A SELF-TUNING FUZZY ROBOTIC FORCE CONTROLLER

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Abstract

Most industrial robots are controlled as position servo-based manipulators. This has made most advanced force control algorithms unpractical and difficult to implement. In this paper a position based fuzzy PID force controller is proposed to regulate contact force of a six degree of freedom industrial robot where the environment contact stiffness varies considerably. Based on a relationship between fuzzy PID and conventional PID control laws and the application of a simple fuzzy self-tuning method, the controller is tuned and satisfying experimental results have been obtained to validate its efficiency.

Key words : *self-tuning, robot, controller*

1. Introduction

Many industrial robotic tasks, such as deburring, grinding and assembly, require the end-effector of the manipulator to maintain a stable specified contact force with the environment while the tool is moved along the profile of the workpiece. To implement such a task, both force and position of the robot should be controlled simultaneously. These control strategies have been classified into two main categories, namely hybrid position/force control and impedance control. Unfortunately both of these methods require an accurate dynamic model of the contact force interaction and of the manipulator. These algorithms also need to directly control motor torque, which makes them difficult to implement on typical industrial manipulators that are designed for accurate position control.

Fuzzy control is fast becoming recognised as one of the most active and effective methods to control complex systems that are structurally difficult to model, or the model is too complex. In recent years there have been several practical studies of fuzzy controller applied to robot control, and other industrial applications. However, a major obstacle in the implementation of fuzzy control is tuning, which is time consuming and generally reliant on specialist knowledge and experience. PID controllers on the other hand, have been widely used for control of many industrial processes due to their simplicity and effectiveness, and systematic tuning methods are readily available. In fuzzy controller design, fuzzy PI, PD and PID controllers are the most utilized forms of dynamic compensation to improve steady state or transient response. There are several structures available for PID type fuzzy logic controllers, some of which are based on heuristic knowledge, whereas others are derived from conventional PID control laws. It therefore seems feasible to construct some kind of relationship between conventional PID and fuzzy PID parameters. Based on these relationships and conventional PID tuning methods, fuzzy PID tuning is no longer a pure knowledge or expert based process and thus has the potential to be more convenient to implement.

A PID fuzzy controller has been applied to a robotic force control task in which different stiffness environments were encountered. Using a simple fuzzy parameter tuning method, based on a number of experimental tests, satisfactory results have been obtained. In the future this technique will be applied to the problem of gear deburring.

2. Force Control Algorithms

As shown schematically in Figure 1, the robot end-effector or tool of a typical six degree of freedom industrial manipulator is shown in contact with a workpiece. The objective is to bring the tool quickly into contact with the workpiece, apply a specified contact force, which is maintained whilst the tool tip follows the profile of the component part to be machined. The simplest method to fulfil the above objective is to control the orientation of end-effector, and to make the tool always normal to profile of the workpiece. This then requires only the composite force in F_Y and F_Z direction to be regulated. The force control system architecture is shown in figure 2, and can be described as a position-based controller with an outer PID fuzzy force control loop. Profile data for the workpiece can be generated off-line and stored as a reference trajectory for the robot to follow. Because of displacement and geometric errors in the workpiece location and other fine errors, the tool cannot maintain the specified contact force by simply moving along the specified profile trajectory stored in microprocessor memory. There therefore needs to be an external force control loop in order to achieve a practical trajectory.

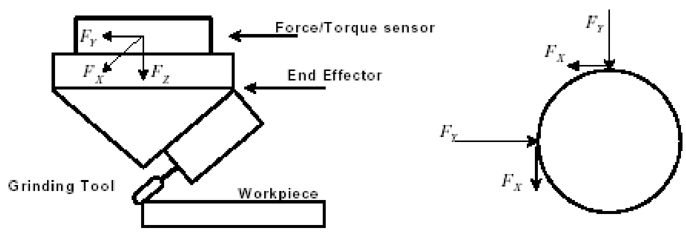

Figure 1 Contact diagram of tool and workpiece.

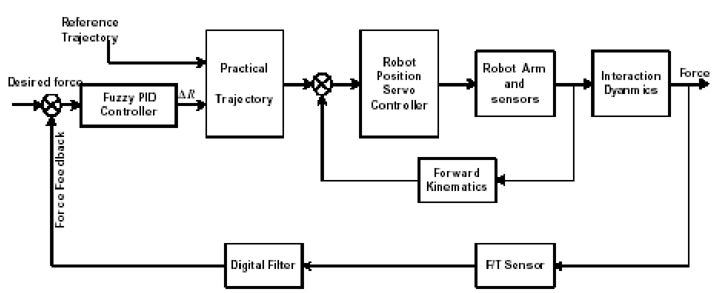

Figure 2. Block diagram of force control algorithm.

3. Fuzzy PID Controller Design

Typical conventional PI, PD and PID controller can be described mathematically as below:

$$u^{PD} = K_P.e + K_D.\dot{e} = K_P.(e + T_D.\dot{e}) \quad (1)$$

$$u^{PI} = K_P.e + K_I.\int e.dt = K_P.\int\left(\dot{e} + \frac{e}{T_I}\right).dt \qquad (2)$$

$$u^{PID} = K_P.e + K_I.\int e.dt + K_D.\dot{e} \qquad (3)$$

Here the gains K_P, K_I, and K_D are the so-called proportional, integral and derivative gains, and e and $\dot{e}$ are error and error rate respectively. There exist systematic tuning methods to obtain these parameters, such as Cohen-Coon and Ziegler-Nichols methods. There are several methods available for the implementation of fuzzy PID controllers, one of which utilizes the variables of the error, integral of error and derivative of error. This method leads to too many rules, and its realization in practice is considered difficult to implement and tune. Another realisation of a fuzzy PID controller is the parallel combination of fuzzy PI and PD controllers. The rule base is simpler because each one has only two fuzzy input variables, and from the deduction process the relationship between conventional PID parameters and fuzzy ones can be built up, making it possible to apply conventional PID tuning methods.

For a two input fuzzy PID force controller, two input variables are defined, namely force error Fe(t) and rate of force error Fet(t) as:

$$F_e(t) = F_d - F_{mea} \qquad (4)$$

$$F_{et}(t) = d\,\frac{F_e(t)}{dt} \qquad (5)$$

Where F_d denotes desired force and F_{mea} is measured force. From equations (1) and (2), and using variables $F_e(t)$ and $F_{et}(t)$ as fuzzy variables, the above will become a fuzzy PI and fuzzy PD type force controller respectively. The realization of this dual fuzzy controller is shown schematically in figure 3.

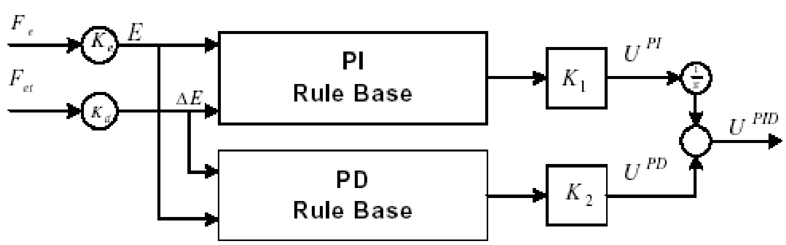

Figure 3. Fuzzy PID controller

$$U_k^{PI} = U_{k-1}^{PI} + K_1.F_{PI}\{K_e.F_e, K_d.F_{et}\} \qquad (6)$$

$$U_k^{PD} = K_2.F_{PD}\{K_e.F_e, K_d.F_{et}\} \qquad (7)$$

$$U_k^{PID} = U_k^{PI} + U_k^{PD} \qquad (8)$$

Here K_1, K_2 are the controllers output gains, where K_e and K_d denote the scaling gains. The relationship between these gains and practical fuzzy PID parameters can be expressed as follow:

$$K_P = K_1.F_{PI}\{K_d\} + K_2.F_{PD}\{K_e\} \qquad (9)$$

$$K_I = K_1.F_{PI}\{K_e\} \qquad (10)$$

$$K_D = K_2.F_{PD}\{K_d\} \qquad (11)$$

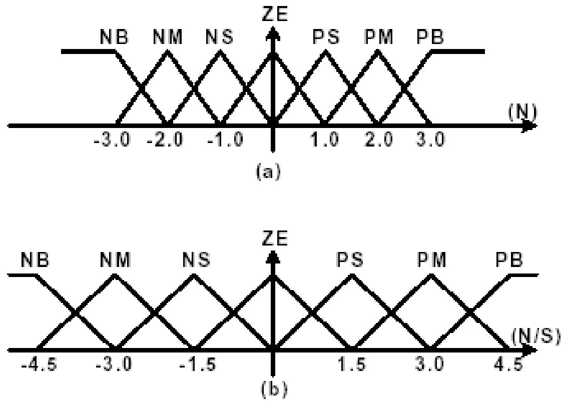

Figure.4. Membership function of force error (a) and rate error (b)

A typical triangular membership function was adopted for the fuzzification of the two control inputs $F_e(t)$ and $F_{et}(t)$ as shown in figure 4, in which the de-fuzzification of the control output dealt with the COG method. The method involves first choosing the scaling gains to fixed values, followed by identifying the membership function such that K_eF_e and K_DF_{et} covers the whole scale of the chosen membership under a specified control precision. Only the output gains and non-linear fuzzy gain remains to be tuned. From equations (9-11) a quantitative relation between output gains and Fuzzy PID parameters can be obtained, although there is some coupling between them. Based on this relationship, the PID tuning concepts also fit the fuzzy PID tuning parameters:

- Increasing K_1 leads to a higher integral effect and increased fuzzy proportional gain.
- Increasing K_2 leads to stronger derivative influence and increased fuzzy proportional gain.
- Adjusting scaling gains K_e and K_d could balance the integral and derivative effects.

The rule base design of PI type and PD type fuzzy controller are slightly different, some reported investigations have used the same rule base for both the PI and PD type fuzzy controller for simplifying the implementation of fuzzy PID control. In this paper we will use different rule base for PI and PD respectively to achieve greater flexibility during tuning. The rule base can be designed from a typical step response :

Table 1. Rule bases for fuzzy PI controller

De/e	NB	NM	NS	ZE	PS	PM	PB
PB	O	Ps	Pm	Pb	pb	Pb	Pb
PM	Ns	O	Ps	Pm	pb	Pb	Pb
PS	Nm	Ns	O	Ps	pm	Pb	Pb
ZE	Nb	Nm	Ns	O	ps	Pm	Pb
NS	Nb	Nb	Nm	Ns	O	Ps	Pm
NM	Nb	Nb	Nb	Nm	ns	O	Ps
NB	Nb	Nb	Nb	Nb	nm	Ns	O

Table 2. Rule base for fuzzy PD controller

De/e	NB	NM	NS	ZE	PS	PM	PB
PB	Ns	Ns	Ns	Ps	pb	Pb	Pb
PM	Ns	Ns	Ns	Ps	pb	Pb	Pb
PS	Nm	Ns	Ns	Ps	pm	Pb	Pb
ZE	Nb	Nm	Ns	O	ps	Pm	Pb
NS	Nb	Nb	Nm	Ns	ps	Ps	Pm
NM	Nb	Nb	Nb	Ns	ns	Ps	Ps
NB	Nb	Nb	Nb	Ns	ps	Ps	Ps

4. Self Tuning Algorithm

Experiments have shown that environment stiffness has a big influence in tuning of the fuzzy PID parameters. For an unknown or variable stiffness it is difficult to choose appropriate scaling gains for the controller designed in the above section. Several environment stiffness detection techniques and estimators are proposed to enable the controller gains to be switched accordingly but the estimation process is both time consuming and unreliable in the presence of force transducer noise. To address this problem here a fuzzy scaling gain tuning algorithm is proposed, (as illustrated in figure 5) based on a simple stiffness detection method which uses a position only force controller. There is an intuitive direct relationship between contact force and change of contact position, after contact is made. In this case, the force controller regulates force by changing the radial position of the end-effector with respect to the workpiece. Thus the following equation can be used as a stiffness rule:

$$K_s \propto \left| \frac{F_{et}}{R_{et}} \right|$$

where K_s denotes stiffness and R_{et} is the change in the tool's radial position, which can be obtained from the output of force controller. Because this process is very sensitive to force sensor noise and impact between tool and workpiece, it is difficult to obtain a stable or precise stiffness value. A fuzzy logic tuning procedure is a reasonable and appropriate choice for its renowned capability of dealing with this uncertainty.

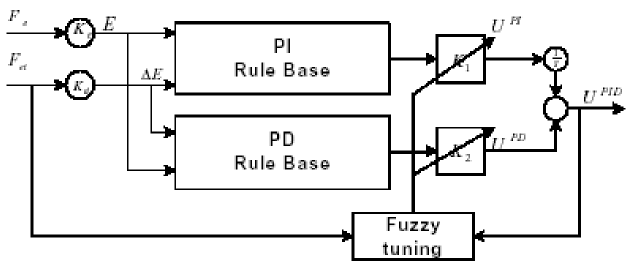

Figure 5. Fuzzy tuning strategy

The tuning strategy is such that when the contact is perceived as flexible the proportional gain should be increased to secure a fast rise time, with a corresponding larger derivative gain to minimise overshoot. From initial tests with the contact changing between hard and soft environments appropriate parameter range for K_1 varied between 0.0004 and 0.0012, and for K_2 between 0.0045 and 0.015. By applying the above reasoning and test results, a fuzzy tuner was constructed to allow the scaling gains K_1 and K_2 to be tuned with F_{et}/R_{et} as fuzzy input. The fuzzy input and tuning outputs membership functions for K_1 and K_2 are shown in Figure 6 (a) - (c), respectively. The tuning rule base is shown below in table 3, where VS means very small (soft), S means small, B means big and VB means very big (very hard), M means median gain.

Table 3. Tuning rules

$\lvert F_{et} / R_{et} \rvert$	ZE	VS	S	B	VB
K_1	VB	B	M	S	VS
K_2	VB	B	M	S	VS

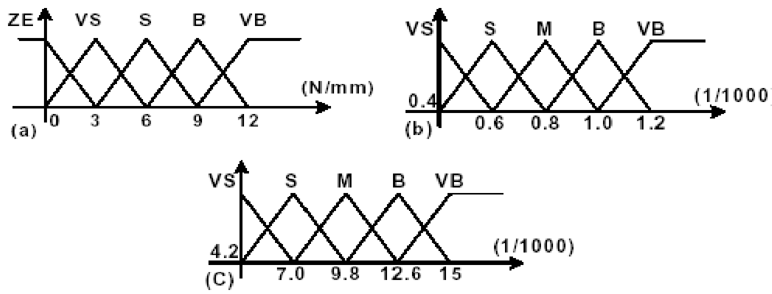

Figure 6. Membership functions of tuning variables.

5. Experimental Results

Contact force control experiments were performed using a six degree of freedom Puma 762 industrial manipulator with an ATI wrist mounted force/torque sensor system. The fuzzy PID control algorithm is written using C. An ethernet link is used to provide fast bi-directional data transmission between the host PC, robot controller and F/T system.

A steel pipe, nominally of 65mm diameter, is rigidly fixed to a vice in a vertical position. Initial tests were performed using a non-rotating tool, the tip of which was brought into hard contact with the workpiece at a specified contact force, using a PID force controller. The robot is programmed to rotate the tool around the end of pipe profile. Figures 7 and 8 illustrate the force response of the PID force controller, to hard contact and soft contact, respectively. A compliant rubber sleeve was fitted to the tool tip, in order to simulate a soft contact. Reasonably good force control has been achieved within the extremes of hard and soft contract, illustrating the ability of the fuzzy controller to accommodate a wide range of environmental stiffness conditions.

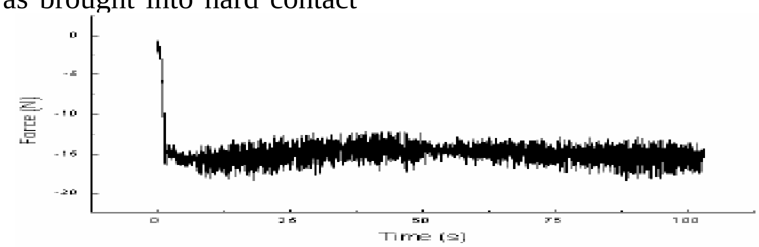

Figure 7. Force regulation (N): hard contact

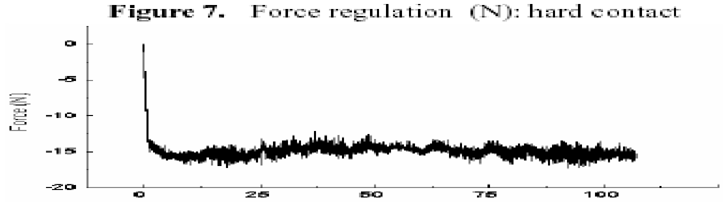

Figure 8. The force response (N): soft contact.

Conclusions

A fuzzy PID controller has been proposed to address the problem of robot force control and which has proven to be robust to changes of environmental stiffness and more convenient for parameters tuning. Based on a relationship between fuzzy gains and similar conventional PID parameters, the fuzzy controller tuning problem is now not mainly based on operator expertise but is rather more quantitative. This has made it much more convenient than applying a conventional fuzzy PID controller in terms of rule base construction and parameters tuning. As a position based force controller it is easier for practical application and it's implementation can be compared with that based on exact dynamical model and torque or impedance force controller. However, there is still the remaining problem of how to deal with sluggish response of output force. The next phase in the development of this controller will be its application to gear deburring in order to validate its efficiency in similar industrial applications.

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