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Composite Disturbance Rejection Control for Ball Balancer System

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Abstract

2 Degree Of Freedom(2DOF) Ball Balancer system is a highly nonlinear system where the position of the ball is controlled by controlling two servo motors simultaneously. This system is an advanced version of ball and beam system 1 Degree Of Freedom (1 DOF). The physical significance of the ball balance system are pan and tilt cameras for surveillance and satellite position correction. In general conventional PID controller is used in order to control the position of ball on plate in both axes (X , Y). PID controller is used to obtain an acceptable satisfactory response of the system. However, an exact nonlinear compensator is included to assure the closed-loop system stability. The major issue of conventional PID cannot give good eliminated results when external disturbance is more. This problem can be improvised by implementing Disturbance observer enhanced PD or PID controller(DOB). In this work the performance of Disturbance observer(DOB) enhanced PD controller is compared with the conventional PD controller response. In DOB enhanced PD the observer used is the inverse of the system transfer function and it observes the externally applied disturbance and make the system response to perform better in an environment prone to disturbances. The results are illustrated via simulation.

Keywords: 2DOF Ball balancer; Disturbance observer; PID

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1. Introduction

Generally, the sensors used for sensing the position of the ball in plate can be divided into two main categories, the touch screen layer on the plate and the overhead high-resolution camera. The ball balancer consists of a horizontal plate, which is tilted along in two horizontal axes due to this a ball can be controlled to roll to any require position on the plate.

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1.1. Visual servo Tracking

In the visual servo tracking of a Ball and Plate system the position of the ball is measured with the machine vision software installed in the system. The image processing algorithms of the machine vision system are implemented on a field programmable gate array (FPGA) device to satisfies real time constraints [3].In touch screen method ball can easily lose contact with the touch screen plate during the motion and may causes discontinuity in the ball position measurement. In overhead cameras method the sampling rate of a general camera(30 Hz) is limited, by using general camera for sensing the ball position may causes constraints in real time systems. The Visual servo tracking control method uses visual information in feedback control loops. Image data acquisition and processing are the major issues in visual servoing applications in real time processing. For the quick decisions making high frame rate and low processing latency are essential for the information extracted from the scene. A high computation, high pixel processing, parallel computation and efficient hardware utilization are required in real time image processing. General purpose processors are not suitable to fulfill real time requirements for image processing [4]. Vision sensor imitates the human sense of vision and without physical contact to the objects measurements are done. Visual sensing process and its manipulation is combined in the fashion of open loop. The accuracy of the visual sensor is directly responsible for resulting operation accuracy. The accuracy of these systems can be increase by using visual feedback control loop and which will also increase the overall accuracy of the system [3]. For the manipulator system, Visual servoing controller generates a velocity screw as the control input which guides the end effector towards the target.

1.2. Ball and plate system

The 2DOF Ball Balancer (2DBB) system is one of the challenging control bench-marking systems integrated into many practices and techniques is a common experimental setup used in control laboratories. Various control techniques can be explore by the users to stabilize the position of a ball on a plate. The system consists of a horizontal plate, which is tilted in two horizontal directions the ball can be controlled to roll to any position on the plate. The underlying principles of nonlinear dynamics and control theory are visually demonstrated and reinforce by this system. This system is widely used to test the performance and effectiveness of new control algorithms or technology due to its inherent nonlinearity, instability, and under actuation nature[3].

In general practice for a ball and plate system, sensors used for sensing the position of the ball can be provided in two main different types, the touch screen and the overhead camera. Both these two types of sensing devices suffer from certain shortcomings. There may be a possibility for the ball to lose its contact with the touch screen plate during the motion, and the discontinuity in the position measurement may occurs. Since the sampling rate of a common camera (30 Hz) is limited, use of a common camera for sensing the position of the ball imposes real time constraints on the system. Visual servoing is a control framework that incorporates visual information in feedback control loops. Realtime image data acquisition and processing is a critical issue in visual servoing applications. A high frame rate and low processing latency are essential since the visual servoing system must make quick decisions based on the information extracted from a scene. Realtime image processing requires a high pixel processing rate, massive and parallel computation, and efficient hardware utilization [4].

To build a reliable and accurate simulation model the detailed dynamic model is adopted to validate the closed loop performance of the control system, once a controller design is available. In the case of control design, the detailed dynamic model is very much complex process. we can achieve approximate input output feedback linearization approach to design a controller for trajectory tracking by neglecting high order coupling terms, for this purpose ball and plate system is simplified into two decoupled ball and beam systems[3]. For the high-speed/precision robotic applications the development of effective adaptive controllers required. The parameters are difficult to compute or measure Even in a well structured industrial facility, due to this robots may face uncertainty. To achieve the desired trajectory in less time the visual servoing and adaptive control must estimate a set of parameters more quickly[4].The control signal u(t) applied to the plant model generated by error signal $\theta(t)$ which is used to generate the proportional, integral, and derivative actions with the resulting signals weighted and summed with it. But in presence of disturbances conventional PD fails under most cases and hence novel methods are proposed in literature which will take care of disturbance rejection. Composite DOB has been proven in literature as an alternate to PID and used for the control of permanent magnet synchronous motor[14], surface vessels[13], hydraulic transmission[15]. In Composite DOB the feedforward control and feedback control are exploited to reject system disturbances. The novel contribution of the work is the comparison of conventional PD with DOB PD both in the presence and absence of disturbances. The simulations are demonstrated using MATLAB for square and saw tooth input trajectory under low and high frequencies.

2. System Modelling

2.1. System description

In 2DOF Ball Balancing system two rotary servo base unit devices, visual sensor and the plate are used which is symmetrical, hence the dynamics of each axis is assumed as same. Hence the 2DOF Ball Balancer is modelled as two de-coupled "ball and plate" systems where we assume the angle of the x-axis servo machine only affects the x direction ball movement only. The equation of motion which represents the ball's motion along the x-axis relative to the plate angle is developed.

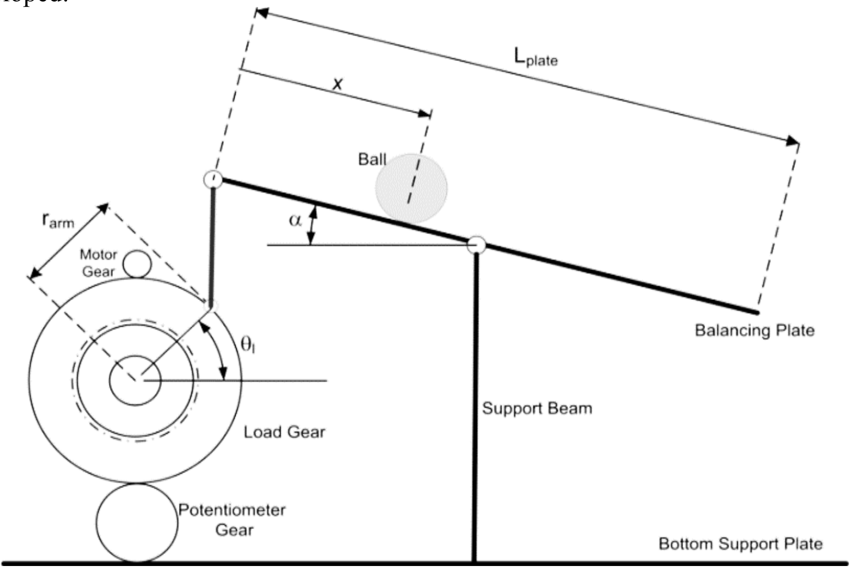

Fig 1 Modeling of ball on plate in one dimension

Table 1. System Parameters

Symbol	Parameter
m_b	Mass of the ball
L_{plate}	Length of the plate
r_{arm}	Radius of the servo gear
x	Ball displacement
$b\,\gamma$	Ball angle
$b\,r$	Radius of the ball
$b\,J$	Ball moment of inertia
θ	Angle subtended by rotary servo gear
α	Angle subtended by plate
h	Height of gear shaft from base

2.2. Modeling

Fig. 1 illustrates the free body diagram of ball and plate system then the Table 1 illustrates the different parameters of the system, the equation of motion, relating to the motion of ball, x, to the angle of beam, α can be found. According to the Newton's First Law of Motion, the sum of forces acting on the ball along the plate equals. The open loop system of the 2DOF Ball Balancer is represented in the Fig 2. The dynamics between the servo motor input voltage and the resulting load angle is represented by the rotary servo unit transfer function $P_s(s)$. The angle of the servo load gear and the position of the ball dynamics is described by the transfer function $P_{bb}(s)$. This is a decoupled model which means the x-axis servo does no effect the y-axis response [6]. From Fig.2 $X(s)$ and $Y(s)$ represents the measured ball position in the x and y direction i.e. in the Cartesian Coordinate system,$\theta_{l,x}(s)$ and $\theta_{l,y}(s)$ represents the load angle for the shaft to rotate for x-axis and y-axis motors,$V_{m,x}(s)$ and $V_{m,y}(s)$ are the respective input voltages generated to give the respective load angles.
The 1DOF Ball Balancer transfer function is derived

$$P(s) = P_s(s)P_{bb}(s) \tag{1}$$

Where

$$P_{bb}(s) = \frac{X(s)}{\theta_l(s)} \tag{2}$$

is the servo angle to ball position transfer function and

$$P_s(s) = \frac{\theta_l(s)}{V_m(s)} \tag{3}$$

The above equation represents the voltage to servo angle transfer function. The servo load gear position $\theta_l(t)$ with respect to the servo input voltage, $V_m(t)$ gives the transfer function of the servo motor as

$$P_s(s) = \frac{K}{s(s\tau+1)} \tag{4}$$

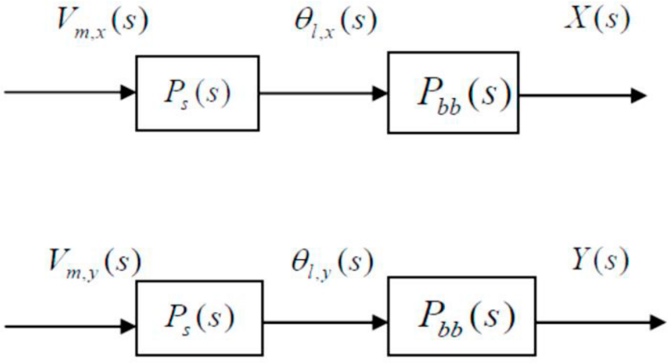

Fig 2 DOF Ball Balancer open-loop block diagram

Where K is the steady state gain of the motor and τ is the time constant of the motor. These values are calculated from the parameters of the device. The nominal model parameters are $K = 1.76 rad\ V/s$,$\tau = 0.0248$sec. The servo angle to the ball position transfer function, $P_{bb}(s)$, can calculated by taking the laplace transform of the linear equation of the motion is given by

$$P_s(s) = \frac{X(s)}{\theta_l(s)} = \frac{K_{bb}}{s^2} \tag{5}$$

Where

$$K_{bb} = \frac{2r_{arm}m_b g\, r_b^2}{L_{plate}(m_b r_b^2 + J_b)} \tag{6}$$

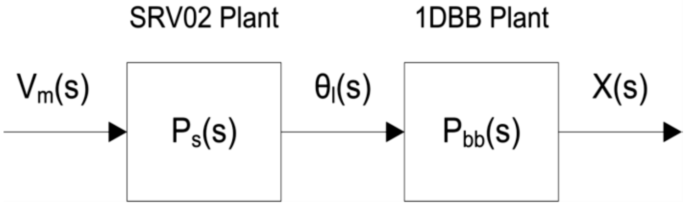

Fig 3 2 DOF Ball Balancer open-loop block diagram

From Fig 3 both systems are in series, the complete process transfer function can be obtained as follows

$$P_s(s) = \frac{X(s)}{V_m(s)} = \frac{K_{bb}K}{s^3(s\tau+1)} \tag{7}$$

This is servo voltage to ball displacement transfer function.

3. DOB Enhanced PD Controller Design

A composite control scheme is proposed to control the position of the ball on the plate by analysing the HD cameras information. It enhances the performance of the classical PD feedback controller by adding a disturbance observer, which can reconstruct and reject the unwanted perturbation, including the modelling discrepancies and the external disturbances[1].

3.1. Disturbance observer-enhanced pd algorithm

In composite control a disturbance observer is added. The observer is linear and is based on frequency domain design[8]. Inverse of the nominal model is required in the construction of the disturbance observer. Fig 3 depicts the block diagram of the control method. The disturbances directly act on the output variable through the disturbance models[2]. For those cases where the disturbances act on other places, such as the input channel or the process plant, the corresponding control structures can be equivalent to that in the Fig 4 by changing the disturbance models. This implies that the control structure in Fig 3 is a generic form. In Fig 3, r(s) denotes the reference curve of controlled variable. $\widehat{D}_g$(s)is the disturbance estimation. *N(S)* represents the PD controller output. The output can be represented as

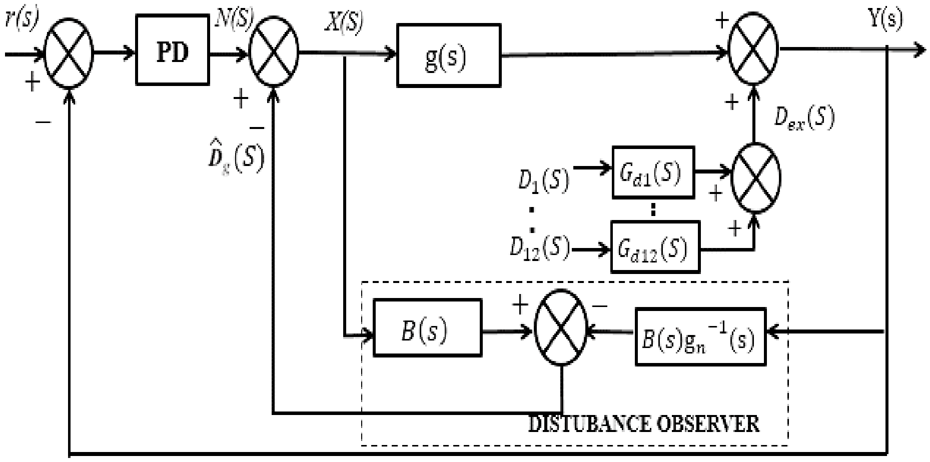

Fig. 4 Disturbance observer-enhanced PD controller

$$\mathrm{Y(s) = Gco(s)N(s) + Gdo(s)Dex(s)} \tag{8}$$

$$G_{c0}(s) = \frac{g(s)}{1+B(s){g_n}^{-1}[g(s)-g_n(s)]} \tag{9}$$

$$G_{d0}(s)=\frac{1-B(s)}{1+B(s){g_n}^{-1}[g(s)-g_n(s)]} \tag{10}$$

From equations (8) to (10), it can be inferred that the disturbance rejection performance depends mainly on the design of filter B(s). The relative degree of B(s), that is, the order difference between the denominator and the numerator, should be no less than that of the nominal model gn(s).This design principle is to make sure that the control structure is realizable, i.e. B(s)${g_n}^{-1}$(s) should be proper. Moreover, it can be found thatGdo(s) = 0 when B(s)is selected using a low-pass filter whose steady-state gain is 1, i.e. $\lim_{w\longrightarrow 0} B(JW) = 1$. This means that low-frequency disturbances can be rejected asymptotically. In this work, B(s) is chosen to be a second-order low-pass filter whose steady-state gain is 1.

It can be represented as

$$\mathrm{B(s)} = \frac{1}{(\lambda S+1\,)^2}\lambda>0 \tag{11}$$

As for the robustness analysis of the proposed DOB, it will be analysed as below. From Fig 3, the output Y(s) can be represented as

$$\mathrm{Y(s) = g(s)X(s) + Dex(s)} \tag{12}$$

$$\mathrm{Y(s) = gn(s)X(s) + Din(s) + Dex(s)} \tag{13}$$

where the term Din(s) is the internal disturbances generated from model mismatches. It can be denoted as

$$\mathrm{Din(s) = [g(s) - gn(s)]\,X(s)} \tag{14}$$

Next, the lumped disturbance Dsu(s)is defined as the sum of external disturbances Dex(s) and internal disturbances Din(s), that is

$$\mathrm{Dsu(s) = Dex(s) + Din(s)} \tag{15}$$

Then the output can be obtained that

$$\mathrm{Y(s) = gn(s)X(s) + Dsu(s)} \tag{16}$$

From Fig 3, the following equations hold

$$\mathrm{X(s) = N(s)} - \widehat{D}_g\mathrm{(s)} \tag{17}$$

$$\widehat{D}_g\mathrm{(s)} = B(s){g_n}^{-1}(s)y(s) - B(s)X(s) \tag{18}$$

Substituting equation (16) into equation (18), we can get that

$$\widehat{D}_g(s) = B(s){g_n}^{-1}(s)\mathrm{Dsu(s)} \tag{19}$$

Defining $\widetilde{D}\mathrm{g(s)}$ as the error between the real lumped disturbance and the estimation value, then

$$\widetilde{D}\mathrm{g(s) = Dsu(s) - gn(s)}\widehat{D}_g(s) \tag{20}$$

Substituting equation (19) into equation (20), yields

$$\widetilde{D}\mathrm{g(s)} = [1 - B(s)]\mathrm{Dsu(s)} \tag{21}$$

Employing the final-value theorem, it can be obtained from equation (21) that

$$\widetilde{D}\mathrm{g}(\infty) \lim_{s\longrightarrow 0} S\,\widetilde{D}\mathrm{g(s)} \tag{22}$$

$$\widetilde{D}\mathrm{g}(\infty) = \lim_{s\longrightarrow 0}[1 - B(s)] \lim_{s\longrightarrow 0} s\,\widetilde{D}\mathrm{g(s)} \tag{23}$$

$$\widetilde{D}\mathrm{g}(\infty) = \lim_{s\longrightarrow 0}[1 - B(s)] \lim_{s\longrightarrow 0} s \tag{24}$$

Thus, $\widetilde{D}\mathrm{g}(\infty)$ can be obtained when satisfying that the steady-state gain of B(s)is 1. This means that the disturbances can be asymptotically attenuated as indicated in [4]. The implementation of DOB is also very convenient and the computational effort and complexity will not be large[6]. So the disturbance observer is very effective and hence it is often used to deal with the process with time delays. The disturbance estimation accuracy mainly relies on the filter parameter λ in $B(s)$. From (24), the disturbance estimation property is determined by the frequency responses of the transfer function$1 - B(s)$. Smaller the value of λ, smaller the magnitude of the transfer function $1 - B(s)$. is. This implies that the disturbance estimation error can conveniently converge to an arbitrarily small value provided a small enough parameter λ is chosen in the filter $B(s)$.

4. Results and Discussions

4.1. DOB enhanced PD controller for Ball Balance system

This system was tested by giving 2 types of input like square wave and saw tooth inputs. A sum of external disturbance was given which is first order transfer function.

$$\frac{20}{5.1s+1} \tag{25}$$

$$\frac{0.35}{5.7s+1} \tag{26}$$

The disturbance may be step input or any other types of disturbance input the system must be overcome the disturbance and it should track the set point without losing the trajectory. For this system which is operated along with Disturbance observer tracks the trajectory much better than the system without disturbance which is operated only with PD controller both conditions were discussed here[10].From that comparison it can observed that the system with square input tracks the trajectory well which is the settling time, percentage overshoot and steady state error are satisfies the required specification which is discussed in the comparison Table 2. For the saw tooth input the system doesn't track completely the trajectory compare to square wave input.

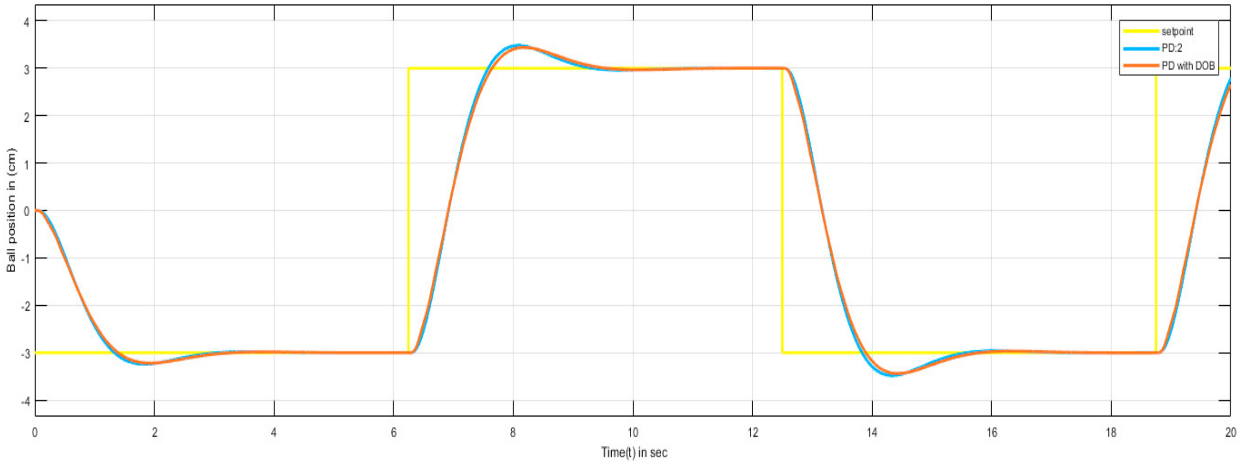

Fig. 5 DOB without disturbance (square input)

In Fig 5 the system is operated without externally applied disturbance with implemented DOB. We can see than there is no big changes between with and without DOB where the blue colored response which represents system without DOB having very slight overshoot comparing to red colored response which represents system with DOB.

4.2. Ball balancer response for applied disturbance

Fig 6 represents the system response for the applied disturbance. The system with DOB satisfies the given system specification in Table 1 by observing the externally applied disturbance, then controller neglects the disturbance. The system without DOB gives oscillatory response which dissatisfies the given specific constrains. From this we can say that the system with DOB provides better response comparing to system with only PD controller. For saw tooth input in Fig 7 system will not provide optimal result comparing to square input even though, for DOB based system provides better result comparing to system with only PD controller.

Table 2. Time domain Performance indices

Parameter	DOB Enhanced PD with disturbance	PD with disturbance
Steady State Error	0.045mm	0.4mm
Settling time	2.85 sec	4.35 sec
Peak Overshoot	8.3%	23.3%

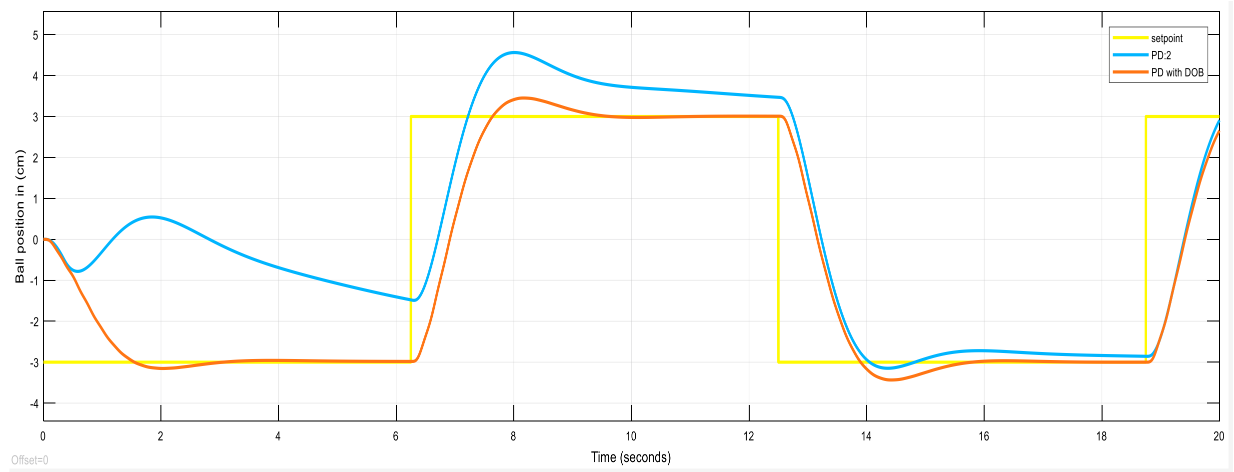

Fig. 6 Simulation of system with disturbance (square input)

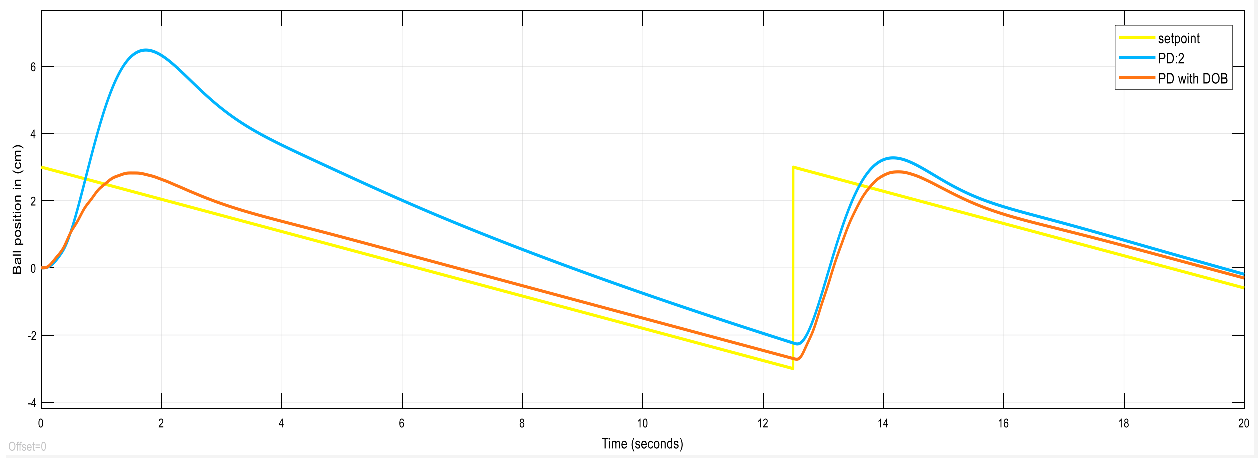

Fig. 7 Simulation of system with disturbance (saw tooth input)

4.3. Ball balancer response for increased frequency

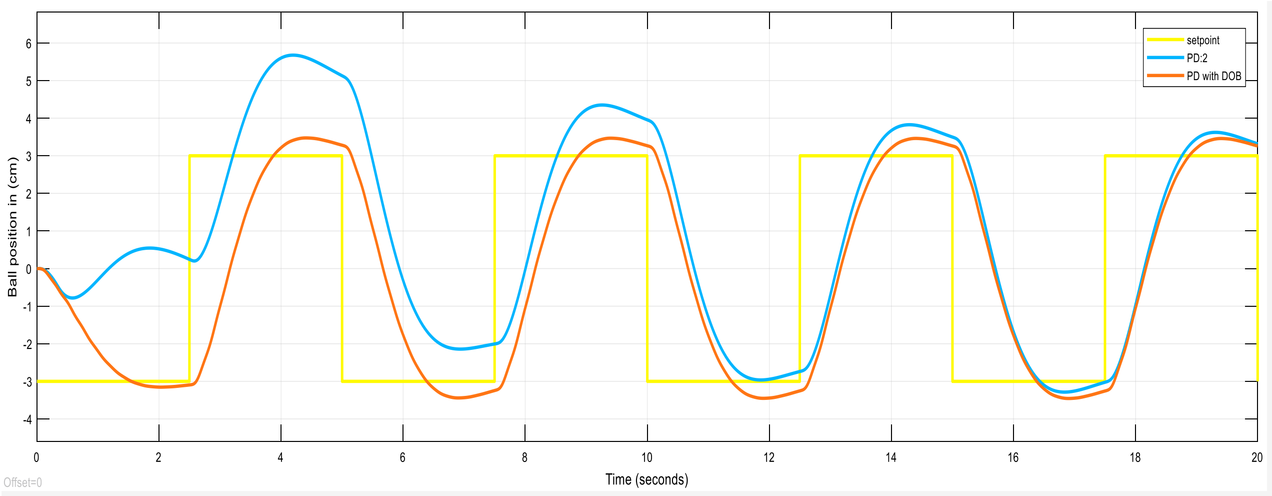

Fig 8 Simulation of system for increased frequency (square input)

In Fig 8 the system is operated with the input frequency of 0.08 HZ but when we increase the frequency to 0.2 HZ (25% of 0.08) the ball position will not tracks the set point properly but as per the comparison, system with DOB gives better result. But for the saw tooth input the system is not tracking well that is response is no merging with the set point which is provided in the Fig 9.

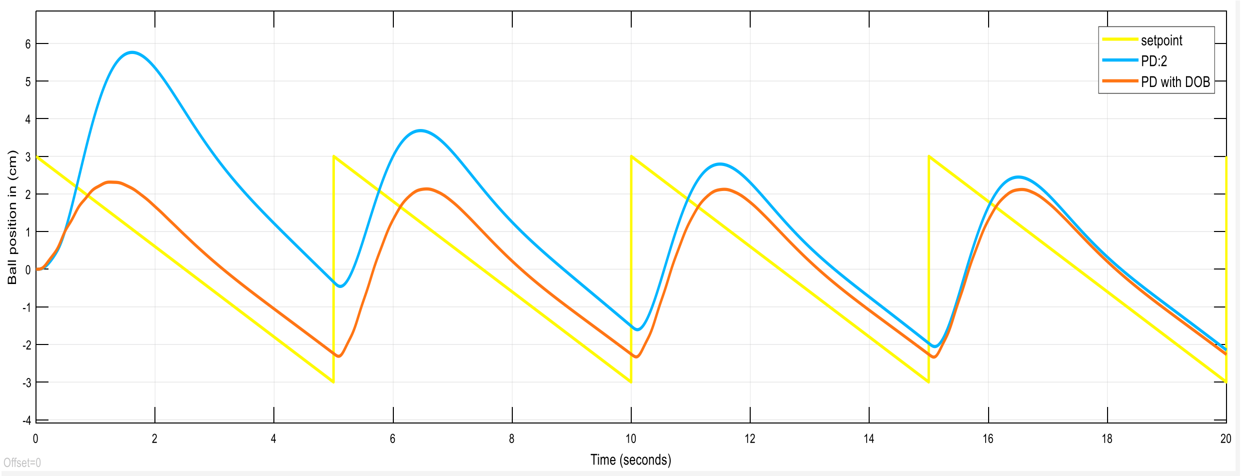

Fig. 9 Simulation of system for increased frequency (saw tooth input)

5. Conclusion

A conventional PD control is designed by means of pole placement technique A Disturbance Observer enhanced PD controller is designed for enhancing the system performance under disturbance. It can be seen from the simulation results that in the presence of disturbances the DOBPD performs better and is illustrated with the help of performance indices namely steady state error, percentage overshoot and settling time. In the absence of disturbance, it is inferred that the performance of both the conventional PD and DOB PD are the same. But in the presence of disturbances the effect of inclusion of the observer could be very well seen. DOB PD outperforms the conventional PD in terms of very low steady state error, percentage overshoot and settling time which is very much desired and essential in practical applications including pan and tilt cameras for surveillance and satellite position correction.

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