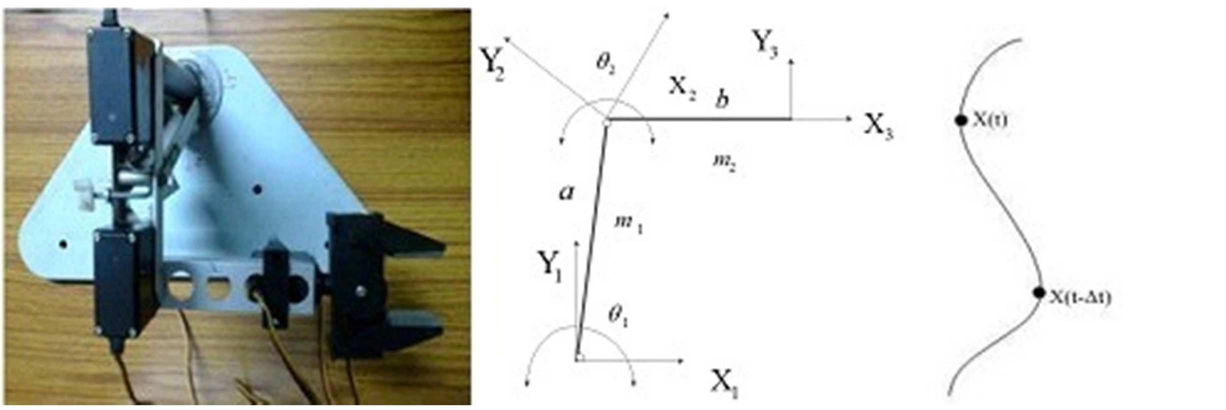


Fig. 1 (a) Actual Manipulator, (b) Representation of the manipulator, (c) a typical end effector trajectory

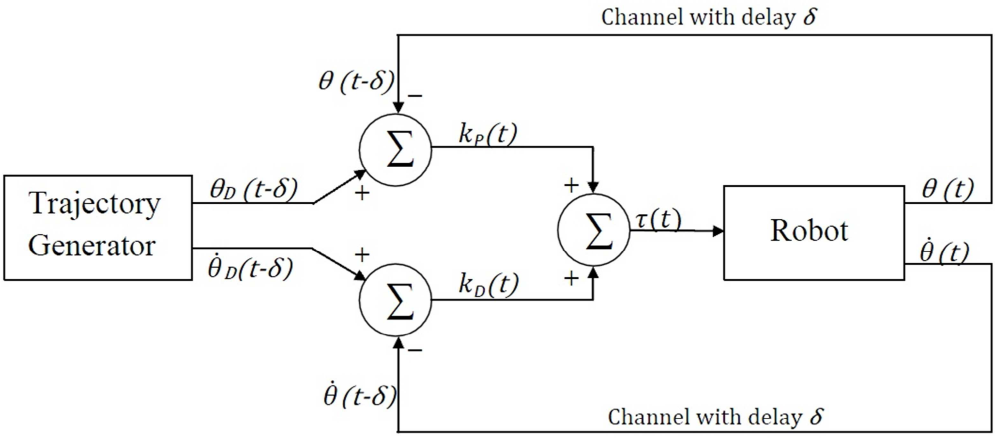


Fig. 2 Block Diagram of Robotic System

These delays often vary with distance to the device along with the network connection. The present work analyses the effect of time delays on such a system and attempts to correlate time delay with the accuracy of the robotic arm. For the analysis, it is assumed that the user inputs a time varying input (end effector path) to the controller. The accuracy of the robotic arm can be visualized by the deviations of the robot's output (generated path) from the user input. Analytically, these deviations can be quantified using the Hausdorff distance [12-13] between the two paths.

II. MODELLING OF THE RR MANIPULATOR

The actual manipulator as shown in Fig. 1(a), is a revolute-revolute joint type manipulator. The Denavit-Hartenberg representation and parameters can be seen in Fig. 1(b). Figure 1(c) depicts a typical smooth required end effector trajectory input by the user. The links are assumed to be uniform thin cylindrical rods and the mass of the end effector or tool and joint actuators are assumed to be negligible with respect to the link weights. The gravitational force on the manipulator is neglected due to the horizontal plane of motion of the manipulator. Forces exerted on the tool have also been neglected in this analysis. The mass of link 1 and link 2 are taken as m_1 and m_2 respectively and the corresponding lengths are a and b respectively.

The user enters the required end effector trajectory to the controller at the user's end. The input trajectory $X(t)$ is then in real time converted to the required joint path profile using standard inverse kinematic relations. The joint path is then planned using a trapezoidal trajectory generator. This process is continued until the user stops providing input. The torque equations for the joints are derived from the standard Lagrange Euler formulation [14] as.

$$\tau_1 = \left[\left(\frac{m_1}{3}+m_2\right)a^2 + m_2 ab\cos\theta_2 + \frac{m_2 b^2}{3}\right]\ddot{\theta}_1 + \left[\frac{m_2 ab\cos\theta_2}{2}+\frac{m_2 b^2}{3}\right]\ddot{\theta}_2 - m_2 ab\sin\theta_2\left[\dot{\theta}_1\dot{\theta}_2 + \frac{\dot{\theta}_2^{\,2}}{2}\right] \quad (1)$$

$$\tau_2 = \left(\frac{m_2 ab\cos\theta_2}{2}+\frac{m_2 b^2}{3}\right)\ddot{\theta}_1 + \frac{m_2 b^2}{3}\ddot{\theta}_2 + \frac{m_2 ab\sin\theta_2}{2}\dot{\theta}_1^{\,2} \quad (2)$$

These equations can be rewritten in the following form

$$\tau_2 = k_1\cos\theta_2\ddot{\theta}_1 + k_2\ddot{\theta}_1 + k_3\ddot{\theta}_2 + k_4\sin\theta_2\dot{\theta}_1^{\,2} \quad (3)$$

$$\tau_1 = k_5\ddot{\theta}_1 + k_6\cos\theta_2\ddot{\theta}_1 + k_7\ddot{\theta}_2 + k_8\cos\theta_2\ddot{\theta}_2 + k_9\sin\theta_2\dot{\theta}_1\dot{\theta}_2 + k_{10}\sin\theta_2\dot{\theta}_2^{\,2} \quad (4)$$

where $k_1 = \frac{m_2 ab}{2}$, $k_2 = \frac{m_2 b^2}{3}$, $k_3 = \frac{m_2 b^2}{3}$, $k_4 = \frac{m_2 ab}{2}$

$k_5 = \left(\frac{m_1}{3}+m_2\right)a^2 + \frac{m_2 b^2}{3}$, $k_6 = m_2 ab$, $k_7 = \frac{m_2 b^2}{3}$,

$k_8 = \frac{m_2 ab}{2}$, $k_9 = -m_2 ab$ and $k_{10} = \frac{-m_2 ab}{2}$

The desired joint displacement, velocity and acceleration at any instant is calculated from the generated required joint trajectory. A feedback PD (proportional and derivative) control torque is applied on the joints as *T=PD(desired(θ(t))-actual(θ(t)))*. The *desired(θ(t))* is the input path trajectory generated from user input path and the *actual(θ(t))* is the output path trajectory which the robot follows. Practically *actual(θ(t))* can be measures using angular displacement sensors. The user hence obtains the desired end effector configuration.

The controller of the robot receives the input from the user and after processing it triggers the manipulator. The manipulator then positions or orients it or both accordingly and sends the feedback to the controller. But this feedback of current joint state takes a finite amount of time which introduces a "delay" that needs to be taken care of for accurate manipulator control.

The control torque due to the time delay now becomes *T=PD(desired(θ(t))-actual(θ(t-δ))*where δ is the time delay i.e., the time taken by the feedback signal to reach the controller. The accuracy with which the manipulator generates the desired path profile is greatly affected by the delay. The way in which introduction of delay parameters effect the joint torques and the deviations of the path generated from the path desired are discussed analytically as follows:

The PD feedback control incorporates the tuning parameters of proportional gain k_p and derivative gain k_d. The delayed joint angles $\theta_1^{/}(t)$ and $\theta_2^{/}(t)$ that are received by the controller at time *t* is given by

$$\theta_1^{/}(t)=\theta_1(t-\delta),\theta_2^{/}(t)=\theta_2(t-\delta) \tag{5}$$

Now from PD control one can get the equations

$$\tau_1 = k_{p_1}\left(\theta_{req_1}-\theta_1^{/}\right)+k_{d_1}\left(\dot\theta_{req_1}-\dot\theta_1^{/}\right) \tag{6}$$

$$\tau_2 = k_{p_2}\left(\theta_{req_2}-\theta_2^{/}\right)+k_{d_2}\left(\dot\theta_{req_2}-\dot\theta_2^{/}\right) \tag{7}$$

Putting (6) in (4) and (7) in (3), one gets

$$\begin{aligned} k_{p_1}\left(\theta_{req_1}-\theta_1^{/}\right)+k_{d_1}\left(\dot\theta_{req_1}-\dot\theta_1^{/}\right) &= k_5\ddot\theta_1+k_6\cos\theta_2\ddot\theta_1 \\ &+k_7\ddot\theta_2+k_8\cos\theta_2\ddot\theta_2 \\ &+k_9\sin\theta_2\dot\theta_1\dot\theta_2 \\ &+k_{10}\sin\theta_2\dot\theta_2^{\,2} \end{aligned} \tag{8}$$

$$\begin{aligned} &k_{p_2}\left(\theta_{req_2}-\theta_2^{/}\right)+k_{d_2}\left(\dot\theta_{req_2}-\dot\theta_2^{/}\right)=k_1\cos\theta_2\ddot\theta_1 \\ &+k_2\ddot\theta_1+k_3\ddot\theta_2+k_4\sin\theta_2\dot\theta_1^{\,2} \end{aligned} \tag{9}$$

On further manipulation, one gets $\ddot\theta_1$ and $\ddot\theta_2$ as

$$\begin{aligned} \ddot\theta_1 = &\frac{k_{p_1}\left(\theta_{req_1}-\theta_1^{/}\right)+k_{d_1}\left(\dot\theta_{req_1}-\dot\theta_1^{/}\right)}{k_5+k_6\cos\theta_2} \\ &-\frac{(k_7\ddot\theta_2+k_8\cos\theta_2\ddot\theta_2)}{k_5+k_6\cos\theta_2} \\ &-\frac{(k_9\sin\theta_2\dot\theta_1\dot\theta_2+k_{10}\sin\theta_2\dot\theta_2^{\,2})}{k_5+k_6\cos\theta_2} \end{aligned} \tag{10}$$

$$\begin{aligned} \ddot\theta_2 = &\frac{k_{p_2}\left(\theta_{req_2}-\theta_2^{/}\right)+k_{d_2}\left(\dot\theta_{req_2}-\dot\theta_2^{/}\right)}{k_3} \\ &-\frac{\left(k_1\cos\theta_2\ddot\theta_1+k_2\ddot\theta_1+k_4\sin\theta_2\dot\theta_1^{\,2}\right)}{k_3} \end{aligned} \tag{11}$$

On solving (10) and (11) to decouple $\ddot\theta_1$ and $\ddot\theta_2$, one obtains

$$\begin{aligned} \ddot\theta_1 = \ &[k_3k_{p_1}(\theta_{req1}-\theta_1^{'})+k_3k_{d_1}(\dot\theta_{req1}-\dot\theta_1^{'}) \\ &-(k_{p_2}k_7)(\theta_{req2}-\theta_2^{'})+k_{p_2}k_8\cos\theta_2(\theta_{req2}-\theta_2^{'}) \\ &-(k_7k_{d_2})(\dot\theta_{req2}-\dot\theta_2^{'})+k_{d_2}k_8\cos\theta_2(\dot\theta_{req2}-\dot\theta_2^{'})] \\ &/[k_5+k_6\cos\theta_2+k_7k_1\cos\theta_2+k_7k_2 \\ &+k_8k_1(\cos\theta_2)^2+k_8k_2\cos\theta_2] \end{aligned} \tag{12}$$

$$\begin{aligned} \ddot\theta_2 = \ &[(k_{p_2}k_5+k_{p_2}k_6\cos\theta_2)(\theta_{req2}-\theta_2^{'}) \\ &+(k_{d_2}k_5+k_{d_2}k_6\cos\theta_2)(\dot\theta_{req2}-\dot\theta_2^{'}) \\ &-(k_4k_5+k_4k_6\cos\theta_2)\sin\theta_2\dot\theta_1^2 \\ &-(k_1k_{p_1}\cos\theta_2+k_2k_{p_1})(\theta_{req1}-\theta_1^{'}) \\ &-(k_1k_{d_1}\cos\theta_2+k_2k_{d_1})(\dot\theta_{req1}-\dot\theta_1^{'}) \\ &-k_9\sin\theta_2\dot\theta_1\dot\theta_2 \\ &-(k_1k_{10}\cos\theta_2+k_2)\sin\theta_2\dot\theta_2^2] \\ &/[k_3+k_7k_1\cos\theta_2+k_7k_2+k_8k_1(\cos\theta_2)^2 \\ &+k_8k_2\cos\theta_2] \end{aligned} \tag{13}$$

Using the state variables $y_1=\theta_1$; $y_2=\dot\theta_1$; $y_3=\theta_2$ and $y_4=\dot\theta_2$ with $\dot y_1=y_2$ and $\dot y_3=y_4$ one can solve the delay differential equations (12) and (13).

The adaptive control parameters are calculated as:

$$k_{p_1}=(w_1^2)/C;\ k_{d_1}=(2\zeta w_1-B)/A;\ k_{p_2}=(w_2^2)/R; \\ k_{d_2}=(2\zeta w_2-Q)/P; \tag{14}$$

where

$$\begin{aligned} &A=k_3/(k_5+k_6\cos(\theta_2^{'})+k_7k_1\cos(\theta_2^{'}) \\ &\quad +k_7k_2+k_8k_1(\cos(\theta_2^{'}))^2+k_8k_2\cos(\theta_2^{'})); \\ &B=(k_3k_9\dot\theta_2^{'}\sin(\theta_2^{'})+(k_4k_8\cos(\theta_2^{'})+k_4k_7)\dot\theta_1^{'}\sin(\theta_2^{'}))/(k_5+k_6\cos(\theta_2^{'}) \\ &\quad +k_7k_1\cos(\theta_2^{'})+k_7k_2+k_8k_1(\cos(\theta_2^{'}))^2+k_8k_2\cos(\theta_2^{'})); \\ &C=A; \\ &P=(k_5+k_6\cos(\theta_2^{'}))/(k_3+k_7k_1\cos(\theta_2^{'})+k_7k_2 \\ &\quad +k_8k_1(\cos(\theta_2^{'}))^2+k_8k_2\cos(\theta_2^{'})); \\ &Q=(k_9\dot\theta_1^{'}\sin(\theta_2^{'})+(k_1k_{10}\cos(\theta_2^{'})+k_2)\dot\theta_2^{'}\sin(\theta_2^{'}))/(k_3+k_7k_1\cos(\theta_2^{'}) \\ &\quad +k_7k_2+k_8k_1(\cos(\theta_2^{'}))^2+k_8k_2\cos(\theta_2^{'})); \\ &R=P; \end{aligned}$$

Here w_1, w_2 and ζ are the control parameters. A large value of w_1 and w_2 would increase the value of proportional component of control, while a large value of ζ will increase the value of the derivative component of control.

$$P_x=a\cos\theta_1+b\cos(\theta_1+\theta_2);\ P_y=a\sin\theta_1+b\cos(\theta_1+\theta_2) \tag{15}$$

Now by using the direct kinematic equations (15), the controller produces the end effector trajectory from the generated joint trajectory. Here Px and Py are the positions of the end effector with respect to a coordinate system fixed to the base of the robot.

However, due to the delay involved in fulfillment of the desired manipulation and the feedback to the controller, the manipulator is often unable to generate the desired trajectory. This deviation from the desired trajectory has been calculated using Hausdorff distance [12-13]. Mathematically, the Hausdorff distance measures how far two subsets of a metric space are away from each other. Hausdorff distance d_H between two sets A and B is defined as:

$$d_H(A,B) = \max\{\sup_{a\in A}\inf_{b\in B} d(a,b), \sup_{b\in B}\inf_{a\in A} d(a,b)\} \quad (20)$$

where sup represents the supremum and inf the infimum of their arguments. *d(a,b)* is the Euclidean distance between the points *a* and *b*. The two sets *A* and B can be thought of as the set of desired path points and the set of generated path points respectively. However a modified version of the Hausdorff metric is used in the path deviation analysis. The modified metric is defined as:

$$d_{HM}(A,B) = \frac{\sum_{a\in A}\inf_{b\in B} d(a,b) + \sum_{b\in B}\inf_{a\in A} d(a,b)}{car(A+B)} \quad (21)$$

where *car(A+B)* is the sum of the number of elements in sets *A* and *B.* Hausdorff distance helps in comparing two shapes in a metric space which is the Euclidean space in the present case. On the basis of a predetermined value of this distance, two shapes can be deemed different or identical. So it can be used to find out the error between two shapes, which for this purpose are the generated and the desired path profiles.

III. NUMERICAL RESULTS

For numerically analyzing the effects of time delay on the accuracy of the manipulator, a task is taken to draw a circle by using the two link manipulator with different delay parameters. The mass of both the links (m_1, m_2) are taken as 0.1 kg and the lengths (a,b) are taken as 0.3 m.

Using the inverse kinematic relations, the end effector points (which is following a circle in real time) is first converted to joint profiles. The joint trajectory is then generated using a smooth trapezoidal trajectory generator. Using the control scheme described in (6) and (7), control is applied on the robot to achieve the user input path in real time. The joint state is then derived by numerically integrating equations (12) and (13). The above process continues in a loop until the user stops providing input. On termination, the error between the generated path is compared with the user input path (a circle in this simulation).By varying the control parameters w_1, w_2 and ζ one can obtain a variety of generated paths.

Plots of Time-lag vs Error at a fixed natural frequency are studied here to show the dependence of this error and its growth in response to the system frequency factors w_1 and w_2. The factors w_1 and w_2 are assumed to be equal and denoted by w. The system damping factor ζ is kept at 1 in the simulations as it signifies a critically damped operation.

Five different values of *w* are taken and the variation of error with time lag has been analysed as shown below. The lower limit of the time delay for the simulations is taken as a small value (typically 0.1s).

Fig.5. (a)-(o) are graphs that display the increase in error with increase in time delay for five different values of *w* as well as the associated decrease in accuracy as the time-lag is varied between its upper and lower bounds. From these plots the following inference can be drawn:

1. The error at smaller time delays is larger for smaller *w* as compared to higher values of *w*.

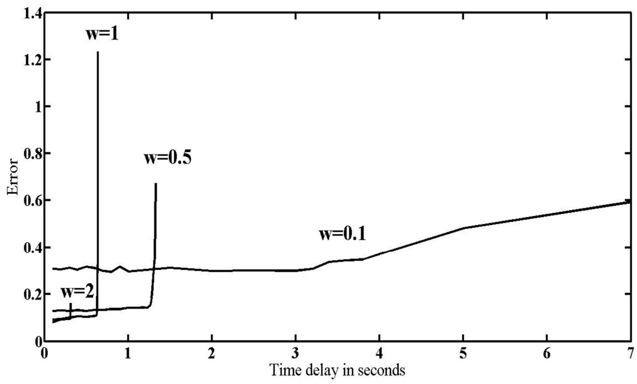


Fig. 3: Graph displaying the growth of error with increase of time delays for different *w*

2. The maximum allowable time delay is larger at lower values of *w* but this range narrows down sharply with increasing *w*; that is to say large time delays are allowable only for lower values of *w* while even slightly large delays are unacceptable for higher values of *w*. This gives rise to the notion of a critical delay or the maximum allowable delay for a given system as depicted in the figure below. The critical delay can be defined as the maximum allowable time delay for which the control system is capable of accurately controlling the robot.

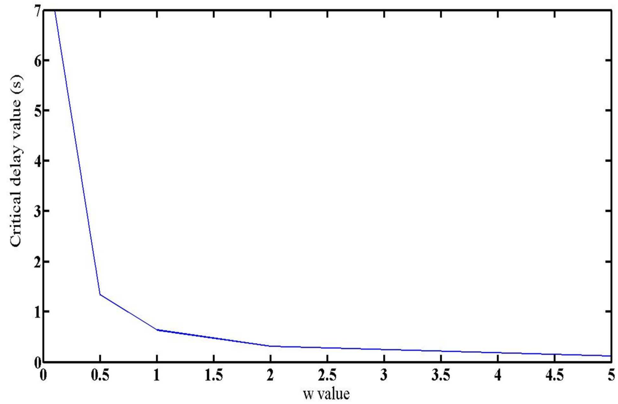
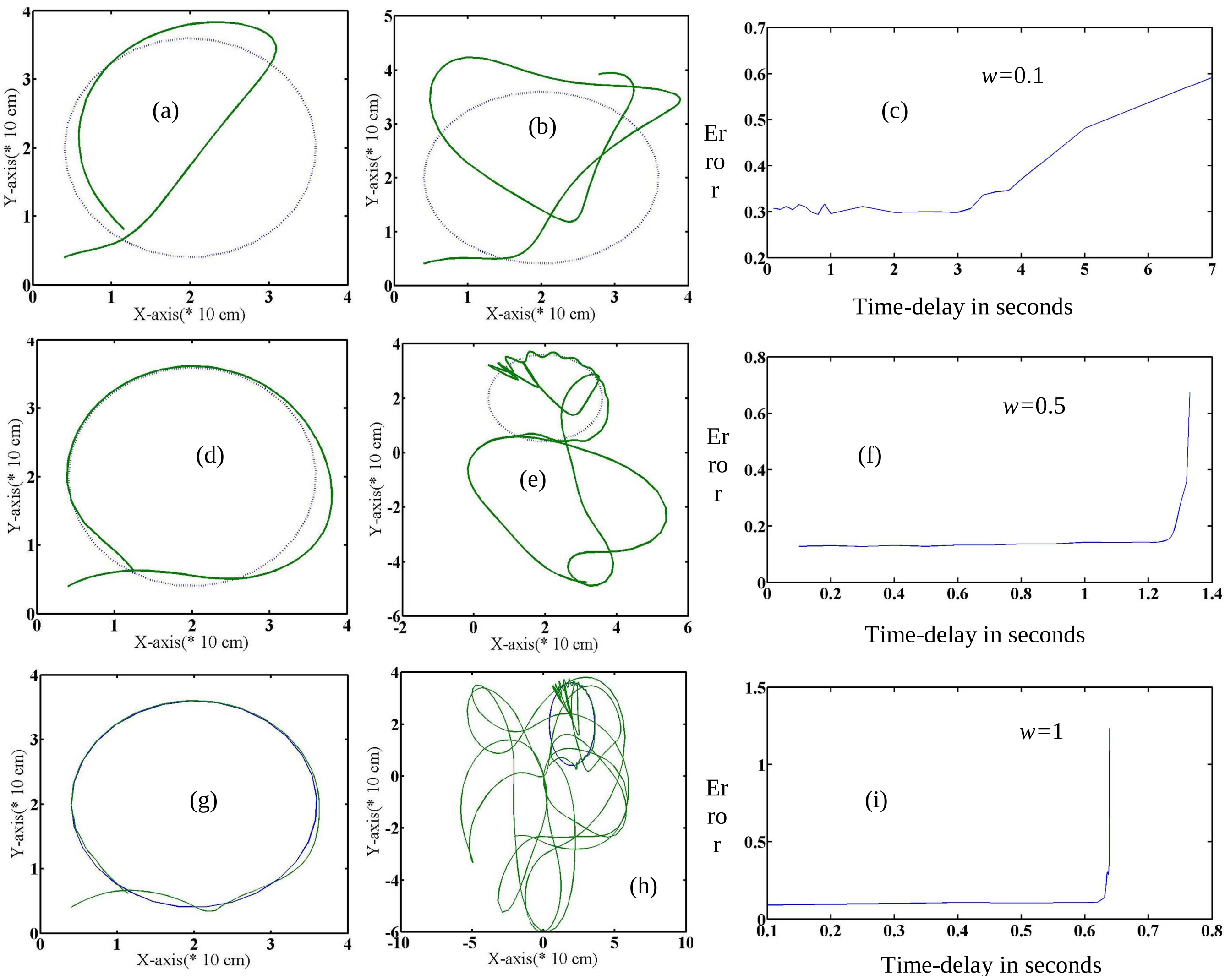


Fig.4: Graph displaying the “critical lag” or the maximum allowable delay for different *w*.



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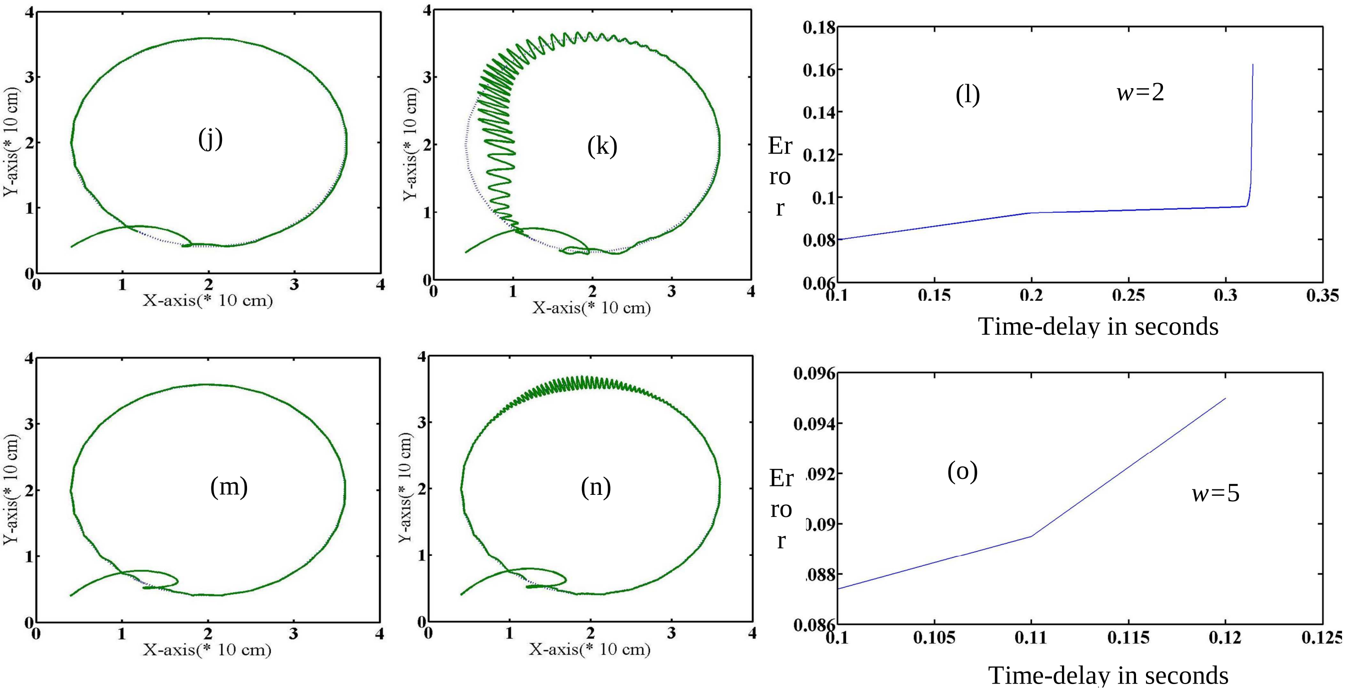

Fig.5 (a)-(o): Graphs of time-delay vs error (last column) and corresponding plots of desired trajectory vs actual trajectory at the lower(first column) and upper limits of the allowable time-delay(second column).

In short, the error increases slowly with increase in time lag for lower values of *w* thus allowing tolerable values of error at larger delays but the error increases very rapidly even for small increases of time lag at higher values of *w*.

IV. CONCLUSION

In this work delay differential equation for finding the torque of a RR manipulator has been developed. These equations have been solved numerically to obtain the end effector trajectory of the manipulator for different time delays and for different values of the control parameters. In this work an attempt has been made to plot a circle by the end effector of the RR manipulator using a PD control. It has been seen that for smaller values of the natural frequency, the error is quite high even for small time delays but it allows greater relaxation of the limit to which the time delay can be extended. In other words, even for larger delays of time, the manipulator is able to generate the desired trajectory with some tolerable error. But for larger values of the system frequency, the error at small values of time delay is minimal and manipulator accuracy is higher than at smaller values of the system frequency. But as the time delay is increased in small amounts, the error is found to increase very sharply for systems with larger frequency; hence for such systems larger time delays result in unacceptable errors of trajectory generation. Depending on our application and given the time delay existing in the system, we may choose our control parameters and thus tune our manipulator to perform with the required accuracy. The future work remains in verifying the derived results experimentally.

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