Hardware in the Loop (HIL) Analysis of Fuzzy Controller for Ball and Beam System

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ABSTRACT:
Ball and beam system is a nonlinear and unstable system which is used as an applied sample in research laboratories as a tool to represent the performance of different control algorithms. The present study utilizes hardware in the loop realization of classic (PID type) and fuzzy controllers by Sugeno fuzzy inference approach in order to evaluate their performances. All activities for design and simulation of controller were performed by MATLAB and Simulink software. Then, the simulation environment of MATLAB was linked to the operator interface as well as actuators and sensors in hardware in the loop structure by writing a real time kernel through DAQ interface cards. Simulation results show the appropriate performance of fuzzy controller in comparison to PD and PID controllers. By using fast processors for implementation of fuzzy controller, settling time, overshoot percentage and steady state error of the closed loop system were significantly improved in comparison to the common classic structure. Also, all simulation results were verified by hardware in the loop test.

KEYWORDS: ball and beam, fuzzy control, hardware in the loop, HIL, classic control

1. INTRODUCTION
Ball and beam system is one of the most popular and important laboratory models to understand the performance of common control methods. Ball and beam system belongs to under actuated mechanisms. There are always two main issues in harmonization of controller with ball and beam mechanical structure as well as adaptation of controller hardware with limitation in performance and responding speed of ball and beam in such a way to prevent the un-stabilization of this system.

For the frictionless ball-and-beam model, Barbu first dealt with a three-state subsystem via state-dependent saturation, and then took a back stepping procedure to achieve the stabilization design of the whole system [1]; For the frictionless ball-and-beam system, Barbu et al (1997) first dealt with a three-state subsystem via state-dependent saturation [3] and then used the homogeneity theory to assign saturation level functions [2].

The most common control structures that are used in ball and beam system are: LQR (linear quadratic regulator), PID (proportional- integral –derivative controller), PD (proportional- derivative) and sliding mode. It is obvious that many articles have been published in this regard and most of them compared the performance of these methods based on software simulation [4], [5], [6].

In recent years, fuzzy systems have significantly helped solving control problems in research laboratories and some of them are identified in the field of software simulation of fuzzy control methods related to ball and system [7], [8], [9].

The present study aims to examine the results of the implementation of both classic (PID type) and fuzzy control mechanisms in a hardware in the loop structure based on computer control in MATLAB software. It is obvious that the more effective performance that was examined in relation to using fuzzy controller in software simulations will be verified as real time in hardware for the loop structure in figure 1.
2. INTRODUCTION OF BALL AND BEAM DYNAMIC MODEL

Based on figure 2, a ball is put on a beam in which the ball is allowed to move along the beam with a degree of freedom. A lever at the end of the beam and the other end of the lever is joined to a gear servo. By rotating the servo and gear angle, the beam moves upwards and downwards. When the beam angle changes from the horizontal state, gravity makes the ball to move on the beam. For this system, controller will be considered, so that the ball position can be changed and controlled.

Fig.2. Physical structure of system

3. INTRODUCTION OF THE SYSTEM PARAMETERS

For this problem, we assume that the ball does not slip on the beam and the friction between the beam and the ball is insignificant [1], [2]. Constant and variable for this example are defined as follows:

- (m) Mass of the ball 0.033 kg
- (R) Radius of the ball 0.019
- (d) Lever arm offset 0.04 m
- (g) Gravitational acceleration 9.8 m/s^2
- (L) Length of the beam 0.5M
- (J) Ball’s moment of inertia 7.94e-6 Kg.m^2
- (r) Ball position coordinates
- (α) Beam angle coordinate
- (θ) Servo gear angle

4. SYSTEM EQUATIONS

The second derivative of input angle affects the second derivative (r). However, we ignore this portion. Lagrange equation of the ball’s movement is expressed as follows:

\[ 0 = \left( m + \frac{J}{R^2} \right) \ddot{r} + mg \sin \alpha - m r \alpha^2 \]  

(1)

Linear approximation of the system on condition \( r = 0 \) will give us the following equation:

\[ \left( m + \frac{J}{R^2} \right) \ddot{r} = -mg \alpha \]  

(2)

Also, according to the length of the link related to servo and servo angle, the beam’s angle to horizontal can be approximated by the following linear equation:

\[ \alpha = \frac{d}{L} \theta \Rightarrow \left( m + \frac{J}{R^2} \right) \ddot{r} = -mg \frac{d}{L} \theta \]  

(3)

Now, by transferring the above differential equation to Laplace space, we have:

\[ \left( m + \frac{J}{R^2} \right) R(s)s^2 = -mg \frac{d}{L} \theta \]  

(4)

Thus, the Transfer function of this linear system is obtained as follows:

\[ P(s) = \frac{R(s)}{\theta(s)} = -\frac{mgd}{L(R^2+m)} \frac{1}{s^2} \]  

(5)

It should be noted that the presence of second integral in the denominator of transfer function is the main challenge on the stability of the system.

By applying the amount of variables in the obtained differential equation, the system’s transmission function will be obtained as follows:

\[ P(s) = -0.47/s^2 \]

5. HARDWARE IN THE LOOP STRUCTURE

Hardware companies like QUANSER make different models of ball and beam for laboratories researches. In this work, we have made structures for the mechanical parts of this study using BB01 and SRV02 QUANSER models [10].

One of the most important issues in making ball and beam structure is to select related sensors. Because estimation of ball position by using non-contact sensors according to the small ball is a difficult task and the presence of noise and turbulence is inevitable.

Sharp company has introduced a family of infrared sensors over the last years [11]. These sensors have small packaging, very low consumption and different outputs. These distance meter present much freedom in comparison to the status of ambient light due to new methods of measuring distance. These distance meters have smaller CCD linear arrangement to calculate distance or the presence of objects in fields of view. The main idea is that a pulse is emitted from IR light by emitter. This light heats the object in the transmitted field of view or goes on. In case of no barrier (object), the light will be never reflected and no range will be shown. If light is reflected from an object, it will return to sensor and will create a triangle like figure 3 points of reflection, emitter and sensor.
Fig. 3. GP2DXX sensor structure with CCD arrangement

CCD arrangement can determine the angle of the reflected light and thus can calculate the angle of the reflected light and thus can calculate the angle to the object.

This new method of measuring distance is almost isolated against the involvement of ambient light and shows a significant unwillingness or non-tendency against the color of the identified object. Now, the identification of a black wall in the sunlight is possible.

Fig. 4. GP2D120 sensor output

As figure 4 shows, the relationship of sensor output and its input is non-linear and an equation from order 5 will be obtained to interpret the relationship between output and input, recognize the ball position and implement the performance of sensor in simulation by using the curve fitting which is illustrated in figure 5.

Fig. 5. Sensor’s Input – Output Relation

Related polynomial for input-output function of the sensor is approximated by MATLAB as follows:

\[ F = p_1 \times X^5 + p_3 \times X^3 + p_4 \times X^2 + p_5 \times X + p_6 \]

Where the Coefficients are:

- \( p_1 = 4.11e^{-005} \)
- \( p_2 = -0.003196 \)
- \( p_3 = 0.9051 \)
- \( p_4 = -1.092 \)
- \( p_5 = 8.447 \)
- \( p_6 = 70.08 \)

Furthermore, using the Ziegler Nichols’s method, a PID controller is designed with MATLAB and will be evaluated in the SIMULINK as indicated in figure 6.

Fig. 6. Analysis PID controller in Simulink
6. FUZZY CONTROLLER AND LOGIC

The main purpose of this study is to compare the performance of fuzzy controller and prove its superiority in terms of behavior to classic controllers by using hardware in the loop assessment. Fuzzy systems are considered very appropriate for the systems from which mathematics cannot have an accurate and simple description. Fuzzy algorithms have relative superiorities. For example, promoting the control system and using language description process in fuzzy logic is an approach that is not possible in mathematics. Also, the additional input variables and rules are simply included in the fuzzy logic. In fact, in most functions of fuzzy logic, a fuzzy solution is the interpretation of the solution provided by human in fuzzy logic language. Fuzzy logic is an appropriate method for mapping the input space into output space. Mapping from input to output is considered as starting point of all operations.

7. DESIGN OF FUZZY CONTROLLER FOR BALL AND BEAM

Fuzzy controller has two inputs and includes error signals set with the input name of $e$ and error derivate or $\dot{e}$. Fuzzy set and fuzzy rules were made in fuzzy toolbox and the relevant structure is seen in figure 7.

Membership functions for the first input of ball and beam system, i.e. the error signals are as figure 8.

Also, the membership functions for the second input of error derivative are as figure 9.

We have nominated five fuzzy variables namely as NF (negative far), NS (negative small), ZE (zero), PS (positive small), and PF (positive far) for the fuzzy controller. The input range of fuzzy control was selected according to the system input and a ratio of the beam length or structure beam.

![Fig.7. Fuzzy controller](image1)

![Fig.8. Membership function of error input](image2)

![Fig.9. Membership function of error derivative input](image3)

![Fig.10. Fuzzy output signal](image4)

![Table1. Fuzzy Controller rules](table1)

To simulate and apply the controller, the ball and beam reference model was used in Simulink environment of MATLAB software. The file of fuzzy rules designed by Sugeno method was applied on this modeling. In the following figure, the simulated model connected to ball and beam structure with fuzzy controller can be observed.
8. COMPARISON OF CLASSIC AND FUZZY CONTROLLER PERFORMANCE

In figure 12, the impact turbulences entered the ball for more than 1 minute was repeatedly examined. In this test, the ball position that is the system input was adjusted on a certain value and by applying random impacts to the ball, the system was removed out of balance mode and the performance of controller to remove the created turbulence is observed. The controller is PID and the impacts created to the ball are a random value in the operating range of the system.

Having large overshoot, long settling time and also having too much steady state error in the behavior of the above closed loop are the weakness of this controller which is validated by implementation in the hardware in the loop test.

As can be seen, the reduction of settling time, overshoot and steady state error are some obvious advantages of fuzzy controller in this test and more rapid stability and less fluctuation in relation to the performance of this controller were verified in hardware in the loop test.

To better understand the subject, we repeat the test again with step input in order to study the obtained results. To do this, the ball position that is the system input is changed with random pulses in the input range that is the beam length. In the following figures, the response of ball and beam system to the inputs given to the actual model with random range and time can be observed.

In figure 13, we repeated the same test with our designed fuzzy controller.
Then, we repeat the test for fuzzy controller.

The obtained results show that the method presented in fuzzy model has a better performance in terms of stabilization speed compared to PID controller method (It should be noted that the performance of fuzzy controller in hardware in the loop test was attached as a multimedia file to this article).

Finally, the authors declare that there is no conflict of interest regarding the publication of this paper.

9. CONCLUSION

Classic controller is much simpler than fuzzy controller in terms of implementation on a microchip. One of the requirements of fuzzy control implementation is availability of high-speed processor for controller hardware; however, there is no concern in this regard due to the considerable growth in this field over the last years. In terms of the stability, short settling time, minimum overshoot percentage and smooth response of the closed loop system, designed fuzzy control is much better than classic control. Fuzzy controller performance is more robust in case of uncertainty or small changing of ball weight which was evaluated in the hardware in the loop tests. Hardware in the loop test results exploited the fact that the proposed fuzzy controller is successfully applied to ball and beam system and achieves the almost disturbance decoupling and of the controlled system comparing with PID controller (as identified in the simulation results).

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