EXPERIMENTAL VALIDATION OF MODEL PREDICTIVE CONTROL FOR NONLINEAR SYSTEM WITH DELAY

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Abstract: Industrial processes have inherent nonlinearity, process delay, transportation delay, and might suffer from inverse response. Every control action is performed based on the error calculated at that instant. But in systems encountering transportation delay, this is not possible because, at every instant only the past information could be made available to the controller for taking corrective measures. Predictive controllers could well handle this issue. They predict the system behaviour by using the past behaviours of the plant and so they could overcome the issues faced by transportation delay. This paper presents the real-time implementation of model predictive controller for a level process with delay. The performance of this controller for this system when transportation delay is intentionally included to the system is compared with the performance of the classical PID controller.

Keywords: Model Predictive Controller, Delay, Non linear system, stability

1. Introduction

Process industry is characterized by product quality specifications, productivity demands, new environmental regulations and fast changes in the economical market. The liquid level in tanks has to be controlled not because for the want to keep those levels constants, but such a control is essential to assure that the integrated plant can run safely, smoothly and profitably. A Proportional Integral Derivative (PID) controller used in industrial control systems have difficulties in the presence of non-linearities/changing process behaviour, cause trade-off between regulation and response time and lag in responding to large disturbances.

To overcome the drawbacks of PID controller, Model Predictive Control (MPC) is used in this work. Model Predictive Control does not refer to an individual control strategy but to a relatively a large range of control methods which uses a model of the process to obtain the control signal by minimizing an objective function. The main advantage of using a MPC is that it can easily handle constraints in both manipulated variable and controlled variable. MPC is more of a methodology than a single technique. The difference in the various methods is mainly the way the problem is translated into a mathematical formulation, so that the problem becomes solvable in a limited amount of time.

The theoretical background of linear MPC and recent evolutions on the speeding-up of algorithms to solve the quadratic optimization problem (QP), the heart of these controllers were discussed in [1]. Hence, MPC can be employed for fast systems as well as for embedded applications.

The effects of MPC when used to control water level in steam generators of nuclear power plants were explained in [2]. Frequent reactor shutdowns may occur due to poor control of the steam generator water level. Such shutdowns are caused by violation of safety limits on the water level and are common at low operating point where the plant exhibits strong non minimum phase characteristics and flow measurements are unreliable. In order to overcome these issues, systematic investigation of the problem of controlling the level is required. The paper presents a framework for addressing this problem based on an extension of the standard linear model predictive control algorithm to linear parameter varying systems.

The influence of the prediction horizon on Dynamic Matrix Control (DMC) were proposed in [3]. This is a particular type of Model Predictive Control (MPC), which is framed as advanced controller. Here a set of indices were defined to

measure the system performance. The system on which the influence of the parameter has been analysed has been chosen because it has shown to be difficult to control using classical control schemes, as a discretized Proportional Integral Derivative (PID) control tuned by means of the Ziegler-Nichols method.

The issues of importance that any control system should address were stated in [4]. MPC techniques are then reviewed in the light of these issues in order to point out their advantages in design and implementation. A number of design techniques emanating from MPC, namely Dynamic Matrix Control, Model Algorithmic Control, Inferential Control and Internal Model Control, are put in perspective with respect to each other and the relation to more traditional methods like Linear Quadratic Control is examined. The effectiveness of handling the constraints by MPC is addresses to be excellent.

The optimal control profile is a piecewise affine and continuous function of the initial state were discussed in [5]. For discrete-time linear time-invariant systems with constraints on inputs and states, they have described a method to determine explicitly, as a function of the initial state, the solution to optimal control problems that can be formulated using a linear program (LP). So, as the control signal is calculated at each step, it permits to eliminate on-line LP, as the computation associated with MPC becomes a simple function evaluation.

Generalized Predictive Control which uses a transfer function model of the process which is well understood in industry is covered in [6-13]. This method is middle of the road between industry and academy, where state space-based methods are more attractive because they allow easy analysis of stability and robustness.

The design and implementation of model predictive controller in both continuous and discrete mode are explained in [14-16].

This paper deals with the control of level in a cylindrical tank which has a process delay. The performance of the controller even if a transportation delay occurs in the system is addressed here.

2. Hardware Description

The process station (Fig.1) consists of a single cylindrical tank of uniform cross sectional area. Water from the reservoir is pumped through a rotameter and a control valve into the cylindrical tank. Delay coils are provided in the setup to introduce transportation delay into the system. Inlet of the tank has a control valve (Normally closed) and the outlet valve is manually operated hand valve. Differential pressure level transmitter is used to measure the level of water in the tank

When the pump is turned on, the water starts flowing into the cylindrical tank through the control valve. The level of the tank is measured by the differential pressure transmitter. The transmitter signal ranges from 4mA to 20mA which is sent to current to voltage (I to V) converter. From I to V converter, a voltage signal of range (0-5)V reaches the data acquisition unit. The required corrective control action will be calculated using the algorithm in the processor. The control action will be implemented in the form of opening or closing of the control valve at the inlet of the tank. From the processor, control signal in the form of voltage, ranging from (0-5)V reaches the data acquisition unit, from where the voltage is given to V to I converter. The current signal is then given to the current to pressure converter. This pressure signal ranging from (3-15)psi is applied to the pneumatic control valve, thus implementing the control action.
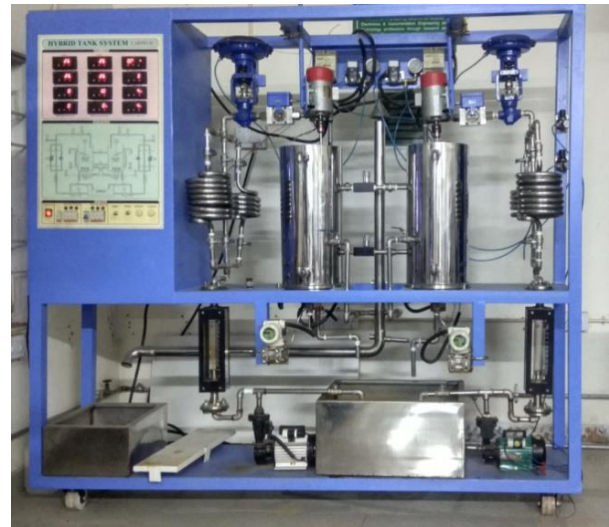

Fig. 1. Experimental setup with delay coils

3. Controller design

The equation governing the conventional PI controller whose integral term will eliminate the offset of the process variable is characterized by (1)

$$u = k_p e_p + \frac{1}{\tau_i} \int \tag{1}$$

where, u is the control signal, e_p is the error signal generated as the difference between the process variable and the set point and τ_i is the integral time.

Model Predictive Control:

The system is represented in state space and their augmented model is calculated. With the available information of the state variables, the future state variables are predicted for N_p number of samples where N_p is the prediction horizon, which can also be used as the length of the optimization window. With the information of the state variables, the control signal is calculated for N_c instants, where N_c is the control horizon, but only the control signal at the first instant is used to rectify the error in the process varaible.

The state space model of the system is as indicated in equ. (2), (3)

$$\dot{x} = Ax + \qquad (2)$$
$$y = Cx \qquad (3)$$

where x is the state variable, A is the system matrix, B is the input matrix, u is the control signal, y is the output signal and C is the output matrix.

The future state variables are predicted using (4) as

$$x(k_i + N_p|k_i) =$$
$$A^{N_p}x(k_i) + \Sigma_{i=1}^{N_c} A^{N_p - N_c} B \Delta u(k_i + N_c - 1) \qquad (4)$$

where k_i is the sampling instant. For every value of N_p from $(0-N_p)$ a state equation is formed.

The predicted output variables are calculated using the predicted state variables as in (5)

$$y(k_i + N_p|k_i) =$$
$$CA^{N_p}x(k_i) + \Sigma_{i=1}^{N_c} CA^{N_p - N_c} B \Delta u(k_i + N_c - 1) \qquad (5)$$

The control objective is reflected in the cost function (6) which is,

$$J = (r_s - y)^T(r_s - y) + \Delta U^T \bar{r} \qquad (6)$$

where, r_s is the set point.

The optimal solution for the control signal is obtained by minimizing J .

4. Results

The open loop response of the system was obtained for a step change in input.
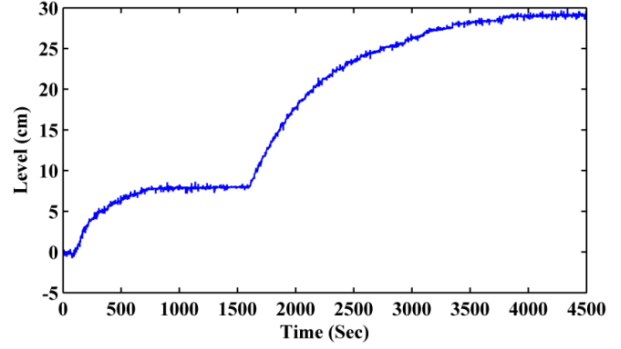

Fig. 2. Open loop response of the system when delay is not introduced

The transfer function of the system was obtained using open loop method from the responses shown in Fig 2 and Fig 3. When delay was not introduced, the gain of the open loop system was 24.4 with a time constant of 600.284 and the process delay of 17 seconds.

The gain was 11.165 and time constant was 1185.185 when the transportation delay was 40 seconds.
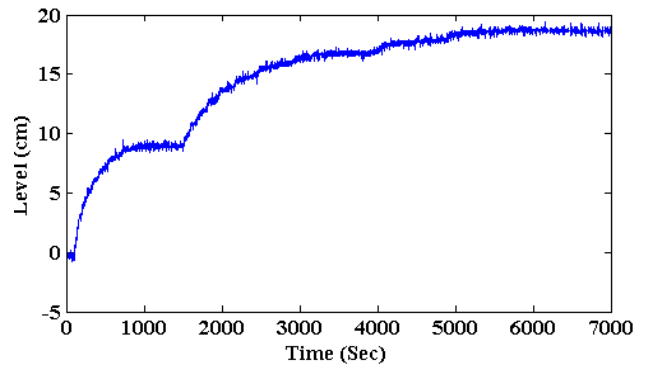

Fig. 3. Open loop response of the system when delay is introduced

The system was controlled using PI controller initially to analyse the significance of delay in the overall performance of the system. As level is an integrating process, PI controller was chosen. The tuned PI controller parameters are

Case 1: without including transportation delay:
Proportional gain   = 0.6529
Integral gain   = 1.1979 sec^{-1}

Case 2: including transportation delay:
Proportional gain   = 1.1979
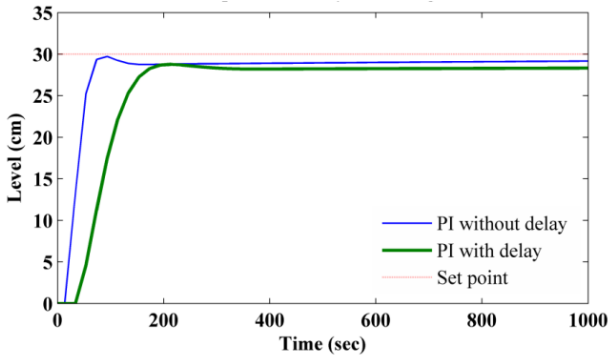Integral gain   = 0.0078 sec^{-1}

Fig. 4. Simulation response of the system using PI controller

From Fig 4 and Fig 5, it is evident that though the overshoots or oscillations are not present, the rise time and settling time of the system have increased when transportation delay is present in the system. From the response of the system it is understood that, delay could not be effectively handled by this controller.
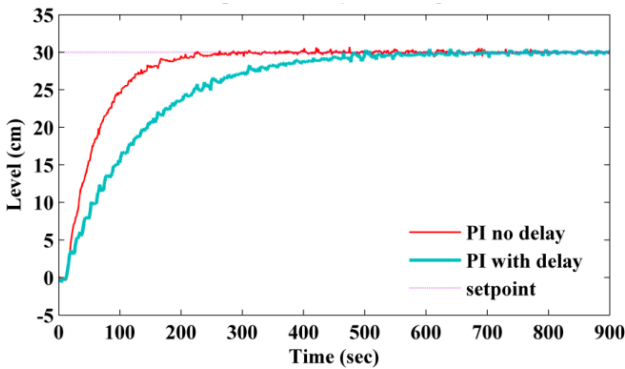

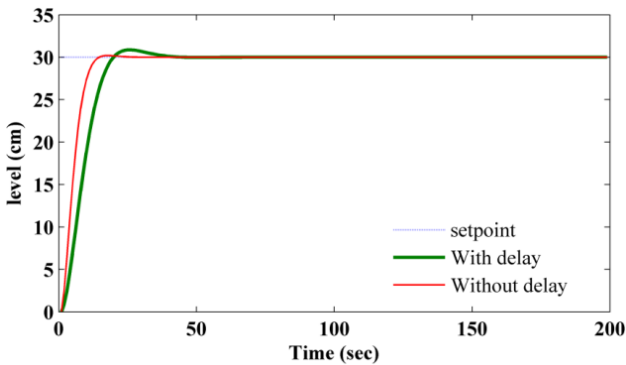Fig. 5. Real time response of the system using PI controller

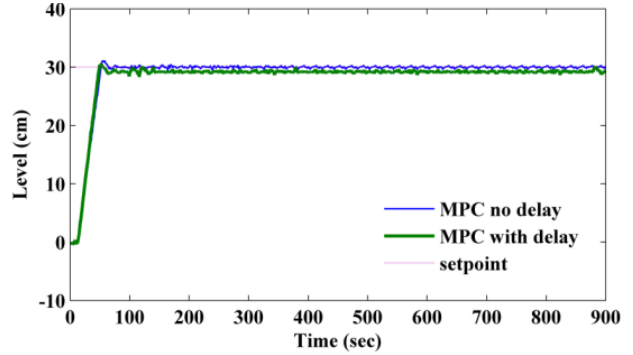Fig. 6. Simulation response of the system using MPC controller

Fig. 7. Real time response of the system using MPC controller

The MPC controller parameters were tuned with prediction horizon 12, control horizon 5 with a weighing factor of 0.1 for both cases with and without delay as it gave an acceptable performance. This stands as an advantage of MPC.

From Fig 6 and Fig 7, it is clear that, when MPC is used, the rise time and the settling time of the system has decreased and there is a very mere impact of transportation delay in the controlled process. Table 1 and 2 gives the overall performances of the system.

Table 1: Simulation results

Controller	condition	Rise time (sec)	Settling Time (sec)	Offset (%)	Delay time (sec)	RMSE
PI	Without introducing delay	50	159.4	1.33%	33.3	10.078
	When delay is introduced	173.3	336.3	5.8%	83.3	11.029
MPC	Without introducing delay	10	26.25	-	5	3.92
	When delay is introduced	15	48.75	-	8.12	3.12

Table 2:Real time results

Controller	condition	Rise time (sec)	Settling Time (sec)	Offset (%)	Delay time (sec)	RMSE
PI	Without introducing delay	106.3	473	-	49.3	6.1

	When delay is introduced	250	90.2	-	93.8	8.34
MPC	Without introducing delay	31.6	88.6	-	30.4	5.05
	When delay is introduced	25	783	0.86	28	1.32

From the closed loop response obtained, the closed loop transfer functions were found using the set of input and output data acquired from the real time experimentation. The accuracy of the transfer function obtained using this method was checked using curve fitting Fig 8, Fig 9.

Case1 : without including transportation delay:
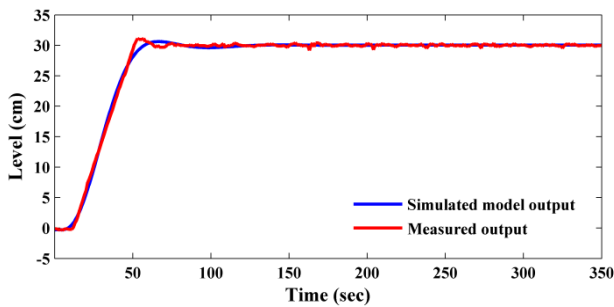The fitness was obtained as 94.84%

Fig. 8. Curve fitting for validating the closed loop system using MPC controller without introducing delay

Case2: including transportation delay:
The fitness was obtained as 93.3%
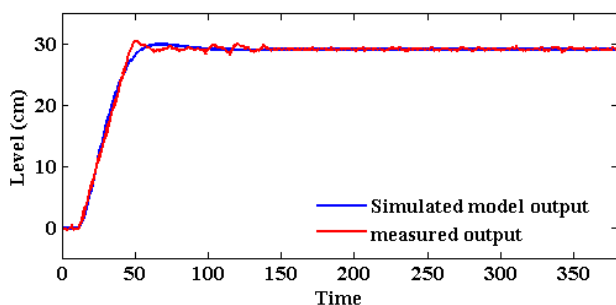These fitness values serves as a validation for usage of the obtained transfer functions.

Fig. 9. Curve fitting for validating the closed loop system using MPC controller on introducing delay

When using PI controller, the transfer functions were obtained as in (7), (8).
Case 1: without including transportation delay:

$$G(s) = \frac{0.99968(1-0.53459s)}{(1+5.0066s)(1+0.5887}$$ (7)

Case 2: including transportation delay:

$$G(s) = \frac{0.99985(1-0.53459s)}{(1+12.1945s)(1+0.2499}$$ (8)

when MPC is used as the controller, the overall system transfer functions are obtained as
Case 1: without including transportation delay:

$$G(s) = \frac{1.0024(1-1.003s)}{(1+1.2658s)(1+1.244}$$ (9)

Case 2: including transportation delay:

$$G(s) = \frac{0.9741(1-1.2486)}{(1+1.1714s)(1+1.173}$$ (10)

5. Stability Analysis

When MPC controller is designed there is always a possibility that the system may go unstable. In order to ensure stability of the closed loop system, two methods are used here.

a. Using Lyapunov stability analysis

As per Lyapunov stability theorem, the system is said to be stable if,

$$A^T P + PA =$$ (11)

where, A is the system matrix, P is a symmetric positive definite matrix and Q is any positive definite matrix.

Case 1: without including transportation delay:
For this system, using equ (9), the system matrix is found as

$$A = \begin{bmatrix} -1.5934 & -0.63 \\ 1 & 0 \end{bmatrix}$$ (12)

and P is calculated as

$$P = \begin{bmatrix} 0.8082 & 0.78 \\ 0.7878 & 1.76 \end{bmatrix}$$ (13)

Case 2: including transportation delay:
Using equ (10), the system matrix is,

$$A = \begin{bmatrix} -1.7058 & -0.72 \\ 1 & 0 \end{bmatrix}$$ (14)

and P is obtained as

$$P = \begin{bmatrix} 0.696 & 0.68 \\ 0.6873 & 1.67 \end{bmatrix}$$ (15)

In both the cases, the determinant value of both P_{11} and P are positive, which reveals that the system is stable for the chosen values of controller parameters.

b. Using Eigen value approach

Stability was also checked using Eigen value approach.

Case 1: without including transportation delay:
The values of λ were found to be -1.5525 , -0.04085 .

Case 2: including transportation delay:
The values of λ were found to be -0.8529, -0.8527.

In both the cases, both the values of λ are negative, which confirms that the system is stable.

6. Conclusion:

On comparing PI controller for a system with delay and without delay, the performance of the system is such that, the rise time, settling time, delay time, and offset increases with the increases in delay being introduced. This reveals that the PI controller is not capable of handling and overcoming delays in the system. But in the case of MPC, the rise time, settling time, delay time does not vary much even when a transportation delay is introduced into the system. From this it is evident that, MPC can well handle delays. Also, the PI controller required different sets of tuning parameters to enhance the performance when delay is introduced whereas MPC requires no such tuning because the controller itself suppresses the effect of disturbance introduced.

References

1. Bart Huyck, hans Joachim Ferreau, Moritz Diehl, Jos De Brabanter, Jan F M Van Impe, Bart De Moor, Filip Logist: *Towards online Model Predictive control of a programmable logic controller: Practical considerations:*, In: Mathematical Problems in Engineering, (2012), pp. 1 – 20.
2. M.V. Kothare, B. Mettler, M. Morari, P. Bendotti, C.M. Falinower: *Level Control in the Steam Generator of a Nuclear Power Plant*. In: IEEE Transactions on Control Systems Technology, 8 (2000), No1.
3. Jose Manuel Lopez-Guede, Borja Fernandez-Gauna, Manuel Graña, Fernado Oterino: *On the Influence of the Prediction Horizon in Dynamic Matrix Control.* In; International Journal of Control Science and Engineering, 3 (2013), No 1, p. 22-30.
4. Carlos E. Garda,t David M. Preti't, Manfred Morari: *Model Predictive Control: Theory and Practice: A Survey*. In:International Federation of Automatic Control, 25 (1989), No 3, p. 335-348.
5. Alberto Bemporad, Francesco Borrelli, Manfred Morari: *Model Predictive Control Based on Linear Programming — The Explicit Solution*: In:IEEE Transactions on Automatic Control, 47(2002), No 12, p.1974-1985.
6. E.F.Camacho, C.Bordons: *Model Predictive Control*, Second Edition, Springer-Verlag London Limited. 2007.
7. S.Joe Qin, Thomas A Badgwell: *A Survey of Industrial Model Predictive Control Technology*: In: Control Engineering Practice, 11 (2003), p.733-764.
8. Saverio Bolognani, Silverio Bolognani, Luca peretti, Mauro Zigliotto: *Design and Implementation of Model Predictive Control for Electrical Motor Drives*: In: IEEE Transactions on Industrial Electronics, 56, (2009), No 6, p. 1925-1936.
9. K.S.Holkar, L.M.Waghmare: An Overview of Model Predictive Control: In: International Journal of Control and Automation, 2, (2010), No 4, p.47-64.
10. Naresh N nandola, Sharad Bhartiya: *A multiple Model Approach for Predcitive Control of Nonlinear Hybrid Systems*: In: Journal of Process Control, 18 (2008), p.131-148.
11. keck Voon Ling, Weng Khuen Ho, Yong Feng, Bingfang Wu: *Integral Square Error performance of Multiplexed Model Predictive Control*: In: IEEE Transactions on Industrial Informatics, (2011).
12. Manfred Morari, Jay H Lee: *Model Predictive Control: Past, Present and Future*: In: Computer and Chemical Engineering, 23 (1999), p. 667-682.
13. Rolando Zanovello, Hector Budman: *Model Predictive Control with Soft Constraints with Application to Lime Kiln Control*: In: Computers and Chemical Engineering, 23 (1999), p. 791-806.
14. Liuping Wang: *Model Predictive Control System Design and Implementation Using MATLAB*, Springer-Verlag London Limited, (2009).
15. Nima Vaezi, Mahmood Khatibi, Ali Karimpour: *An Extended Linear MPC for Non Linear Processes*: In: Modares Journal of Electrical Engineering, 16 (2016), No 4, p.10-14.
16. Thomas Glaser, Constantijin F W Sanders, Fu Y Wang, Lan T Cameron, James D Litster, Jonathan M H Poon, Rohit ramachandran, Charles D Immanuel, Francis J Doyle: *Model Predictive Control of Continuous Drum Granulation*: In: Journal of Process Control, 19 (2009), p. 615-622.