Problems and Research Issues Associated With the Hybrid Control of Force and Displacement*

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1 Introduction

Robots working in a perfectly structured world do not need sensing: a structured world in which the dimensions of all parts are within tolerance and in which careful planning has taken place to ensure that such parts can be assembled, a world in which everything is precisely located and everything functions as planned, a world in which all necessary jigs[1] have been designed and provided. Such a world is the production engineer's dream and will probably never exist. Even in today's most automated and structured factories there are still operators present to "un-jam" the perfect machines when the structure gets a little out of line. These machines, which we call robots, are of course only *programmable universal transfer devices*, machines which can be programmed to move tirelessly from position to position as perfectly as the parts and machines they work with. Real robots don't belong in factories any more than people do; what is needed in factories is well designed automation tended by operators.

Of course there is a limit to the number of well designed pieces of automation we can have. In the home, for instance, a sewing machine and a food-processor do their jobs much better than humans[1], but the modern kitchen is slowly beginning to fill up with such special purpose devices, which the displaced humans now spend their "leisure" time fixing. Humans are needed to provide the structure required by these devices. The dish-washer functions well in its own environment[1], but who puts the dishes in and takes them out? Further, the automation of many tasks such as dishwashing requires the substitution of massive quantities of energy and natural resources (The Regular Cycle uses 20 gallons of water which must be heated to at least 180°) in place of intelligence ("That plate's o.k.,"he didn't use it, just brush off the crumbs,").

When any lack of structure occurs, however, we must rely on sensors. If something is misplaced, or if something will not fit, relying on a sensor-less, geometry controlled approach would be a disaster. Sensors have two roles, to monitor task execution and to establish the state of the world. Both these tasks require the use of a world model. Both tasks also require reasoning and planning. Establishing the state of the world requires a sensor strategy and the interpretation of sensor data in terms of the world model. Monitoring task execution also requires sensor strategies and interpretation of sensor readings in terms of the world model. Errors, when they occur, are detected by the interpretation of sensor data, once again in terms of the world model. If this is to be done reliably a number of independent sensors is needed (sensors fail also). Once an error state is determined, appropriate recovery action must be planned. If a part is dropped on the floor, then it may be left, but if it is dropped inside a mechanism where it could prevent functioning, then it must either be retrieved or the mechanism replaced. Error recovery is not simple.

Of all the sensors that a robot might have, *force sensing is the most fundamental. Blind people function quite well in the world but people who have no kinesthetic feedback are totally helpless.* Consider the well structured world of manufacturing with a task fully under position control: the detection of any unexpected force is a clear indication that something has gone wrong. *Force sensing can provide this vital information.* In any situation where complete structure is absent, force sensing becomes primary in the sequencing of a task. Consider teleoperation where tasks have some structure[2].

The general-purpose manipulator may be used for moving objects, moving levers and knobs, assembling parts, and manipulating wrenches. In all these operations the manipulator must come into physical contact with the object before the desired force and movement can be made on it. A collision occurs when the manipulator makes this contact. General-purpose manipulation consists essentially of a series of collisions with unwanted forces, the application of wanted forces, and the application of desired motions. The collision forces should be low, and any other unwanted forces should also be small.

Goertz identifies three clear states:

1. Motion in free space.

3. The exertion of a force.

This work of Goertz influenced the use of force sequencing in the manipulator control system WAVE[3] and later that of Inoue[4]. Two types of commands were included in a language WAVE describing a sequence of manipulator motions.

STOP terminate the current motion when a force equal to the argument is detected, also known as a "guarded move"[5].

FORCE during the next motion, the force in a given direction, is to be controlled to the value given as an argument. If the force is specified to be zero then the manipulator is "free" to move in the direction specified.

A further command allowed for a force to be applied by the manipulator, of course, the manipulator would have to be free in the direction In the "Force Vector Assembler Concept [6]" commanded manipulator Cartesian velocities could be modified by measured end-effector forces and moments

$$v = v_0 - [M] f \qquad (1)$$

Off-diagonal elements of the matrix M allowed for motion to be specified in directions orthogonal to an applied force. A curious side effect of this produced a switching phenomenon similar to that described above—a continuous control system with two states. *The end effector would trace along an edge until a corner was reached and then proceed to trace along the next edge.* Unfortunately it was not possible to continue in this fashion along the following edge. A similar "switching" phenomenon occurs in a special device for making chamfer-less insertions. *The pin is brought into the hole at an angle, on contact a linkage rotates the pin to align it with the hole axis whereupon insertion occurs.* These phenomena are, however, limited to only two states and do not generalize further. Recently this type of control has formed the basis of more complex insertion strategies [7] in the form of a "generalized damper" in which the force expected is proportional to the velocity error along some direction. Both of these strategies are limited to two-state systems. A task to insert a key into a lock, turn the lock 180 degrees, and then withdraw the key, cannot be characterized by such a continuous system. It is, however, simple to describe such a task in terms of force/displacement transitions and control mode switches such as used in WAVE [8].

We may then characterize manipulator control into two basic states and transitions between them:

- When a manipulator is moving in free space it controls displacement and monitors force. The detection of any unpredicted forces indicates a serious error state.

- When a manipulator is constrained by the environment it controls force and monitors displacement. The detection of any unpredicted displacement indicates a serious error.

- On contact, or on breaking contact, the control and monitoring modes switch. As contact is made the reaction forces rise, indicating contact. When the desired contact force is obtained the control mode switches from displacement control to force control and the contact force is maintained at the required value. As contact is broken the reaction forces go to zero and the control mode switches to displacement control with the contact force maintained at zero.

The detection of contact is a problem for a rigid manipulator of finite inertia. When contact is detected the manipulator is brought to rest discontinuously — *it is stopped.* The kinetic energy is dissipated by various mechanisms, some potentially destructive. Given the stiffness of the manipulator and of the environment there is a clearly defined maximum speed at which contact may be safely detected and controlled.

2 Force and Position Controlled Degrees of Freedom

When a manipulator is constrained by the environment, force is controlled. There are, however, six environment constraints, three of translation and three of rotation. For each of these six degrees-of-freedom either force control or position control may be specified[3].

A robot manipulator closing a door by grasping the handle firmly has only one degree of rotational freedom — the rotation of the door about the hinge axis. In this situation force control is required along all three translation axes and force control is required about the two rotation axes perpendicular to the hinge axis. Rotational position control is required about the hinge axis. Note that one doesn't simply push on the door handle to close the door but one controls the angle of closing as a function of time — how fast the door is closed — "Don't slam the door!" All the remaining axes are in a force control mode with a desired force of zero along and about all other axes. Notice also in the above example that the forces and displacement control modes may be simply described in some orthogonal coordinate frame. In the example given, the origin of the coordinate frame would be along the hinge axis with one of the axes aligned with the hinge axis. If the z axis were aligned with the hinge axis then

we could specify the compliance needed as shown in Figure 1. Notice the motion request ROTATE and the motion

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WITH
    FORCE  X = 0,
    FORCE  Y = 0,
    FORCE  Z = 0,
    TORQUE X = 0,
    TORQUE Y = 0
    ROTATE ABOUT Z
UNTIL
    TORQUE Z = 100;
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Figure 1: A Program to Close a Door

termination specification UNTIL TORQUE Z = 100.

Manipulators are controlled by actuators located at their joints. To provide for the control of the six Cartesian environment variables, position and rotation, six joints are required. If a degree of freedom of the manipulator is constrained then attempting to control all six joints will result in an over-constrained system; large internal forces can result. If one of the joints which contributes to motion in the constrained direction or axis is controlled in force in place of displacement, the overconstraint disappears and the system is controllable. This approach was first used by Inoue in turning a crank[9] and later formed the basis of the compliance used in WAVE[3]. If more than one degree-of-freedom of constraint exists then additional joints must be force controlled to provide for each constraint. In the door closing example given above, five joints of a six-degree-of-freedom manipulator would be force controlled at zero force, and one joint, whose principal motion was in the door closing direction, would be displacement controlled.

If the motion of the joint selected to provide a degree-of-freedom does not correspond completely with the constrained direction then the the position of the manipulator will be modified in the unconstrained directions In turning the crank, the crank would be either slightly ahead or behind its correct position. If this matters it may be compensated for by modifying the commanded Cartesian position[10,11]. The major problem with compliance provided in this manner is in selecting the appropriate joints to provide the compliance. While it is always obvious which joints should be controlled in any given situation, there is as yet no formal algorithm to select these joints automatically. Another drawback is that in certain motions the joint to provide the compliance changes as the motion is made. Consider turning a crank: with the crank at the top of its motion, a joint which controls vertical motion would be appropriate to provide the necessary radial compliance, but as the crank is turned the radial direction requires a joint which controls horizontal motion. Switching between joints can be done[3] but it is difficult.

This form of compliance is very simple to implement in manipulators whose actuators are powered by electric motors as motor current is directly proportional to torque[3]. Joint friction and gearing, however, detract from this simple form of control and various attempts have been made to close a torque control loop around the joint[12]. These methods have met with only moderate success as the control coupled two rigid systems of comparable frequency response[13].

In 1981 Raibert and Craig developed a control method called "Hybrid Position/Force Control[14]," based on the theoretical formulation of the above compliance methods by Mason[15]. In this method not only was the compliance specified in an appropriate Cartesian coordinate frame but the control separation between position and force was also performed in Cartesian coordinates. The observed joint position of the manipulator was converted into Cartesian coordinates and subtracted from the desired Cartesian coordinate position yielding Cartesian position errors. Any position errors in a complying or force control direction were then set to zero and the remaining errors were transformed back into joint coordinates using the Jacobian inverse. These errors were then fed to a PID controller to reduce errors in position controlled directions to zero. Note that no position feedback is applied in any complying direction. Similarly, force errors were compared to the desired force to yield force errors in the Cartesian control frame. Any errors in a non-compliant or position controlled direction were then set to zero before these force errors were transformed into joint torque errors by the Jacobian transpose. Note that no forces were specified in any position controlled direction. In the system implemented by Raibert and Craig[14] a force and torque sensor was mounted at the wrist of the manipulator to provide feedback for the force loop. Stabilization of the force loop was, however, marginal with resort to ad hoc control methods necessary. Once again we have two rigid systems of comparable frequency response, the manipulator and the force sensor, such a system is very difficult to stabilize [13]. A similar system making use of the relationship between motor currents and joint torques has also been implemented[11]. This system, with open-loop torque control, does not suffer from the stability problems but does suffer from frictional and gearing disturbances.

In 1983, Khatib, at Stanford University went one step farther and resolved the manipulator joint inertias into effective Cartesian Inertias seen from the end-effector of the manipulator[16]. Once Cartesian position errors were detected, using the hybrid position/force control scheme, a PID controller was implemented in Cartesian end-effector coordinates to produce corrective accelerations which were then transformed into corrective forces by the effective Cartesian inertias. The resulting forces were transformed into joint torques in order to control the manipulator, again using the Jacobian transpose relationship between forces and joint torques. Unfortunately, as the manipulator configuration changes, the rate of change of effective Cartesian joint inertia varies much more rapidly than does the corresponding joint inertias. This is a considerable computational burden. A second problem is that feedback gains are applied in Cartesian coordinates while the manipulator is actuated in joint coordinates, and while it is possible to set constant high gains in joint coordinates it is not clear if similarly high gains are possible in Cartesian coordinates. No comparison between control methods for the same manipulator has been made.

3 Stability

In the previous Section we described the hybrid control of position and force. This represent the two states described by Goertz[2]. In this Section we will consider the stability of these two modes and the problems of transitions between them. In the position control of manipulators high stiffness is desired so that the manipulator will be unaffected by disturbances. We would like the manipulator to move swiftly from position to position, stopping as quickly as possible with no overshoot. When the manipulator is begin controlled at some position, we would like it to be unaffected by the application or any external forces of moments. It should act like a very stiff damped spring, very hard to deflect and *dead-beat* in its response to external disturbances. This is achieved by the application of feedback. Position feedback is required to provide stiffness, velocity feedback to provide damping, and integral feedback to provide for the removal of any bias forces. Feedback gains are limited by the stiffness of the manipulator itself. The setting of gains and the design of a manipulator for a given stiffness are a difficult engineering problems. The result is a system which has a well behaved basic response with a number of high frequency modes which decay slowly when excited. Such systems behave adequately in position mode but perform poorly in force control. The force sensor and environment are, unfortunately, both systems with natural frequency responses of the same order of magnitude as that of the manipulator. When these are coupled by contact of the manipulator with the environment then the resulting system is very difficult, if not impossible, to stabilize [17,13,18,19,12,14]. Whitney and Eppinger in their papers both indicate that stability may only be obtained when the sensor is stiff and the environment soft or when the sensor is soft and the environment stiff. Unfortunately, a soft sensor completely negates the stiffness required for position control.

The remaining problem is the implementation of the transitions between position and force control. This occurs when the manipulator makes contact with the environment. Contact between a rigid manipulator and a rigid environment is not well defined—the manipulator is moving at some velocity and then it is stopped. Where does the energy go? It is absorbed by the compliances in the system and, hopefully, dissipated. This can be destructive of many mechanical components such as, precision gears, shafts, actuators, etc. To run any commercially available robot into a brick wall would result in considerable damage! The use of any form of force sensing aggravates this problem as the force sensor is typically the least stiff member of the system, the most fragile, and absorbs all the energy. The design problem of Scheinman's "Maltese Cross" wrist force sensor was not the sensor itself but the force overload mechanism needed to protect it from damage. No form of force sensor based feedback changes this problem as the time constant of the interaction is much shorter than that of the regulator. On contact, the force sensor sees a rapidly increasing force and the sensor output goes immediately off-scale. The time scale of this interaction is of the order of a few microseconds. This signal is processed by a regulator which has a well defined minimum time response of the order of milliseconds. Contact is long since over before the regulator can respond and any damage to occur has already occurred. The *contact* problem is unsolved for *rigid* manipulator, *rigid* sensor, *rigid* environment problems.

4 Mechanical Compliance

Based on a careful analysis of a peg-in-hole insertion [20] and the force-vector steering method [6], a mechanical implementation of an insertion algorithm was developed at Draper Laboratories, the "remote center compliance — RCC" [21]. This device provided the necessary compliance to make peg insertions into low clearance holes from a vertical direction. The compliance was provided passively by springs. [1]

In the initial version of the remote center compliance no displacement sensing was provided, making the device very susceptible to damage if the displacement capacity of the device was exceeded. However, a later version, "the Instrumented Remote Center Compliance — IRCC" also provided displacement sensing which could be monitored to prevent damage. Both devices could be locked for position control to provide the two necessary control modes. The device was low inertia with high bandwidth so that contact could be made at high speed by the manipulator with the small energy of contact (due to the low inertia of the RCC) absorbed by the passive compliance. The use of *passive* compliance solves the *contact* problem[2] although the device must be locked to provide for position control and the stiffness *k* is defined mechanically and may not be programmed.

In order to overcome the locking problem Roberts[23] investigated an instrumented single compliant link. The displacement of the link was used to stiffen the link for position control and to soften the link for force control. In the position control mode any displacement of the end of the terminal link caused the manipulator to move in the opposite direction so as to restore the initial position. In the force control mode any displacement of the terminal link would cause the manipulator to move so as to restore the initial displacement. Contact could be detected by the deflection of the terminal link and the resulting motion, while the manipulator was brought to rest, absorbed by the compliant link as in the IRCC. It was shown that both modes were stable. We are currently working on a six-degree-of-freedom version of the device and hope to show stability and function.

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[1] Hanafusa and Asada made use of a spring loaded hand to provide compliance between the workpiece, the manipulator, and the environment but did not directly address the contact problem [22].

5 Conclusions

The hybrid control of force and position is basic to the science of robotics but is only poorly understood. Before much progress can be made in robotics, this problem needs to be solved in a robust manner. However, the use of hybrid control implies the existence of a model of the environment, not an exact model (as the function of hybrid control is to accommodate these errors), but a model appropriate for planning and reasoning. The monitored forces in position control are interpreted in terms of a model of the task as are the monitored displacements in force control. The reaction forces of the task of "writing" are far different from those of "hammering." The programming of actions in such a modeled world becomes more complicated and systems of "task level" programming need to be developed.

Sensor based robotics, of which force sensing is the most basic, implies an entirely new level of technology. Indeed, robot force sensors, no matter how compliant they may be, must be protected from accidental collisions. This implies other sensors to monitor task execution and again the use of a world model. This new level of technology is the "task level," in which task actions are specified, not the actions of individual sensors and manipulators.

6 Research Issues

We may identify the following research issues in position and force control:

- Matching individual joints to Cartesian degrees-of-freedom.

- Control of the force of all the links of a manipulator not simply control of the force exerted at the end-effector.

- The hybrid position/force control of redundant manipulators.

- Robust rigid manipulator, rigid environment force and contact control.

- Contact transitions

- Compliant end-effector control of robot manipulators to provide for both position and force control.

- Compliant manipulator control to provide for both position and force control.

- Task level systems to provide for the protection of sensors.

- Motion modeling.

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[2]This was graphically demonstrated by Dan Whitney at a conference in which he marched, arm rigidly outstretched, towards a an unknown wall. Without the compliance of a bent arm (to provide mechanical compliance) he would not have been able to react fast enough (regulator) to avoid hurting himself on contact

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