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Intelligent Control of AC Induction Motors

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1. Introduction

It has been proven that fuzzy controllers are capable of controlling non-linear systems where it is cumbersome to develop conventional controllers based on mathematical modeling. This chapter describes designing fuzzy controllers for an AC motor run mechanism. It also compares performance of two controllers designed based on Mamdani and Takagi-Sugeno with the conventional control scheme in a short track length, following a high disturbance. Fine and rapid control of AC motors have been a challenge and the main obstacle in gaining popularity in use of AC motors in robots actuators. This chapter reviews how use of intelligent control scheme can help to solve this problem.

2. Cart and Pendulum Problem

Design and implementation of a system is followed by vigorous testing to examine the quality of the design. This is true in the case of designing control systems. One the classical systems to test quality and robustness of control scheme is inverted pendulum. In recent years, the mechanism of an inverted pendulum on a moving cart has been used extensively and in many different types. The cart and pendulum mechanism has become even more popular since the advent of intelligent control techniques. This mechanism is simple, understandable in operation, and stimulating. It has a non-linear model that can be transformed into linear by including certain condition and assumption in its operation. For the above reasons, inverted pendulum's performance has become a bench mark for testing novel control schemes. In this chapter the focus is on the driving power in balancing the inverted pendulum which is an electrical motor. Traditionally, DC motors are used for this type of tasks. However, in this chapter the focus is on AC electrical motors for producing the torque required for the horizontal movements of the inverted pendulum. A simplified control model for the AC motor is used which includes the motor's equivalent time constant as the crucial parameter in producing rapid responses to the disturbances. In the modeling of fuzzy controllers for the inverted pendulum, the input to the pendulum block is considered to be a torque. This torque is produced by an electrical motor which is not included in the model. That is, the torque is output of the motor. A disadvantage in this modeling is that the electrical motor dynamics is not built-in in the control system independently. On the other hand, not including the electrical motor in the control scheme of the pendulum mechanism provides the freedom to alter the electrical motor and examine the performance of the pendulum with different types of the drive. Here, a simplified model of an AC electrical motor is incorporated into the system. The electrical motor receives its

inputs as current or voltage and produces a torque as output to control the balance of the mechanism.

The new approach in modeling a fuzzy control system assists in achieving a number of goals such as: examining use of AC motors in producing rapid response, selecting sensitive parameters for an optimum high performance electrical motor capable to stabilize the inverted pendulum system, designing a Takagi-Sugeno type fuzzy controller, and comparing the effectiveness of inclusion of fuzzy controller along with the conventional control scheme.

3. Conventional Controllers & Fuzzy Controllers

The conventional approach in controlling the inverted pendulum system is to use a PID (Proportional, Integral, and Derivative) controller. In order to model the system the developer would have to know every technical detail about the system and be able to model it mathematically. Fuzzy Logic control (FLC) challenges this traditional approach by using educated guesses about the system to control it (Layne & Passino 2001). Passino states that differential equations are the language of conventional control (PID), while "rules" about how the system works is the language of fuzzy control (Passino and Yurkovich, 1998).

Fuzzy logic has found its way into the everyday life of people, since Lotfi Zedah first introduced fuzzy logic in 1962. In Japan, the use of fuzzy logic in household appliances is common. Fuzzy logic can be found in such common household products as video cameras, rice cookers and washing machines (Jenson 2005). From the weight of the clothes, fuzzy logic would be able to determine how much water as well as the time needed to effectively wash the clothes. Japan developed one of the largest fuzzy logic projects, when they opened the Sendai Subway in 1987 (Kahaner 1993). In this subway, trains are controlled by fuzzy logic. Fuzzy Logic is a subset of traditional Boolean logic. Boolean logic states that something is either true or false, on or off, 0 or 1. Fuzzy logic extends this into saying that something is somewhat true, or not completely false. In fuzzy logic there is no clear definition as to what is exactly true or false. Fuzzy logic uses a degree of membership (DOM) to generalize the inputs and outputs of the system (Lin and Lee 1996). The DOM ranges from [0 1], where the degree of membership can lie anywhere in between.

The majority of Inverted pendulum systems developed using fuzzy logic, are developed using a two dimensional approach, where only the angle and angular velocity of the pendulum's arm are measured. The following research will show why this method is insufficient for the development of an inverted pendulum on a limited size track. To have an efficient fuzzy controller for an inverted pendulum, the system must also include inputs for the position of the cart that the pendulum is balanced upon and the velocity of the cart. Two-dimensional fuzzy controllers are very simple examples of fuzzy control research. Many of them will balance the inverted pendulum, but are not in control of the cart's position on the track. Adeel Nafis proposed a two-dimensional fuzzy controller to balance the Inverted pendulum on a track (Nafis 2005). Tests showed that the controller would balance the pendulum but neglected to control the position of the cart and eventually the cart's position would exceed the length of the track. Another FLC was proposed by Passino; again this cart had the same result as the previous FLC (Passino and Yurkovich, 1998).

Control of the system requires that the cart holding the pendulum be moved by some mechanism. For simulation purposes, in this experiment a field oriented AC motor was used (Bose 1997).

4. Effect of Number of Inputs on Designing Fuzzy Logic Controllers

In a simple control mechanism there is one input and one output. Fuzzy Logic Controllers can have more than one input. Two-input FLC's are easy to implement and receive great performance responses from simulations. Layne (Layne & Passino 2001) modeled a fuzzy controller that had great performance balancing the pendulum but the cart's positioning was unstable, making it an impractical rule set for real life implementation. Two-input FLC's are the most commonly researched inverted pendulum systems. One of the most commonly researched types fuzzy controllers is two-input inverted pendulum systems. The 2-input system receives angle θ and angular velocity ω as its inputs. The system uses 5 membership functions for each input, and another 5 for the outputs which is the Force. The system consists of 25 (that is 5 to power 2; 52) rules. Table 1 shows the rule base for the inverted pendulum system. According to Table 1 a value of NL represents a negative large angle or angular velocity, and PL represents a positive large angle/angular velocity. As Table 1 indicates, if there is a situation where the angle is Zero (ZE) and the angular velocity is PS then the rule NS will be fired. Where, NL, NS, ZE, PS, PL are linguistic values of negative large, negative small, zero, Positive small, and positive large.

θ/ω	NL	NS	ZE	PS	PL
NL	PL	PL	PL	PS	ZE
NS	PL	PL	PS	ZE	NS
ZE	PL	PS	ZE	NS	NL
PS	PS	ZE	NS	NL	NL
PL	ZE	NS	NL	NL	NL

Table 1. Rule-base Matrix for the Inverted Pendulum.

A simulation that runs for 2 seconds is shown in Figure 1. The pendulum has an initial angle of 0.2 radians (dashed line). When the simulation is run, the angle of pendulum balances quickly, in about 1 second, but the position of the cart is not controlled (continuous line) so the cart's position will eventually drift off into the end of the track, even though the pendulum's arm is balanced.
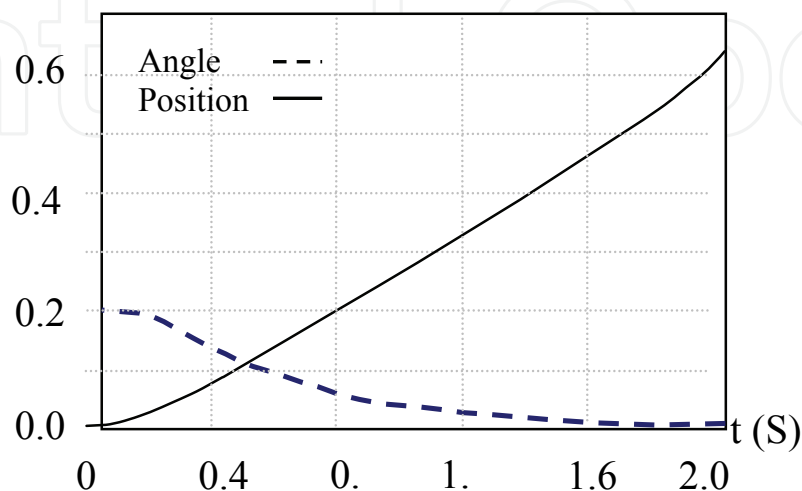

Figure 1. Variation of angle θ (rad) and position X (m) of pendulum vs. time t (s).

The benefit of adding two more inputs to the system to control the X-position of the cart and the velocity of the cart will greatly benefit the stability of the system. There is a cost for better stability; this is a greater computation time, and greater complexity in the model. The cost of adding more inputs increases exponentially with the number of inputs added. The above two-input system used five membership function for each input used; this resulted in a 25 (i.e. 5²) rule base. By adding two more inputs to the system, the systems rule base would grow to 625 (i.e. 5⁴) rules. Development time for a rule base this size can be very time consuming, both in development and in computational time. Bush proposed using an equation to calculate the rules, rather than taking the time to develop the rules individually (Bush 2001). The system was a 5⁴ system with 17 output membership functions (OMF). The equation used was:

$$\text{Output Membership Function} = I + (J - 1) + (-K + 5) + (L+5) \qquad (1)$$

This equation results in values ranging between 1 and 17. This corresponds to the OMF that is to be used in the calculation of the output. The performance of the system using this approach is not consistent with that of the original simulation, given by the author of the above Equation 1 (Bush 2001). The force given to the cart holding the pendulum was found not to be enough to balance the pendulum and the system failed within a small amount of time. It can be concluded that this system would be a good starting point for one to base a large rule set on, but the system would need some tweaking of the rules and membership functions to get to balance the system effectively. The final FLC controller that was modeled for simulation was a Takagi-Sugeno type fuzzy controller. All the previous FLC's modeled were of Mamdani type. A Takagi-Sugeno type fuzzy controller (Mathswork, 2002), (Liang & Langari, 1995), (Johansen et al. 2000), (Tanaka et al. 2003) varies from the traditional Mamdani type controller by using linear or constant OMF's instead of triangular, trapezoidal, Gaussian or any other method the developer decided to use. The system uses 4-inputs with only 2 input membership functions for each. This resulted in a 2⁴, 16 rule system. The linear output membership functions are calculate using the equation

$$\text{Output Membership Function} = c_0 + (c_1 * x_1) + (c_2 * x_2) + (c_3 * x_3) + (c_4 * x_4) \qquad (2)$$

Where c_n is the parameters of the OMF, and x_n is the values of θ, ω, X and linear velocity V respectively. The system modeled here uses fuzzy logic toolbox of Matlab (Sugeno 2002).
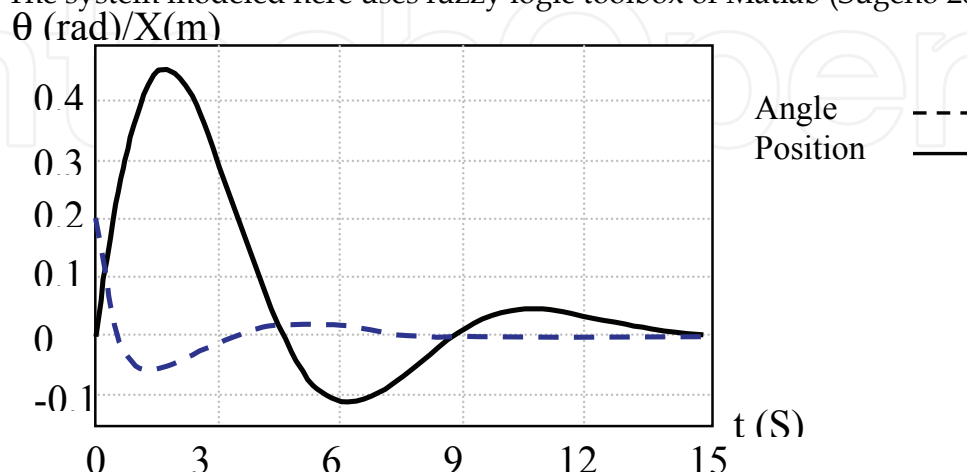

Figure 2. In adjusting the balance of pendulum angle θ (rad), and position X (m) changes with time t (s).

The control of all 4 parameters with only 2 membership functions causes the system to run very quickly. The down side to this quick response is that it takes more time for the system to stabilize when there are so few membership functions. The system will overshoot the targeted position and eventually come to rest. The settling time of this system takes more time than any other system.

Figure 2 is the result of the simulation. The pendulum is started with an initial disturbance of 0.2 radians. As shown, the fuzzy controller overcompensates for this initial disturbance and sends the pendulum's angle (dashed line) in an opposite direction in an attempt to balance it, this is the overshoot. It takes approximately 5 seconds for the pendulums arm to balance.

5. Mathematical Modeling of Field Oriented AC Induction Motors

The motor chosen for the simulation is an AC motor. The motor is modeled, Figure 3, using field oriented control scheme (Bose 1997).

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega_e \varphi_{ds} \tag{3}$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega_e \varphi_{qs} \tag{4}$$

$$0 = R_s i_{qr} + \frac{d}{dt}\varphi_{qr} + (\omega_e - \omega_r)\varphi_{dr} \tag{5}$$

$$0 = R_r i_{dr} + \frac{d}{dt}\varphi_{dr} + (\omega_e - \omega_r)\varphi_{qr} \tag{6}$$

$$T_e = 1.5 p \frac{L_m}{L_r}(\varphi_{dr} i_{qs} - \varphi_{qr} i_{ds}) \tag{7}$$

$$\begin{cases} \varphi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \varphi_{ds} = L_s i_{ds} + L_m i_{dr} \end{cases} \tag{8}$$

$$\begin{cases} \varphi_{qr} = L_r i_{qr} + L_m i_{qs} \\ \varphi_{dr} = L_r i_{dr} + L_m i_{ds} \end{cases} \tag{9}$$

$$\varphi_{qr} = 0 \Rightarrow \frac{d}{dt}\varphi_{qr} = 0 \Rightarrow \varphi_{dr} = \varphi_r \tag{10}$$

$$\omega_{sl} = (\omega_e - \omega_r) = \left(\frac{L_m R_r}{\varphi_r L_r}\right) i_{qs} \tag{11}$$

$$T_e = 1.5p\frac{L_m}{L_r}(\varphi_r i_{qs}) \tag{12}$$

$$\varphi_r + \tau_r \frac{d}{dt}\varphi_r - L_m i_{ds} = 0 \tag{13}$$

Where: $\tau_r = L_r/R_r$ is the rotor time constant.

Figure 3. Magnetic Flux Control Scheme in Induction Motors

The field-oriented scheme makes control of AC machine analogous to that of DC machine. This is achieved by considering the d-q model of the AC machine in the reference frame rotating at synchronous speed ωe. In this model ids and iqs are current components of the stator current on d-q axis, where ids component is aligned with the rotor field. The rotor flux and torque can be controlled independently by ids and iqs, shown in Figure 4. The electric torque Te is proportional to the quadrature-axis current iqs, component of the stator current Is, and the rotor flux ψr can be controlled by the direct-axis current ids, of Is, where: Is = ids + J iqs.

Fig 4. iqs and ids components of Is on a d-q axis

The transfer function of this AC motor yields angular velocity (ω) as the motor shaft output. In the simulation, ω was easily converted into the force on the cart. The motor responded well, reaching its maximum force exerted on the cart in less than 2.5 seconds.

6. Discussion and Results

The simulation consists of four main components, the fuzzy controller, AC motor, the cart and the inverted pendulum, Figure 5. The cart passes the fuzzy controller four parameters θ, ω, X, V. Based on these four parameters the fuzzy controller outputs a voltage to the motor. The motor in turn calculates the force that will be exerted on the cart. The system then calculates the new values for parameters θ, ω, X, V and the cycle will be repeated.
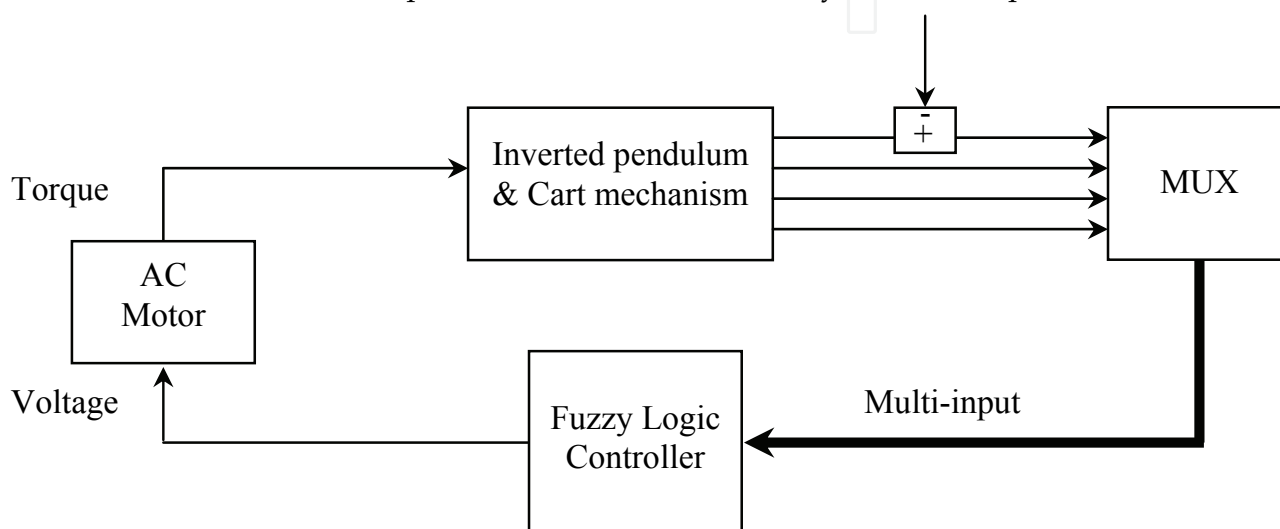
Figure 5. Schematic diagram of fuzzy controller for the inverted pendulum.

The fuzzy controller used in the simulation, with the AC motor included, is a 24 FLC as described above. The system runs identical to the 24 system only the settling time for the simulation, with the motor included, is larger. Figure 6 shows the results of the simulation using the same fuzzy controller as (Sugeno 2002) with the AC motor included in the simulation.

The AC motor has a delay, where it takes the motor a given time to reach a maximum force. This in turn causes the simulation take longer to reach steady state. Parameters used in the simulation of the motor are listed in Table 2.

T_r	=	0.06 S	Rotor time constant
L_m	=	75 mH	Magnetizing inductance
K_t	=	1.00	Motor torque constant
Rating	=	1.0HP	Motor rating
J	=	0.06kgm^2	Moment of Inertial of the motor and the load
b	=	0.002 kgm^2/S	Coefficient of friction

Table 2. Parameters of the Model Motor.

Figure 6 shows that it takes approximately 12 seconds for the pendulum's angle to become steady, and even longer for the cart's position to stabilize. The difference in the response time of this system can be found in the motor. The motor has a time constant which delays the motor's response time to an inputted voltage. A typical AC motor has a time constant larger than that of a DC motor. The shorter the time constant of the motor, the quicker the system will respond. Therefore, it can be expected that it takes longer for AC motor to balance the pendulum.
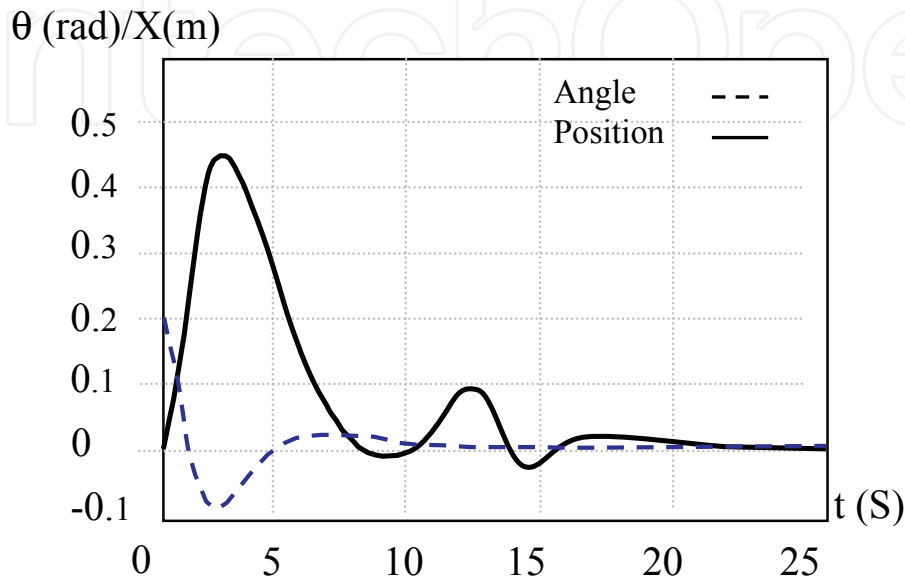
Figure 6. Variation of angle θ (rad) and position X(m) of the pendulum with time t(s).

The simulation shows that the system responds well even with a motor attached to the system. The cost of implementing a motor into the simulation is response time for the pendulum to stabilize. Simulations done without the addition of the AC motor can not be considered for real life implementation because the motor is needed to investigate the response time that the system will observe in real life.

In a series of tests carried on without the use of fuzzy controller, it was revealed that the pendulum can hardly overcome any disturbances. If the disturbance is very small, it takes twice longer for the pendulum to balance again in an upright position.

Performances of vector control AC induction motors are comparable to that of DC motors; however, AC motors are rugged and low cost. Therefore, whenever possible, usage of AC motors will greatly reduce the capital cost of equipment and devices.

7. Conclusion

In this chapter design of a Fuzzy Logic Controller for a multi-input output system is described. It demonstrates a trade-off between precision which requires complex design and simplification which achieves less precise system. There is no absolute solution in developing fuzzy logic controllers. Designer of a FLC system must consider whether precision will be sacrificed for performance and simplicity. The 52 system developed in this work was very simple and computed quickly. The drawback of this initial design was that

precision was compromised. The 24 system was also very simple and ran quickly but the performance of the system was not satisfactory. The settling time for the cart pendulum was required to be quicker. The 54 system was very complex and performance was slow, but if tuned correctly, a system of this size would be very precise.

Implementation of the system requires a high performance AC motor. Simulation results showed that the system would work for this type of motor. Having a smaller time constant in the AC motor would result in a shorter response time of the system. The FLC would need to be fine tuned for other types of motors.

With the AC motor implemented in the simulation model, the system did not react as well to high disturbances as it did when the motor was neglected in the simulation, or a DC motor was used. This indicates that the system will react well to small disturbances and be able to recover from them quickly. As the results indicates, in order for this system to handle large disturbances a motor with high performance dynamics need to be used that has a very small time constant. Use FLC made significant improvement to the controllability of the inverted pendulum by improving the response time.

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Mobile Robots: Perception & Navigation

Edited by Sascha Kolski

Today robots navigate autonomously in office environments as well as outdoors. They show their ability to beside mechanical and electronic barriers in building mobile platforms, perceiving the environment and deciding on how to act in a given situation are crucial problems. In this book we focused on these two areas of mobile robotics, Perception and Navigation. This book gives a wide overview over different navigation techniques describing both navigation techniques dealing with local and control aspects of navigation as well es those handling global navigation aspects of a single robot and even for a group of robots.

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