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A HIERARCHICALLY CONTROLLED, SENSORY INTERACTIVE ROBOT IN THE AUTOMATED MANUFACTURING RESEARCH FACILITY

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A HIERARCHICALLY CONTROLLED, SENSORY INTERACTIVE ROBOT IN THE AUTOMATED MANUFACTURING RESEARCH FACILITY

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ABSTRACT

The National Bureau of Standards, Center for Manufacturing Engineering is implementing an experimental factory called the Automated Manufacturing Research Facility (AMRF). The AMRF will operate as a small batch machine shop and is currently configured with three machining workstations, a cleaning and deburring workstation and an inspection workstation. Each of these workstations will employ robotic material handling including machine loading and unloading. At present each workstation is at a different stage of completion. The "Horizontal Workstation" which contains a horizontal-spindle N.C. machine tool and one material handling robot has been completely integrated. The material handling robot is a Cincinnati Milacron T3 (hydraulic) which has been enhanced to meet the requirements of the AMRF. This robot has been equipped with a hierarchical robot control system, a 3-D vision system, a watchdog safety system and an instrumented, servo controlled gripper, all of which were developed at the National Bureau of Standards. Each of these systems is described individually together with a description of the enhanced capabilities of the robot with these systems operating as an integrated package.

1. INTRODUCTION

A hierarchical control system such as the one shown in figure 1 is partitioned vertically into levels of control. The basic command and control structure is a tree, configured such that each computational module has a single superior, and one or more subordinate modules. The top module is where the highest level decisions are made and the longest planning horizon exists. Goals and plans generated at this highest level are transmitted as commands to the next lower level where they are decomposed into sequences of subgoals. These subgoals are in turn transmitted to the next lower control decision level as sequences of less complex but more frequent commands. In general, the decisions and corresponding decompositions at each level take into account: (a) commands from the level above, (b) processed sensory feedback information appropriate to that control decision level, and (c) status reports from decision control modules at the next lower control level.

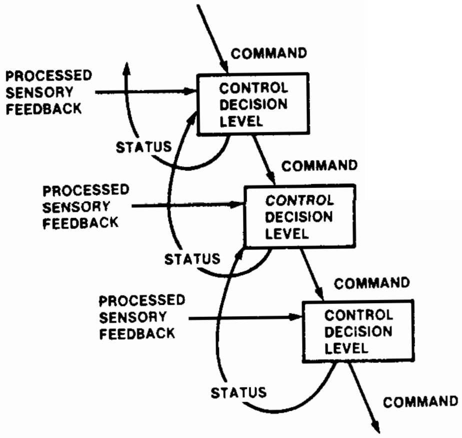

Figure 1.

The hierarchical control structure serves as an overall guideline for the architecture and partitioning of a sensory interactive robot control system. The Industrial Systems Division at the National Bureau of Standards has been working on the design and implementation of this control structure for several years and continues to perform research in this area. It is intended that one of the primary products of this research be a standardizable set of data interfaces and protocols between the various modules of the system so that robots, controllers and sensory systems from different vendors can be plugged together much like stereo components are today. This would allow systems to be configured for specific applications at lower cost and with much greater flexibility. An extension of these concepts, also being implemented as part of the Automated Manufacturing Research Facility, is to define standard interfaces for robot systems, machine tools etc. to be easily integrated into work cells which in turn are integrated to higher levels of factory control using the same hierarchical structure.

This paper describes the initial implementation of a highly integrated robot control system using these techniques. It will concentrate on the structure, interfaces and the resultant capabilities of the system rather than the implementation details internal to the sensory and control modules. Detailed information on each subsystem is available in the references.

2. OVERVIEW

Figure 2 is a schematic block diagram of the integrated control structure as it is currently configured on the Cincinnati Milacron T3 Robot in the Automated Manufacturing Research Facility (AMRF). The system is configured in the hierarchical manner described above and includes five major subsystems: (1) the NBS Real-Time Control System (RCS) (2) the commercial T3 Robot equipment (3) the End-Effector System (4) the NBS Vision System and (5) the NBS Watchdog Safety System. With the exception of the T3 Robot each of these subsystems has been developed in the Industrial Systems Division.

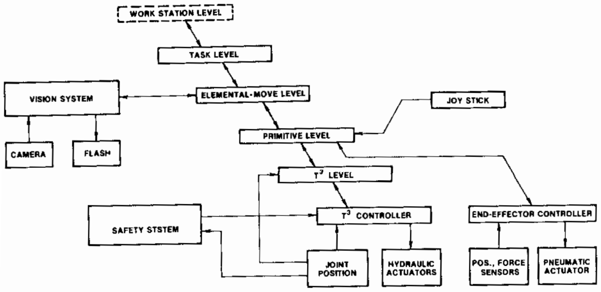

Figure 2.

The Real-Time Control System as shown in figure 2 is composed of four levels: (1) the Task Level (2) the Elemental-Move Level (3) the Primitive Level and (4) the T3 Level. The Task, Elemental-Move and Primitive levels of the controller are considered to be generic control levels. That is, these levels would remain essentially the same regardless of the particular robot (commercial or otherwise) being used. The T3 Level, however, uses information and parameters particular to the T3 Robot and is, therefore, unique to the T3 Robot. The Joystick shown provides an alternate source of commands to the Primitive Level for manual control of the robot and is not used in conjunction with the higher control levels.

The T3 Controller shown in figure 2 is part of the T3 Robot equipment as purchased from Cincinnati Milacron. This controller is subordinate to the T3 Level of the RCS and communicates through a special interface which is discussed in Section 4.1.

The End-Effector System consists of a two fingered gripper equipped with position and force sensing. The gripper is pneumatically actuated and servo controlled by a controller which is subordinate to the Primitive Level of the RCS.

There are three sensory systems on the robot: (1) the finger force and position sensors on the gripper which report data to the End-Effector Controller, (2) the Joint Angle Acquisition System which reports data to the T3 Controller, the T3 Level of the RCS and to the Watchdog Safety System and (3) the Vision System which reports data to the Elemental-Move Level of the RCS. Of the sensor systems, the vision system is obviously the most complex. It performs sophisticated image processing which requires substantial computational time.

The Watchdog Safety System is the only system in figure 2 which does not fit directly into the hierarchical control structure previously described. It is an independent system which monitors robot motions and compares them to previously defined limits in position, velocity and acceleration. The Watchdog System has the power to stop the robot if any limits are exceeded and consequently monitors both the mechanical and control systems of the robot.

3. REAL-TIME CONTROL SYSTEM (RCS)

3.1 Task Level

The Task Level interfaces with the Workstation Level above it and the Elemental-Move Level below it. In the current configuration, the Task Level has no direct interfaces with sensory systems.

The Task Level receives commands from the Workstation Level in terms of objects to be handled and named places in the workstation. For example, the task might be to find a certain part blank on the tray at the load/unload station, pick it up and put it in the fixture on the machine tool. This task could be issued as one command from the Workstation Level to the Task Level of the RCS. The specific commands currently implemented from the Workstation Level to the Task Level are:

Note: Arguments in parentheses are not mandatory.

ACQUIRE OBJ (at A)

From its current position, the robot will go to location A, (SOURCE), and grasp the named object, (OBJ). If no location is specified, then the object will be acquired at the robot's current location.

MOVE (OBJ from A) to B

The robot will acquire the named object, (OBJ) from location A (SOURCE), and will move it to B, (DEST), but will not release the object. If (OBJ from A) is not specified, the robot will move from its current location to location B.

RELEASE (end-at A)

The robot will release the object it is holding and then move to location A. If (end at A) is not specified the robot will move to a predetermined "safe" position associated with its current location.

TRANSFER (OBJ from A) to B (end-at C)

The robot will acquire the named object from location A, (SOURCE), move to location B (DEST), release the object and move to location C. If (OBJ from A) is not specified and if the robot is already holding an object (if not an error is reported to the Workstation) then the robot will move from its current position to location B for the release. If (end-at C) is not specified the robot will move to a predetermined "safe" location associated with location B after the release.

CLEAR drop-at A (end-at B)

The robot will move to location A and release the part it is currently holding (if the robot is not holding a part an error is reported to the Workstation). The robot then moves to location B. If (end-at B) is not specified, the robot will move to a predetermined "safe" location associated with location A.

The Task Level decomposes these commands into the required robot and end-effector actions and generates the appropriate commands to the next lower control decision level called the Elemental-Move (E-Move) Level. The commands generated are in terms of elementary robot motions and gripper actions rather than the objects and locations received from the workstation level.

3.2 Elemental-Move Level

The E-Move Level interfaces with the Task Level above it and the Primitive Level below it. In addition, the E-Move Level interfaces with the Vision System from which it acquires part position and orientation data. This interface is discussed in detail in Section 5.

The E-Move Level receives commands from the Task Level which are elemental segments of the Task Level command under execution. These are generally single moves from one named location to another. If a part acquisition is involved, data from the Vision System is requested to determine the exact location of the next goal point. The E-Move Level then develops a trajectory between the new goal point and its current position. A trajectory may be simply a straight line move to the goal point or a more complex move, involving departure, intermediate and approach trajectories. These trajectories can be constructed using prestored trajectory segments or data acquired from the Vision System. If no prestored segments are found for the desired move and the use of vision data is not appropriate, then a straight line path to the new goal point is calculated. The specific commands currently implemented from the Task Level to the E-Move Level are:

MOVE-TO A

The robot will move from its current location to the named destination location A.

MOVE-TO-OBJ OBJ, A

This command is exactly the same as MOVE-TO except that the gripper approach opening for the named object is retrieved from the database and before moving, the gripper fingers are positioned to a predetermined opening.

PICK-UP OBJ

The gripper parameters for the specified object are retrieved from the database and the object is grasped (see GRASP OBJ under Primitive Level).

LOCATE OBJ

This command is issued by the Task Level after the robot has been moved to where the wrist mounted Vision System camera has the named object in view. The Vision System is then interrogated to determine the exact position of the object in question (detailed scenario described in Vision section). The robot is then moved to the required position to PICK-UP the object.

RELEASE OBJ

The release opening for the specified object is retrieved from the database. The gripper is opened to this position.

The E-Move Level decomposes these commands into the required trajectories and breaks these trajectories into a series of points in space through which the tool point (tool point is defined as a point centrally located between the gripper fingers) must pass en route to the desired new location. These points in space are used as arguments in the commands issued to the Primitive Level. End-effector commands are interleaved with the motion commands to the Primitive Level.

3.3 Primitive Level

The Primitive Level interfaces with the E-Move Level above it and the T3 Level and End-Effector Controller below it. As stated earlier, the Primitive Level is the lowest level in the RCS which is robot or device independent. Subsystems subordinate to the Primitive Level are considered to be at the device level in the control hierarchy. In this system, these subsystems or devices are the robot and the end-effector. The T3 Level (Section 3.4) shown in figure 2 is not a true control decision level by itself and could be logically combined with the T3 Controller at the device level. The robot and end-effector are, therefore, at the same control decision level subordinate to the Primitive Level.

Additionally, the Primitive Level interfaces with the Joystick. The Joystick is a peripheral device which is used for manual operation of the robot. Using the Joystick, the operator can control robot motion in several coordinate systems (world, tool or individual joint motions). Under Joystick control the human operator assumes the higher level planning and control duties normally handled by the E-Move and Task Levels when the robot is operating automatically.

The actual Joystick unit has groups of small joysticks, rotory and rocker switches dedicated to each coordinate system. These are configured such that the robot will move basically the way the lever is pushed or the switch turned, giving the operator a relatively intuitive feel for the motion produced.

The Primitive Level receives commands from the E-Move Level in terms of goal points in cartesian space. These points differ from those received by the E-Move Level from the Task Level in that they are not named locations and therefore assume no knowledge of the Workstation layout. These points are typically more closely spaced than those at the higher levels although this is not necessarily the case. The specific commands currently implemented from the E-Move Level to the Primitive Level are:

GOTO POINT

The robot will move the tool point (see section 3.4) in a straight line to the designated goal point and stop using a known acceleration and deceleration profile.

GOTHRU POINT

The robot will move the tool point in a straight line toward the designated goal point. When it gets to a specified "breakpoint" distance from the goal point it does not decelerate but reports a DONE status for the current command to the E-Move Level. The E-Move level then sends down the next goal point while the robot continues to move.

The Primitive Level computes a straight line trajectory to the desired goal point and issues closely spaced interim goal points to the T3 Level. These goal points are currently issued every 40 msec. and are valued according to the desired velocity and acceleration of the robot. In the current configuration of the system there is no sensory data interfaced to the Primitive Level for real-time path modifications, as with the Vision/E-Move interface, but the RCS is designed to accommodate sensory interaction at all levels.

As mentioned above, there are end-effector commands interleaved with the robot motion commands from the E-Move to the Primitive Level. These commands reference specific part types and control gripper pre-grasp finger positioning, grasp finger position and force, and post-release finger positioning. The system database includes an end-effector parameter table for each part type or object known to the system. These tables specify the desired approach opening, grasp opening, grasp force and departure opening for each part. The specific commands currently implemented from the E-Move to the Primitive Level are:

APPROACH-POSITION-FINGERS OBJ

The gripper fingers are positioned to the desired approach opening for the specified object.

DEPARTURE-POSITION-FINGERS OBJ

The gripper fingers are positioned to the desired departure opening for the specified object.

GRASP OBJ

The prespecified gripping force for the named object is retrieved from the database along with the size of the object. Then the gripper is closed until the specified force is achieved. The gripper finger opening is then compared (using status information returned from the End-Effector Controller) to the expected size of the object and an error is reported to the E-Move Level if the opening is not within tolerance.

The Primitive Level reformats these commands into specific gripper commands which include the necessary force and finger position data as retrieved from the data base.

3.4 T3 Level

The T3 Level interfaces with the Primitive Level above it and the commercial Cincinnati Milacron T3 Robot Controller below it. In addition, there is a sensory interface which supplies the six individual joint angles.

The T3 Level is so named because elements of it are peculiar to the T3 Robot. From a control hierarchy point of view the T3 Level does not constitute a logical control decision level but is, in fact, a "gray box" necessary to transform command and feedback formats between the Primitive Level and the T3 Controller.

The T3 Level receives a new goal point from the Primitive Level every 40 msec. These goal points are sent as the command:

STRAIGHT-LINE POINT

This commands the robot to go to the specified point while describing a straight line with the tool point. Since the T3 is a six degree of freedom machine the desired goal point must actually be specified as a unique robot pose including both tool point position and end-effector orientation. The Primitive Level issues goal points to the T3 Level in the RCS cartesian format. This format is defined as the x,y,z components, in the world reference frame, of the following three points (see figure 3); (1) the center point of the robot wrist plate, called the wrist point (2) the tool point, and (3) the tip of a unit vector orthogonal to the wrist/tool point vector called the finger point. These three points define a plane which, in turn, uniquely specifies the robot pose.

Using the T3 mechanical specifications (link lengths, velocity and acceleration limits) the T3 Level transforms these three world reference frame points into the x,y,z, roll ,pitch and yaw required by the T3 Controller to achieve the desired pose. This is called the T3 format and consists of the x,y,z position of the wrist point and 3 Euler angles; epsilon, delta, and rho (about the z,y,x axes respectively).

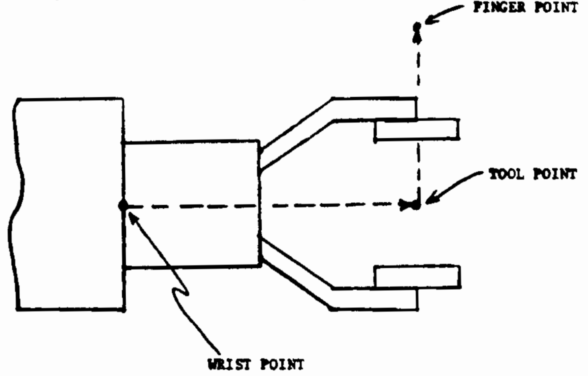

Figure 3.

The other primary function of the T3 Level is to perform the transform from joint angles to RCS cartesian format. This is called the forward transform and the results are returned to the Primitive Level every 40 msec.

4. T3 ROBOT

The T3 Robot is a six-axis servo-controlled articulated arm type manipulator powered by hydraulic actuators. It is manufactured by the Cincinnati Milacron Company located in Cincinnati, Ohio. All of the actuators, except the one on the elbow joint, are rotational actuators. The actuator on the elbow is a linear piston type actuator. All of the joints, including the elbow are rotational and give the T3 six degrees of freedom. The actuators support and move the mass of the T3 and provide a rated lifting capacity of 100 pounds.

4.1 T3 Controller

The T3 Controller interfaces with the RCS T3 Level above it and the hydralic actuators and joint angle resolvers below it. It also interfaces with the Watchdog Safety System which can command it to do a Hold/Set (pause) or an Emergency Stop.

The T3 Controller is normally a stand-alone system which is teach programmable. That is, a sequence of points can be "taught" to the Controller which then has the capability to move through these points using internal programs. When the T3 is under the control of the RCS, these higher level control capabilities are not functional. Instead, only the low level joint servo control portion of the T3 Controller is used.

The T3 Level of the RCS communicates with the T3 Controller via a special external host computer interface on the T3. This interface, called Dynamic External Path Control (DEPC), is a function which puts the T3 Controller into a mode whereby an external computer (i.e., the RCS) can dynamically control the path of the robot. Using an RS232 serial communications link, the RCS transmits x, y, z, delta, epsilon, rho to the T3 Controller at approximately a 50 Hz rate. By properly spacing the coordinates, the RCS controls the position, velocity and acceleration of the robot. The T3 Controller transforms these coordinates into the required joint angles and performs the lowest level joint position servoing. Unfortunately, the DEPC interface does not provide robot position feedback to the host computer except at time of initialization. Therefore, in order to properly close the control loop with the RCS, a joint angle system separate from the one used by the T3 Controller was added to the robot.

4.2 Joint Angle Acquisition System

Each joint on the T3 has a Position Analog Unit (PAU). Each PAU contains a resolver and tachometer which provide joint position and velocity feedback to the T3 Controller. As part of the Joint Angle Acquisition System built at NBS, an additional resolver was added to each PAU to provide an independent source of joint position data to the RCS and the Watchdog Safety Computer. Each resolver is gear coupled to the rotational mechanism of the joint and returns an analog signal proportional to the resolver shaft angle. This analog signal is converted to digital form by R/D (resolver-to-digital) converters. The gearing in the PAU's is such that the resolvers go through multiple revolutions while the joint travels through its range of motion. Therefore, the resolver revolutions are counted. The Joint Angle Acquisition System electronics provides for R/D conversion and shaft rotation counting. The output is a 17 bit number for each joint angle. All six joint angles are measured and the data latched simultaneuosly to provide a coherent measure of robot position. A block diagram of the Joint Angle Acquisition System is shown in figure 4.

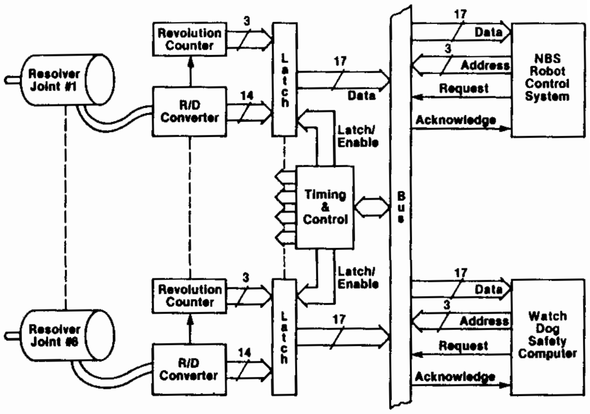

Figure 4.

5. NBS VISION SYSTEM

The NBS Vision System, as currently configured on the T3 Robot, performs two major functions. These are; object location and object identification. The capabilities of the Vision System are used to allow the robot to pick up objects placed in unknown positions and orientations. Also, prior to pick up the robot controller can verify object identity.

There are six degrees of freedom that define the position and orientation of any object relative to the robot gripper. All six must be determined for the robot to grasp the object in a precisely specified manner. To obtain this information, the NBS Vision System uses two frames of video data. The first frame is illuminated by two parallel planes or lines of light and the second frame is illuminated by a flood source of light. In this system both the light projectors and the camera are mounted on the end of arm in the configuration shown in figure 5. Both light projectors employ flash tubes. The dual line flash generator uses a single tube with mirror optics and two slits as shown. The flood flash uses a ring shaped flash tube mounted around the base of the camera lens.

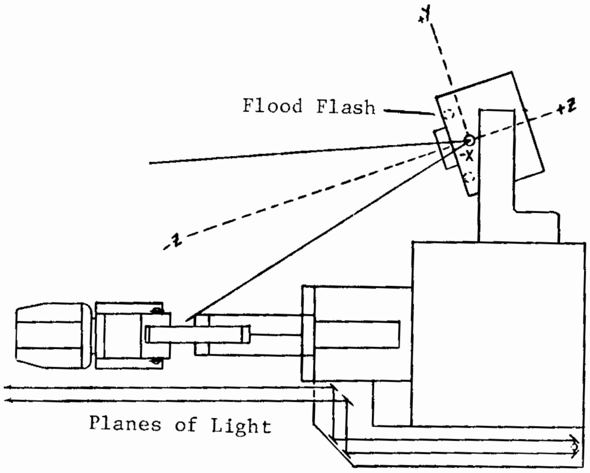

Figure 5.

From the image produced when the dual line flash is fired, it is possible to compute the range and the pitch and yaw orientations of any simple geometrical shaped surface. From the flood image the vertical and horizontal positions of the surface can be computed and with additional computation (using two points on the surface) the roll orientation of the surface can be calculated. Thus, all six degrees of freedom are determined.

The image data is further processed for specific part identification. It is processed into a form required for comparison with the catalog of part data already resident in the robot data base. Part identification is then accomplished by seeking a match between incoming image data and stored part description data.

The Vision System interfaces to the Elemental-Move Level of the RCS and is currently used to locate, identify and acquire disoriented parts whose approximate location is known. This is a three step process which consists of three interrogations of the Vision System by the RCS. These interrogations define the formal interface between the Vision System and the RCS and take the form of commands between control levels. They are; FAST FLOOD, LINE FLASH and FINAL FLOOD. The following is the scenario for the acquisition of an object:

Step 1

Assume that the Workstation has given the robot a command such as MOVE (OBJ from A to B). Further assume that location A is not specified as a robot pose but is, instead, only the approximate location of the object to be moved. The RCS will recognize this as a situation calling for use of the Vision System. The robot will move to a pose from which it can "view" the object. That is, the object should be within the field of view of the camera from this vantage point. The E-Move Level will then issue the following request to the Vision System:

Note: Arguments in parenthesis are passed from the RCS to the Vision System as part of the request.

FAST FLOOD (expected distance to object)

The Vision System fires the flood flash and returns the following four pieces of data:

(1) The x position of the centroid of the object in camera coordinates.
(2) The y position of the centroid of the object in camera coordinates.
(3) The cosine of the x component of the angle between the z axis and the line to the centroid of the object.
(4) The cosine of the y component of the angle between the z axis and the line to the centroid of the object.

Step 2

Using the location of the object from Step 1 and its knowledge of the camera and line flash geometry the RCS moves the robot to a pose such that when the line flash is fired the lines of light will fall on the object. The E-Move Level then issues the following request to the Vision System:

LINE FLASH (obj-id, expected range, expected surface normal vector)

The Vision System fires the line flash and returns the following two pieces of data:
(1) Measured range
(2) Measured surface normal vector

Several of the test parts manufactured in the Automated Manufacturing Research Facility have identical footprints and can only be distinguished by their thickness. Therefore, the measured range provides verification that the correct part is being observed. Ranges can be resolved to approximately 1 mm and surface orientation to approximately 2%.

Step 3

Using the data from Step 2 the RCS moves the robot camera into position for a final flood picture. This pose will have a precisely known range and be normal to the object. The E-Move Level then issues the following request to the Vision System:

FINAL FLOOD (obj-id, expected range)

The Vision System fires the flood flash and returns the following three pieces of data:

(1) Confidence measure for expected object observed best fit.
(2) Observed z axis range based on area x and y position of centroid.
(3) Roll angle of longest straight side to x axis.

After the successful completion of Step 3 the Vision System has verified the identity of the object and has supplied sufficient position and orientation data to the RCS so that it can pick up the object.

6. END-EFFECTOR SYSTEM

The End-Effector System consists of two major components; a two fingered, pneumatically actuated gripper and a controller implemented on a dedicated single board computer. The gripper (figure 6.) is instrumented with finger position and gripping force sensors and is servo controlled using sensory feedback. The controller is implemented in two levels. The lower level provides servo control of the gripper jaws; the upper level interprets commands from and provides status to the Primitive Level of the RCS. Both the gripper hardware and the controller software were designed and implemented at NBS.

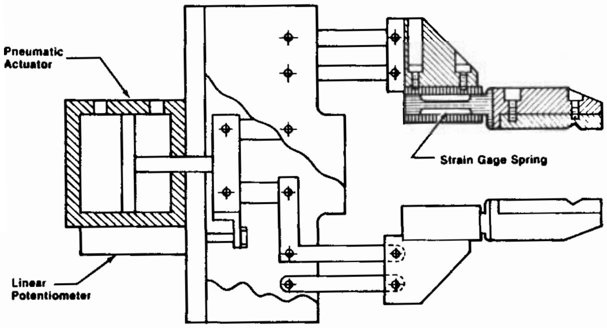

Figure 6.

6.1 Gripper

The gripper employs a four bar linkage to produce a parallel jaw action. The throw range is 15.24 cm (6 in) fully open and the jaws can be completely closed. The nominal gripping force is 500.4 N (112.5 lbs) using a 689.5 kPa (100 psi) air supply. The actuator is a dual ported pneumatic piston type and the linkage is designed to produce a 3:1 ratio of jaw opening to piston displacement. The gripper is equipped with a linear potentiometer that measures piston displacement which is linearly related to jaw opening. Each finger is instrumented with a full bridge strain gage circuit to measure normal contact forces (gripping force or forces applied to an individual finger).

6.2 Servo Control

The pneumatic cylinder is driven by four fast-acting, two-way, open/close valves. The valves are configured such that either side of the cylinder can be pressurized, blocked or vented to the atmosphere. The configuration is schmatically illustrated in figure 7. Each of the control modes consists of an action and two modifiers. The actions are OPEN, CLOSE, LOCK, FREE and CLAMP. The modifiers are SPEED and DAMPING. The functions of OPEN and CLOSE are obvious. LOCK closes all valves which inhibits piston motion. FREE opens the vent valves and closes the supply valves which permits free motion of the piston. CLAMP opens the supply valves and closes the vent valves which clamps the position of the piston.

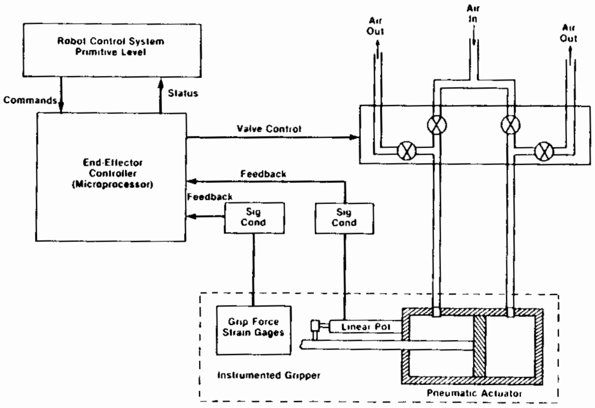

Figure 7.

The servo control algorithm, implemented on the dedicated microprocessor, chooses among the possible valve actuation patterns each control cycle to control the action, speed and damping. The processor samples the sensors, executes the control algorithm and drives the valves at fixed intervals.

6.3 Command Interpretation

The upper level of the controller interprets commands from Primitive Level of the RCS and decomposes them into the required actions and sequences discussed earlier. These serve as the input to the servo level of the gripper controller. The following commands are currently implemented from the Primitive Level to the End-Effector System:

Note: Arguments in parentheses are not mandatory.

POSITION position, (force), (velocity)

Gripper fingers are servoed to the specified position. If a force is specified and if either finger detects a normal force greater than that force the operation is suspended. Finger velocity is observed if specified otherwise max velocity is assumed.

LEFT FORCE force, (position), (velocity)

RIGHT FORCE force, (position), (velocity)

Left or right finger is servoed to the specified opposing force. If a position is specified and the finger reaches the position before the specified force is achieved the operation is suspended.

RELEASE (force), (position), (velocity)

This command is a subset of POSITION with the default position at full open.

MEASURE (force), (position), (velocity)

This command is also a subset of POSITION but usually executed from a full open position. The default values are maximum gripping force, fully closed and maximum finger velocity.

GRASP (force), (position), (velocity)

This command closes the gripper to maximum gripping force on whatever object unless optional arguments are specified.

LOCK

Gripper fingers locked in current position.

FREE

Gripper fingers permitted free motion.

7. WATCHDOG SAFETY SYSTEM

Due to the experimental nature of the robotics activities at the NBS, it became evident that a special emphasis needed to be placed on safety. The Watchdog Safety System has been developed in response to this need. The purpose of the system is to prevent the robot from damaging itself or any of the equipment on or around it in the event of a hardware malfunction, software bug or operator error.

7.1 Watchdog Safety Computer

The primary component of the safety system is the Watchdog Safety Computer (WDSC). The WDSC is a stand-alone microcomputer system that monitors robot operations. Its function is to detect operations which are outside the range of normal conditions and to stop the robot before a collision or other damage can occur.

On the T3, the WDSC monitors the individual joint and tool point motions of the robot and various status signals from the hydralic pump unit and the T3 Controller. The WDSC measures the amount of rotation from a known home position, the rotational velocity and the rotational acceleration of each of the six robot joints using joint angle information received from the Joint Angle Acquisition System described earlier in the paper. It compares these measurements with a set of maximum values, which are operator selectable, and if in any instance a maximun is exceeded, it halts the robot. The WDSC executes the foward transform (joint angle-to-tool point position) and performs a similar set of comparisons for the tool point velocity and acceleration. The hydralic pump unit and T3 Controller status checks are simple go/no-go tests. Figure 8 is a functional block diagram of the Watchdog Safety System as currently configured on the T3 Robot.

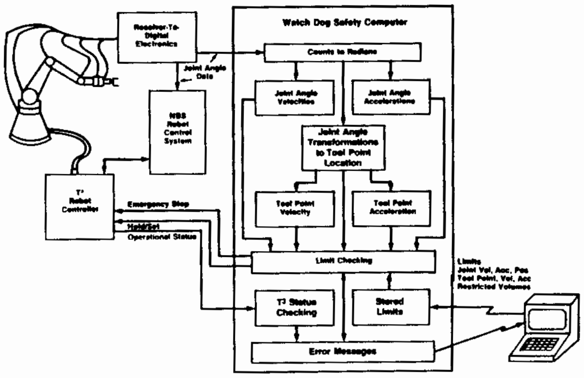

Figure 8.

Also incorporated in the WDSC is a forbidden volume check. These volumes are regions in the robot work space (e.g.,the location of a machine tool, an operator's workstation,or the floor, into which the tool point of the robot must not intrude. Forbidden volumes are defined by the combination of imaginary planes which have been programmed into the WDSC. These planes are programmed into the WDSC by moving the tool point of the robot (using the Joystick) to three points in space which define the plane. The forbidden side of the plane is also defined by a forth point. At each of these points, the WDSC computes the tool point location in world coordinates and from these, the location and orientation of the plane in space. For each plane a safety margin is assigned which accounts for the distance required to stop the robot. If the tool point of the robot attempts to enter one of these forbidden volumes, the WDSC halts the robot motion.

7.2 T3 Interface

There are two mechanisms available on the T3 to perform a halt. The first is called HOLD-SET and is essentially a software halt of the robot by the T3 Controller upon external command. This type of halt leaves the robot under servo control and operations can be easily resumed when the problem is cleared. The second type of halt is called

EMERGENCY STOP. This is a much more drastic action because the hydraulics are shut down and the arm can settle to the floor. This can result in damage to the end-effector and equipment on the floor. Also recovery from an EMERGENCY STOP requires that thwe robot be returned to its home position.

When the WDSC detects an error it first issues a HOLD-SET command to the T3. It then continues to monitor the motion of the robot and if the robot fails to stop within a predetermined time, the WDSC issues an EMERGENCY STOP.

8. CURRENT APPLICATION

The robot described in this paper is part of the Horizontal Workstation in the Automated Manufacturing Research Facility at the National Bureau of Standards. The Horizontal Workstation is so named because it contains a numerically controlled horizontal spindle machine tool used for small batch parts production. The material handling functions in the Workstation are performed by the enhanced T3 Robot described in this paper. The following describes the basic functions of the robot in the Workstation.

8.1 Unload Tray

Part blanks are delivered to the Workstation in a tray on a robot cart. The tray is transferred to an unload station within the workspace of the robot. The Workstation Controller has been informed from a higher control level what part blanks are on the tray and their approximate locations. The Workstation Controller commands the robot to TRANSFER each part blank on the tray to a parts buffering table in the Workstation. The RCS is only given an area in the tray where the part is supposed to be located. This is the "object location" argument in the TRANSFER command. The RCS employs the Vision System in the manner described in Section 5 to find the part and acquire it. The part is then placed on the buffer table (the RCS maintains the locations and parts inventory on the buffer table). The RCS then reports DONE to the Workstation Controller. The Workstation Controller continues to issue TRANSFER commands to the RCS until all the required part blanks on the incoming tray have been removed or until the robot is commanded to do something of higher priority. A higher priority task might be to remove a finished part from the machine tool fixture.

8.2 Load/Unload Machine Tool

The other function of the robot is to load and unload the machine tool. The Workstation Controller can request that a certain type part blank be taken from the buffer table and placed in a particular fixture on the machine tool or that a finished part be taken from a fixture on the machine tool and placed in an outgoing parts tray. The robot also does refixturing of parts that require multiple cuts on the machine tool. All of these robot actions are accomplished via the Task Level commands described in Section 3.1.

9. CONCLUSIONS

The enhanced robot presented here represents the first integration of the Control, Vision, End-Effector, and Safety Systems developed at the National Bureau of Standards onto one robot. Each of these systems is still undergoing research and development and many improvements will hopefully be forthcoming. Ultimately, we hope that the subsystem interfaces developed through this work will become the basis for standards leading to "plug compatible " industrial automation systems.

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NOTE

Commercial equipment is identified in this paper in order to adequately describe the systems that were developed. In no case does such identification imply recommendation by the National Bureau of Standards, nor does it imply that this equipment was necessarily the best available for the purpose.

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