Design of intelligent multifinger gripper for a robotic arm using a DSP-based fuzzy controller

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3 authors, including:


Momoh Salami
International Islamic University Malaysia


Naim Sidek
International Islamic University Malaysia

Design of Intelligent Multifinger Gripper for a Robotic ARM Using a DSP-Based Fuzzy Controller

Momoh-Jimoh E. Salami, Nazim Mir-Nassiri and Shahrul Naim Sidek
Kulliyyah of Engineering,
International Islamic University Malaysia,
Jalan Gombak, 53100 Kuala Lumpur
Malaysia.
E-mail:momoh@iiu.edu.my

Abstract: The design and modeling of a robotic arm gripper that has elements of intelligent decision making while grasping object has been recently discussed. This new system is different in using an appropriate controlling scheme so that the correct force is applied to pick an object without dropping or crushing it. This is achieved by controlling the shear stresses at the interface material between finger-ends and the object using smart sensors and intelligent controller. A new slip sensor that is based on the operation of optical encoder is used to monitor the slip rate as a result of insufficient force being applied to pick an object. A two-stage control scheme is suggested for the implementation of this system. First a limit switch is used to control the positioning of the fingers thereby solving the problem of uncertainty in the location and orientation of the object. Then, to ensure that an appropriate force is used in picking up an object a fuzzy logic controller is used. The use of TMS320C24XX series DSP controller to implement the control strategy provides the flexibility needed in altering the control code and the prototype can be tested at low cost.

Key words
Intelligent gripper, slip sensors, fuzzy controller, DSP processor.

1. Introduction

The main objective of the research is to design a robotic arm gripper along with its controller, which has both mechanical and electronic elements of intelligent decision making while grasping an object. This gripper has a great ability to work with wide range of objects having different shapes, surface hardness, weights and uncertainty in location and orientation. This new system is different from the conventional one in its structure, use of sensors and controlling methodology so that an appropriate force is issued to pick an object without slipping or crushing it. This is achieved by controlling the shear stresses at the interface material between finger-ends and the object using smart sensors and intelligent controller. A new slip sensor that is based on the operation of optical encoder is used to monitor the slip rate as a result of insufficient force being applied to pick an object.

Previous studies have suggested a two-stage control scheme for the implementation of this system [1,2]. As shown in Fig. 10, the output of the limit switch is used to control the positioning of the fingers thereby solving the problem of uncertainty in the location and orientation of the object. Once the fingers are properly positioned then the output of the slip sensors are fed to the controller so as to determine the gripping force that should be applied in order to ensure a firm grasp of the object. This control scheme can be implemented using either a microprocessor-based or DSP-based PID, however as discussed in [2] the latter approach is preferable as a result of its greater flexibility and faster processing time. Both approaches require laborious tuning and this can limit the overall performance of this system. There is need to find an alternative method that speeds up its tuning process as well as retaining the advantages of the digital signal processor.

This paper examines the use of DSP-based fuzzy controller for controlling the force needed by a robotic gripper in picking objects of different weights and structures. Some advantages of fuzzy logic controllers are well known, especially in its ability to either handle complex problems or deal with imprecise or uncertain information. The controller must provide fast response time with very small steady-state error. Here the fuzzy controller works by controlling the force applied to the fingers of the robot using set of rules created from its knowledge base. The input for the fuzzy controller comes from the slip sensor attached to the fingers of the robot. The output is the strength of the grasp. Indeed the controller mimics human-like behavior in learning to pick an object, that is, a person strengthens his grip in order to prevent a loose object from falling off from the hand. A simulated study of this system has been carried out using MATLAB fuzzy logic toolbox and the results obtained compared favorably with the conventional PID controller.

2. Mechanical Design of the Gripper

The gripper is designed so that it can accomplish the following two tasks: to provide a condition when all fingers are in simultaneous contact with an object and to provide a condition when frictional forces at the interface finger tips/object are just sufficient to pick up an object. It is well known that a gripper is an essential part of any robotic arm and its complexity depends in which technological operation the gripper is used. For example, during assembly operations a robot has to grasp a variety of dissimilar objects having different weights. That is where intelligence concept must be applied to the gripper in addition to the

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flexibility of the whole robotic arm system. The most versatile grippers are the human-like hands, such as CTSD I hand, CTSD II hand, Stanford/JPL hand, UTAH/MIT dexterous hand and so on. However, the routing of tendons through three degree of freedom wrists still has to be solved. Furthermore, current models of grasping are inadequate for control. The design of three-finger gripper mechanism having special slip sensor at each finger is aimed at resolving many grasping problems. An arrangement of fingers within a robotic arm is shown in Fig. 1.

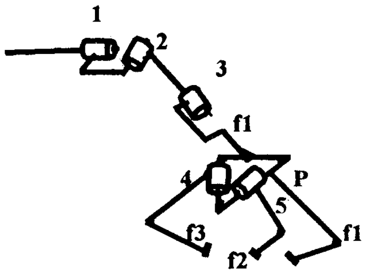

Figure 1

In this figure **f1**, **f2** and **f3** are three curved fingers, where **f2** and **f3** are driven by separate servomotors attached to two separate axes 4 and 5 whereas the third finger **f1** is driven by actuators 1, 2, and 3 of the robot wrist mechanism. Thus, there is no need to have a separate drive for the finger **f1** as it becomes a part of the wrist of the robotic arm. Control of the grasping process can be done in the following sequence. Robot first moves its first finger **f1** to the object. As soon as this finger is in contact with the surface of the object it will stop. This step will also assure that the remaining two fingers are in proper locations with respect to the object and the grasping process can be carried out successfully. Then, the second finger **f2** will move to the object until it touches it. Finally, the third finger **f3** will also move to the object until it touches it. Now all three fingers are in proper location to start the grasping of the object. The main objective of the *slip sensor* design is to enable the gripper to pick objects without prior knowledge of their weights. It also takes care of fragility of the object since fragility of the object is assumed to be proportional to its weight.

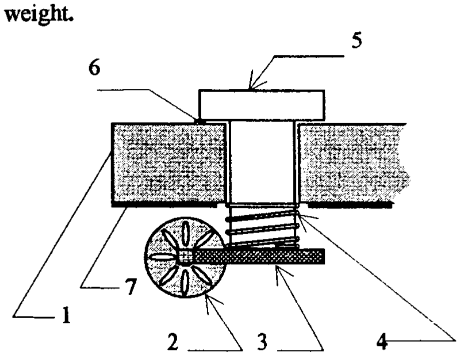

Figure 2

The components of the sensor are shown in Fig. 2. In this Fig. 1 is a tip of the finger, 2 is a wheel with spokes, 3 is a photodiode device, 4 is a spring, 5 is a movable stem of the sensor, 6 is a limit switch, 7 is a special coating on the finger tip.

The wheel 2 is a low friction, low inertia pulley, with an attached photodiode 3 that monitors its motion. The rolling speed of the wheel indicates the rate of slipping between the finger- tip and the object. The wheel generates a signal for the controller monitoring gripping process. The spring 4 is used to imitate the compliance of human fingers and to damp the inertial forces applied by moving finger on the stationary object when the finger strikes the object. The coating 7 is used to produce minimum possible frictional force between the finger top 1 and the wheel 2 when gripping force has been applied to the finger through the controller. The role of limit switch 6 is to detect if the finger 1 has been touched the object through its wheel 2 and to trigger the control system. Due to the special geometry this gripper is capable of generating only the forces that are normal to the surface of the object. Thus, net force on the object is zero. This condition can be observed in Fig. 3.

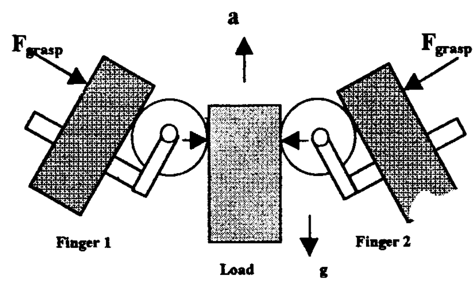

Figure 3

The dynamic analysis of the gripper is quite simple. It can be used to prove an ability of the gripper to carry an object safely with two wheels by applying minimum possible force F_{grasp}. Note again, the weight of the object mg is not predefined. Free body diagram of the object is shown in Fig. 4.

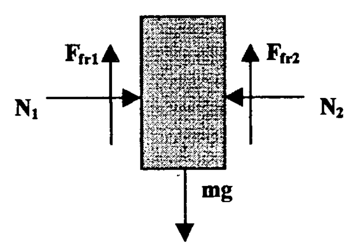

Figure 4

There could be two types of friction at the interface between the wheels and the object. They are:

- static friction, when there is no slip between the wheels and the object. That means the object can be safely carried by the wheels provided the wheels do not rotate

- kinetic friction, when there is a slip between the wheels and the object. That means the object will eventually slip out of the fingers even though we stop rotation of the wheels.

The dynamic equation for the second condition is as follows:

$mg - F_{fr1} - F_{fr2} = ma$

or $mg - 2F_{fr1} = ma$

since $N_1 = N_2$, $F_{fr1} = N_1\mu_o$ and $F_{fr2} = N_2\mu_o$, where μ_o is coefficient of static or kinetic friction at the interface between the object and the wheel. The equation above shows that if $mg > 2F_{fr1}$ then there is acceleration a of the object with respect to wheels and μ_o is due to the kinetic friction. However, N_1 is a controlled variable in the system and it is gradually increasing. Then, at a certain instant of time when $2F_{fr1}$ reaches mg, acceleration a becomes zero and μ_o converts into the coefficient of static friction μ_o^S. This is the value of static friction force F_{fr1} that we have to maintain by the controller together with non-rotating condition for the wheels. The amount of actual static friction force F_{fr1} and corresponding amount of normal reaction force $N_1 = N_2$ required to maintain this friction force can be calculated from the equation of static equilibrium:

$F_{fr1} = mg/2, \quad N_1 = mg/ 2\mu_o^S$

Obviously, when the three fingers interact with the object we have

$F_{fr1} = mg/3, \quad N_1 = mg/ 3\mu_o^S$

Free body diagram of the wheel lifting an object is shown in Fig. 5.

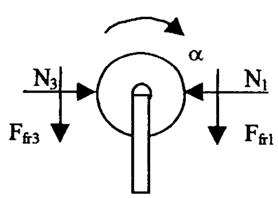

Figure 5

In this figure, F_{fr3} (coefficient μ_{fin}) is a friction force at the interface between wheel and special low friction coating on the finger, F_{fr1} (coefficient μ_o) is a friction force at the interface between wheel and surface of the object. The friction force at pin connection of the wheel is relatively small and can be neglected. The dynamic equation of the wheel rotation can be written as follows:

$N_3 = N_1$,

$r\,(F_{fr1} - F_{fr3}) = I\alpha$,

where I is a mass moment of inertia of the wheel, α is an angular acceleration of the wheel and r is a radius of the wheel. Obviously, $F_{fr1} > F_{fr3}$ since $N_3 = N_1$ and μ_{fin} is intentionally selected to be less than μ_o. Therefore, for a low values of controlled normal reaction force $N_3=N_1$ the wheel will accelerate in clockwise sense. During this stage of force control the wheel rolls without slipping on the surface of the object but in mean time it slips on the surface of the finger. When we increase gripping force $N_3 = N_1$ both F_{fr1} and F_{fr3} will increase simultaneously. However, when F_{fr1} attains its maximum value $F_{fr1} = N_{11}\mu_o^S = mg/3$ ($N_{11} = N_{31}$) it will cease to increase while another friction force F_{fr3} keeps increasing its value and the wheel keeps rotating. Therefore, at a certain instant of time F_{fr3} becomes sufficient to stop rotation of the wheel since

$$F_{fr3} = N_{32}\,\mu_{fin}^S = F_{fr1} = N_{11}\mu_o^S = mg/3, \quad \ldots\ldots\ldots \quad (1)$$

$N_{32} = N_{12}$

Therefore, α becomes zero since $F_{fr3} = F_{fr1}$ and the wheel does not rotate anymore. Thus, we can conclude that N_{31} is the gripping force needed to stop slipping of the object along the stationary wheel and N_{32} is the gripping force needed to stop rolling the wheel along the stationary object. Since N_{32} is obviously bigger than N_{31} the controller must maintain value $N_3 = N_{32}$ in order to avoid both adverse scenarios that can disturb successful completion of gripping process. The amount by which N_{32} exceeds N_{31} can be calculated from equation (1) for static friction condition as

$N_{32} = N_{31}\,(\mu_o^S/\mu_{fin}^S)$

Since $N_{32} > N_{31}$ by default, a firm grasping condition has been ensured for the object. Furthermore, maintaining zero angular acceleration of the wheel by providing proper value of gripping force N_3 can also guarantee zero slip of the object with respect to the fingers.

3. DSP-based PID Controller

The use of DSP-based PID controller to control the robot gripper has been discussed in [1,2]. This controller offers many advantages over other processors such as high speed and resolution and the ability to implement the mathematically intensive algorithms fast. The new generation of TI DSP possesses these features as well as fast processing capability as they are driven at high clock frequency. The primary task of the controller is to ensure that the right force is applied to the gripper without crushing, damaging or dropping the object. A PID controller is used in order to have a fast response time, low steady-state error and a stable system. The output of the PID controller is used to drive the armature-controlled dc motor whose speed is proportional to the torque that is being applied to the gripper. In such case the goal of the PID controller is to nullify the error or difference between a force command (reference) and the force from the slip sensor output. An analog PID controller has the transfer function

$$G_c(s) = K_P + sK_D + \frac{K_I}{s},$$

where K_P, K_D, and K_I are its gain constants. By using the bilinear transformation an equivalent digital controller having transfer function

$$G_c(z) = K_P + K_D \frac{(z-1)}{Tz} + K_I \frac{Tz}{(z-1)} \quad \text{..........(2)}$$

is obtained [4, 5], where T is the sampling period. The design of the PID controller is actually equivalent to the tuning of the controller through which the gain constant K_P, K_D, and K_I are determined. A Ziegler-Nichols method [6] of tuning has been used in [2]. This is an iterative procedure to search for the best values of the PID gain constants that will lead to good performance of the overall system. First the computation time for the gain constants depend on the starting values which in turn depend on the sensor output. That is a large overshoot may persist for a long time during the tuning process. Results of simulation studies in [2] have indeed shown that a lot of efforts are needed to reduce the overshoot and settling for this compensated system. The laborious steps in implementing this controller have led to the development of fuzzy controller so as to meet our objectives.

4. DSP-based Fuzzy Controller

This paper considers the use of fuzzy logic controller to control the robot gripper in order to avoid the complex and time-consuming method of tuning the PID. Fuzzy engineering technology has seen a rapid growth in its applications since several years ago and the trend continues. The main feature of this new control tool is its ability to tolerate imprecision, uncertainty, partial truth and approximation to achieve tractability, robustness and low solution cost [6-10]. Consequently, the fuzzy logic controller is suitable for controlling the robot gripper, as the overall system will mimic the way human grips and picks up an object. In fact the control objective is to avoid the gripper from crushing the object while grasping it. In this system, the inputs of fuzzy controller are the slip rate and the derivative of slip rate. The slip rate is sensed and measured by the slip encoder. The output is the necessary force to be exerted on the object so as to avoid the object to continuously slip. The inference engine of the fuzzy controller will take the following form:

IF *slip rate is no motion* AND *derivative of slip rate is negative* THEN *force is zero*
IF *slip rate is slow* AND *derivative of slip rate is zero* THEN *force is weak*
IF *slip rate is moderate* AND *derivative of slip rate is positive* THEN *force is strong*
....

Data from experts give some ideas on the construction of the rules set. For both inputs, set of 5 and 3 triangular membership functions are used to reflect the gripping behaviours. The consequent part of the rules also consists of 5 triangular membership functions. Fig. 6 depicts the inputs membership functions and Table 1 shows the fuzzy associative memory (FAM) where

N: negative
Z: zero
P: positive
NM: no motion
SL: slow
M: moderate
F: fast
VF: very fast
W: weak
S: strong
VS: very strong

Slip rate, error (cm/s) \ Derivative of slip rate, d/dt(error)	N	Z	P
NM	Z	Z	Z
S	W	W	M
M	W	M	S
F	M	S	VS
VF	S	VS	VS

Table 1

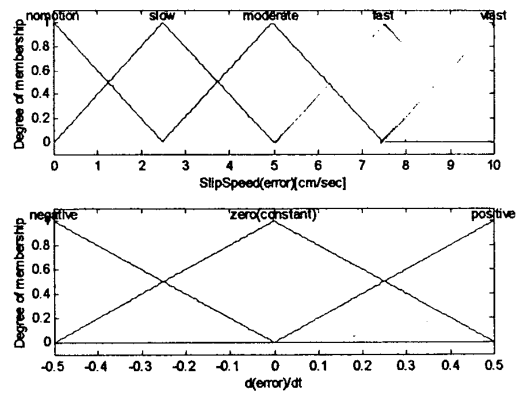

Figure 6

Indeed this kind of representation utilizes Mamdani model of fuzzy controller [11]. For defuzzification process, method of centroid of area is employed as follows:

$$z_{COA} = \frac{\int_Z \mu_A(z) z \, dz}{\int_Z \mu_A(z) dz}$$

where $\mu_A(z)$ is the aggregated output membership function. The control output surface shows the fuzzy controller inherits smooth transition from one case to the others as depicted in Fig. 7. Eventually the system turns out to have 15 rules to describe the control action of the robot gripper. A heuristic trial and error tuning method is applied to enhance the performance of the controller.

5. Simulation Studies

A MATLAB software with Fuzzy Logic Toolbox is used to run the simulation studies. The robot gripper is modeled by a second order transfer function, and it is assumed that the slip rate is inversely proportional to the force applied on the object and always positive. In particular, the slip encoder senses the slip so as to determine whether the force commanded is sufficient, in order to grasp the object firmly. The simulation shows excellent result and indicate that fuzzy controller can indeed be used to control the gripper. The response is found to be always overdamped so as to avoid the object from being crushed. As shown in Fig. 8 and 9, both graphs depict the input reference and output response respectively.

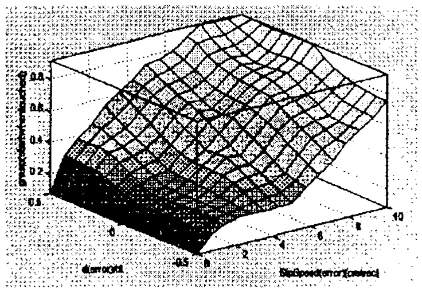

Figure 7

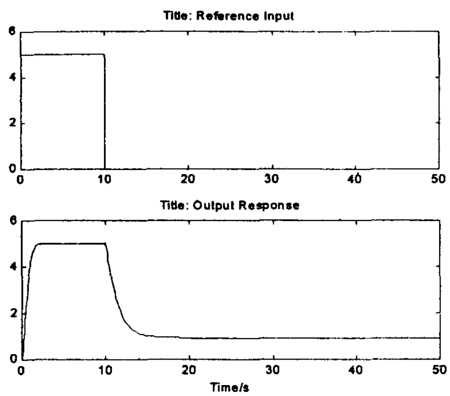

Figure 8

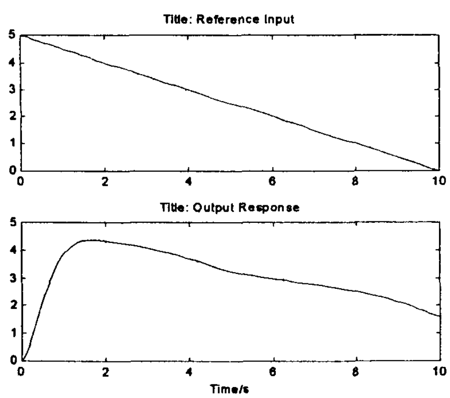

Figure 9

6. Conclusion

This paper has discussed the use of DSP-based fuzzy controller for enhancing the performance of the new robotic arm gripper. The TMS320C24XX series can enhance the performance of this system since it is driven by high clock frequency. It has been shown that the combined use of slip and DSP-based fuzzy controller can ensure that the correct force is applied in picking up object of varying structures and weights. This new system is practicable and can be developed to handle wide range of applications from industrial to household equipment. By integrating fuzzy logic with other soft computing techniques like neural network and genetic algorithm the performance of the controller can also be further upgraded. Further research work is directed towards the hardware implementation of this system, which will be cost effective and robust.

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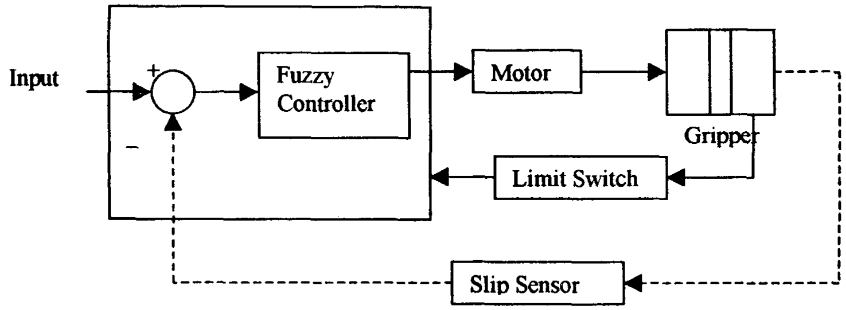
Input
+
−
Fuzzy
Controller
Motor
Gripper
Limit Switch
Slip Sensor

Figure 10