FUZZY CONTROL FOR CIRCULAR INVERTED PENDULUM

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Abstract: This paper offers alternative solutions to existing problems in inverted pendulum designs. Three main problems can be listed as limited track length, hardware complexity and inappropriate control algorithm usage. Circularly moving cart was proposed to provide unlimited track length. In order to reduce the hardware complexity, the system was controlled by a microcontroller. Finally, fuzzy control was used for the control algorithm because of its efficiency, robustness and simplicity. Efficiency of the system is presented by carrying out experiments on developed inverted pendulum control system.

1 INTRODUCTION

Inverted pendulum, used as a control system throughout the study, is composed of a rod attached to a moving cart. Aim of the inverted pendulum is to stabilize the pendulum vertically by moving the base whose action is determined by the control algorithm. One can find different designs for inverted pendulum in the literature like supported inverted pendulum (Joldis, 2006), dual inverted pendulum (Lundberg, Roberge, 2003) or 360 degree inverted pendulum (Tsai, Lin, 2003).

Main methods used for control can be listed as PID, genetic algorithms, rule-based learning, neural networks and fuzzy control (Gupta, Sinha, 1995). Fuzzy control differentiates from others because it facilitates the modeling of complex systems as in real world. In addition to modeling, design and simulation of these processes can be acquired by fuzzy logic without using complicated mathematical models because it uses linguistic variables like in real world to represent the systems.

(Mirza, Hussain, 1998) developed an inverted pendulum using PID modes for non-linear systems. (Wang et al. 2004) proposed a method to balance a rotary inverted pendulum in the minimum time. Fuzzy control was used in rotary pendulum balancing problem by (Yurkovich, Widjaja, 1996). Swing up and balancing control were applied for several phases of the process. It was seen that fuzzy logic provided better solution to control problem when system constraints were fully determined. (Ray, Das, Tyagi, 2005) used a similar approach to balance inverted pendulum moving in a limited track.

Most of these studies intend only balancing pendulum without considering all limitations like lack of memory space, excessive hardware parts and finite track length. For this reason, this study focuses on designing an ideal control system with appropriate control algorithm to overcome the abovementioned problems. The main objectives of the study are as follows:

- Building an inverted pendulum system with minimum hardware configuration.
- Determining the effects of control algorithm on system control.
- Designing inverted pendulum to provide unlimited track length.

2 SYSTEM COMPONENTS

In this section, two main parts forming the inverted pendulum system, control method and hardware, will be introduced in detail.

2.1 Control Method

Fuzzy controller comprises four main parts: rule-base, fuzzification, interface mechanism and defuzzification.

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Error, difference between vertical and actual position of pendulum, has major impact on control. So, we can assign error as our first input. Change in error defines how fast pendulum changes its position, which is another important factor for control. Then, change in error can be assigned as second input.

Rules include knowledge of how system works. Each linguistic variable takes linguistic values that change from negative large to positive large. Since we have two inputs and an output it is easy to list all the rules in a tabular form as follows. One can create the tabular form for 3 and 7 linguistic values.

"PWM"		"change-in-error"				
		0	1	2	3	4
"error"	0	4	4	4	3	2
	1	4	4	3	2	1
	2	4	3	2	1	0
	3	3	2	1	0	0
	4	2	1	0	0	0

Figure 1: Rule-base with 25 rules.

In Figure 1, body represents the linguistic values for output (PWM force), left column and top row represent linguistic values for Error and Change in Error respectively. Numbers represent the magnitude of the linguistic values, i.e. "0" for "neglarge", "2" for zero and "4" for "poslarge".

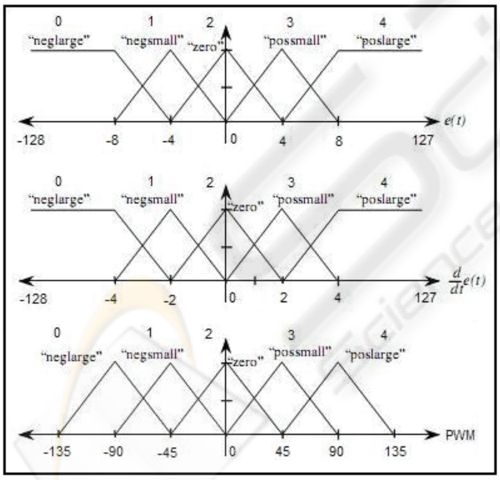

Figure 2: Fuzzy membership functions for 5 linguistic values.

Mamdani type system was selected for inference systems where minimum of the active membership degrees were operated. Center of Gravity (COG) defuzzification method was used because the universe of discourse of the output PWM(force) was continuous. As a result of this calculation, a crisp output is produced which is the force to be applied to DC motor at a time.

2.2 Hardware

In this stage, construction of the inverted pendulum control system will be explained. Input signals will be obtained from a potentiometer attached to the pendulum. According to the inputs, the microcontroller computes the control action and transfers it to the manipulating element which is a DC motor in our situation. Basic control operation can be summarized in a number of steps. The analog input from the potentiometer must be converted into a digital word in order to be processed. The microcontroller inputs these signals periodically via its internal analog-to-digital converter and calculates the required output. The electrical power supplied to motor is determined by a pulse-width modulated voltage derived using the Pulse Width Modulation (PWM) peripheral within the microcontroller. The current available from the microcontroller is insufficient to drive the motor directly so an H-bridge motor driver IC must be used. Since the motor driver system operates at a higher voltage than the microcontroller and a single power supply is to be used, a step-down voltage regulator was employed to power the microcontroller system.

Figure 3: Geared DC motor (top) and Potentiometer (bottom).

In order to provide unlimited track length, a circularly moving inverted pendulum trolley was designed in the shape of a triangle as shown in Figure 5. Control board to be attached on pendulum platform was a 9cm x 9cm stripboard comprising a 40 pin PIC 18F4620 microcontroller, LM7805 voltage regulator and L6203 H-bridge motor driver. Using all these parts in such a small space enabled us achieving minimum hardware object.

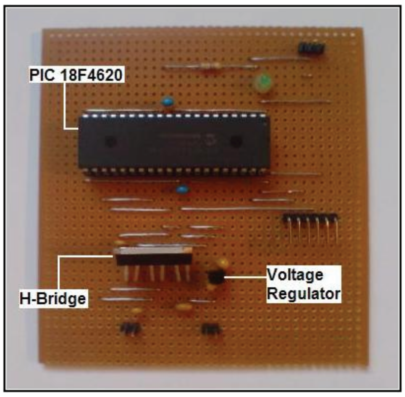

Figure 4: Control board.

The control board was used for three main operations. First, voltage was regulated in order to be used for different components throughout the control board. Second, error was read from the pot and transferred to microcontroller for processing. And lastly, PWM output produced by microcontroller was processed in H-bridge for driving the motor.

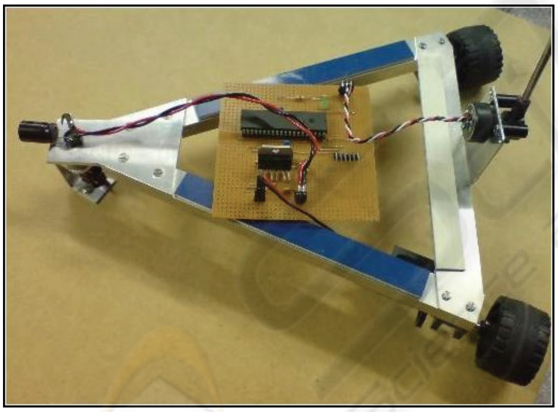

Figure 5: Side view of the pendulum trolley.

3 PERFORMANCE EVALUATION

For performance evaluation, three different fuzzy controllers defined in previous phase were embedded into inverted pendulum system one at a time. Effects of variation in control algorithm were observed experimentally in terms of system oscillation, balance angles and steady state.

Number of membership functions and rule base to be applied should be selected carefully such that system provides low PWM output for small error range and high PWM output for large error range. In the first design, three membership functions for each inputs and output were defined as well as 9 rules. For this design, system managed to lift the pendulum up by applying high pulse to motor for large errors. On the other hand, pendulum could not be balanced due to high oscillation because control action produced large PWM output even for small errors.

Fuzzy inference system with seven membership functions and 49 rules gave opposite results. Control output was small enough to balance the pendulum in very limited error angle. If pendulum starts to move away from balance limits, motor power is slowly increased by control action to keep the pendulum within the boundaries. Nonetheless, pendulum falls down to extreme edges due to inadequate acceleration.

Final fuzzy inference system design was composed of five membership functions and 25 rules. Advantages of the first two systems were included in the last version that was capable of balancing pendulum for small angles and lifting it up for relatively large angles.

	Number of Membership Functions		
	3	5	7
Lifting up angle (in degrees)	45°-50°	45°-50°	20°-25°
Oscillation in terms of angle (in degrees)	45°-50°	2°-5°	2°-10°
Steady State(S) or Dead-Band(D)	None	Yes (S or D)	Yes(S)

Figure 6: Performance comparison in terms of fuzzy membership functions.

Let us look at the situation where pendulum was balanced while platform was rotating. Main reason of this is narrow dead-band which can be defined as angle range at which pendulum is balanced and motor stops. For the project, dead-band was automatically created as narrow based on the definitions of membership functions. Since dead-band was small, pendulum was able to stay steady at the points close to the range. Thus, balance is achieved while pendulum platform rotates.

Circular movement of pendulum platform is a good way for lifting the pendulum up only if enough acceleration is provided which is dependent on sudden change of speed. Acceleration rate can be changed by adjusting sampling time of Error and Change in Error. Longer sampling time results with higher alteration rate. Nevertheless, longer sampling time has negative effects on system control. If one selects sampling time close or bigger than falling time, system will not stabilize the pendulum. Besides, higher sampling time causes oscillation in the system between the positive and the negative sides of the vertical because of the magnitude of the PWM output. To solve this dilemma, appropriate sampling time must be selected. During inverted pendulum development process, several artificial sampling times (30 ms, 60 ms, 125 ms, 250 ms and 500 ms) were created using delay function. Test results indicated that oscillation decreases for smaller sampling times. That’s why, for inverted pendulum system the fastest internal oscillator option was employed without any delay function to provide the shortest calculation interval possible.

4 CONCLUSIONS

In this paper, we focus on developing an inverted pendulum with the aim of minimizing the size and the cost of the system structure while increasing the reliability and performance. By using a microcontroller, hardware requirements are greatly reduced as well as total cost. A new approach to inverted pendulum design is proposed so that unlimited circular movement is assured. Fuzzy inference system with five triangular membership functions and 25 rules provide an appropriate way of control as far as low memory capacity of the microcontroller is concerned. Empirical results show that pendulum is balanced vertically either in steady-state or in dead-band.

Inverted pendulum control system can be improved in a number of ways. Lifting the pendulum up from extreme edges can be achieved by replacing the current pendulum with a lighter and/or shorter one. A mass can be added at the top of the pendulum in order to provide steady movement and to facilitate the stabilization but such a modification changes the place of center of gravity to a great extent. Type of the motor and size of the wheels affect the acceleration. Motor can be changed with a powerful one or/and size of the wheels can be bigger to provide more speed and acceleration correspondingly.

It is known that oscillation can be reduced by decreasing sampling time. Lower sampling time can be achieved by using higher processor speeds. In the project, sampling time was determined by the 8 MHz internal oscillator. So, a crystal oscillator may be added to system as external clock source. Such a modification increases the processor speed from 8 MHz up to 40 MHz.

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