Fuzzy-PI Force Control for Industrial Robotics

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Abstract. Increasingly, robot programs are generated off-line, for example, through a virtual model of a robotic cell. However, when the virtual model does not reproduce exactly the real scenario or the calibration process is not performed correctly it is difficult to generate reliable robot programs. In order to circumvent this problem, it was introduced sensory feedback (force and torque sensing) in a robotic framework. By controlling the robot end-effector pose and specifying its relationship to the interaction/contact forces, robot programmers can ensure that the robot maneuvers correctly, damping possible impacts and also increasing the tolerance to positioning errors from the off-line programming process. In this paper Fuzzy-PI and PI reasoning was proposed as a force control technique. The effectiveness of the proposed approach was evaluated in a serie of 20 experiments that demonstrated that Fuzzy-PI controllers are more suitable to deal with this type of situations.

Keywords: Robotics, Fuzzy-PI, Force control.

1 Introduction

Increasingly, robot programs are generated off-line, without interrupt robot production. Through a virtual model of a robotic cell it is today possible to generate a robot program. These off-line programming systems present a satisfactory performance if the virtual model reproduces exactly the real scenario; however, in some situations this “ideal situation” is not always achievable. In certain circumstances robot programs are generated with errors, for example, when the virtual model has dimensional inaccuracies and in the presence of inaccuracies created in the calibration process (virtual-real environment). In these cases, robots have to autonomously acquire the information to support decision making.

In this paper it is proposed the introduction of sensory feedback (force and torque sensing) in a robotic framework. By controlling the end-effector pose and specifying its relationship to the interaction/contact forces, robot programmers can ensure that the robot maneuvers in an a real environment safely, damping possible impacts and increasing the tolerance to positioning errors from the off-line programming process. Also, when any contact occurs between the robot tool

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and its surrounding environment the interaction forces are controlled properly, otherwise they may damage the working objects and robot tools. The proposed approach focuses on the use of two force control techniques, PI and Fuzzy-PI reasoning. The robot program was generated off-line from a CAD model [1]. The effectiveness of the proposed approach was evaluated in a series of experiments. The robot ability to track the desired path (extracted from CAD) and to adapt/adjust to the environment was analyzed. Finally, results are discussed and some considerations about future work directions are made.

1.1 Force Control for Robotic Systems – An Overview

Many robot tasks require contact with the surrounding environment of the robot. That interaction generates contact forces that should be controlled in a way to finish the task correctly. Those contact forces depend on the stiffness of the tool and working objects/surfaces and should be properly controlled. The option for a particular control technique depends on identifying if we have a passive force control or an active force control method [2]. In the first case, contact forces produce an undesirable effect on the task; they are not necessary for the process to be carried out. In the second case, the contact forces are necessary to finish the task correctly, i.e., the contact forces should be controlled, making them assume some particular value. Up to now, many kinds of robotic systems using force control strategies have been developed and successfully applied to various industrial processes such as polishing [3], deburring [4,5] and high-precision assembly [10]. A large number of force control techniques (Fuzzy, PI, PID, etc.) with varying complexity have been proposed thus far [8,9]. Fuzzy control was first introduced and implemented in the early 1970's [11] in an attempt to design controllers for systems that are structurally difficult to model due to naturally existing nonlinearities and other modeling complexities. Fuzzy logic control appears very useful when the processes are too complex for analysis by conventional quantitative techniques.

2 Proposed Approach

A force/torque (F/T) sensor was attached to the robot wrist. The real-time force and torque feedback data from the F/T sensor will be required to achieve displacement control of the robot end-effector. By analyzing the incoming data from the F/T sensor, the implemented control system decides which displacements should be applied to achieve satisfactory robot performance, making the system adaptive to the working environment as desired. The automatic end-effector adjustment is achieved by a closed loop position control of the robot end-effector provided by F/T sensor data and Fuzzy-PI reasoning. If the contact force exceeds an acceptable range, the force control system will maneuver the robotic arm until that force falls within an acceptable range. The experimental setup of the proposed robotic system is the following:

- An industrial robot Motoman HP6 equipped with the NX100 controller.
- A personal computer running Microsoft Windows Xp.
- A six degrees of freedom F/T sensor from JR3, equipped with a PCI receiver and processing board installed on the computer PCI bus.
- A local area network (LAN), Ethernet and TCP/IP based, used for robot-computer communication. The network is isolated from the laboratory traffic using a properly programmed high speed (100 Mbps) network switch.

The computer is running the software application that manages the cell (acquires data from the F/T sensor and sends displacement commands to the robot). The MotomanLib is a Data Link Library created in our laboratory to control and monitoring the robot remotely. Using an ActiveX component named JR3PCI [4], the F/T sensor measures forces and torques real-time with a sample rate of 8 KHz (Figure 1).

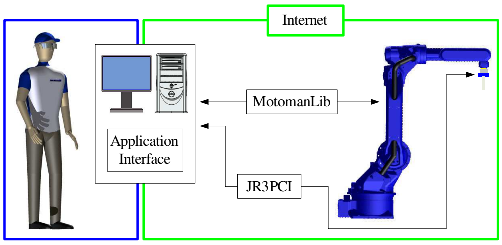

Fig. 1. Communications and system architecture

3 Force Control

Associating the proportional integrative control (PI) and Fuzzy logic we have a polyvalent controller with the ability to be adjusted to any object, regardless to its base or contact surface. Thus, a fuzzy logic controller type Mamdani based on the traditional PI controller was implemented [11]. The PI controller provides a good performance when applied in practical situations. The controller with derivative factor help to diminish the correction time, however, it is very sensitive to noise, precluding their use in our framework. Our preference for the controller type Mamdani is due to its easy implementation and the good results usually obtained, besides that do not need a rigorous mathematical model of the system. The fuzzy controller should respect the following stages:

- Definition of input and output variables.
- Fuzzification.
- Definition of a group of rules to model the application (knowledge base).
- Design of the computational unit that accesses the fuzzy rules.
- Defuzzification.

The force control system collects inputs from the F/T sensor and processes that inputs according to the rules specified in the fuzzy logic memberships. The outputs are presented as the displacement (mm) at which the robotic arm should be moved to obtain the desired contact range of forces and torques (Figure 2).

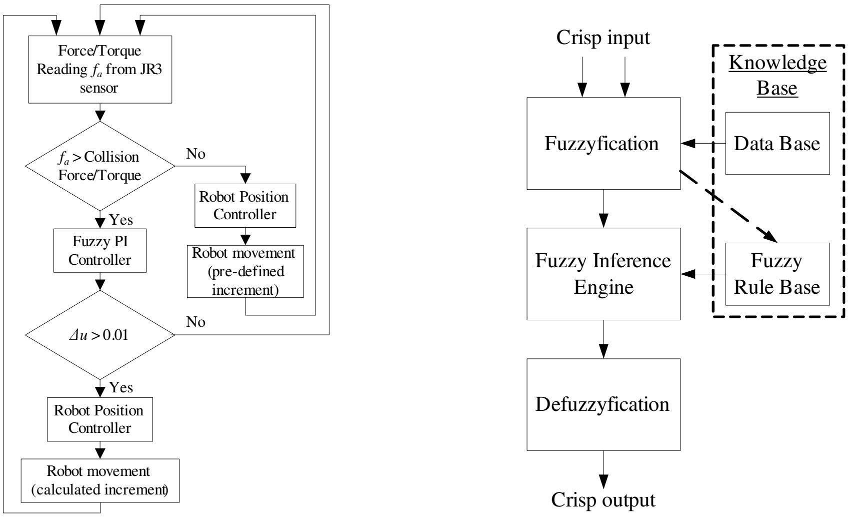

Fig. 2. Flowchart of the fuzzy-PI controller (left). Fuzzy-PI controller (right).

3.1 Fuzzy Control Architecture

The Fuzzy concept has been used to control the force limits of robotic arms [4]. It is ideal for controlling nonlinear systems and for modeling complex systems where an inexact model exists. It is also potentially very robust, maintaining good closed-loop system performance over a wide range of operating conditions. In this paper, the controller input variables are the force/torque error e (1) and the change of the error de (2), where f_a is the actual wrench and f_d is the desired wrench (set point). The controller output is the position/orientation accommodation for the robot (robot displacements).

$$e_k = f_{d_k} - f_{a_k} \tag{1}$$

$$de_k = e_k - e_{k-1} \tag{2}$$

3.2 Fuzzy-PI

From the conventional PI control algorithm:

$$u(t) = K_P \cdot e(t) + K_I \cdot \int e(t)dt \tag{3}$$

where u is the robot displacement and K_P and K_I are coefficients constants. Transforming (3):

$$u_k = u_{k-1} + \triangle u_k$$

$$\triangle u_k = K_P \cdot de_K + K_I \cdot e_K \tag{4}$$

If e and de are fuzzy variables, (4) becomes a fuzzy control algorithm. A practical implementation of our fuzzy-PI concept is simplified in Figure 3. Finally, the center of area method was selected for defuzzify the output fuzzy set inferred by the controller (5), where μ_i is the membership function which takes values in the interval [0, 1].

$$\triangle U = \frac{\sum_{i=1}^{n} \mu_i \cdot \triangle U_i}{\sum_{i=1}^{n} \mu_i} \tag{5}$$

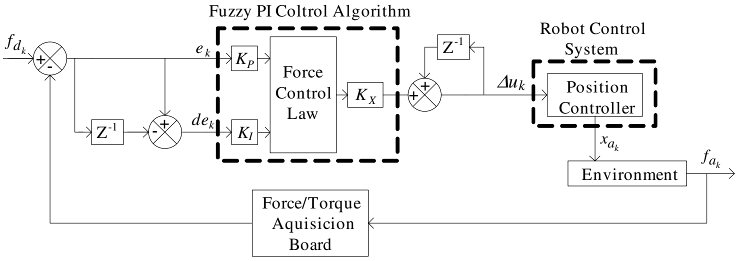

Fig. 3. Implemented fuzzy logic controller with PI function

3.3 Knowledge Base

The knowledge base of a fuzzy logic controller is composed of two components, namely, a data base and a fuzzy control rule base. Each control variable should be normalized into seven linguistic labels. The most common labels used are: positive large (PL), positive medium (PM), positive small (PS), zero (ZR), negative large (NL), negative medium (NM) and negative small (NS). The grade of each label is described by a fuzzy set. The function that relates the grade and the variable is called the membership function, Figure 4. The well-known PI-like fuzzy

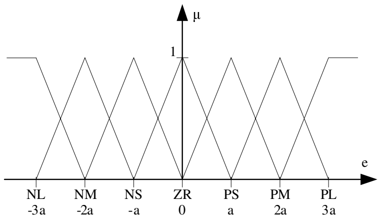

TABLE I
Representation of the Rule Base

de \ *e*	NL	NM	NS	ZR	PS	PM	PL
PL	nl	nm	ns	zr	pm	pl	pl
PM	nl	nl	nm	zr	pm	pl	pl
PS	nl	nl	ns	zr	ps	pl	pl
ZR	nl	nm	ns	zr	ps	pm	pl
NS	nl	nl	ns	zr	ps	pl	pl
NM	nl	nl	nm	zr	pm	pl	pl
NL	nl	nl	nm	zr	ps	pm	pl

Fig. 4. Membership functions for the input variables (left), and the rule base (right)

rule base suggested by MacVicar-Whelan [12] is used in this paper (Figure 4), allowing fast working convergence without significant oscillations, and preventing overshoots and undershoots. Recently, the MacVicar-Whelan rule base has been improved [13].

3.4 Tuning Strategy

Fuzzy logic design is involved with two important stages, knowledge base design and tuning. The objective of tuning is to select the proper combination of all control parameters so that the resulting closed-loop response best meets the desired design criteria. In order to adapt the system to various contact conditions and scenarios the scaling factors should be tuned, namely K_P, K_I and K_X. Reference [7] proposes an adjustment where the scaling factors are dynamic and thus they have been adjusted along the task. The utilization of different tables of rules accordingly the task to be performed and the materials involved are presented in [6]. In our paper, the scaling factors are set to appropriate constant values, achieved by the method of trial and error.

4 Experiments, Results and Discussion

The effectiveness of the proposed approach was evaluated in a series of 20 experiments, more specifically making the robot follow a surface profile by maintaining a set force normal to the workpiece surface, Figure 5. This test case was chosen as many others with workpieces with similar stifness could have been chosen, even though they had different geometries. The initial robot program was generated off-line from a CAD drawing. The aim is that the force system absorbs the error from the calibration process, workpiece surface irregularities and from the positioning accuracy of the workpiece. When the robot starts the contact with the workpiece, the force control system assumes the robot control, adjusting the end-effector to the environment, in other words, adjusting the pre-programmed paths from CAD. The force control ensures that the contact forces and moments converge to a desired value.

The experiments showed force control results similar to that presented in Figure 5 for fuzzy-PI and PI. The figures report the contact forces between the end-effector and workpiece, and the robot displacement. Although both systems have the capability of disturbance rejection, in the PI control, when the robot starts to move down the contact force deviates from the set force. So, it was established that an approach based on fuzzy-PI reasoning produce better results (smaller offset and overshoot). It seems to be clear that force control improves significantly robot performance, making robots more flexible and with capacity to make decisions. However, Fuzzy-PI controllers provide adequate performance when they are tuned to a specific task, but if the environmental stiffness is unknown or varying significantly, performance is degraded.

As a future work, the speed of convergence to the set forces and torques should be increased and comparisons with other force controllers will be made.

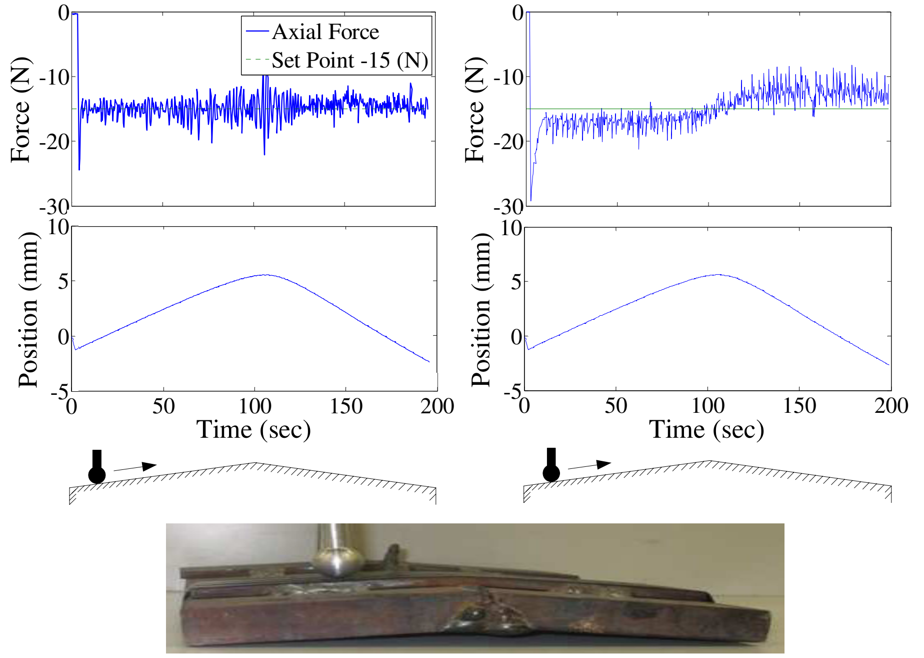

Fig. 5. Experimental results by using fuzzy-PI controller (left) and PI controller (right)

5 Conclusion

Owing to the implemented force control system the robot is able to respond to high degree of environment uncertainty. The effectiveness of the proposed approach was proved through the experiments, showing that force control improves significantly robot performance, making robots more human-like, flexible and with capacity to make decisions. The fuzzy-PI controller showed better results than the traditional PI controller (smaller offset and overshoot). The proposed robotic platform increases the "intelligence" of the robot in several ways, allowing the robot to deal with uncertainty and helping to reduce the set up time required to start robot operation.

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