THE MECHANICAL AND CONTROL SYSTEM DESIGN OF A DEXTEROUS ROBOTIC GRIPPER

Seguna, C.M.

(Student Member IEEE, ASME, SME, ASEE)

Saliba, M.A.†

(Member IEEE, ASME, APS)

Department of Manufacturing Engineering,
University of Malta.
Msida. MSD06. Malta.

ccsegu@eng.um.edu.mt

masali@eng.um.edu.mt

ABSTRACT

The design and development of dexterous robotic end effectors has been an active research area for a long while. This paper reviews the design and construction of a versatile robotic gripper used to grasp objects of arbitrary shape, size and weight. This is achieved through a mechanical design that incorporates multiple fingers and multiple joints per finger, through the installation of proximity and force sensors on the gripper, and through the employment of an innovative and practical control system architecture for the gripper components. The gripper is installed on a standard six degree-of-freedom industrial robot, and the gripper and robot control programs are integrated in a manner that allows easy application of the gripper in an industrial pick-and-place operation where the characteristics of the object can vary or are unknown.

Index Terms

Anthropomorphic hands, Dexterity, Flexibility, Grasping, Robot grippers, Software control and electronic interfacing.

1.0 INTRODUCTION

The design and construction of highly dexterous robot hands has been a major research and development objective for at least the past two decades. Inspired by the well-known Utah/MIT [1] and Stanford/JPL [2] hands during the 1980's, many research institutions have subsequently developed a large number of other robot hands, to varying degrees of complexity (e.g. [3], [4], [5], [6], [7], [8]).

Many of the above robot hands have the general objective of achieving a high degree of dexterity in a wide variety of situations, and this generality in their objective may sometimes lessen their effectiveness in specific classes of applications. In our work, we decided to focus on the development of a universal robot gripper for use in automated assembly operations in industry.

† *corresponding author*

Our objective was to maximize the dexterity and versatility of our gripper for this class of applications, while at the same time minimizing the weight, size, complexity and cost of the device. We therefore set out to design and construct a dexterous robotic gripper with the following general features:

- an ability to conform to different shapes, sizes and weights of objects;
- the utilization of a minimum number of actuators, located remotely from the gripper;
- an ability to sense the presence of an object within the workspace of the gripper;
- an ability to sense the magnitude of the grasping forces that are being applied by the gripper on the object;
- the installation of the gripper onto a standard six degree-of-freedom industrial robot, and the integration of the gripper and the robot control systems in the accomplishment of pick-and-place operations using different objects.

The accent throughout the entire work is one of practicability, achieved through the use of a versatile mechanical design, and through the innovative integration of standard components into a widely-applicable control system. The gripper utilizes a minimal amount of hardware, and can be controlled via a Pentium PC using a standard digital data acquisition card (DAQ). The gripper/robot combination may be employed in a wide variety of pick-and-place applications with minimal changes to the mechanical and control program configurations.

2.0 MECHANICAL DESIGN OF THE GRIPPER

2.1 General Design Description

The mechanical design of the robotic gripper needed to address the required interaction between the robot and the environment in order to grasp and hold the object securely and to execute the operation [9]. When objects to be grasped are of different shape and size the friction method is normally used whereby the part is

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restricted from moving by the friction present between the fingers and the object. In this way the fingers exert sufficient force to hold the part against gravity, acceleration and any other force that might arise during the holding portion of the work cycle. Although our gripper was designed to cater for many object shapes, only cylindrical, spherical and prismatic objects were considered for prototype testing, their size ranging from 30 to 80mm in diameter and their weights not exceeding 4N.

2.2 Geometric and Kinematic Considerations

The size and type of objects to be grasped determine the number of digits and links that the gripper should have. Schlesinger [10] divides human-hand grasping into six different types of prehension modes. A two-fingered configuration would not ensure a safe grasp as sideway slip can easily occur if any irregularities are present on the object's surface [11]. For an 'N'-fingered configuration (N>2), the finger layout, as assembled to the palm, must be selected so as to maximize the workspace volume, thus enhancing object-handling capability. Through an '*N*'-fingered configuration, sideway slip, which is present in the two-fingered configuration, is eliminated. Since no manipulation tasks were to be executed, a three-fingered end-effector having three links per finger satisfied our project objectives. The dimensions of the finger phalanges were based on that of an average adult human hand. From two-dimensional finger kinematics [8] the phalange dimensions were selected such that the perpendicular distance from the palm to the fingertips when the fingers curl up to their maximum extent (without the presence of any mechanical stops), would be greater than zero.

To achieve static equilibrium conditions when grasping an object with three fingers, the three grasping forces must pass through a single point and the angle spacing between any two finger forces must be less than 180° [11,12]. In a *cylindrical* grasp configuration, two fingers are placed so as to oppose the third finger (figure 1a). This configuration is useful for grasping prismatic objects. The *spherical* grasp configuration, where the three fingers are positioned approximately 120° apart (figure 1b), is preferred for the grasping of round objects. In order to increase the versatility of our gripper it was designed to achieve both configurations, through a special base for each finger that allowed manual adjustment of the finger orientation angle in 15° increments.

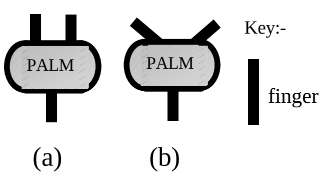


Figure 1:- (a)*Cylindrical* (b)*Spherical* grasp configurations

2.3 Finger Actuation

In order to maintain a low weight of the gripper, we opted to operate the fingers using a remotely located actuator, and to transmit the actuation to the fingers using a cable and pulley mechanism. A system consisting of three pulleys and two idlers, based on [8], was chosen since pulleys and idlers are lightweight and provide high strength and low friction operation (figure 2). This configuration is such that the link having the pulley with the largest radius rotates first. A single 0.95mm diameter cable consisting of many steel strands coated with nylon, acts as the digit's antagonistic tendon. Although withstanding a tension of 350N this cable is quite flexible. It is attached to the distal phalange, routed around the pulley/idler mechanism and attached at the other end to a sheathed (bicycle brake) cable, which in turn is connected via appropriate gearing to the remote actuator. When the cable is pulled, the tension increases and forces the fingers to close. Helical torsional steel springs were used to open the fingers, forcing them to go back to their initial position when the cable tension was relieved.

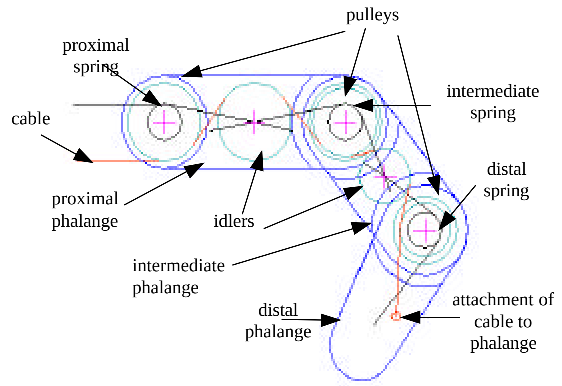


Figure 2:- Cable transmission system for the finger

2.4 Gripper Forces

In order to determine the grasping forces that were needed we used the formula by Engelberger, viz.

$$m\, n_f F_g \;=\; W g \qquad (1)$$

where m is the coefficient of friction between the object surface and the finger surface, n_f is the number of contacting fingers, F_g is the gripping force, W is the weight of the object, and g is a factor that depends on the anticipated acceleration forces during lifting of the grasped object (see, for example, [13]). In our case n_f = 3, W = 4N, and g=3. Rubber pads were attached to the fingers (in order to increase m, and in order to protect the force sensors, see section 3.4), however we used a conservative value for m of 0.25. A further safety factor of 1.5 was applied to equation (1), giving a required value for the grasping force of F_g = 24N.

In order to obtain reliable information relative to the required cable tensions, we built a prototype finger and performed an experiment to measure the relationship between the cable tension T and the fingertip force F_g for our design. A drawing of the experimental test rig is shown in figure 3. The fingertip force F_g was increased to 30N in increments of 0.5N, and the corresponding values of T, that would counterbalance these fingertip forces, were determined. The results are shown in figure 4.

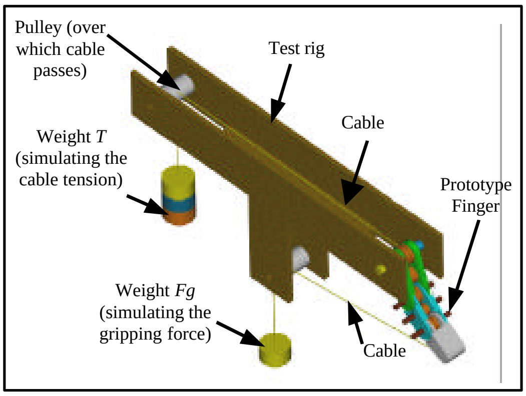


Figure 3:- The finger TestRig (designed using *Mechanical Desktop®* [1])

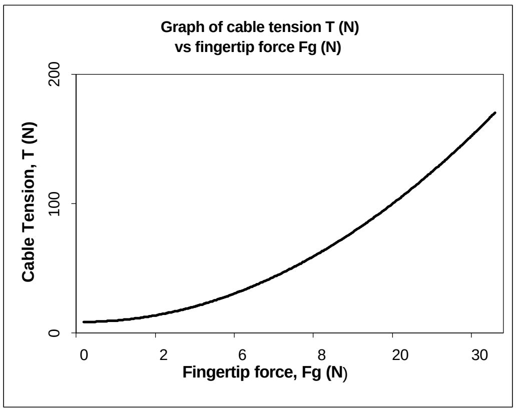


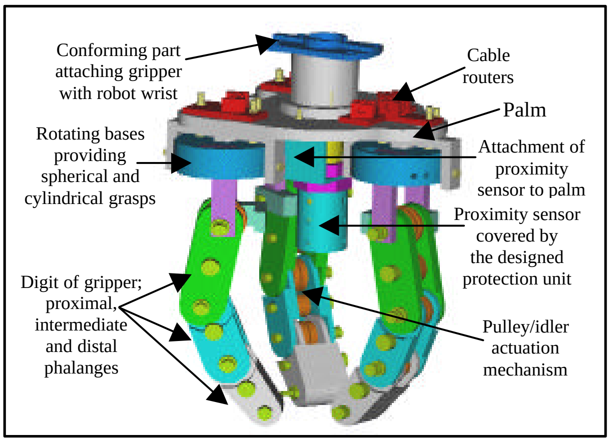
Figure 4:- Graph of Tension T against Force F_g

2.5 Material Selection

Since weight limitation was important the materials used in the construction of the gripper were PolyTetraFluorEtylene (PTFE) and Aluminium. Besides having low densities these materials also have good yield strength properties and are easy to machine. Unlike Acetel or Nylon, PTFE provides easy swarf removal during machining, thus safeguarding both the machinery and the machine tools, and allowing a higher accuracy in part dimensions to be obtained. The weight of the gripper after installation of all accessories was of about 0.6kg.

2.6 Design Methodology

Concepts of 'Design for Manufacture' and 'Design for Assembly' were utilised during the entire design process. Ease of maintenance was also given priority to ensure that all the designed components were modular and could be replaced/re-machined if damaged without having to perform modifications to the mating parts. The modularity also provided ease of assembly and disassembly. The new gripper could also be attached to other robots having higher payload handling capabilities. A three-dimensional drawing of the gripper (designed using *Mechanical Desktop®*[1]) is shown in figure 5a. The completed gripper is shown in figure 5b.



(a)

(b)

Figure 5:- The new gripper (a) design drawing, (b) as installed on the PUMA robot

3.0 CONTROL SYSTEM DESIGN OF THE GRIPPER

3.1 General Design Objectives

Integration of the gripper control system with the PUMA robot control system was achieved through feedback control and through two-way communication between the two systems. The necessary interfacing between the DAQ installed on the PC, the robot controller and the sensory equipment was attained through appropriate electronic circuitry. Digital control was used in most parts since it is less susceptible to noise and data transmission is faster. The grasping forces were measured using force sensors that were installed on the fingertips of the gripper. A proximity sensor installed at the center of the gripper palm detected the presence of the object at a distance of about 25mm from the palm. In the final demonstration both the gripper control program and the robot control program are executed simultaneously, and the two-way communication is achieved via the DAQ card. The gripper, mounted on the PUMA robot wrist, approaches the object of unknown weight, size and shape at the *pick* location from above. When the object is within the grasp space of the gripper, the robot motion stops, and the gripper fingers close until predetermined forces on the fingertips are reached. The object is taken towards the predetermined *place* location, and using the knowledge gained from the *pick* location the object is lowered to the correct height for placement. The gripper then opens, releasing the object, and the robot returns to the standby location awaiting the next picking operation to be executed.

3.2 Gripper Actuation

Several actuation methods for the gripper were evaluated, and preference was given to digital (stepper) motors due to the ease with which these could be integrated into our overall control system. Since our gripper was not intended to carry out manipulation of the object within its grasp, a single motor, that would operate all the three fingers simultaneously, was deemed sufficient for the actuation of the gripper. In this way the grasping operation would be automatically self-centering, and the overall gripper costs would be minimised. The stepper motor was rigidly fixed beside the robot, and the transmission of the motion/torque to the sheathed cable transmission (see section 2.3 above) was achieved via a worm and wheel mechanism. The flexible sheathed cable allowed for continued, uninterrupted transmission of force as the gripper moved about in space during the object relocation process. A tension limiting mechanism was included in the mechanical circuit to prevent the cable tension from exceeding the design specifications. This limiter provided an electrical signal that turned off the stepper motor, halting the grasping operation and thus protecting the hand and robot from being damaged.

3.3 Proximity Sensor

Since the operation needed to be completely autonomous and different objects (in particular, objects of different height) needed to be grasped, the gripper needed to be able to detect the presence of the object. Thus a proximity sensor was mounted at the centre of the palm and perpendicular to it. The selected sensor was of the photoelectric type, whereby a beam of infra-red light is transmitted by the sensor and is reflected back to the sensor by the object. This type of sensor has the advantage of detecting quite a variety of object materials, the only limitation being that the detectable range varies slightly with the object's material, surface flatness, opacity and reflectivity. As the gripper approaches the object from above (see section 3.5), data are sampled to identify whether the sensor is at logic *'LOW'* (object not within sensing range) or logic *'HIGH'* (object within sensing range). In order to avoid damaging the sensor's lens if the gripper accidentally impacts with the object, a special protection device for the sensor was designed and mounted to the palm of the gripper.

3.4 Force Sensors

The force sensors to be installed onto the fingertips of the gripper needed to be as small and light as possible, and needed to be able to measure the forces to an accuracy of about +/-10%. We opted for force sensing resistors (FSRs) made of polymer thick film (PTF) [14] (figure 6). These sensors are very thin and have negligible weight. They exhibit a decrease in resistance with an increase in the force applied to the effective surface area of the sensor, and are designed for applications where human touch control has to be simulated. However they are temperature dependent, they cannot be bent at any radius of curvature, and constant actuation cycle times are needed for good results to be generated. Since for correct data acquisition non-fluctuating readings were required, the use of an actuating slab on the effective area of the sensor, the use of a thin elastomer between this slab and the FSR and the use of an outside cover of BTTR (bicycle-tyre tube repair) rubber all helped to provide consistent reading and maintain the repeatability of the sensor. The full assembly of the FSR to the fingertip is shown in figure 7.

Experiments were carried out to calibrate the sensors (i.e. to determine the voltage response of the FSR with respect to the applied force) under different ambient temperatures and humidity, type of actuating device used and type of elastomer used to provide damping for the FSR, prior to installing them to the fingertips of the end effector. For each test, the data obtained were plotted and analysed to find out which elastomer would result in the best agreement between the experimental and theoretical curves of the sensor. This was mostly satisfied by *Latex Rubber*. *Mathematica*®[2] was used to fit fourth-order polynomials to the data relating the Average FSR Output Voltage (V) and the Applied Force (g) for different temperature and humidity conditions. These equations were then used in the gripper control program to convert the output voltage read by the Analogue-to-Digital Converter (ADC) of the DAQ card from each FSR output circuit into the actual applied force by each finger, and to stop the finger actuation when the threshold force was reached.

Tests were carried out to identify the level of noise present in the ADC of the DAQ card when no stimulus was subjected to the FSRs, and also to study the level of fluctuation from the sampled data. In the latter case a fluctuation of about 0.2%, equivalent to a variation of +/- 3gram force, was noted. This is quite comparable to the performance of a human hand, since, as identified in [14], studies have shown that accurate human hand repeatability is very difficult to achieve by touch alone.

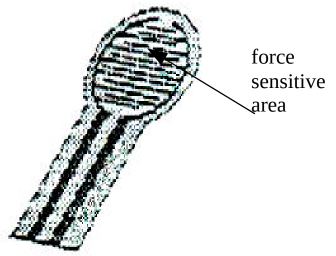


Figure 6:- Force Sensing Resistor (FSR) (reproduced from [14])

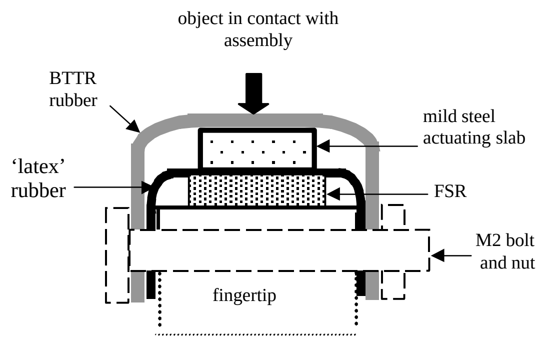


Figure 7: Assembly of FSR to fingertip (front view cross section)

3.5 Control programs

The gripper control program, written in C and running on the PC, and the robot control program, written in VAL-II and running on the robot controller, are executed simultaneously. Control is transferred between the two programs as different stages of the relocation operation are reached. The main features of the flow for the two programs are shown in figure 8.

When the main (gripper) control program is executed the user is prompted for the type of object to be grasped. The user selects from "hard", "medium" or soft" object and the FSR force thresholds are set accordingly (high for hard, low for soft objects). A signal is sent to the robot controller input module to execute the *pick.object* subprogram in Val II. At the same time the main program samples the proximity sensor's logic state. When the object is detected, the program instructs the stepper motor to start closing the gripper, and simultaneously starts to sample data from the fingertip force sensors. When the predefined threshold on any one of the FSRs has been reached, the stepper motor is stopped, and a signal is sent to the robot controller to initiate the *place.object* VAI-II subprogram. The main program waits for a ready signal from the robot. When this signal is received, the stepper motor is activated in the reverse direction so as to relieve the cable tension, thereby releasing the object from the grasp. A signal is then sent to the robot to instruct it to send the gripper to a standby location.

The PUMA control program that is executed simultaneously first awaits the initial signal from the main program. When this is received, the *pick.object* subprogram is executed, whereby the gripper approaches the object slowly from above, while simultaneously sampling the data from the proximity sensor. If the gripper gets too close to the table (i.e. the gripper moves down to a predetermined height limit) the whole exercise is aborted. Otherwise when the proximity sensor is activated robot motion stops and the object height is inferred from the gripper location. The robot now awaits a signal from the main program that the object has been successfully grasped. When this is received, the robot executes the *place.object* subprogram and transfers the object to the *place* location. A ready signal is sent to the main program for the object release sequence to commence. When a return signal from the main program indicates that the object has been released, the robot returns to its standby location.

3.6 System Integration

Interfacing circuits were required to provide the necessary communication link between the different components of the control system thus taking into account the impedance matching between the robot module [15], the DAQ input/output modules and the sensory equipment circuitry. Although the circuits utilized very small currents, the inputs of the DAQ were isolated from the circuit connections as a safety precaution by using an opto-isolator (ISQ74) in all the interfacing circuits. This ensured that if the current rose unexpectedly, exceeding the specified limits of the DAQ [16], the latter would not be damaged. The main software program running on the host computer provided a user-friendly interface, with various messages indicating program status being displayed on the screen while the operation was executed.
A schematic representation of the gripper/robot control systems is shown in figure 9, where DIO denotes the *digital input/output* of the DAQ card, and FSRC1, FSRC2 and FSRC3 denote the FSR circuits for each of the three digits.

4.0 CONCLUSION

A new dexterous robotic end effector has been designed, built, installed onto the PUMA 200 robot and tested successfully (figure 10). Through the use of multiple fingers, multiple joints per finger, and proximity and force sensors, the end effector is able to grasp various objects of different shapes, sizes, weights and surface characteristics.

The use of a single remotely located actuator reduces the weight, size, complexity and cost of the end effector. Two-way communication between the actuator, sensors and the robot and gripper control programs enables easy integration of the hand/robot system into a flexible manufacturing environment.

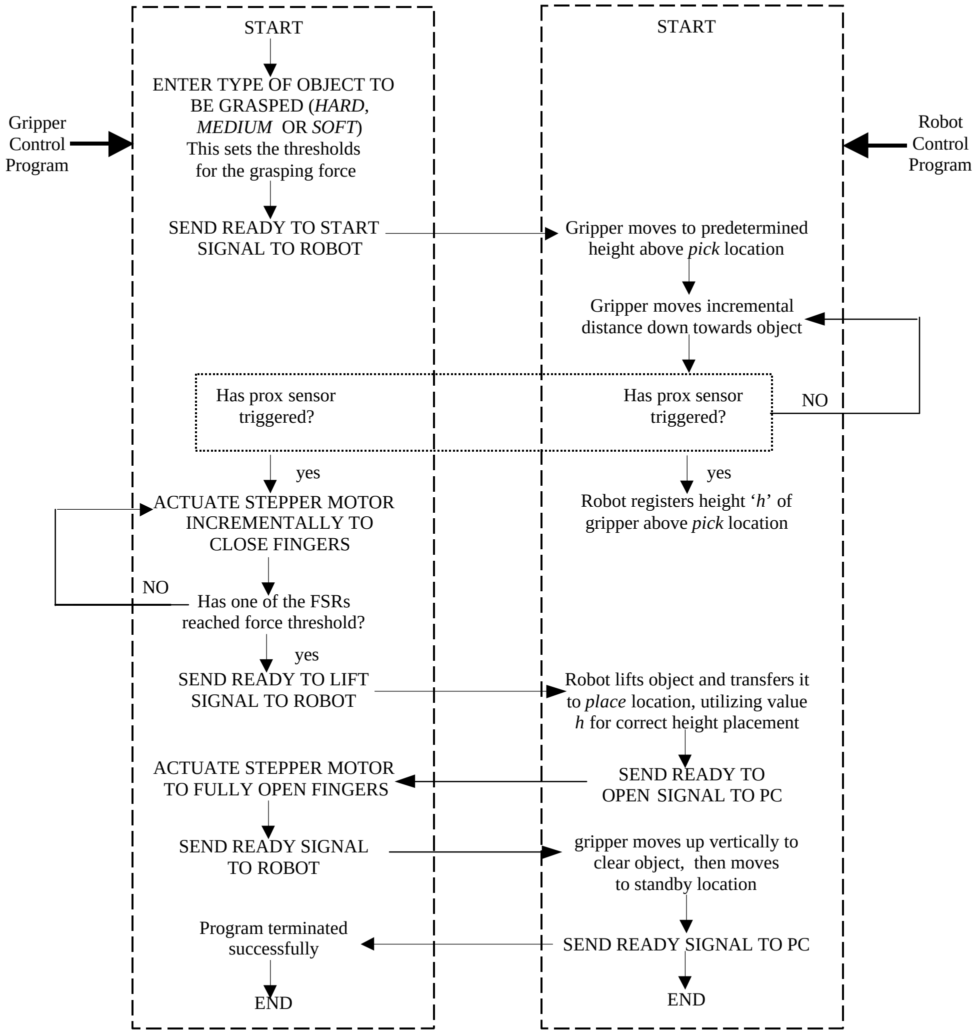


Figure 8:- Gripper/Robot Control System flowchart

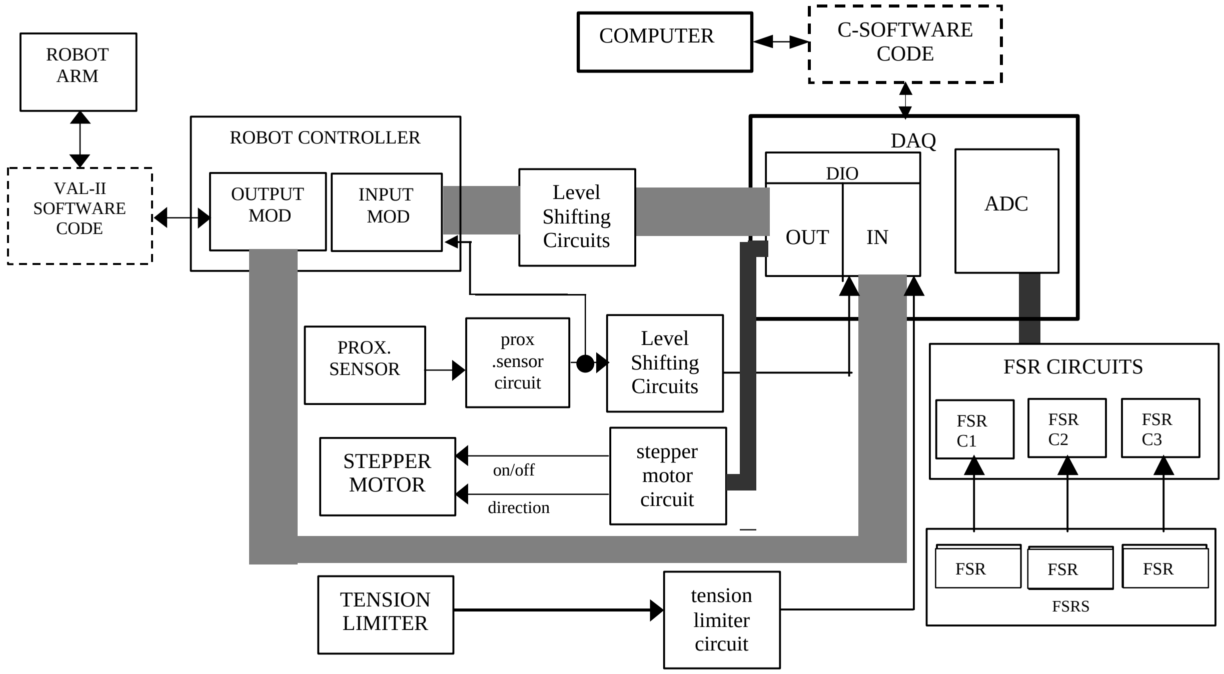
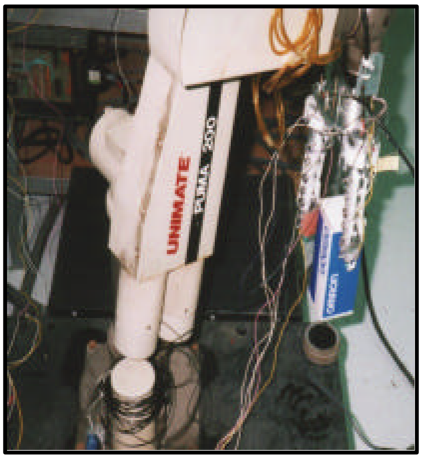
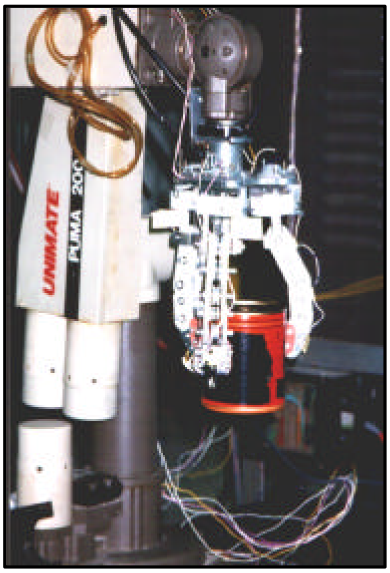


Figure 9:- Schematic representation of the control system



(a)



(b)

Figure 10:-End effector grasping (a) a cardboard box (b) a cylindrical object

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