Adaptive Fuzzy Control of a Direct Drive Motor *

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Abstract

This paper presents a state feedback adaptive control method for position and velocity control of a direct drive motor. The proposed control scheme allows for integrating heuristic knowledge with mathematical knowledge of a system. It performs well even when mathematical model of the system is poorly understood. The controller consists of an adaptive fuzzy controller and a supervisory controller. The supervisory controller requires only knowledge of the upper bound and lower bound of the system parameters. The fuzzy controller is based on fuzzy basis functions and states of the system. The adaptation law is derived based on the Lyapunov function which ensures that the state of the system asymptotically approaches zero. The proposed controller is applied to a direct drive motor with payload and parameter uncertainty, and the effectiveness is verified by simulation results.

Keywords: Fuzzy Control, Adaptive Control, Stability, Direct Drive Motors.

Introduction

Direct drive motors have received increasing attention since they do not have a backlash or dead zone which are caused by gears. The high torque of the direct drive motor allows for the direct connection of the load to the motor axis. Since they are used in high-precision robot and machine tool applications, they must have high resistance to external disturbances. The absence of gear reduction leads to great sensitivity for the motor to variations in the load inertia. In fact, direct drive motors require more robust torque control than the conventional servo motors.

As a result, a linear controller cannot provide a good response under varying load conditions. Variable Structure System (VSS)-type self-tuning control [1], Bang-Bang control [2], and adaptive control [3, 4] have been proposed to handle such problems. However, none of the above mentioned approaches have taken advantage of the robustness of fuzzy logic in the controller design of direct drive motors.

This paper presents a state feedback fuzzy adaptive control method for position and velocity control of a direct drive motor for more robustness to system disturbances, The proposed control scheme does not require an accurate mathematical model of the system. It allows for integrating heuristic knowledge with mathematical knowledge. It performs well even when mathematical model of the system is poorly understood. The controller consists of an adaptive fuzzy controller and a supervisory controller. The supervisory controller requires only knowledge of the upper bound and lower bound of the system parameters. The fuzzy controller is based on fuzzy basis functions and states of the system. The adaptation law is derived based on the Lyapunov function which ensures that the state of the system asymptotically approaches zero. The proposed controller is applied to a direct drive motor with payload and parameter uncertainty, and the effectiveness is verified by simulation results.

Our objective is to control a Direct Drive motor (DD) to follow a desired trajectory. The high torque of DD motors allows for the direct connection of the load to the motor axis. Because of this, the motor becomes very sensitive to the load inertia applied. Therefore, we must design a controller that is robust with respect to the applied loads to the motor. In this paper a first-type adaptive fuzzy controller, i.e. one in which the adaptive parameters are linear, is used to meet our objective.

In the following section a linear model of a direct drive motor is presented. The next section shows the derivation of the first-type fuzzy adaptive controller, where stability is guaranteed by the Lyapunov based
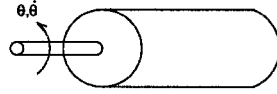
Figure 1: Direct-drive motor and the control parameters

supervisory controller. Then simulations of the DD motor which shows robustness of the fuzzy controller to parameter variations within the model of the DD motor is shown.

Mathematical Model

A DD motor is modeled and a state-space model is developed. Figure 1 shows the control parameters, θ and $\dot\theta$, which correspond to $\dot x_1$ and $\dot x_2$, respectively. The mathematical model of a DD motor is represented by the following differential equations,

$$J\ddot\theta + D\dot\theta = \tau \tag{1}$$

where,

J - Inertia moment of the system load and rotor
D- Coefficient of viscous friction term
19- Angular displacement of the motor (output)
τ - Output torque of the motor (control input, $u = \tau$)

Describing (1) in state space form we have a second-order system of the form,

$$\dot x_1 = x_2 \tag{2}$$
$$\dot x_2 = f(x, \dot x) + bu \tag{3}$$

where f is an unknown function, b is an unknown constant, and u and y are the input and output, respectively. After substitution, the above equation become,

$$\dot x_1 = x_2 \tag{4}$$
$$\dot x_2 = \frac{-D}{J}x_2 + \frac{1}{J}u \tag{5}$$

from which,

$$f(x_1, x_2) = \frac{-D}{J}x_2 \tag{6}$$
$$b = \frac{1}{J} \tag{7}$$

b is lower bounded and f is upper bounded and both exist.

Stable Direct Adaptive Fuzzy Controller

BACKGROUND

The adaptive fuzzy controller designed for the control objective follows the work of Wang [5], refer to Figure 2 for a block diagram of the control scheme. The resulting control law is the summation of a basic fuzzy controller, u_c, and a supervisory controller, u_s,

$$u = u_c(x|\theta) + u_s(x) \tag{8}$$

The basic fuzzy controller, $u_c(x|\theta)$ is a fuzzy logic system of the form,

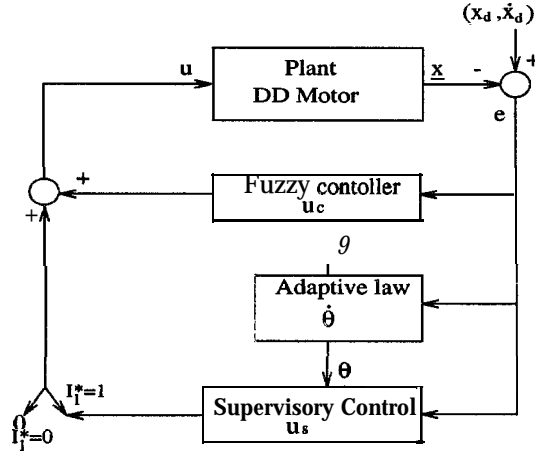$$u_c(x|\theta) = \underline\theta^T \underline\xi(x). \tag{9}$$

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Figure 2: Block diagram of direct adaptive fuzzy control system

where $\underline{\theta}$ are the adjustable parameters, and the fuzzy basis function, $\underline{\xi}(\underline{x})$ is defined as,

$$\xi^{(l_1,l_2)}(\underline{x}) = \frac{\prod_{i=1}^{2} \mu_{F_i^{l_i}}(x_i)}{\sum_{l_1=1}^{m_1} \sum_{l_2=1}^{m_2}(\prod_{i=1}^{2} \mu_{F_i^{l_i}}(x_i))} \tag{1o}$$

where m_i is the number of fuzzy rule bases and μ_{F_i} are the fuzzy logic rules. By substituting (8) into (3), the state equation becomes,

$$x^{(2)} = f(a) + b[u_c(\underline{x}|\underline{\theta}) + u_s(\underline{x})]. \tag{11}$$

If $f(\underline{x})$ and b are known, we know the control,

$$u^* = \frac{1}{b}[-f + y_m^{(n)} + \underline{k}^T \underline{e}] \tag{12}$$

will force the error to converge to zero, where $(\underline{e}) = (e, \dot{e})^T$ and $(\underline{k}) = (k_2, k_1)^T$. There fore, the error equation becomes, after adding and subtracting u^* to u,

$$\dot{\underline{e}} = \Lambda_c \underline{e} + b_c[u^* - u_c(\underline{x}|\underline{\theta}) - u_s(\underline{x})] \tag{13}$$

where Λ_c is a positive definite matrix and b_c is a vector defined respectively as

$$AC = \begin{bmatrix} 0 & 1 \\ -k_2 & -k_1 \end{bmatrix} \tag{14}$$

$$b_c = \begin{bmatrix} 0 \\ b \end{bmatrix} \tag{15}$$

such that the values of k_1 and k_2 are chosen so the roots of $s^2 + k_1 s + k_2 = O$ are in the open left half plane.

Letting $V_e = \frac{1}{2}\underline{e}^T P \underline{e}$ it follows that,

$$\dot{V}_e = -\frac{1}{2}\underline{e}^T Q \underline{e} + \underline{e}^T P \underline{b}_c[u^* - u_c(\underline{x}|\underline{\theta}) - u_s(\underline{x})] \tag{16}$$

$$\leq -\frac{1}{2}\underline{e}^T Q \underline{e} + |\underline{e}^T P \underline{b}_c|(|u^*| + |u_c|) - \underline{e}^T P \underline{b}_c u_s. \tag{17}$$

The resulting equation for $\dot{V}_e$ is used to construct the supervisory control. We need for $\dot{V}_e \leq 0$ when $V_e > \bar{V}$, (a constant defined by the user). In order to meet the above objective, a supervisory controller, u_s, is designed according to the following assumptions. A function $f^u(\underline{x})$ and a constant b_L are determined such that $|f(\underline{x})| \leq f^U(\underline{x})$ and $0 \leq b_L \leq b$. Now u_s is constructed as follows:

$$u_s = I_1^* sgn(\underline{e}^T P \underline{b}_c)[|u_c| + \frac{1}{b_L}(f^U + |x_d^{(n)}| + |\underline{k}^T \underline{e}|)] \tag{18}$$

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where $I_1^* = 1$ if $V_e > \bar{V}, I_1^* = O$ if $V_e \leq \bar{V}$.

    Now the basic controller is replaced with a fuzzy logic system and an adaptive law is developed to adjust the parameter vector, $\underline{\theta}$. Next, the optimal parameter vector and the minimum approximation error are defined, respectively as,

$$\underline{\theta}^* \equiv argmin_{|\underline{\theta}| \leq M_\theta}[sup_{|\underline{x}| \leq M_x} |u_c(\underline{x}|\underline{\theta}) - u^*|] \tag{19}$$

$$w \equiv u_c(\underline{x}|\underline{\theta}^*) - u^* \tag{20}$$

where M_θ and M_x are constraints defined by the user. The error equation is rewritten as

$$\underline{\dot{e}} = \Lambda_c \underline{e} + b_c \underline{\phi}^T \underline{\xi}(\underline{x}) - b_c u_s - b_c w \tag{21}$$

where $\underline{\phi} \equiv \underline{\theta}^* - \underline{\theta}$ and $\underline{\xi}(\underline{x})$ is the fuzzy basis function defined in (10). Since Λ_c is a stable matrix there exists a unique positive definite symmetric 2x2 matrix P which satisfies the Lyapunov equation

$$\Lambda_c^T P + P\Lambda_c = -Q. \tag{22}$$

For a more detailed description on the derivation of the adaptive fuzzy controller and the adaptive law refer to [5].

DESIGN

The first-type direct fuzzy adaptive controller, is designed to control the direct drive motor. The controller is designed to be stable in the sense of Lyapunov, where the Lyapunov equation must be satisfied. The matrix P was arbitrarily chosen to satisfy the Lyapunov equation as,

$$P = \begin{vmatrix} 3 & 1 \\ 1 & 1 \end{vmatrix}. \tag{23}$$

    The Lyapunov equation was solved using matlab with the P and Λ_c matrices as defined earlier. In our case, we chose $k_1 = 2$ and $k_2 = 1$ for the Λ_c matrix, which placed the roots of $s^2 + k_1 s + k_2 = O$ at s = −1, −1. The resulting matrix Q was

$$Q = \begin{vmatrix} 2 & 0 \\ 0 & 2 \end{vmatrix} \tag{24}$$

a symmetric positive definite matrix, thereby satisfying the criterion for stability in the sense of Lyapunov.

    The values of $f^U(\underline{x})$ and b_L are calculated. From the state equations we see the values of $f^U(\underline{x})$ and b_L are dependent on the J and D parameters of the motor. The parameters are motor dependent. In our case the values of J and D were chosen, respectively as $0.3 \leq J \leq 1.0$ and $0.001 \leq D \leq 0.1$. Therefore the values for $f^U(\underline{x})$ and b_L are $0.001 x_2$ and 1, respectively.

    Next, three fuzzy sets for xl and x_2 whose membership functions uniformly cover U were defined as

$$\begin{aligned} \mu_{F1}(x) &= 1/(1 + exp(x + 2)) \\ \mu_{F2}(x) &= exp(-x^2) \\ \mu_{F3}(x) &= 1/(1 + exp(-(x - 2))) \end{aligned} \tag{25}$$

Fuzzy basis functions are constructed using the above three fuzzy membership functions according to the relation (10).

    The following adaptive law adjusts the state vector θ

$$\underline{\dot{\theta}} = \gamma \underline{e}^T \underline{p}_n \underline{\xi}(\underline{x}) \tag{26}$$

where γ is a constant, $\underline{e}^T$ is the desired trajectory minus the actual trajectory, and $\underline{p}_n$ is the last column of P.

Simulation

The adaptive fuzzy controller was simulated on Matlab using the ODE45 command to solve the differential equations. An M-file was written to describe the system of ordinary differential equations. A simulation was
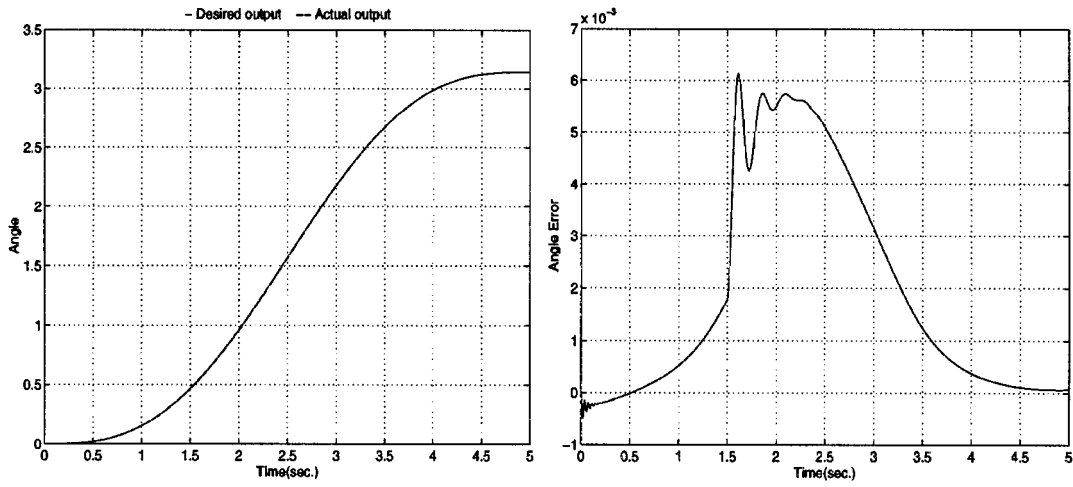
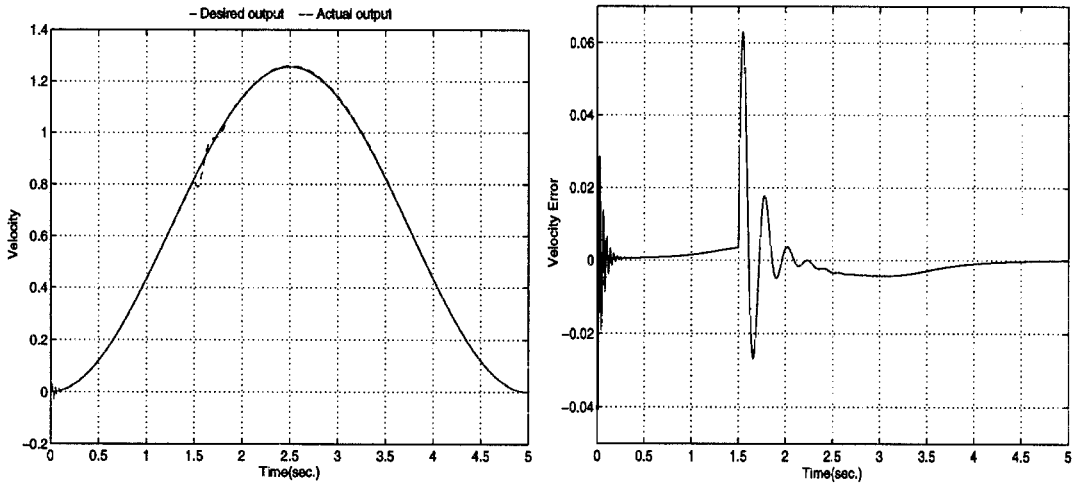Figure 3: Plot of the angular and angular error response of the motor

Figure 4: Plot of the velocity and velocity error response of the motor

run for 5 seconds using zero for the initial conditions of xl and x_2. A disturbance, a change in the load, was introduced after the simulation was started,

In order to simulate a change in load, the values of J and D were init ally 0.31 and 0.0077 then were changed 1.5 seconds after the simulation start ed to 0.5 and O. 1, respect ivel y. The desired trajectory is defined as

$$x_d = 0.5\big(0.4\pi t - sin(0.4\pi t)\big)$$
$$\dot{x}_d = 0.2\pi\big(1.0 - cos(0.4\pi t)\big)$$

for x_1 and x_2, respectively.

Figure 3, shows the difference between the angle of the actual position and the desired position. It is shown that the difference in the desired and actual output is negligible. After the disturbance is applied, referring to Figure 5, the controller is able to adapt within 1 second.

In Figure 4, it is shown that the actual velocity response differs only at the start of the simulation and when the disturbance is introduced to the system. Figure 4 shows the adaptive fuzzy controller is robust with respect to variations in the motor load.

Figure 5, shows the adaptive fuzzy controller is robust with respect to variations in the motor load. Looking at the graph we are able to deduce the adaptive fuzzy controller is able to stabilize the system after the disturbance is introduced within 5 seconds. The controller quickly adapts to compensate for the changing load/inertia condition.
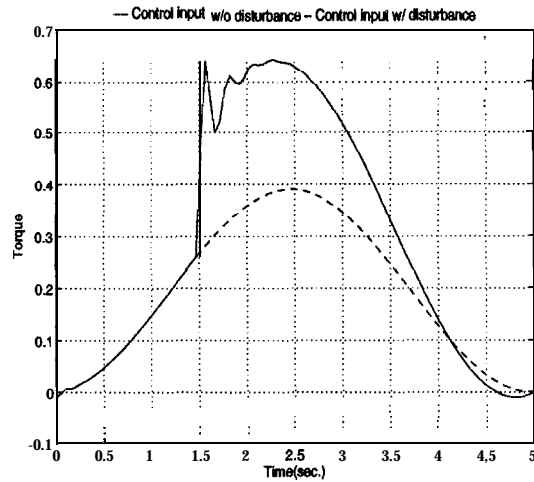
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Figure 5: Plot of the control input DD with and without a disturbance used to control the DD motor

Conclusion

In most practical systems, some type of a mathematical model is available. Although this mathematical model is often corrupted by unknown parameters, disturbances, etc., it still constitutes a very important portion of a systems engineer's knowledge base. In this paper, heuristic knowledge (fuzzy logic rule base) is allowed to combine with a model-based controller to achieve a more robust control system.

A first-type fuzzy adaptive control method was introduced for position control of a direct drive motor. The control method presented does not require an accurate mathematical model of the control system, it is capable of incorporating fuzzy control rules directly into the controller and guarantee global stability of the resulting closed-loop system in the *sense* that all signals are asymptotically convergent. The controller was adaptively changed by monitoring the difference between the desired trajectory and the actual trajectory.

The control method discussed was shown to be robust with respect to the load on the motor, i.e. the system can be adaptively stabilized even though the load on the motor changes.

Future research topics include experimentally verifying the results of the simulation, using the DD motor and hardware available, to run real-time experiments. Also in future research, other autonomous methods will be implemented for generating the rule bases used to design the controller.

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