A Servo-Controlled Robot Gripper with Multiple Sensors and its Logical Specification

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Received February 10, 1986; accepted May 2, 1986.

The logical specification of a microprocessor-based air-servo-controlled robot hand is presented, as well as its actual implementation. This hand can accommodate a wide variety of workpieces and allows for flexible assembly through the use of an automatic quick-change fingertip. The changeable set of gripper fingers is equipped with sensors, including a tactile force sensor, a crossfire sensor, a proximity sensor, and a slip sensor. A changeable set of gripper fingers with different sensing ranges can cope with certain subranges of the workpiece spectrum. A considerable cost saving is achieved by not changing the gripper itself. This specially designed hardware and software system includes position and force feedback. A PUMA 560 is used to test the success of the entire process.

本論文では、マイクロ・プロセッサにより制御されるエア・サーボ駆動型ロボット・ハンドに用いられる論理回路の仕様について述べる。ここに述べるロボット・ハンドは多様な形状・サイズのワーク・ピースを取り扱うため、グリッパ端を自動的にかつ迅速につけ換えることにより、柔軟な組立て作業を可能にする。可換グリッパ端には触覚、近接およびスリップ・センサなどを装備している。これらセンサは特定の範囲のワーク・ピースのスペクトラムを取り扱える。グリップ全体を取り換えるわけではないのでコスト的に安くなる。この特注のハードウェアとソフトウェアは位置および力フィードバックがかけられるよう設計されている。PUNA 560を用いて実験を行い、全プロセスが完璧に動作することを確認した。

Journal of Robotic Systems, 3(4), 409–420 (1986)
 CCC 0471-2223/86/040409–12$04.00

I. INTRODUCTION

Industrial robot systems have been found to be tremendously effective tools for the flexible automation of many manufacturing tasks. To accomplish many automatic manufacturing processes using industrial robots, for example, in material handling and assembly jobs, requires a considerable improvement in the capability of the robots to perceive and interact with the surrounding environment. In particular, it is desirable to develop sensor-based, computer-controlled interactive systems that can emulate human capabilities. Based upon sensor signals and stored computer programs, a control computer can automatically perform assembly with minimum assistance by human operators. Sensors for general automation applications have been presented elsewhere.[1–4]

The key element of a flexible assembly robot is its grippers, which can accommodate a variety of workpieces. These should have intelligent sensory feedback, and should be lightweight, fast, accurate, powerful, and inexpensive. To this end, we developed an air-servo-controlled gripper with an integrated sensor system, which allows the use of a greater torque-weight actuator, greater clamping force, and a relatively simple design.

The specification of a sensor system is also an important area of research.[5,6] Although such specifications are most useful when applied to large and complex systems, we will demonstrate how logical sensor specifications can bring out quite clearly the important aspects of even relatively simple sensing and control systems. We have designed a servo-controlled robot hand which is equipped with various specification system sensors and is managed by the logic sensor.

To perform most assembly tasks, a robot gripper will need to handle many different workpieces during the assembly process. But a single gripper cannot effectively handle both very large and very small parts. A way to cope with the diversity of parts is to prepare several grippers, corresponding to the classes of parts, and to change them in the course of assembly operations. However, this inevitably requires time and expense for changing the grippers.

We have designed automatic quick-change fingertips which are equipped with a variety of sensors[7,8] so that a changeable set of gripper fingers with different sensing ranges can cover certain subranges of the workpiece spectrum. It provides considerable cost savings due to the elimination of the need for frequent changing of custom-designed grippers during the work process.

II. LOGICAL STRUCTURE OF THE GRIPPER SENSING AND CONTROL

A. Definition of Logical Sensors

Logical sensor specification provides a way to detail a sensing and control system in terms of the information which is passed from one part of the system to another. Such systems are defined in terms of a network of logical sensors. The abstract view of a logical sensor is shown in Figure 1. Each logical sensor is comprised of several parts.

(1) A logical name. This is used to uniquely identify the logical sensor.
(2) A characteristic output vector. This is basically a vector of types which serves as a description of the output vectors that will be produced by the logical sensor. Thus, the

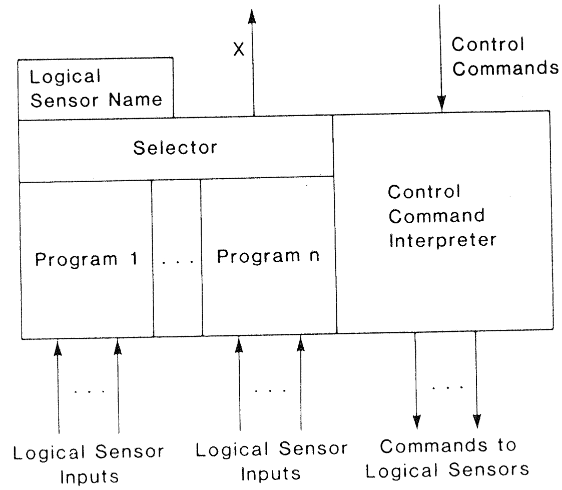

Figure 1. The organization of a logical sensor.

output of a logical sensor is a set (or stream) of vectors, each of which is of the type declared by that logical sensor's characteristic output vector. The type may be any standard type (e.g., real integer), a user-generated type, or a well-defined subrange of either. When an output vector is of the type declared by a characteristic output vector (i.e, the cross product of the vector element types), we say that the output vector is an "instantiation" of that characteristic output vector.

(3) A selector whose inputs are alternate subnets and an acceptance test name. The role of the selector is to detect failure of an alternate and switch to a different alternate. If switching cannot be done, the selector reports failure of the logical sensor.

(4) Alternate subnets. This is a list of one or more alternate ways in which to obtain data with the same characteristic output vector. Hence, each alternate subnet is equivalent, with regard to type, to all other subnets in the list, and can serve as backups in case of failure. Each alternate subnet in the list itself is composed of: (a) A set of input sources. Each element of the set must be itself a logical sensor, or the empty set (null). Allowing null input permits physical sensors, which have only an associated program (the device driver), to be described as a logical sensor treatment. (b) A computation unit over the input sources. Currently such computation units are software programs, but in the future hardware units may also be used.

(5) Control command interpreter. The control command interpreter takes strings (defined by some grammar) from the control line and produces: (a) the required control if at a physical device, or (b) the appropriate set of command strings for the logical sensors which provide input data to the current logical sensor. In this way, "logical controllers" can be implemented.

A logical sensor can be viewed as a network composed of subnetworks which are themselves logical sensors. Communication within a network is controlled via the flow of data from one subnetwork to another. Hence such networks are *data-flow* networks.

Logical Specification of the Gripper

In this article we are concerned with two major issues: (1) the description of an actual mechanical gripper, and (2) the specification of the logical characteristics of the gripper. In accordance with top-down design principles, we first describe the

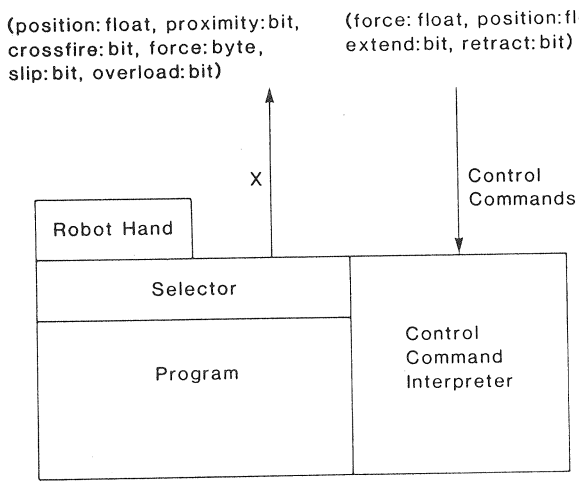

Figure 2. The logical sensor for the robot gripper.

functional and behavioral aspects of the gripper, before giving the implementation details (see Section III). That is, we first specify an abstraction which emphasizes the characteristics of the gripper that are most useful and high level.

The most straightforward way to characterize the gripper is shown in Figure 2. That is, we view the gripper and all of its sensing as a single entity. Since a special-purpose

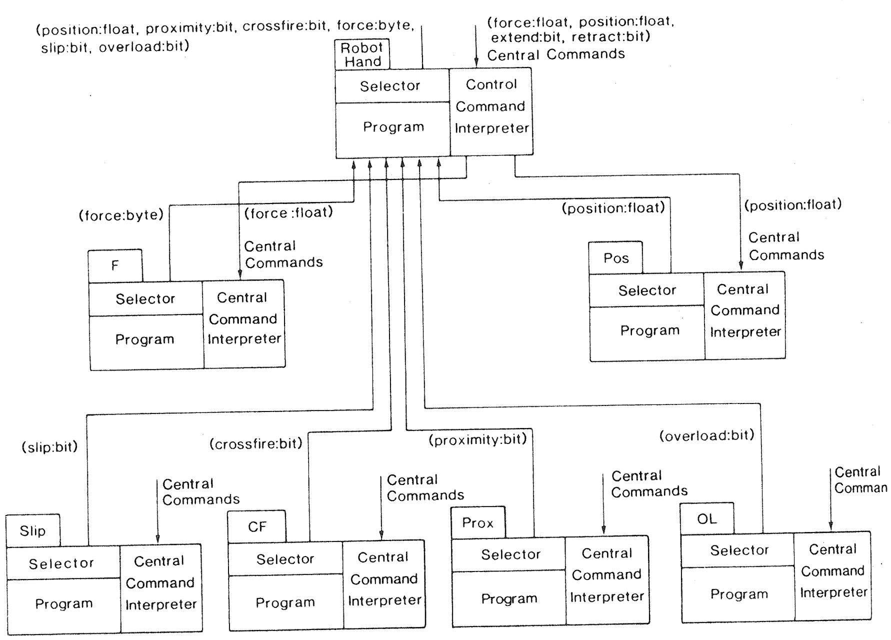

Figure 3. An alternative specification for the robot gripper.

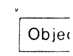

Figure 4. Multisensor context f

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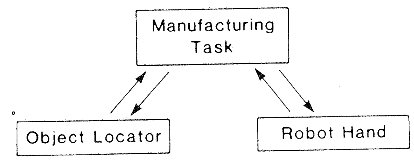

Figure 4. Multisensor context for gripper specification.

hardware and software system has been built to implement the gripper, the level of description shown in Figure 2 could suffice as a specification.

Alternatively, it may be desirable to view the sensors involved as separate specifications (see Figure 3). The motivation is simply to make the sensing and control aspects more evident. This could be useful to many different users ranging from management to technical staff. It would, for example, make clear which subsystems could be made into independent modules. It would also make it possible to isolate subsystems with respect to failure analysis, etc. However, in the application presented in this article, all of the sensed data is interfaced to the same digital multiplexer, and Figure 2 is a more appropriate specification.

Another important aspect of the specification is the context in which the gripper is used. Figure 4 shows a scenario in which the gripper is used in a multisensor task specification. The essential idea is that independent software and hardware can be easily and understandably interconnected to achieve a goal.

III. DESIGN OF MULTISENSOR-BASED GRIPPER

A. Robot-Hand–Based Sensors

As mentioned before, frequently changing work environments are commonly encountered in robot workstations. Therefore, it is desirable to develop a sensor-based robot to accommodate the change of environments. Basically, the robot sensors can improve the capabilities of the robot through three stages, namely, (a) before contact (use vision and/or proximity sensors), (b) during contact (use touch, slip sensors), (c) after contact (use force/torque sensors). We can roughly categorize these sensors into two types: visual and nonvisual. Among these sensors, the visual sensor has attracted the greatest research effort.[9] In this article we have presented the development of a variety of nonvisual sensors which consist of force, slip, crossfire, proximity, and overload sensors to demonstrate how logical sensor specification can bring out the important aspects of even relatively simple sensing and control systems. It is noted that the information provided by these sensors normally is not contained in visual data, and it can be treated as supplemental visual information for control. For example, the force/torque sensor will extract the amount of force/torque information exerted by hand on objects along three hand-referenced orthogonal directions; the slip/touch sensor will extract the distribution and amount of contact-area pressure between hand and objects. With the cooperation between slip and force sensors, it permits adjustment of the grasping force adaptively.[10] Currently, we have used a novel capacitive force sensor which can sense the force in the range of 0.1 to 10 lbs with a resolution of ± 0.01 lb and a sensitivity of 2 V/lb.[7] We have mounted a roller-type capacitive slip sensor onto the gripper. The slip sensor detects the change of phase angle, while the change of capacitance is sensed through the rotation motion of rollers contacting the object. The amount of detected phase shift is the measured quantity of the slip displacement. The sensor can detect the slippage with the resolution of $\pm 0.06°$, and the sensitivity is 0.5 V/degree.

B. Mechanical Structure of the Gripper

The gripper is designed as a parallel-jaw type with parallelogram finger structure. It consists of a cylindrical housing and two parallel fingertips. A perspective view of the gripper is shown in Figure 5.

The gripper is attached to the wrist of the robot arm by means of the top plate of a compliant overload structure. This structure maintains a rigid relationship between the gripper and mounting plate until an excessive upward vertical force or excessive lateral forces are exerted on the gripper. The overload threshold is determined by the tension exerted by three preloaded compression springs. The overload signal is detected by a through-beam electro-optical sensor. We chose the electro-optical sensor because of its noncontact nature.

A specially designed small air cylinder serves as an actuator, controlled by an air-servo valve. A linear slide-type potentiometer is attached to the piston of the air cylinder located inside the cylindrical gripper housing. Position feedback signals are furnished

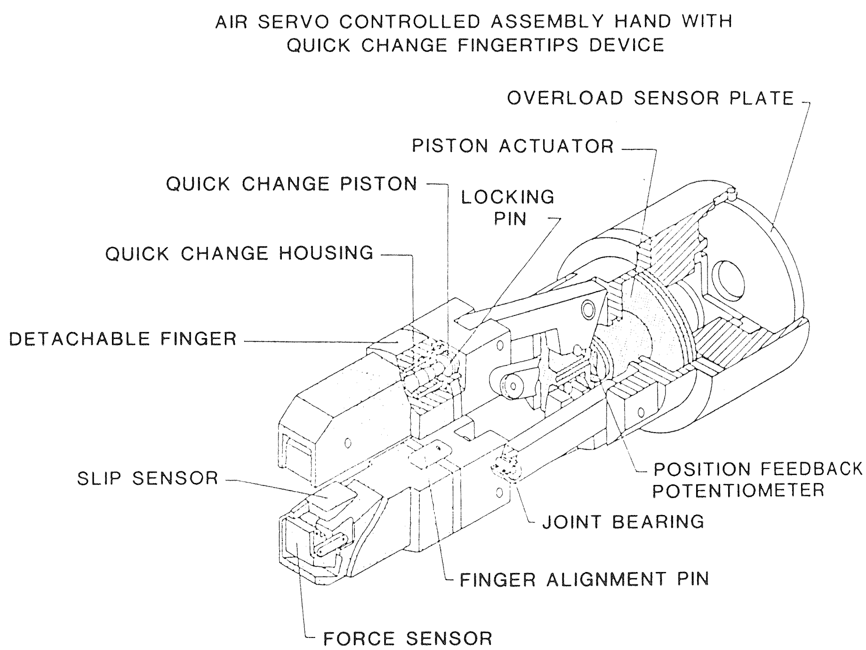

Figure 5. Structure of the air-servo-controlled gripper with quick-change fingertip mechanism.

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D. Microprocessor-Based and Force Feedback

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to the controller by the change of resistance of the potentiometer. The linkages are attached to finger support blocks and the joint of the linkages are supplied with bearings to allow smooth operation.

The fingertips allow fully automatic interchangeability using quick-change mechanical and electrical connections. On the linkage block, a very small air cylinder is designed and built which permits a double-action motion to manipulate the connection pins between fingertip and linkage block. Once the piston is extended, the fingertip is connected in place with the linkage block through the latching of the pins between the fingertip and linkage block. By the retraction of the piston, the fingertip can then be released from the linkage block.

C. Electropneumatic Servo Valve

An important component for the gripper servo-control system is the servo valve. The servo valve receives small electrical signals from the controller and causes air to flow to and from an actuator. Most servo valves used in industry have a two-stage design with a "flapper-nozzle" or "jet-pipe" first stage. Generally, such a servo valve has a torque motor, jet-pipe or flapper-nozzle pneumatic preamplifier (first stage), and a four-way sliding-spool second stage with a force feedback closed-loop servo system to control it. By controlling the input signal of the servo valve we would be able to control the actuator of the gripper, as well as the open-close of the gripper, proportionally.

D. Microprocessor-Based Servo Control with Position and Force Feedback

A flip-flop SN74373 with three-state bus-driving outputs and eight-bit latches which allows full parallel access for loading, was selected as a bidirectional bus driver. In combination with two other similar eight-bit latches flip-flops can be used as a multiplexer as shown in Figure 6. The multiplexer was used as an interface between the microprocessor and all sensor feedback signals. The eight latches of the SN74373-A are transparent D-type latches, meaning that while the enable (G) is high the Q outputs will follow the data D inputs. When the enable signal goes "high," the eight-bit output signal from the microprocessor is loaded into a module n counter. Here we use SN74191 BCD synchronous up/down counters. It is enabled to count down by connecting the DOWN input with "high." The outputs of the four master-slave flip-flops are triggered on a low-to-high–level transition of the clock input if the enable is low. Figure 6 shows the circuitry for a microprocessor-based servo-controlled system with position feedback.

An oscillator generating 800-Hz frequency as a carrier signal controls the down-counting process by using the "load" input. If the count number of a complete cycle from 800 Hz is set for 255, a clock with 200 kHz will be needed. As the 800-Hz carrier signals are triggered by low-to-high transiency, it will start to count down the counter and enter four-bit data at the data inputs until the "ripple clock" output goes "low." This time period $T1$ is variable depending on the data inputs. This signal will

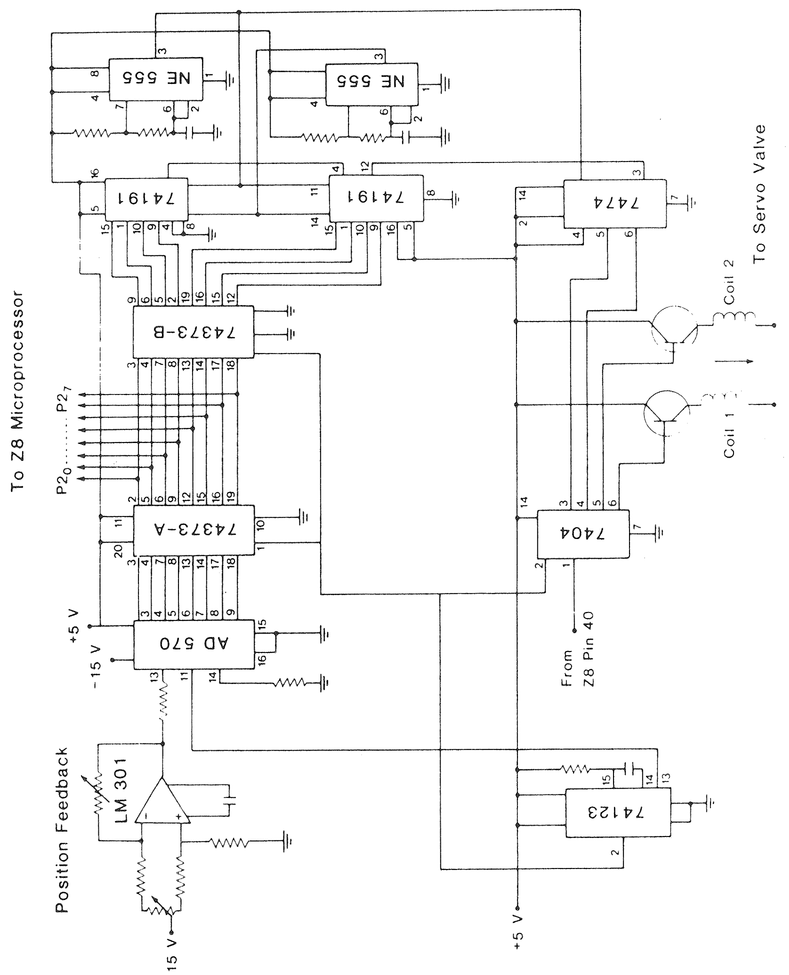

Figure 6. Microprocessor-based servo-control system with position feedback.

then cascade by feeding it into the enable input of the succeeding counter 2. Counter 2 then starts to count down and enters the other four-bit data input until the minimum count output is reached. The output produces a high-level output pulse with a duration approximately equal to one complete cycle of the clock. This output will serve as a clock for the flip-flop SN7474 which extends the pulse of the remaining period of the 800-Hz carrier clock. The flip-flop is reset by the falling edge of the carrier clock. It will then produce two contrary output signals.

Through suitable transistor switching we make sure the current will not exceed 30 mA for controlling both coils to the servo valve. The movement of the piston of the air cylinder, as well as the opening and closing of the gripper, will be modulated by the pulse-width difference in coil 1 and coil 2 of the servo valve.

1. Position Feedback

To achieve position feedba of the air cylinder. It provi output in the range of 0–10 analog-to-digital converter A continue through the bidirec croprocessor.

2. Force Feedback

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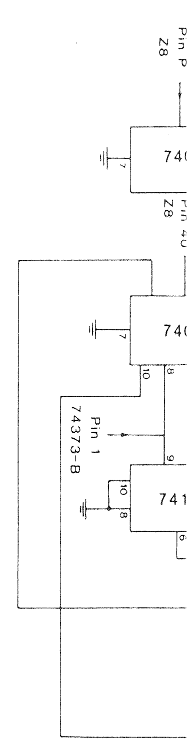

Figure 7. Servo-control syste

1. Position Feedback

To achieve position feedback, a potentiometer is mechanically attached to the piston of the air cylinder. It provides feedback gain through a differential amplifier, with output in the range of 0–10 V. This 0–10 V analog feedback signal is then fed to an analog-to-digital converter AD570 to get an eight-bit digital signal. This signal will continue through the bidirectional bus driver SN74373-B and be loaded into the microprocessor.

2. Force Feedback

For sending the digital force feedback signal from force sensors to the microcomputer, a third bidirectional bus driver (SN74373-C) is used; the appropriate control circuitry is shown in Figure 7.

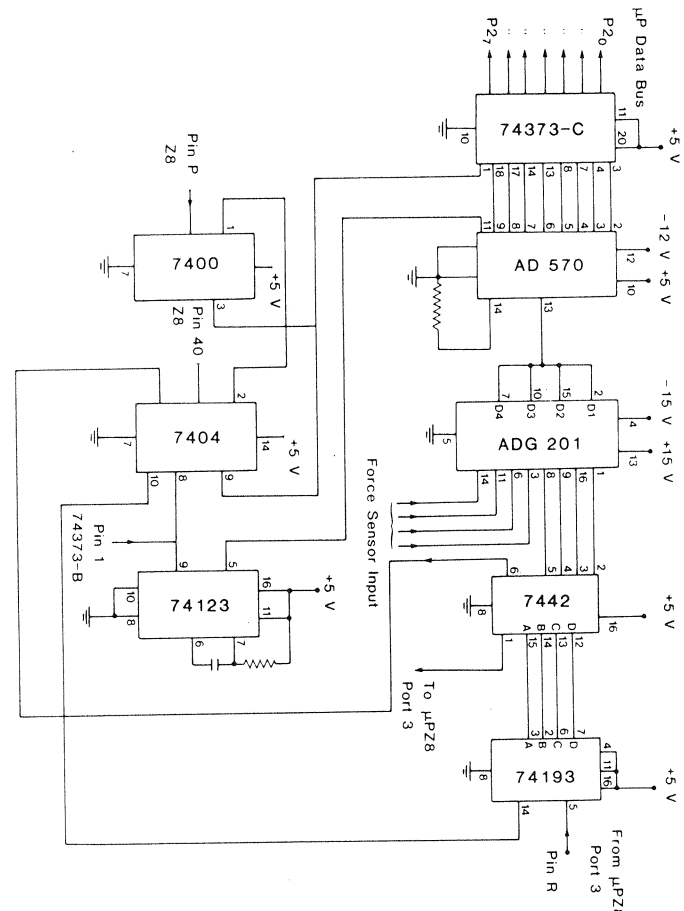

Figure 7. Servo-control system with force feedback.

Many different force-sensor signals can be used by providing an ADG201 analog switch, which acts by break-before-make. A monolithic decimal 4-to-10–line decoder (SN7442) is served as switch controller for manipulating the different force-sensor signals in appropriate order during the process.

To begin the switching control process, the output number of the SN7442 must be initialized; i.e, pin 1 of the SN7442 must be read by the microprocessor as "low." The initialization can be done by giving a pulse from the microprocessor to the synchronous up/down counter (SN74193) and incrementing it until the pin-1 output of SN7442 is read as "low." Through programming, we can select any of the sensor signals for processing by pulsing the counter (SN74193) the number of times corresponding to the coded number of the desired force-sensor signal. The ADG201 permits the input voltage from 0 to 10 volts. Each time, the ADG201 will allow one analog force signal to feed into A/D converter AD570. As soon as the bidirectional bus driver SN74373-C is enabled, the eight-bit digital signal is loaded into the microprocessor for further processing.

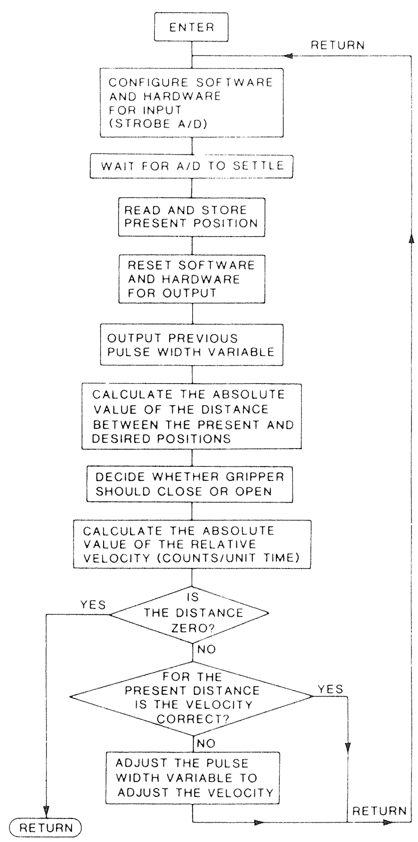

Figure 8. Flow chart of the algorithm for position feedback.

3. *Servo-Control Software*

The software for the servo control is written on a Zilog Z8 microprocessor. The Z8 is a flexible single-chip microcomputer that under software control can take many different memory and (input/output) I/O configurations. It has 32 pins dedicated to input and output. These lines are grouped into four parts of eight lines each and configurable as input, output, or bidirectional.[9]

The force signal retrieval and feedback control through the software program are similar to position feedback. A flow chart of the algorithm for position feedback is shown in Figure 8.

E. Quick-Change Fingers with Tactile Force Sensors

Industrial robots are expected to handle more parts of very heavy and very light weights, ranging in weight from below 0.1 lb to over 100 lbs. However, a single gripper cannot effectively handle both very heavy and very light pieces.

A changeable set of gripper fingers with a variety of sensors, which can cope with certain subranges of the workpiece spectrum, provides considerable cost savings through elimination of the need for frequent changing of custom-designed grippers during the work process.

The mechanical structure of the quick-change device and its operation principle are described in Section III. Upon having the automatic quick-change fingertip device, we can employ many fingertips with different kinds of sensors to perform assembly tasks or other industrial robot applications. An automatic quick connect and disconnect mechanism between the fingertips and the gripper linkage block has been designed and successfully tested.

IV. CONCLUSION AND FUTURE RESEARCH

We have described both the abstract specification and the physical implementation of a servo-controlled gripper. The gripper has several sensors and demands an efficient and fast regime. We believe that the successful development of useful and modular robotics devices requires that a great deal of care be taken in developing both the specification and the implementation.

Currently we have continued the research with the addition of a robot eye-in-hand vision systems; there are several research issues to be emphasized, such as sensor error detection, verification, classification, and the automated recovery.

This work was supported in part by NSF Grants No. MCS-8221750, No. DCR-8506393, and No. DMC-8502115.

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