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Predictive Input Delay Compensation with Grey Predictor for Networked Control System

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Abstract: The performance of networked control systems is affected strictly by time delay. Most of the literature in the area handle the problem from a stability perspective. However, stability optimized algorithms alone are not sufficient to reduce synchronization problems caused by time delay between the action and reaction in geographically distant places, and the effect and performance of other system components should also be taken into account. In teleoperation applications the reference is often provided by a human, known as the operator, and due to the nature of the human system, references provided by the human operator are of a much lower bandwidth when compared to common control reference inputs. This paper focuses on the operator, and proposes an approach to predict the manipulator's motion (created by the operator) ahead of time with an aim to reduce the time delay between the master and slave manipulator trajectories. To highlight the improvement offered by the developed approach, hereby called Predictive Input Delay Compensator (PIDC), we compare the performance with the only other study in the literature that handles this problem using the Taylor Series approach. The performance of these two approaches is evaluated experimentally for the forward (control) path on a PUMA robot, manipulated by a human operator and it has been demonstrated that the efficient latency in the forward path is decreased by 100ms, on average, reducing the forward latency from 350ms to 250ms.
Keywords: communication network delay, delay regulator, Grey predictor, Taylor series, teleoperation.

1 Introduction

Because of their huge potential to contribute to human life in many different ways, teleoperation and bilateral control systems have been attracting significant interest in control and communication communities. Telesurgery using remote medical robots, exploration in hazardous environments using teleoperating robots could be good examples of such promising applications. The ultimate aim of a networked control system is the synchronization of the position and/or force between the master and slave in geographically distant motion control systems. Currently, the most widely used network communication medium is the Internet. However, the Internet brings a variable delay between the transmitted channels. This makes control implementations over the Internet challenging. The problem of variable can be eliminated via delay regulators [1] resulting in constant, and often relatively long delays.

Time delay compensation problem in bilateral control systems has been addressed by many different approaches. To name a few of the major methods, scattering variables [2], wave variables [3], Smith-Predictor (SP) [4], Astrom's modified SP [5], sliding-mode control (SMC) [6] and , via the design of communication disturbance observer (CDOB) [7]. Moreover optimal control methods are used to find an optimal solution in terms of stability and performance constraints of the system [8].

The focus of this study will again be on the performance improvement of master-slave position tracking in networked robot control systems. While the ultimate goal of the networked control is full synchronization, network delay between master and slave is a major obstacle for the desired performance, and network delays happen randomly. In teleoperation applications the reference is often provided by a human, known as the operator. Due to the nature of the human system, references provided by the human operator are of a much lower bandwidth when compared to common control reference inputs, and this can sometimes be problematic. All of the above mentioned studies discuss system stabilization under network delay [9], but do not address the operator delay, which also contributes to the delay between master and slave. Meanwhile, the prediction of the input delay (in this case, created by the human operator) has the potential to reduce this network latency. However, to the authors' best knowledge, the only study in the literature addressing this concept is [9], which uses a Taylor series based analytical approach to handle this problem. Taylor series simply performs the extrapolation of position based on velocity, meanwhile acceleration has significant effect on both velocity and position, and affects the prediction error negatively.

In this study, we propose a method based on Grey Prediction for Predictive Input Delay Compensation, and demonstrate experimentally the advantages of the proposed method over the one using Taylor Series in predicting the operator's motion. The Grey prediction not only performs extrapolation, but unlike the Taylor Method fits a differential equation to the system dynamics. As a result, grey prediction is more effective in considering the transients, hence, the acceleration.

The organization of the paper is as follows. Section II presents the benchmark Taylor Series based predictor. Section III presents Grey Prediction. Section IV introduce the Networking Control System and the application of the both two predictor on it. Section V introduce the experimental setup and results with conclusions in Section VI.

2 Taylor based PIDC as Benchmark System

In this section, we will first discuss the benchmark PIDC approach based on Taylor Series. Subsystems of the human, such as skeleton, muscle, and neural systems behave similar to mass-spring-damper like structures, hence result in a high time constant for the operator. This also makes it acceptable to assume the human motion output to be continuously differentiable in time [9].

By accepting this assumption, future signal values can be predicted using simple geometric approaches. The prediction formula is

$$\lim_{T \to 0} q_{mi}(n+H) \approx (H+1)q_{mi}(n) - Hq_{mi}(n-1) \tag{1}$$

Here $q_{mi}(n+H)$ denotes H step further value , $q_{mi}(n)$ denotes current value and finally $q_{mi}(n-1)$ denotes previous value. We must mention that, there are just two error source which is neglected. One is high order terms and the second is discretization.

3 Grey based PIDC

Grey system theory [10] is developed for systems characterized by uncertain information. Grey Prediction is a scientific quantitive prediction method which is based on the theoretical treatment of the original data to determine the future output of the system [11]. Basically, it can be defined as a local curve fitting extrapolation method, which requires four data sets only. In Grey Systems, $GM(n,m)$ denotes a grey model. Here n denotes the order of the difference equation, and m is the number of the variables. The commonly used Grey Model is of the $GM(1,1)$ type. It represents the first order derivative, and one input variable is used for prediction purposes. The process of the Grey Prediction can be given as below [?]:

Step 1: Collecting the original data sequence, and using generalized coordinate,

$$q_{mi}^{(0)} = \left\{ q_{mi}^{(0)}(1), q_{mi}^{(0)}(2), \ldots, q_{mi}^{(0)}(N) \right\},\ N \geq 4 \tag{2}$$

where

$$q_{mi}^{(0)}(N) = q_{mi}(n) \tag{3}$$

$$q_{mi}^{(0)}(N-1) = q_{mi}(n-1) \tag{4}$$

$$\ldots$$

$$q_{mi}^{(0)}(1) = q_{mi}(n-N+1) \tag{5}$$

$$\tag{6}$$

Here N denotes buffer size, q denotes generalized coordinate, m subscript denotes master side not slave side, i subscript denotes i^{th} joint angle. For instance q_{m3} denotes master manipulators 3^{rd} joint angle. Moreover, $q_{mi}^{(0)}$ denotes zero order AGO of q_{mi}.

Step 2: Conducting an accumulated generation operation, AGO, on the original data sequence in order to diminish the effect of data uncertainty;

$$q_{mi}^{(1)} = \left\{ q_{mi}^{(1)}(1), q_{mi}^{(1)}(2), \ldots, q_{mi}^{(1)}(N) \right\},\ N \geq 4 \tag{7}$$

Where

$$q_{mi}^{(1)}(k) = \sum_{i=1}^{k} q_{mi}^{(0)}(i), k = 1, 2, \ldots, N \tag{8}$$

Here the $q_{mi}^{(1)}$ denotes first order AGO of q_{mi}.

Step 3: Establishing the Grey difference equation and then calculating its background values;

$$q_{mi}^{(0)}(k) = -a_i {z_i}^1(k) + b_i \tag{9}$$

$${z_i}^{(1)}(k) = 0.5 \left\{ q_{mi}^{(1)}(k) + q_{mi}^{(1)}(k-1) \right\} \tag{10}$$

Here the a_i denotes developing coefficient in Grey Theory, b_i denotes Grey input.
Step 4: Constructing data matrix B and data vector Y;

$$B = \begin{bmatrix} -z_i{}^{(1)}(2) & 1 \\ -z_i{}^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z_i{}^{(1)}(N) & 1 \end{bmatrix} \tag{11}$$

$$Y_i = \left[q_{mi}^{(0)}(2), q_{mi}^{(0)}(3), \ldots, q_{mi}^{(0)}(N)\right]^T \tag{12}$$

Step 5: Resolving the matrix;

$$Y_i = B_i \hat{a}_i \tag{13}$$

$$\hat{a}_i = B_i^T B_i^{-1} B_i^T Y_i = \begin{bmatrix} a_i \\ b_i \end{bmatrix} \tag{14}$$

Step 6: Deriving the solution to the Grey difference equation;

$$q_{mi}^{(1)}(k+1) = \left[q_{mi}^{(0)}(1) - \frac{b_i}{a_i}\right] e^{-a_i k} + \frac{b_i}{a_i} \tag{15}$$

Step 7: Conducting the inverse accumulated generation operation to obtain a prediction value

$$q_{mi}^{(0)}(k+1) = \left[q_{mi}^{(0)}(1) - \frac{b_i}{a_i}\right] e^{-a_i k}(1 - e^{a_i}) \tag{16}$$

Step 8: By Substituting k with $N + H - 1$

$$q_{mi}^{(0)}(N + \mathrm{H}) = \left[q_{mi}^{(0)}(1) - \frac{b_i}{a_i}\right] e^{-a_i(N+H-2)}(1 - e^{a_i}) \tag{17}$$

Step 9: By Rearranging formula

$$q_{mi}(n + \mathrm{H}) = \left[q_{mi}(n - N + 1) - \frac{b_i}{a_i}\right] e^{-a_i(N+H-2)}(1 - e^{a_i}) \tag{18}$$

4 A Configuration for the Networked Control System

Here we will introduce our proposed networked control system configuration to explain the requirement and the performance measure of the Predictive Input Delay Compensator ($PIDC$) algorithms. However first, we will introduce our standard configuration without the $PIDC$. In the standard configuration, the operator forces the master manipulator to a desired posture, which in turn will dictate the slave motion. In order for the slave to track the master motion in the closest possible way, on the master side, an Astrom Smith Predictor (ASP) generates the control signal for the model plant. Then the control signal generated on the master side, is transmitted to the slave side passing through a Delay Regulator Send unit (DRS_m)" through the Internet to Delay Regulator Receive unit (DRR_s). On the slave side, a Model Tracking Control (MTC) algorithm inputs the received control to an other model process (same as the model plant at master side) and forces the slave manipulator to track the trajectory of the model plant.

The angular displacement output of the MTC is fed back to the ASP passing through a Delay Regulator Send unit (DRS_s) through the Internet to Delay Regulator Receive unit (DRR_m). [1]

Here $\tau_{oq\{1,2,3\}}$ denote the joint torques generated by the operator, $\tau_{qm\{1,2,3\}}$ denote the joint torques applied to the manipulator after the addition of $g_{qm\{1,2,3\}}$ gravitational compensation terms. $\tau_{mq\{1,2,3\}}$ denote the torque signals fed to DRS_m to be sent to slave side. $\bar{\tau}_{mq\{1,2,3\}}$ denote the delay regulated torque signals coming through the Internet from the master to the slave. $\tau_{cq\{1,2,3\}}$ denote the joint torques generated by MTC, $\tau_{qs\{1,2,3\}}$ denote the joint torques applied to the manipulator after the addition of $g_{qs\{1,2,3\}}$ gravitational compensation terms. Finally $q_{s\{1,2,3\}}$ denote the slave manipulator's joint angle (actual) positions.

In this study, the Predictive Input Delay Compensator ($PIDC$) unit is added to this configuration between the operator and ASP. With this addition, it is now possible to predict and compensate the delay caused by the operator, which will allow sending the master side information to the slave side with less delay. This reduced delay increases the synchronization between the master and slave trajectories. To reduce nonlinearities of the master and slave manipulators, namely to increase the compliance on the master side and compensate the gravity on the slave side, gravity compensation blocks GC_m and GC_s added, respectively. The overall master-slave architecture is given in Fig. 1. However the function detail of each block is outside the scope of this study, and will not be discussed.

5 Experimental System and Results

Next, experiments have been performed to conduct a comparative performance evaluation for the Taylor based and Grey prediction approaches. The 6-DOF PUMA560 Industrial Robot is used for experimentation. The manipulator is operated as a 3-DOF system by the operator as can be seen in Fig. 2.

The well-known Euler-Lagrange based dynmaic model of the manipulator has the following general form:

$$M(q).\ddot{q} + V(q,\dot{q}).\dot{q} + G(q) = \Gamma \tag{19}$$

where,

q : $nx1$ position vector
$M(q)$: nxn inertia matrix of the manipulator
$V(q,\dot{q})$: $nx1$ vector of Centrifugal and Coriolis terms
$G(q)$: $nx1$ vector of gravity terms
Γ : $nx1$ vector of torques

In this study the system will be taken on the consideration as an independent joint control system. This approach allows each manipulator joint to be controlled independently as a SISO system, with the nonlinearities and couplings taken as a disturbance affecting each joint actuator.

For our experimental system, since the human speed is considerably low, the main nonlinearities come from the gravity effect $G(q)$. For that reason, in our experiments we apply system gravity compensation $\tilde{G}(q) \approx G(q)$, to cancel and/or reduce the gravity effect on the experimental system to a negligible level.

The use of an independent joint control system approach, simplifies the system to be estimated to a one-degree-of-freedom process.

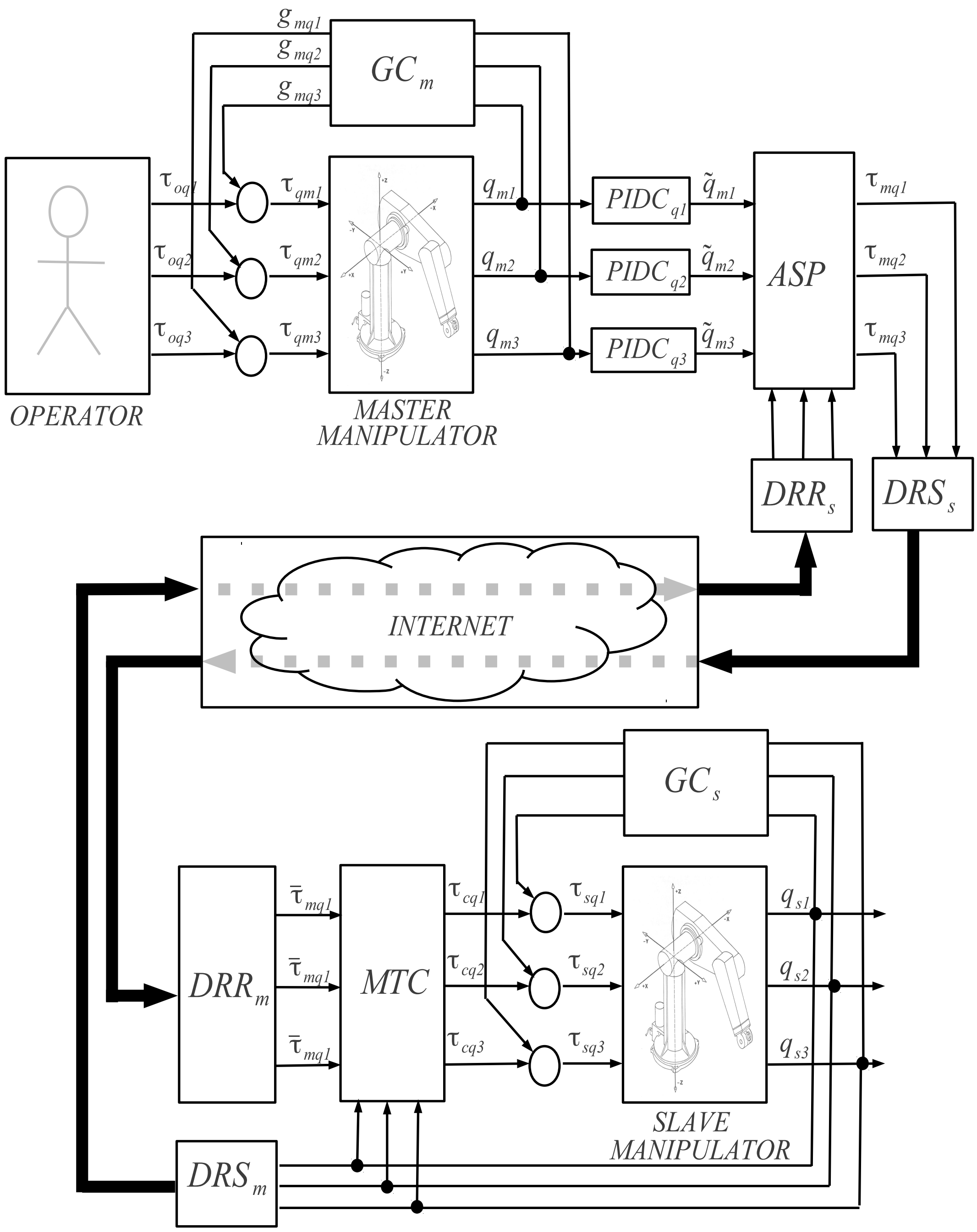

Figure 1: Extended Control Scheme of Networked Control

Experiments are performed for three cases. Then, $\tilde{q}_{mi}$ is also evaluated for three separated case. These cases and evaluation formulas are;

Case 1: No PIDC

$$\tilde{q}_{mi}(n) = q_{mi}(n) \tag{20}$$

Case 2: Taylor Series based Benchmark PIDC

$$\tilde{q}_{mi}(n) = (H+1)q_{mi}(n) - Hq_{mi}(n-1) \tag{21}$$

Figure 2: Experimental Setup

Case 3: Grey Theory based Proposed PIDC

$$\tilde{q}_{mi}(n) = \left[q_{mi}\,(\mathrm{n-N+1}) - \frac{b_i}{a_i} \right] e^{-a_i(n+H-1)}(1-e^{a_i}) \tag{22}$$

The results of those experiments are seen in Fig. 3. Here, Fig. 3a and Fig. 3b depict the results for the first joint , Fig. 3c and Fig. 3d for the second joint, Fig. 3e and Fig. Fig. 3f for the third joint. The performance of each joint is further demonstrated by also highlighting the zoomed version of the region marked in red. The figures in the right are zoomed versions for the highlighted sections in the diagrams on the left side. For each figure, the grey line represents the operator motion, which is taken as the reference motion to be predicted. The solid line depicts the Grey Predictor's output, and finally dashed line demonstrates the output of the benchmark Taylor Series based predictor. In each figure, it is easily seen that when the angular velocity is low, both algorithms demonstrate similar performance. However when the acceleration increases, the performances show differences. Only operation intervals where there is significant operator motion have been selected in the zooms of Fig. 3b, Fig. 3d and Fig. 3f. In all three figures, we see that the Grey Prediction method achieves a faster prediction of $100ms$ on average when compared with the Taylor based approach. On the other hand, the benchmark method demonstrates a prediction performance that varies between $10ms$ and $100ms$, and demonstrates a poor performance in tracking transients as indicated by the high amplitude oscillation observed in Fig. 3b starting at $5.7ms$, and in Fig. 3d starting at $2.8ms$ for the benchmark system output. Hence, it can be said that the proposed Grey based $PIDC$ demonstrates a faster and more accurate prediction performance then the Taylor based $PIDC$.

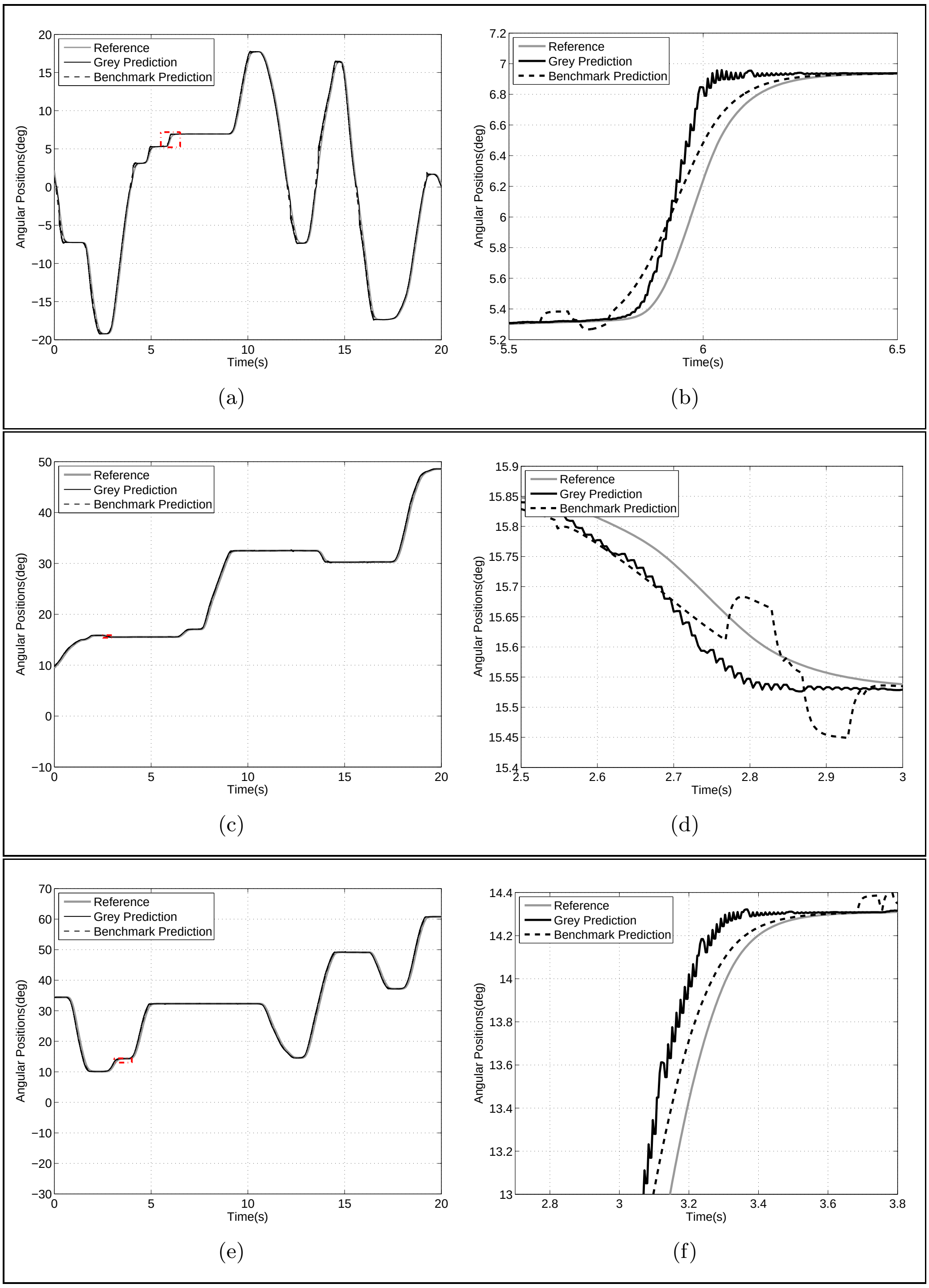

Figure 3: Measured and Predicted Angular Positions of each joint and zoomed versions a) joint 1, b) zoomed area of joint 1, c) joint 2, d) zoomed area of joint 2, e) joint 3, f) zoomed area of joint 3

6 Conclusion

In this study, a Grey system theory based $PIDC$ is developed and implemented for the prediction of the master manipulator motion in order to reduce the transmission latency between the master and slave. Our philosophy is to reduce the latency in every way possible within our capability, considering network latency is unavoidable and random.

Experiments are conducted on a PUMA 560 manipulator which is just compensated for gravitational force to allow easy manipulation for the operator. The operator randomly manipulates the arm, while both the benchmark and proposed schemes predict the future trajectory of the robot motion created by the operator. The proposed approach outperforms the Taylor Series based benchmark approach, by predicting the joint motions approximately $100ms$ ahead on average, while the benchmark's predictor performance varies between $2.8ms$-$100ms$. Based on these results, it can be concluded that Grey Prediction meets our motion prediction requirements better then the Taylor Series based approach, which is currently the only other study in the literature to address input delay compensation.

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Bibliography

[1] Kuzu, A. et al (2011); Control and measurement delay compensation in bilateral position control, *Mechatronics (ICM), 2011 IEEE International Conference on*, April 2011, 1003–1010.

[2] Mori, T (2012); Modified bilateral control by using intervention impedance based on passivity of flexible master-slave manipulators and its design methods, *Control, Automation and Systems (ICCAS), 2012 12th International Conference on*, 748–753.

[3] Hashemzadeh, F (2012); A new method for bilateral teleoperation passivity under varying time delays, *Mathematical Problems in Engineering*, Hindawi Publishing Corporation, http://dx.doi.org/10.1155/2012/792057.

[4] Lai, C.L. and Hsu, P.-L. (2010); Design the remote control system with the time-delay estimator and the adaptive smith predictor, *Industrial Informatics, IEEE Transactions on*, 6(1): 73–80.

[5] Astrom, K. (1994); A new smith predictor for controlling a process with an integrator and long dead-time, *Automatic Control, IEEE Transactions on*, 39(2): 343–345.

[6] Gadamsetty, B. et al (2010); Sliding mode and ekf observers for communication delay compensation in bilateral control systems, *Industrial Electronics (ISIE), 2010 IEEE International Symposium on*, 328–333.

[7] Natori, K. et al (2010); Time-delay compensation by communication disturbance observer for bilateral teleoperation under time-varying delay, *Industrial Electronics, IEEE Transactions on*, 57(3): 1050–1062.

[8] Yashiro, D. and Ohnishi, K. (2008); L2 stable four-channel control architecture for bilateral teleoperation with time delay, *10th IEEE International Workshop on Advanced Motion Control*, 324–329.

[9] Baran, E. and Sabanovic, A. (2012); Predictive input delay compensation for motion control systems, *Advanced Motion Control (AMC), 2012 12th IEEE International Workshop on*, March 2012, 1–6.

[10] Ju-Long, D. (1982); Control problems of grey systems, *Systems & Control Letters*, 1(5): 288–294.

[11] Liu, S. and Lin, Y. (2006); *Grey information: theory and practical applications*, Springer.