Design and Implementation of Efficient Intelligent Robotic Gripper

*A. M. ZAKI, **O. A. MAHGOUB, **A.M. EL-SHAFEI, *A. M. SOLIMAN,
* Power Electronics and Energy Conversion Department
Electronics Research Institute, Cairo
EGYPT
aziza@eri.sci.eg; aymansoliman3000@yahoo.com
** Electric Power and Machines Department
Faculty of Engineering, Cairo University, Cairo
EGYPT
mahgoub04@yahoo.com; alelshafei@hotmail.com

Abstract: - The gripper is a critical component of the industrial robot. It is greatly useful in industrial environments for object grasping during handling process. In this paper, a gripper is designed and implemented to grasp unknown objects with different masses, dimensions, and coefficients of friction. The design and control of the gripper system takes into consideration simplicity in the mechanical system, large variety of grasped objects and low cost. The proposed grasping process during object lifting and handling is mainly based on the slip reflex principle, as applying insufficient force leads to object slipping, and dropping may occur. On the other hand, applying extra force during grasping may lead to object crushing. A new system controller using fuzzy logic based on empirical investigation of the human hand skills is proposed. The target is to control the applied force on the object to avoid object crushing or dropping. Adaptive neuro-fuzzy inference system ANFIS is used to model the assigned robotic gripper based on input/output variables measurements. The performance of the gripper system and the control algorithm was tested first by simulation. Reduction of the distance of the slippage and process time was confirmed experimentally. Simulation and experimental results are presented and discussed.

Key-Words: - Intelligent Robotic Gripper, ANFIS Modeling, Fuzzy Control, Tactile Sensors

1 Introduction

Generally, the main goal of robotic gripper during object grasping and object lifting process is applying sufficient force to avoid the risk of object slipping or crushing. This goal is difficult to achieve because of the nonlinearities in the system. Mechanical system configuration, nature of used sensors and friction forces represent nonlinearities that make system modeling a very difficult task or sometimes a task that could not be achieved. The problem can be posed as an optimization problem [1, 2]. Sensory systems are very important in this field. Two types of sensing are most actively being investigated to increase robot awareness: contact and non-contact sensing. The main type of non-contact sensing is vision sensing where video camera is processed to give the robot the object information. However, it is costly and gives no data concerning forces [3]. Tactile sensing, on the other hand, has the capability to do proximity sensing as well as force sensing, it is less expensive, faster and needs less complex equipment [4-6]. The basic principle of the Slip-Sensitive Reaction used in this work is that, the gripper should be able to automatically react to object slipping during grasp with the application of greater force. A lot of researches have been focusing on fingertip sensors development to detect slippage and applied force [7-10], which requires complicated drive circuit and suffers from difficult data processing and calibration. Polyvinylidene fluoride (PVDF) piezoelectric sensors are presented in [4-6] to detect contact normal force as well as slip. Also, an array 8x8 matrix photo resistor is introduced in [11] to detect slippage. A slip sensor based on the operation of optical encoder used to monitor the slip rate resulting from insufficient force is presented in [12]. However, it is expensive and have some constrains on the object to be lifted. Several researchers handle finger adaptation using more than one link in one finger to verify stable grasping [13-15]. This results in complicated mechanical system leading to difficulty in control and slow response. In [16], variable reluctance technology as an actuator is used in two-fingers gripper that is inherently nonlinear. Stepper actuator is used in [14] where the finger position accuracy depends on the step value. Fuzzy controllers have been very successful in solving the grasping problem, as they do not need mathematical model of the system [17]. In this paper, we present a new design and implementation of robotic gripper with electric actuation using brushless dc servo motor. Standard sensors adaptation in this work leads to maintaining the simplicity of the mechanical design and gripper operation keeping a reasonable cost. The gripper control was achieved through two control schemes. System modeling had been introduced using ANFIS approach. A new grasping scenario is used in which we collect information about the masses of the grasped objects before starting the grasping process without any additional sensors. This is achieved through knowledge of object pushing force that allows applying an appropriate force and minimizing object displacement slip through implementation of the proposed fuzzy control. In section 2, a gripper design and configuration is presented. Section 3 presents the designed gripper and sensors modeling. The two proposed controllers for the gripper system based on different feedback variables are developed in section 4 and simulation results are presented. Experimental results are illustrated and discussed in section 5. Finally, section 6 gives the conclusions of the work.

2 Gripper design and configuration

A proper gripper design can simplify the overall robot system assembly, increase the overall system reliability, and decrease the cost of implementing the system [18]. Hence, the design of the gripping system is very important for the successful operation.

2.1 Gripper design guidelines

It may not be possible to apply all the guidelines to any one design. Sometimes, one guideline may suggest one design direction while another may suggest the opposite. Each particular situation must be examined and a decision must be made to favor the more relevant guidelines [19-20]. The design guidelines may be as follows: -

1- Minimize the gripper weight: This allows the robot to accelerate more quickly.
2- Grasp objects securely: This allows the robot to run at higher speeds thereby reducing the cycle time.
3- Grip multiple objects with a single gripper: This helps to avoid tool changes.
4- Fully encompass the object with the gripper: This is to help hold the part securely.
5- Do not deform the object during grasping: Some objects are easily deformed and care should be taken when grasping these objects.
6- Minimize finger length: Obviously, the longer the fingers of the gripper the more they are going to deflect when grasping an object.
7- Design for proper gripper-object interaction: If, however, a flat surface is being used, then a high friction interface is desired since the part would not be aligned anyway and the higher friction increases the security of the grasp.

2.2 Two fingers gripper selection

The objects may vary in size and shape. Thus the gripper should be able to handle objects of different shapes and sizes in a particular range. Gripper should be compact so that it does not interfere with other equipment. The use of conical fingers “three fingers or more” will help holding the parts securely. But if we have an object larger than these conical fingers, the object could not be gripped properly. Parallel moving fingers are a good solution in this case. This parallel movement also helps in gripping objects internally. Since the force is acting at a point or line in conical form of gripping it may lead to wear and tear of both the object and the finger. But in the parallel finger arrangement, the force will be distributed over an area. The two-fingers grasp may be considered the simplest efficient grasping configuration.

2.3 Gripper configuration

The developed gripper device was configured with a two parallel finger design for its wide applications in spite of its precise control need. One finger is fixed and the other is movable to ease the control and minimize the cost as shown in Fig.1. The fingers are flat and rectangular in shape. The housing of the gripper and fingers were made of aluminum sheet for light weight consideration with proper thickness to ease the machining and holes puncture through edges. This gives simple assembly and ease in maintenance. The movable finger is driven on a lead screw and guided by a linear bearing system with the advantage of self-locking capability, low cost and ease of manufacture [21].

To control the gripping of the object, we need to measure both the force applied to the object and the object slip. A standard commercial force sensor resistor FSR (Flexiforce A201 working in the range of 0-1 lb (4.4N)) [22] is used to measure the applied force. Also Phidget vibrator sensor [23] is adapted as slip sensor to give information about object slip rate in m/sec. These two sensors are tactile sensors. The actuator used to drive the movable finger is a permanent magnet brushless dc motor (BLDC). It has the advantage of high power density, ease of control, high efficiency, low maintenance and low rotor inertia [24]. BLDC servo motor used is an internal rotor motor "BLD3564B" from Minimotor inc. with its drive circuit "BLD5604-SH2P" [25]. The design of the gripper fingers must take some restrictions into consideration. Long fingers require high developed torque and short fingers impose restrictions on object dimensions. Hence fingers are selected to be 15 cm long. Also, a contact rubber material area between the fingers and the object of 25 mm by 25 mm is used to decrease the pressure on the object, increase the friction, and avoid deformation from centric concentrated force. With this gripper configuration, we succeeded to verify all previous design guidelines except guideline no.4 as our proposed gripper doesn't fully encompass the object in order to be able to grasp a greater variety of objects, although this imposes more difficulty in the control during gripping.

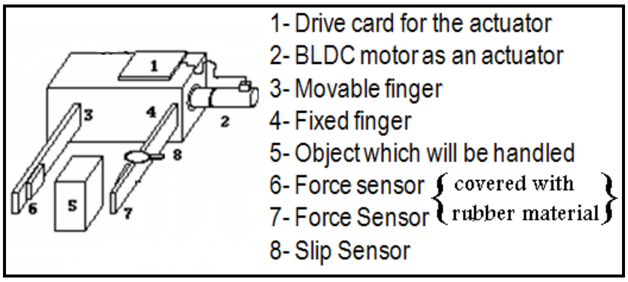


Fig.1 Gripper configuration.

3 Robotic gripper modeling

To build the proposed controller, we need to get information about the system characteristics for use in simulation and experimental work. Hence, input/output variables of the system are measured and processed. The input variable to the system is the speed control command to the servo motor drive expressed as reference voltage V_{ref}. The applied force on the object is the output variable F_{app}. The deformable compliant rubber material covering the contact area of the fingers, as shown in Fig.2, is important to allow a wide range of force control for solid objects as well as decreasing the pressure on the object and increasing the friction. Hence, we need to model the variation of the applied force F_{app} by the gripper finger with time at different reference voltage control commands V_{ref}.

Experimentally, and due to the mechanism constraint according to the gripper design, the applied force by the gripper fingers F_{app} on the objects could not decrease if the reference voltage control command V_{ref} is decreased. To verify the proposed controller, a model was built using MATLAB software package considering the mechanical constraints, which in turn lead to the accumulation of the applied force when V_{ref} is changed. For practical control, a maximum limit was set to the applied force $F_{\max .app}$, Figs 3 and 4. From this simulation model, the set of training data, checking data and testing data to be used for ANFIS model training were prepared.

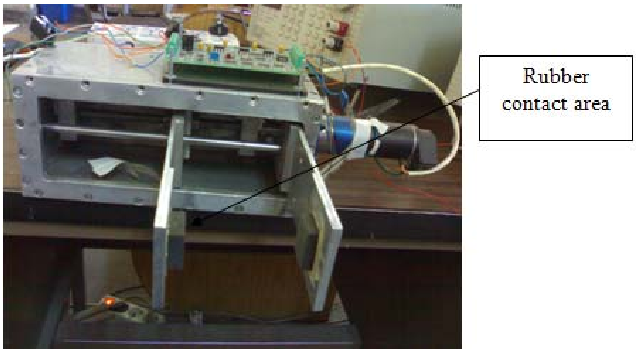


Fig.2 Gripper prototype.

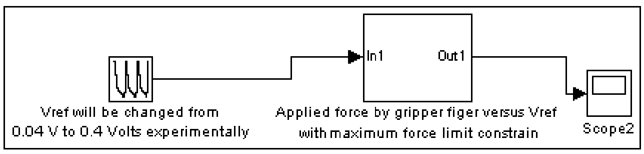


Fig. 3 Gripper simulation using MATLAB considering the maximum applied force.

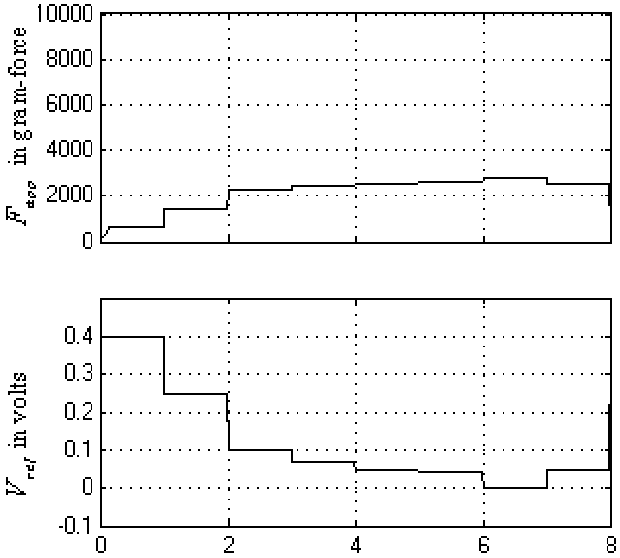


Fig.4 Gripper simulation results considering the maximum applied force

3.1 Force sensor calibration and modeling

The experiment was set up as shown in Fig.5. Different masses were used for calibration considering the maximum force that can be applied to the sensor according to its data sheet. The whole sensitive area should be subjected to the applied force. Using the nonlinear least squares fitter we can fit a function to our recorded measurements as shown in Fig.6. From the force sensor data sheet, the sensitive area is 0.7136 cm2, whereas the contact area between the object and any finger is 6.25 cm2 “the rubber material has a contact surface dimensions 2.5cm x 2.5cm”. Hence, There is a conversion factor, which converts the applied force by the finger on the object to the applied force on the sensor area as follows: -

$$F_{app} = 8.76\ F_{sens} \qquad (1)$$

Using the proposed drive circuit shown in Fig.7, we can deduce a formula that describes the relation between the analog output voltage from the force sensor and the applied force by the gripper finger as follows: -

$$V_{out} = 5 * R_f \ / a * ((F_{app}/8.76) \wedge b) \qquad (2)$$

Where: a = 2807.18, b = -0.69019
and R_f = 65 Kohm

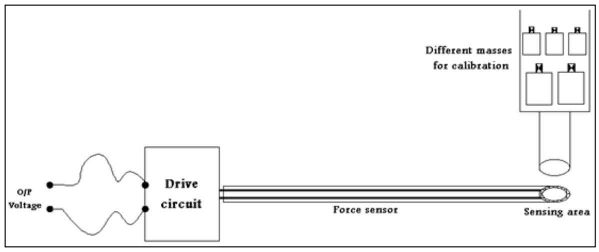


Fig.5 Experimental test for force sensor calibration.

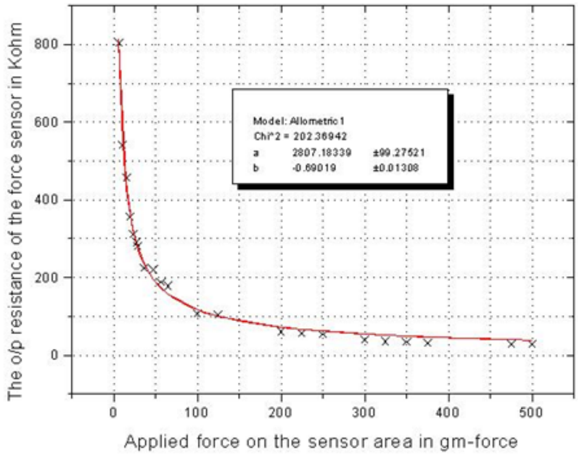


Fig.6Allometric function curve fitting.

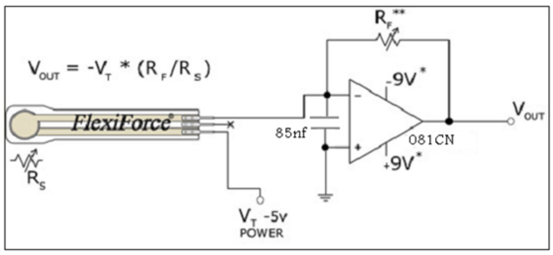


Fig.7 Proposed drive circuit.

3.2 ANFIS modeling for input/output gripper variables

Adaptive Neuro-Fuzzy Inference Systems, ANFIS, are realized by an appropriate combination of neural and fuzzy systems and provide a valuable modeling approach of complex systems [26]. The ANFIS structure is applied on our proposed robotic gripper, Fig.8, based on the measured data which are simulated using MATLAB software package as shown in Fig.3 and Fig 4. We use 161 training data, 46 checking data, and 46 testing data. The training data are shown in Fig.9. The surface rules viewer for the developed FIS model using ANFIS is shown in Fig.10. Simulation results of the gripper using ANFIS modeling is shown in Fig.11.

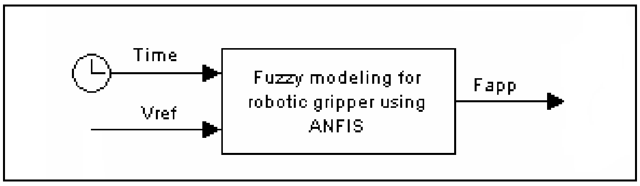


Fig.8 Robotic gripper using ANFIS.

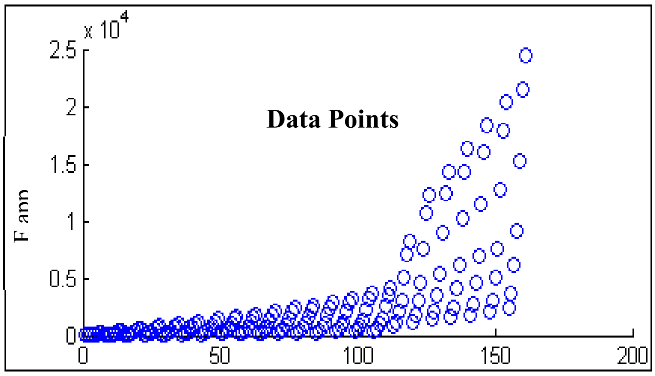


Fig.9 Training data.

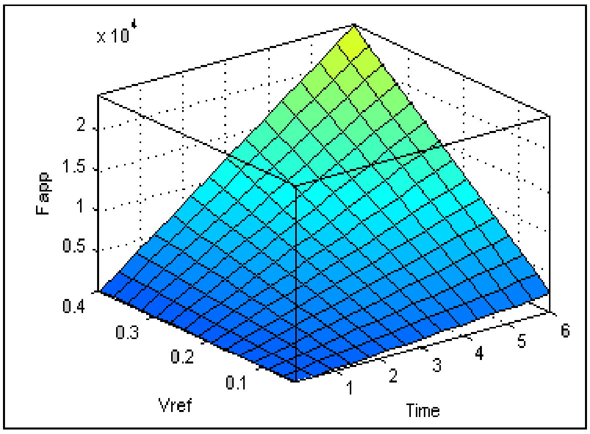


Fig.10 Surface rules viewer for the developed FIS model using ANFIS.

3.3 Object modeling

It is known that the occurrence of slip for a solid object during grasping and lifting mainly depends on its mass, its coefficient of friction and also on the applied forces. If the applied force is not enough,

acceleration is generated which leads to

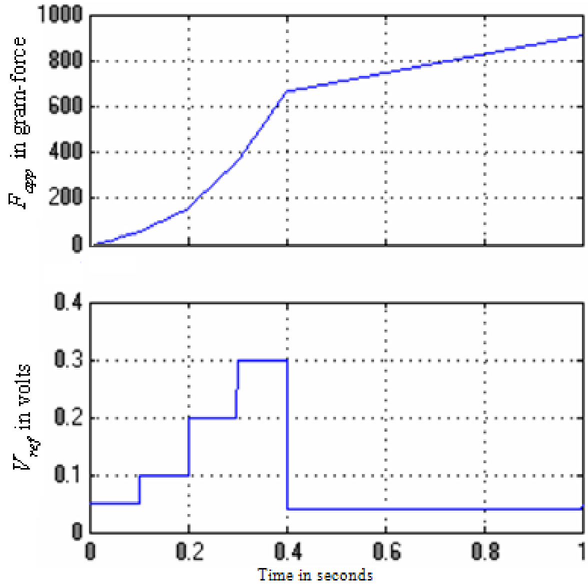


Fig.11 Gripper simulation results using ANFIS modeling.

acceleration is generated which leads to increased rate of slip and object dropping after certain time. This time depends on the applied force, the object mass and the coefficient of friction. Equation 3 determines the object acceleration as a function of the normal applied forces by the gripper fingers and the coefficient of friction as shown in Fig.12. Object simulation result is shown in Fig.13, which indicates that the slippage is stopped after a period of time depending on the rate of force increase.

$$m \times a = m \times g - 2 \times \mu \times F_{app} \qquad (3)$$

Where m is the object mass in kg, μ is the coefficient of friction, g is the earth gravity equal to 9.8 m/s2, and finally α is the object acceleration in m/s2.

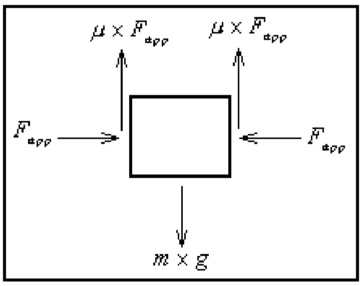


Fig.12 Applied forces on the object.

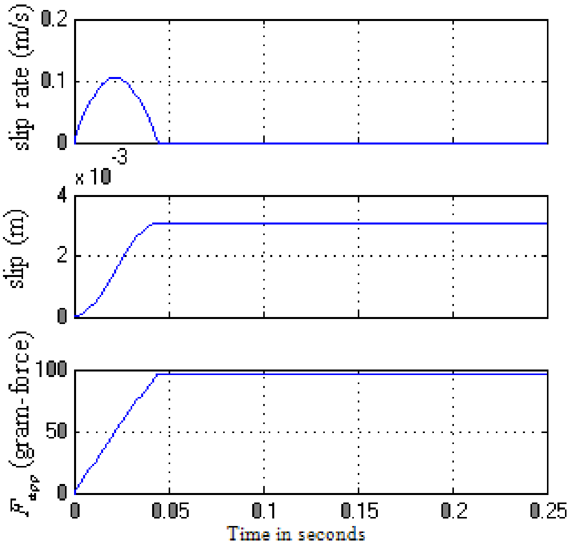


Fig.13 Object simulation results when Mass=100 gm and μ=0.5.

3.4 Slip sensor calibration and modeling

To measure the slip amount for an object subjected to grasping, lifting and handling, a piezoelectric vibration sensor was used. A piezoelectric transducer is displaced from the mechanical neutral axis, bending creates strain within the piezoelectric element and generates voltage signal. Experimentally, if the edge of this sensor is subjected to different speeds, it can generate different values of analog voltage that depend on those speed values. The experiment was set up as shown in Fig.14. The motor was run at different speeds and the output of the sensor was recorded. The speed to which the sensor is subjected equals to (Pi * 5 * rpm/60) mm/sec. Linear curve fitting had been applied to get the optimum modeling for the assigned slip sensor as shown in Fig.15.

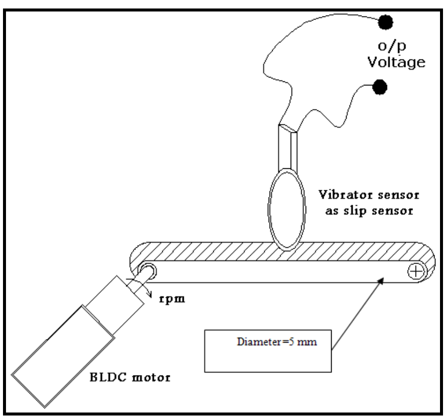


Fig.14 Experimental tests for slip sensor calibration

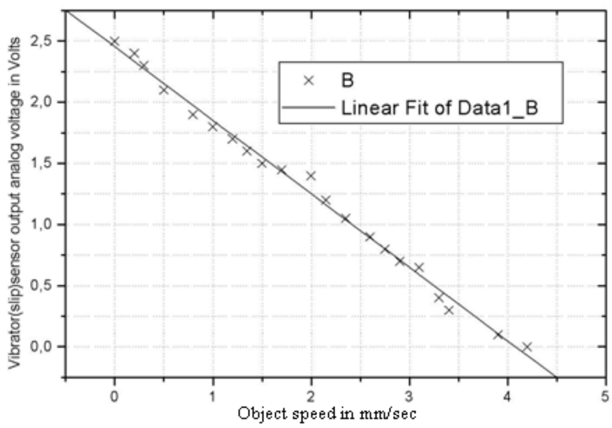


Fig.15 Linear fit for slip sensor based on measured values.

The fitting parameters are recorded as follows:-

$$Y = A + B * X \tag{4}$$

Where: A = 2, 45319, and B = -0, 60114
X is an independent variable that represents the object slip rate "object speed" in mm/sec. Y is a dependent variable that represents the slip sensor analog output voltage in volts.

4 Gripper system controller

Our proposed controller was developed by emulating the action of the human to handle any object during lifting it. First, he touches the object to examine its temperature and stiffness. Then, he tries to lift it by applying small force to move it or lift it in order to acquire some information about its weight and stiffness. Then he estimates the force needed to lift this object and takes the decision if he can lift it or not. Based on these observations, two control schemes were developed with different feedback variables.

4.1 First scheme controller

During object grasping and lifting process, it is not guaranteed that the two fingers will be in contact wth the object at the beginning. Hence, a pushing force will be applied by one finger (the movable finger) until complete contact. Normally, this pushing force is less than the force needed to lift the object, but is a function of the object mass and its coefficient of friction. Fig.16 shows the block diagram of the first proposed controller scheme. Two integrated fuzzy controllers were built in this scheme as follows:-

1. The first fuzzy controller is a reference voltage controller with two input variables, the slip-rate and its derivative.
2. The second fuzzy controller is a gain controller for the output of the first controller with one input variable, the pushing force.

The function of the second controller is to decrease or increase the reference voltage command. The output of this controller is based on the pushing force applied on the object before grasping and lifting process. Figs 17 & 18 show the surface viewers for the two controllers in this scheme. Simulation results show the response of this scheme as shown in Fig 19.

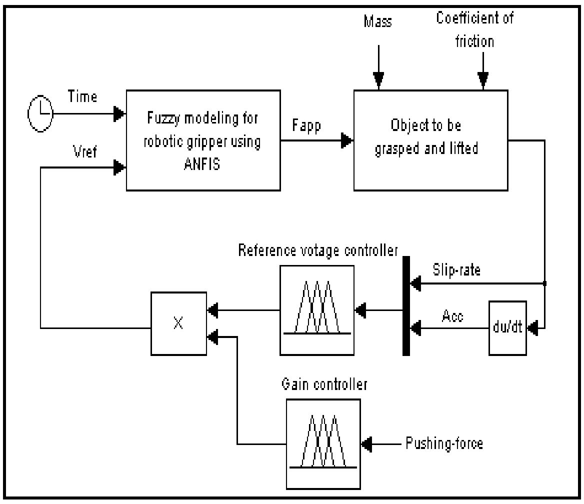


Fig. 16 Block diagram of the first scheme controller

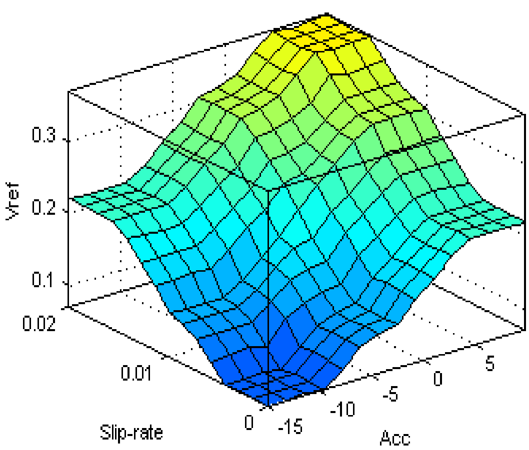


Fig.17 Surface viewer of the reference voltage controller

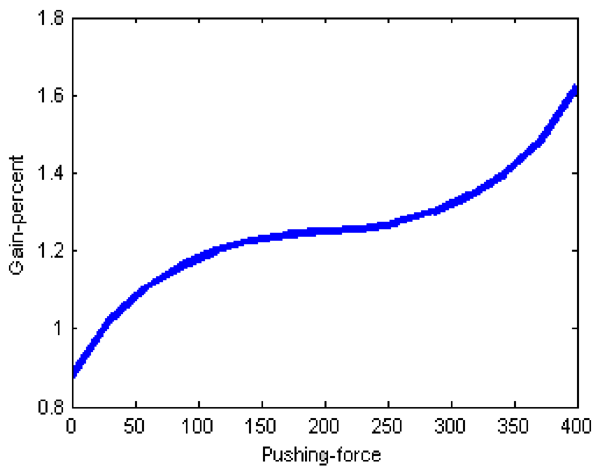


Fig. 18 Surface viewer of the gain controller

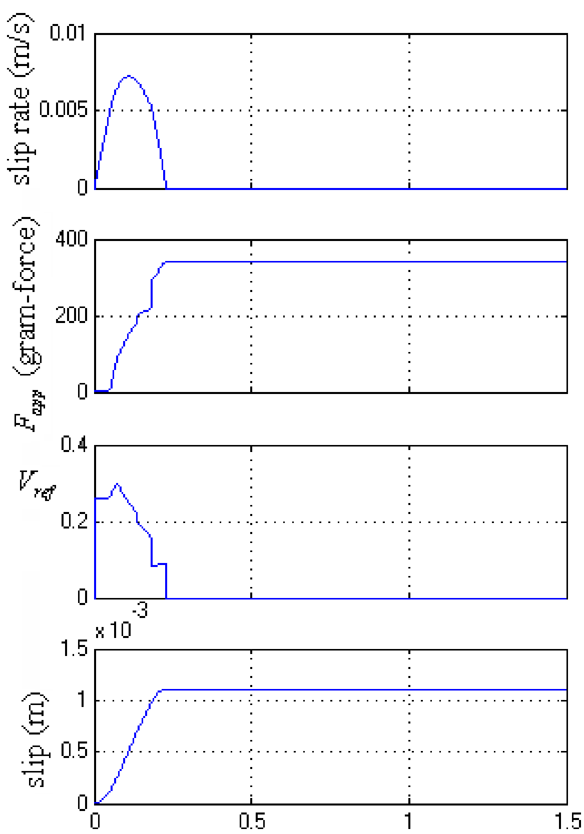


Fig. 19 System response for the first scheme controller

Mass = 300 gm and F_{push} = 150 gm-force

4.2 Second scheme controller

Three integrated fuzzy controllers were built in this scheme as shown in Fig 20:-

1. Guess starter reference voltage controller
2. Increased percent controller for starter reference voltage command.
3. Enhancement controller for the Starter Reference Voltage Command.

The first controller function is to guess the acceleration of the object resulting from small applied force and to give the suitable value of reference voltage command, the second controller function is to sense the pushing force to the object before the grasping process and its output is multiplied by the first controller output, the function of the third controller is to enhance the response of the two previous controllers based on the object acceleration and the applied force feed-back. The controllers receive the object acceleration, object acceleration rate, pushing force and the applied force as feedback variables and adjust the finger motion. The response of this scheme is shown in Fig.21 which indicates a faster response and lower slippage than the first scheme controller. Also, Figs22 & 23 show the effect of pushing force variation on the system response. In the case shown in Fig.23, F_{push} is higher than in the case shown in Fig.22. So the higher value of F_{push} used as feed-back to the control system leads to lower slip amount.

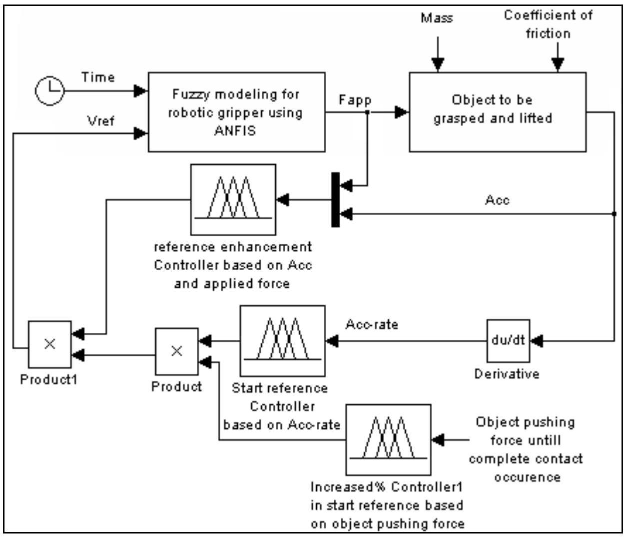


Fig. 20 Block diagram of the second scheme controller

5 Experimental results

Experimental work was established to verify the gripper system performance. Every part of the system was verified from the design concept, the manufacturing and control aspects. The mechanical system performance was tested and suitable refinements were performed. Sensors were calibrated and their necessary drive circuits were built. The actuator characteristics were studied in order to be taken into consideration during grasping process. Fig.24 shows the flowchart that describes the experimental scenario and proposed algorithm.

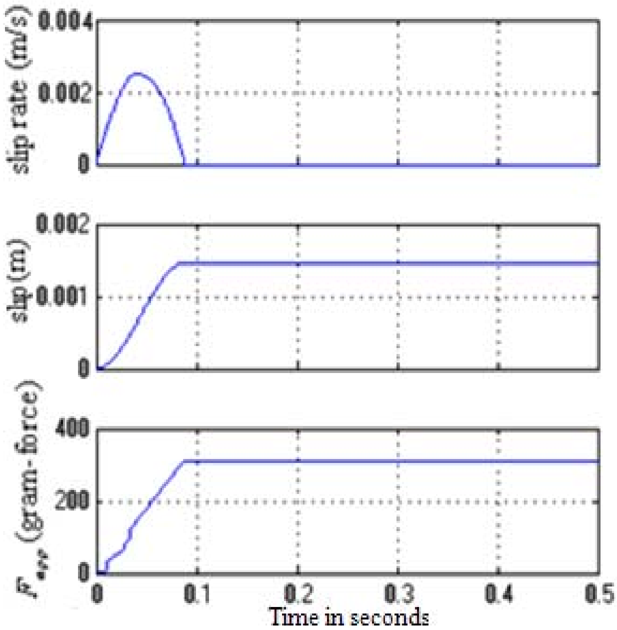


Fig.21 System response for the second scheme controller

Mass = 300 gm and F_{push} = 150 gm-force

Figs 25 & 26 show the system response during grasping and lifting process for 1000gm object mass. Figs 25 (a) & 26(a) show good performance although the start reference controller based on pushing force is not considered. The duration of the grasping and lifting process was in the range of 1 second and the slip displacement is in the range of 2 millimeters.

Considering the start reference controller based on pushing force as shown in Fig.25 (b) and in

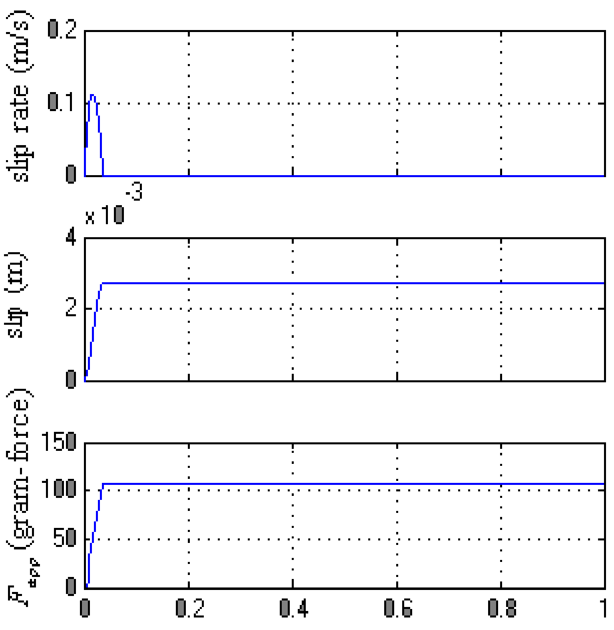


Fig.22 Slippage parameters and applied force when Mass=100 gm, μ=0.5, and F_{push}=20 gm-force

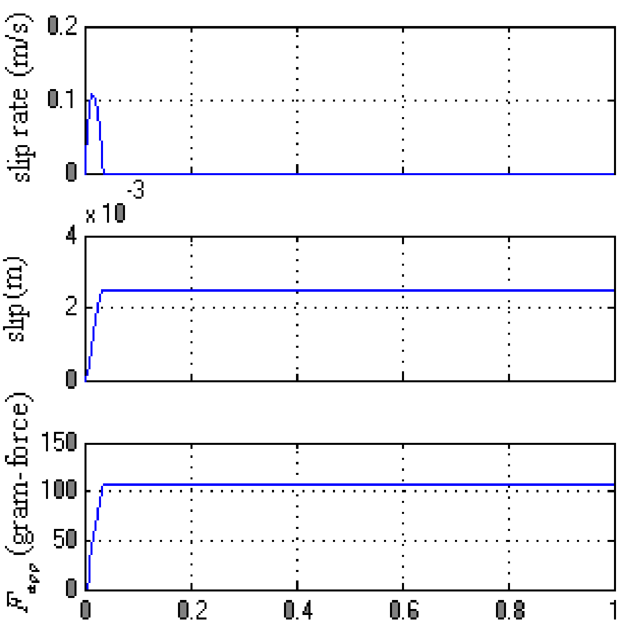


Fig.23Slippage parameters and applied force when Mass=100 gm, μ=0.5, and F_{push}=40 gm-force

Fig. 26 (b), we can minimize the time of the grasping and lifting process. Moreover, a slip displacement reduction was achieved. To confirm and verify the robustness of the developed gripper set-up and its control, we disturb the assigned system by a sudden increase in object mass. The gripper system response was found as shown in Fig.27, which keeps the time of slippage and slip displacement in the range of 1 second and 2 millimeters respectively. In the mean time Table 1 shows a comparison between the two proposed schemes. The enhancement in the response when the pushing force is considered gives us the opportunity to grasp safely objects with higher mass than in the first scheme where F_{push} is not considered. It is clear from the table that the performance of the system in the case of the second controller scheme is better than in the case of the first controller. The duration of the process is lower in the second scheme and also the amount of the slip is reduced for all test cases where the mass of the object is varying between 100g and 1000g. This proves that the feedback variables choice is very important and has a great effect on the system performance.

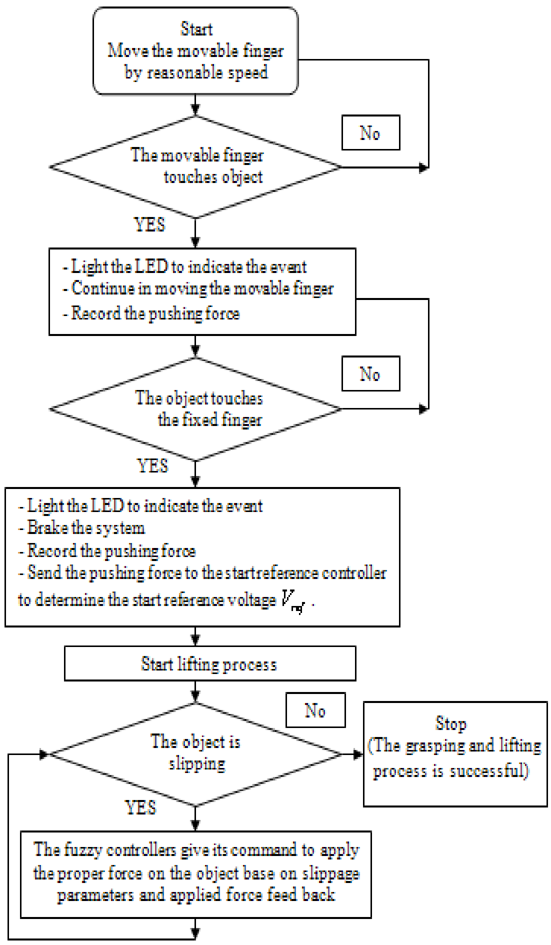
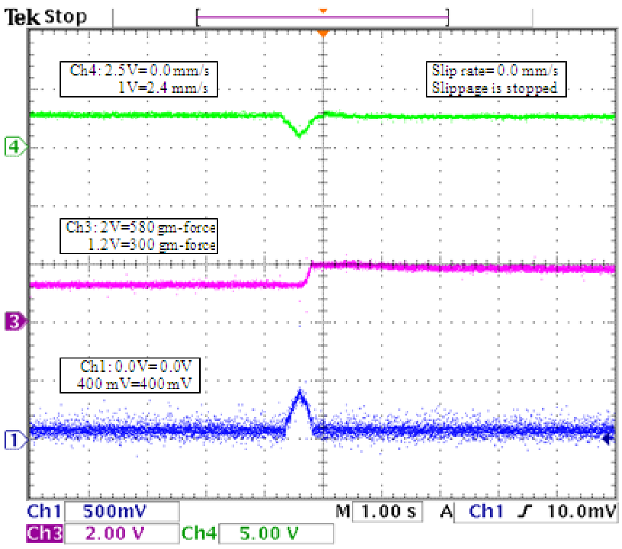
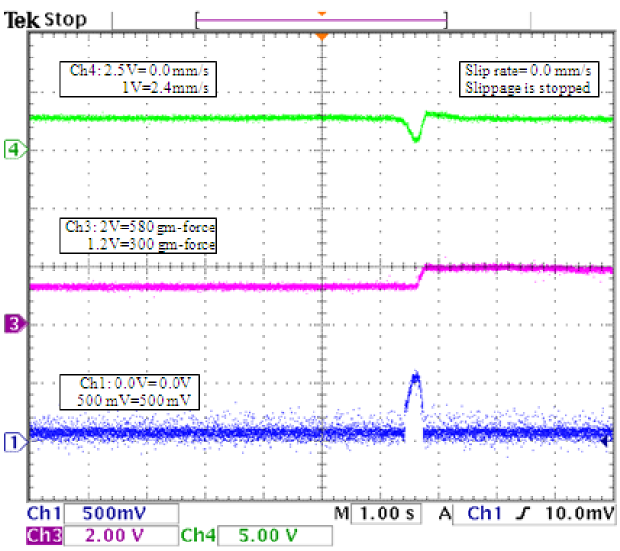


Fig.24 Flow chart of the proposed scenario



Ch4: Slip-rate (mm/s) – Ch3: Fapp (gm-force) – Ch1: Vref (V)

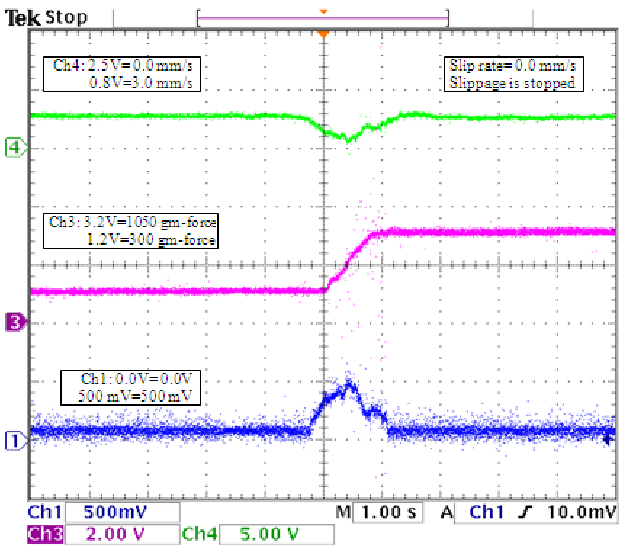
(a) Pushing force is not considered



Ch4: Slip-rate (mm/s) – Ch3: Fapp (gm-force) – Ch1: Vref (V)

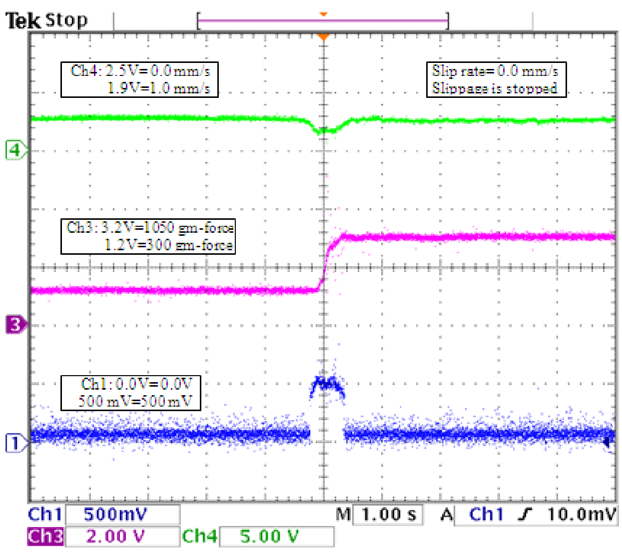
(b) Pushing force is considered

Fig. 25 System response when mass=550gm



Ch4: Slip-rate (m/s) – Ch3: Fapp (gm-force) – Ch1: Vref (V)

(a) Pushing force is not considered



Ch4: Slip-rate (m/s) – Ch3: Fapp (gm-force) – Ch1: Vref (V)

(b) Pushing force is considered

Fig.26 System response when mass=1000gm

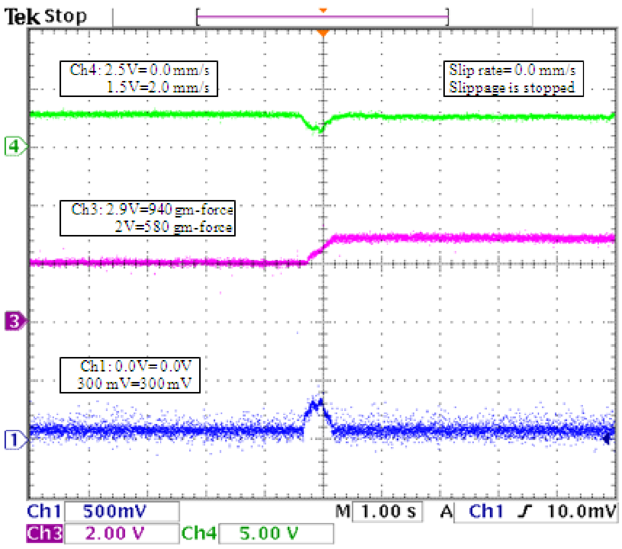


Fig.27 System response when mass is suddenly increased from 550 to 900gm

Table 1

		First scheme controller response		Second scheme controller response	
Mass (gram)	Pushing force (gram-force)	Time of process (sec)	Slip (mm)	Time of process (sec)	Slip (mm)
1000	Considered	0.73	4.15	0.502	3
1000	Not considered	1.35	5.56	1.05	3.9
550	Considered	0.441	2.73	0.312	1.85
550	Not considered	0.872	3.51	0.582	2.42
300	Considered	0.395	2.01	0.285	1.41
300	Not considered	0.623	2.88	0.533	1.95
100	Considered	0.201	1.45	0.19	1.11
100	Not considered	0.291	2.09	0.21	1.62

6 Conclusions

In this paper, a robotic gripper design and implementation was presented. A robotic gripper performance efficiency appears at handling unknown objects with different masses, dimensions, and coefficients of friction. Verifying most of recommended guide lines described in section II in gripper implementation had proved the gripper efficiency. The advantage of using one fixed finger and the other movable appears in the need for only one motor for actuation and also easier control when avoiding complicated mechanical system.

A new grasping and control algorithm was proposed to adjust the motion of one finger of the gripper without the risk of object crushing or dropping and also to maintain the object slip in a reasonable limit. The movable finger is actuated by a brushless dc servo-motor for its several advantages. The gripper design proved to be simple, economical, can handle a wide range of objects and easy controllable. A new commercial sensor (a vibrator sensor) adapted to detect slippage was presented. Owing to the proposed vibrator sensor used as slip sensor, the system is faster in response compared to different designs presented in publications in this area, and the elapsed time for the grasping and lifting process is reduced. A deformable compliant rubber material was added in the contact area of the gripper finger to prevent motor stalling and to simplify the control of solid object grasping. Details of the mechanical system construction was presented in [27]. A new grasping scenario was developed which gives information about the masses of the grasped objects before starting the grasping process without any additional sensors. This information helps the system to be faster. The mathematical modelling of the system was very difficult due to its nonlinearities. Hence, input/output system variables are measured and analyzed to recognize its characteristics. These data were used in modelling the system and for training the ANFIS control scheme. During the simulation stage, the first scheme grasping scenario developed was based on three simple fuzzy logic controllers to control the gripper system. . The first controller was based on guessing the acceleration of the object resulting from low applied force and giving the suitable value of the speed command, the second controller was based on sensing the pushing force which gives an indication of the object mass, while the third controller enhances the resulting action from the two previous controllers based on the object acceleration and the applied force feed-back [28].

All items in gripper construction had been modeled. A new algorithm similar to human behavior for the grasping process was presented. Simple rule base was used. Owing to the proper choice of feedback variables [29], system response and performance are enhanced as in the second scheme controller compared to the first scheme controller. Experimental results using the second scheme controller were obtained for different object masses and system disturbances. These recorded results were presented and discussed. The results show the fast time response in stopping the slippage and also show an appreciated enhancement in the grasping of different objects.

References:

[1] E. Ottaviano, M. Toti, and M. Ceccarelli, "Grasp Force Control in Two-finger Grippers with Pneumatic Actuation", *Proceedings of the 2000 IEEE International Conference on Robotics and Automation*, San Francisco, USA, Vol.2, April 2000, pp. 1976 – 1981.

[2] A. Bicchi and V. Kumar, "Robotic Grasping and Contact: A Review", *Proceedings of the 2000 IEEE International Conference on Robotics and Automation*, San Francisco, CA, 2000, pp. 348–353.

[3] R. D. Lorenz, K. M. Meyer, and D. M. Van de Riet, "A Novel, Compliant, Four degree-of-freedom, Robotic Fingertip Sensor", *IEEE Transaction on Industry Applications*, vol. 26, No. 4, July/August 1990, pp. 613-619.

[4] B. Choi, H. Choi, and S. Kang," Development of Tactile Sensor for Detecting Contact Force and Slip", *IEEE/RSJ International Conference on Intelligent Robots and Systems* (IROS 2005), 2-6 Aug. 2005, pp. 2638- 2643.

[5] G. Cannata and M. Maggiali, " An Embedded Tactile and Force Sensor for Robotic Manipulation and Grasping", *5th IEEE-RAS International Conference on Humanoid Robots*, Dec. 2005, pp. 80- 85.

[6] M.F. Barsky, D. K. Lindner, and R. 0. Claus, "Robot Gripper Control System using PVDF Piezoelectric Sensors", *IEEE Transaction on Ultrasonic, Ferroelectrics, and Frequency Control*, Vol. 36. No. 1, Jan. 1989, pp.129-134.

[7] R. Masuda et al., "Slip Sensor of Industrial Robot and Its Application, "*Electrical Engineering in Japan*, Vol.96, No.5, 1976, pp.129-136.

[8] P. Dario and D. De Rossi, "Tactile Sensors and the Gripping Challenge*", IEEE Spectrum*, No 22, Vol. 5, August 1985, pp.46-52.

[9] R.D. Howe and M.R. Cutkosky, "Sensing Skin Acceleration for Texture and Slip Perception" *Proceeding of the IEEE International Conference on Robotics and Automation*, Scottsdale, Arizona, May 14- 19, 1989, pp.145-150.

[10] W. Friedrich, P. Lim, and H. Nicholls, "Sensory Gripping System for Variable Products", *Proceedings of the 2000 IEEE International Conference on Robotics and Automation*, San Francisco, California, USA, April 2000, pp. 1982-1987.

[11] Ren C. Luo, Kuo L. Su and S. H. Henry phang, "An Implementation of Gripper Control Using the New Slipping Detector by Multi-sensor Fusion Method", , *IECON 2000, 26th Annual Conference of the IEEE Industrial Electronics Society*, Vol.2, pp. 888 - 893.

[12] M-J. E. Salami, N. Mir-Nassiri and S. N. Sidek," Design of Intelligent Multi-finger Gripper for a Robotic Arm using a DSP-based Fuzzy Controller", *Proceedings of TENCON 2000*, Kuala Lumpur, Malaysia, Vol. 3, 24-27 Sept. 2000, pp. 348-353.

[13] A. M. Dollar., R. D. Howe, "Towards Grasping in Unstructured Environments: Grasper Compliance and Configuration Optimization" *Advanced Robotics*, VSP and Robotics Society of Japan, Vol. 19, No. 5, pp. 523–543.

[14] C.M.Seguna and M.ASaliba, "The Mechanical and Control System Design of a Dexterous Robotic Gripper", *the 8th IEEE International Conference on Electronics, Circuits and Systems, ICECS 2001*, Vol. 3, pp. 1195 - 1201.

[15] V.Dubey, and R. Crowder, "Grasping and Control Issues in Adaptive End Effectors", in *ASME Design Engineering Technical Conferences*, Salt Lake City, Utah, September 28 - October 2, 2004.

[16] K.K.-C. Chan, and N.C. Cheung," Grasping of Delicate Objects by a Novel Two-finger Variable Reluctance Gripper", *Thirty-Sixth IEEE Industry Applications Conference*, IAS Annual Meeting. Conference, Vol. 3, 30 Sep-4 Oct. 2001, pp.1969 – 1974.

[17] J. A. Dominguez-Lopez, and D. N. Vila-Rosado," Hierarchical Fuzzy Control to Ensure Stable Grasping", *Seventh Mexican International Conference on Computer Science (ENC'06)*, Sept. 2006, pp. 37 – 43.

[18] R. G. Brown and R. C. Brost, “A 3-d Modular Gripper Design Tool”, *IEEE International Conference on Robotics and Automation Proceedings*, 1997, pp. 2332-2339.

[19] G. J. Monkman, S. Hesse, R. Steinmann, and H. Schunk, “*Robot Grippers*”, Wiley-VCH, 2007.

[20] J. W. Soto Martell, and G. Gini, “Robotic Hands: Design Review and Proposal of New Design Process”, *Proceedings of World Academy of Science, Engineering and Technology*, Vol. 20, April 2007, pp. 85-90.

[21] J. E. Shigley, C. R. Mischke, and R. Gordon, "*Mechanical Engineering Design*", (7th ed.), McGraw Hill, 2003.
[22] Flexiforce sensor, *www.tekscan.com*
[23] Vibrator sensor, *www.phidget-sensor.com*
[24] Bhim Singh, A.H.N.Reddy, and S.S.Murthy, "Hybrid Fuzzy Logic Proportional Plus Conventional Integral-Derivative Controller for Permanent Magnet Brushless DC Motor", *Proceedings of IEEE International Conference on Industrial Technology ICIT 2000*, Vol.1, 19-22 Jan. 2000, pp. 185- 191.
[25] Minimotor SA CH-6980 Croglio, Switzerland, *Faulhaber dc Motors, www.minimotor.ch*.
[26] A. Rezaeeian, A. Y. Koma, B. Shasti, and A. Doosthoseini, "ANFIS Modeling and Feed Forward Control of Shape Memory Alloy Actuators", *International Journal of Mathematical Models And Methods in Applied Sciences*, Issue 2, Vol 2, 2008, pp. 228-235
[27] A. M. Soliman, A. M. Zaki, O. A. Mahgoub, and A. M. Elshafei, "New Fuzzy Control-based Grasping Algorithm for a Novel Compliant Robot Gripper", *IEEE International Conference on Industrial Technology*, Monash University-Gippsland, Australia, 10-13 February 2009.
[28] A.M. Soliman, A.M. Zaki, O.A. Mahgoub, A.M. Ragai, "a Robotic Gripper Based on Advanced System Set-up and Fuzzy Control Algorithm", *Proc. of the IEEE International Conference on Automation and Logistics, IEEE ICAL 2009*, Shenyang, China, 5-7 August 2009.
[29] A.M. Zaki, A.M. Soliman, O.A. Mahgoub and A.M. Elshafei "High Performance Robotic Gripper Based on Choice of Feedback Variables" ,*Proc of IEEE International Conference on Informatics and Automation, ICIA 2010*, 20-23 June,2010, Harbin, China