# STABLE EXECUTION OF CONTACT TASKS USING IMPEDANCE CONTROL

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## ABSTRACT

This paper presents an experimental evaluation of the performance of a nonlinear robot control algorithm on a contact task involving free motion, constrained motion and transitions between the two. The algorithm is an implementation of impedance control which uses end-point force feedback. Stable control of the force exerted on a rigid surface is achieved without recourse to a soft sensor. Motion control is achieved without inverse kinematic computations. It is unnecessary to switch between different modes of control at the moment of contact as the impedance controller is competent in all phases of the task.

## INTRODUCTION: CONTACT TASKS

Applying robots to contact tasks is one of the challenges of developing robot technology. Contact tasks are those in which the robot grasps or pushes or works on its workpiece. They make up a large proportion of the tasks to which robots could be applied. Yet, ironically, to date most of the successful applications of robots are to tasks in which the robot stays clear of the workpiece. Spray-painting is one example; the robot brings the spray gun through a complex path in space, but (if it's working correctly) never touches the workpiece. Seam welding is another example; the robot end-effector tracks the weld seam, but never touches it. Even in those applications where the robot does contact its workpiece, as in materials handling tasks, it generally does so without precise control of the way it interacts with the object.

## CONTACT INSTABILITY

One of the reasons for this state of affairs is the problem of contact instability. Experience to date has shown that even the apparently simple contact task of wiping a surface can be surprisingly difficult. Robot control systems which perform stably and well during free movements can break into unstable oscillation upon contact with a surface. Despite the substantial research effort which has been directed at controlling the force exerted by a robot, attempts to use sensory feedback (e.g. from a wrist force sensor) for this purpose have been thwarted by this problem of contact instability. Indeed, a recent review by Whitney[1] identified this as one of the major challenges of developing robot technology.

In fact, stable control of the force exerted on a surface was reported in the literature about a decade ago[2], but to achieve stability, either the surface pushed on had to be compliant, or the force sensor had to be. Theoretical analysis showed that stability could be achieved if the effective stiffness encountered by the robot (the series combination of the sensor stiffness and the workpiece stiffness) was substantially less than the effective stiffness of the robot itself (which is due to drive systems, servo controllers, etc.). More recent experimental work[3] confirmed this limitation.

Restricting contact tasks to compliant surfaces is clearly unacceptable; most workpieces are quite rigid. Using a compliant force sensor seems more reasonable but has the drawback that the position of anything mounted on the force sensor becomes uncertain due to the compliance of the sensor. A compliant wrist force sensor degrades the positioning accuracy of the end-effector. Compliant force sensors at the tips of the fingers don't eliminate this problem, they simply relocate it; the accuracy with which a held object can be positioned is degraded by compliant finger pads.

## IMPEDANCE CONTROL OF CONTACT TASKS

This paper presents some recent experimental results using a control algorithm which eliminates this problem. It will be shown to achieve stable control of the force exerted on a rigid surface without the need for a compliant force sensor. The algorithm is an implementation of impedance control[4], an approach to robot control which was formulated to deal with contact tasks. Impedance control also provides a unified approach to all aspects of manipulation. In this paper it will be shown that both free motions and contact tasks can be controlled successfully using a single control algorithm; it is not necessary to switch between control modes as task conditions change. Furthermore, the algorithm completely eliminates the need to perform the notoriously difficult inverse kinematic computations.

## MOTION-BASED APPROACHES TO ROBOT CONTROL

Prior work on robot control has been dominated by position or motion considerations, at both the planning and execution levels. It is assumed that the robot's task may be planned and defined in terms of a series of desired or target motions. The execution or implementation problem is then to perform these motions with a minimum of error, usually as fast as possible, given the limitations of the hardware. This approach is eminently reasonable and quite successful for non-contact tasks (e.g. arc-welding or spray-painting) in which the only aspect of the robot's behavior which needs to be controlled is its motion.

Prior approaches to contact tasks have also been built on this motion-control substrate, but they have been less successful. In general, an ideal kinematic constraint divides the workspace of the end effector into two mutually exclusive subspaces, one



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in which no motion is possible but force may be exerted, and one in which no force may be exerted but motion is possible*. In this way[5] a contact task may be translated into two dual geometry problems and the desired forces in the constrained directions planned and defined in a manner exactly analogous to the motions in the unconstrained directions.

Motion control is also at the heart of prior approaches to the execution or implementation of contact tasks (see Whitney[1], for a review). Typically, the robot is designed with a fast (frequently analog) motion control servomechanism for each joint. A force control feedback loop (usually digital and slower) is then closed around this motion controller to generate corrections to the commanded motions so as to regulate the force. Unfortunately, this architecture results in problems with contact instability.

## THE MECHANICS OF INTERACTION

The problem with this motion-based approach is that it unrealistically ignores the fundamental mechanics of interaction in a contact task. The control system senses force and in response tries to dictate the motion of the robot and the grasped workpiece. It embodies an implicit assumption that motions may be imposed on the workpiece and that it will determine how hard to push back in response.

However, if the workpiece is kinematically constrained, the nature of a kinematic constraint is such that arbitrary imposed motions may not be possible. Arbitrary forces may be applied; but the kinematic constraint determines whether the workpiece will move at all and if so, in what way and by how much. The mechanics of this kind of object make it a mechanical admittance.

By this reasoning it might seem that an appropriate strategy would be to control force, not motion[5-7]. But to focus on controlling force alone unrealistically ignores the motions due to dynamic interactions. One must consider the *dynamic relation* between force and motion.

When an object is grasped, and the manipulator pushes on it, the object pushes back; it interacts dynamically with the manipulator. In effect, the grasped object becomes a part of the physical hardware of the control system and changes how the robot responds to its actuators. These changes in the way the physical hardware responds to commands from the controller can have a profound effect on the performance of the robot. In fact they can easily destabilise the control system, causing catastrophically pathological behavior.

If the workpiece produces an output motion for an input force, then, because robot and workpiece are connected, the robot control system must have the opposite kind of behavior. It must accept an input motion and produce an output force, much the way a spring or an automobile shock-absorber does; it must behave as a mechanical impedance. The issue here is not merely one of semantics; it is a matter of what may be treated as an input and what may be treated as an output; a matter of what the robot physically can and cannot do.

The distinction being drawn here is that the motion-based approaches assume the task may be defined in terms of motions. The controller is then designed accordingly as though the interactions with the workpiece were a source of disturbances producing motion errors. The dual approach, force control, assumes the task may be described in terms of forces. The controller is then designed accordingly as though the interactions with the workpiece were a source of disturbances producing force errors.

*An ideal kinematic constraint is assumed to be frictionless.

## AN ALTERNATIVE: IMPEDANCE CONTROL

An alternative is to recognise that the dynamic interactions are not a source of disturbances to be rejected, but an integral part of the task. This is the idea behind impedance control. It is assumed that the robot's task must fundamentally be described, not in terms of motions, nor in terms of forces, but in terms of the relations between them. In the case of a robot performing contact tasks, that relation should be an impedance. Accordingly, in implementation, the controller is designed to modulate and regulate, not the robot's motion, nor the force it exerts, but its output impedance.

In fact, when the interaction between a robot and its environment is considered, *that's what any feedback controller really does.* The control algorithm implements a relation between sensed quantities and actuator efforts. Combined with the hardware, this produces a change in the robot's total dynamic behavior. At the robot end-effector, that change shows up as a modified output impedance. Therefore it makes sense to design the controller to do what it naturally does — modify the robot's output impedance.

How does impedance control compare to some of the alternative approaches? A hybrid combination of motion control and force control in orthogonal directions has been explored[8] but it simply combines the motion control and force control approaches and does not circumvent the problems inherent in each. Another approach is stiffness control[9]. Because the objective of that approach is to implement a relation between force and motion, it is closely related to impedance control. However, stiffness is merely the static component of a robot's output impedance. Impedance control goes further and attempts to modulate the dynamics of the robot's interactive behavior.

Describing the action of the controller in terms of the *dynamic* impedance changes it produces is a considerable aid to — indeed, is the key to — understanding what the controller does. Force feedback does not merely regulate force; it changes impedance. For a typical robot, that impedance change is not a modified stiffness; as we will see next, the principal effect of force feedback is to change the robot's apparent inertia.

## WHAT FORCE FEEDBACK DOES

A common model of a robot assumes that it may be described as an inertial mechanism driven by actuators which exert a controllable torque. An extremely simplified one-dimensional model of the basic mechanics is a mass (representing the inertia of the mechanism) acted on by two (opposing) forces, one due to the actuators and one due to the environment. The mechanics of this system are simple:

$$M_{actual}\, d^2x/dt^2 = F_{actuator} - F_{external} \qquad (1)$$

In the absence of a feedback controller, (i.e. $F_{actuator} = 0$) an observer in the environment would perceive the system as an inertia.

$$M_{actual}\, d^2x/dt^2 = -F_{external} \qquad (2)$$

Now assume the following simple force-feedback control algorithm is implemented.

$$F_{actuator} = G\,(F_{reference} - F_{external}) \tag{3}$$

This controller generates an actuator force proportional to the deviation of the measured external force from a commanded reference force. For simplicity, assume for the present that the reference force is zero. Combining the controller with the physical system:

$$M_{actual}\, d^2x/dt^2 = -\,(G + 1)\, F_{external} \tag{4}$$

Dividing by G + 1 and defining $M \equiv M_{actual}/(G + 1)$

$$M\, d^2x/dt^2 = -\, F_{external} \tag{5}$$

This has the same form as equation 2. From the viewpoint of an observer in the environment, the controller changes the apparent dynamic behavior of the system. In the equations, M plays the role of mass, so for this simple system, negative force feedback reduces apparent inertia. This makes physical sense: whenever an external force is applied, the controller detects it and make the actuators assist the external force so that the mass accelerates more rapidly than it would in the absence of feedback. Thus the force required to produce a given acceleration — the apparent inertia — is reduced. Note that we reach this conclusion without having to make any assumptions about the dynamics of the environment.

A force feedback controller such as the above is usually considered to regulate force. The foregoing analysis does not contradict this, but augments it. To understand this we will make some simple assumptions about the environment, assuming that the workpiece is rigid and the force sensor is modelled as a linear spring of some stiffness, K, with some internal linear damping with viscous coefficient B. These elements generate the external force.

$$F_{external} = B\, dx/dt + K\, x \tag{6}$$

Rearranging and using the Laplace variable, s:

$$x = \frac{F_{external}}{(Bs + K)} \tag{7}$$

Combining equations for the controller and the system we obtain the transfer function:

$$\frac{F_{external}}{F_{reference}} = \frac{(Bs + K)\; G/(G + 1)}{M\,s^2 + Bs + K} \tag{8}$$

This is the transfer function of a simple type-zero controller which regulates the external force to follow the reference force. For example, at steady state,

$$F_{external} = F_{reference}\; G/(G + 1) \tag{9}$$

However, note that to reach this conclusion we had to make assumptions about the dynamics of the environment.

This more conventional description of the controller action is correct, but incomplete. It does not specify how the system responds to its environment. Yet the response of the system to its environment is a major part of what is going on during a contact task. The point is that a feedback controller does not merely regulate a variable such as force or position, it changes the dynamic behavior of the system.

## IMPLEMENTING IMPEDANCE CONTROL

Impedance control is based on the recognition that the controller changes the dynamic behavior of the system. To implement impedance control, the first step is to specify the desired behavior of the robot, the target impedance. To arrive at a reasonable choice, consider the basic mechanics of the robot hardware. A common model of a robot assumes that it may be described as an inertial mechanism driven by actuators which exert a controllable torque.

$$I(\theta)\ddot{\theta} + C(\theta,\theta)\theta = \tau_{actuator} - J^t(\theta)\; F_{external} \tag{10}$$

This is a reasonable model of the mechanism (described below) on which the impedance control algorithm was implemented. The model can be generalised to include terms accounting for gravity and friction in the mechanism without preventing derivation of the control algorithm[4], but this was unnecessary for the work reported here. The dominant behavior of the hardware along each degree of freedom is that of a second order system. Consequently a reasonable target impedance is also second order (but simpler) in each degree of freedom.

$$F_{external} = M\ddot{x} + Bx + K(x - x_0) \tag{11}$$

This target impedance is specified by the programmer or a higher-level supervisory system. The quantity $x_0$ is the nominal equilibrium position of the end effector at steady state in the absence of any external forces. Because it is specified in software, it may go to positions beyond the reachable workspace of the robot and therefore it is referred to as a *virtual position*. It is used in the impedance controller to specify how the robot moves. Note, however, that the target impedance specifies much more than just the robot's motion.

A control system to implement this target impedance can be derived as follows. Purely for the sake of simplifying the derivation, assume that there is a fictitious actuator at the tip of the robot which can generate controllable forces. These controllable forces are related to the controllable torques of the actuators through the Jacobian of the mechanism.

$$\tau_{actuator} = J^t(\theta)\; F_{actuator} \tag{12}$$

The robot dynamic equations now become

$$I(\theta)\ddot{\theta} + C(\dot{\theta},\theta)\dot{\theta} = J^t(\theta)\;(F_{actuator} - F_{external}) \tag{13}$$

The acceleration of the robot joints is

$$\ddot{\theta} = I^{-1}(\theta)[J^t(\theta)\;(F_{actuator} - F_{external}) - C(\dot{\theta},\theta)\dot{\theta}] \tag{14}$$

The corresponding acceleration of the end-effector is

$$\ddot{x} = J(\theta)\ddot{\theta} + \dot{J}(\theta)\dot{\theta} \tag{15}$$

Substituting

$$\ddot{x} = J\, I^{-1} J^t\; (F_{actuator} - F_{external}) - J\, I^{-1} C\dot{\theta} + \dot{J}\,\dot{\theta} \tag{16}$$

For clarity and notational convenience, the dependence of I, J and C on the robot configuration has not been written explicitly.

The quantity $J\ I^{-1}J^t$ has an important physical meaning. It is the mobility tensor[4] of the robot end-point. We will denote it by W.

$$W \equiv J\ I^{-1}J^t \tag{17}$$

Its inverse is the actual inertia of the robot end-point.

$$W^{-1} = M_{actual} \tag{18}$$

Note that $M_{actual}$ depends on the robot configuration θ.

To obtain the control law, we first solve for the fictitious actuator force.

$$F_{actuator} = W^{-1}[\ddot{x} + J\ I^{-1}C\dot{\theta} - \dot{J}\ \dot{\theta}] + F_{external} \tag{19}$$

But the desired acceleration of the end-effector is

$$\ddot{x} = M^{-1}\{K(x_0 - x) - B\dot{x} - F_{external}\} \tag{20}$$

Substituting

$$\begin{aligned} F_{actuator} = {} & W^{-1}M^{-1}\{K(x_0 - x) - B\dot{x}\} \\ & + W^{-1}[J\ I^{-1}C\dot{\theta} - \dot{J}\ \dot{\theta}] + [1 - W^{-1}M^{-1}]F_{external} \end{aligned} \tag{21}$$

Now substitute the controllable actuator torques for the fictitious forces.

$$\begin{aligned} \tau_{actuator} = {} & J^tW^{-1}M^{-1}\{K(x_0 - x) - B\dot{x}\} \\ & + J^tW^{-1}[J\ I^{-1}C\dot{\theta} - \dot{J}\ \dot{\theta}] + J^t[1 - W^{-1}M^{-1}]F_{external} \end{aligned} \tag{22}$$

Finally, use the robot kinematic equations to express the end-point position and velocity in terms of the joint position and velocity.

$$\begin{aligned} \tau_{actuator} = {} & J^tW^{-1}M^{-1}\{K\ (x_0 - L(\theta)) - BJ\dot{\theta}\} \\ & + J^tW^{-1}[J\ I^{-1}C\dot{\theta} - \dot{J}\ \dot{\theta}] + J^t[1 - W^{-1}M^{-1}]F_{external} \end{aligned} \tag{23}$$

This is a nonlinear impedance control algorithm. Given measurements of joint motions and external forces it specifies the actuator efforts required to make the robot end-effector exhibit the specified target impedance.

This algorithm has several interesting features. It requires measurements of joint positions, joint angular velocities and external forces, each of which can be measured with reasonable fidelity in practice. It requires the specification of the target behavior in terms of $x_0$, M, B and K. This information must be supplied by the programmer or a higher-level supervisory system. The impedance controller permits parameter adaptation; each of these quantities may be changed with time to suit a particular task. Note, however, that the components of the target impedance need not be linear. For example, the position-dependent component $K(x_0 - x)$ can be nonlinear, and for some applications this can be quite useful. A nonlinear position-dependent component has been used in an impedance control algorithm which successfully protected a robot from collisions with moving obstacles[10].

## ELIMINATING INVERSE KINEMATICS

The typical motion-based approach to robot control consists of specifying the robot's task in terms of appropriate motions of its end-point. Because the control system which executes this planned task acts on the joints, not the end-point, it is necessary to translate the end-point motion specifications into a corresponding set of joint motion specifications. This requires the inversion of the kinematic equations of the robot mechanism. Unfortunately, this is frequently an extremely complex and difficult computational problem. Its solution is multiple valued and may require iterative procedures (which can be disastrous if the computation is to be performed in a real time control system). It has been described as the most difficult problem in robot control[11] and has received much attention in the literature.

The impedance control algorithm derived above completely eliminates the need to solve the inverse kinematics problem. When the virtual position $x_0$ is moved around the workspace the algorithm will make the actual position of the end-point follow it. How closely it follows is a function of the speed of movement and the choice of the impedance parameters. Given an appropriate choice of M, B and K, the deviation between the two can be kept small, and the algorithm successfully controls motion. But this is achieved without any inverse kinematic computations.

## THE EFFECT OF FORCE FEEDBACK

The terms which multiply the measured external force determine the effective force feedback gain. To understand the action of the force feedback, consider the application of this algorithm to a one degree of freedom system. The term $J^t$ becomes a scaling constant; for simplicity assume it is unity. It can then be seen that the term multiplying the force measurement depends on the ratio of the actual inertia of the end-point (which varies with position) to the target inertia. But (comparing to equation 3) this term is the negative of the force feedback gain, so

$$-G = [1 - M_{actual}M^{-1}] \tag{24}$$

Rewriting, we obtain

$$M = M_{actual}/(G + 1) \tag{25}$$

M is one of the parameters of the target impedance, the apparent inertia imposed by the action of the force feedback. This is exactly the same relation between force feedback and apparent mass obtained earlier. Again, the true action of a feedback controller is to change the dynamic behavior of a system; in this case force feedback changes apparent inertia.

## EXPERIMENTAL HARDWARE

To establish the practicality of this nonlinear control algorithm, it was implemented using the apparatus shown in figure 1. Complete details of the implementation are presented in Wlassich[12]. The hardware consists of a mechanism with two links which are free to move in the horizontal plane. The popular SCARA robot design[13] employs a kinematically similar mechanism. The links are driven by disc-armature DC permanent-magnet motors, both of which are mounted on the supporting base. The inner link is directly mounted on the shaft of one motor. The outer link is driven through a parallel-link mechanism which is mounted directly on the shaft of the second motor.

The motors are driven by transconductance amplifiers with high-gain internal current feedback. Coupled with the low inductance of the iron-less armature, a voltage input to the amplifiers results in an accurately proportional torque between the armature and the stator. Thus, aside from any frictional losses, these actuators produce a controllable torque.

Low-friction ball bearings were used at all joints, so the drive system has an extremely low output mechanical impedance, similar to a Direct-Drive robot[14]. The links and the motor armatures have low inertia and as a result the maximum acceleration and speed of this mechanism are considerably greater than that of a typical commercial robot. In terms of end-point motion, representative values are 100 in/second and 3.3 g respectively[12].

A low-noise analog position potentiometer was mounted at the pivot point of each link. A two-axis analog force joystick was mounted at the tip of the outer link to provide measurement of the horizontal interface forces between the mechanism and its environment. Each of these sensor voltages was digitised by a 12-bit A/D converter. An estimate of joint angular velocity was obtained by digital differentiation of the digitised position measurement.

The controlling computer was a DEC LSI 11/23. The nonlinear algorithm defined symbolically above was implemented in software and the commanded torques transmitted to the hardware through D/A converters. The time required for one computational cycle was 9 milliseconds, resulting in an effective sampling frequency of 111Hz. This means that the effective bandwidth of the controller was approximately 1/20th of this, a little over 5Hz. Translating this performance into movement times, if the robot were peforming repetitive motions between two points, each point-to-point move would last about 1/10th of a second.

Because this mechanism was designed as a laboroatory-scale bench-top test apparatus, and was therefore not subject to the constraints imposed on a commercial robot, its performance far exceeds that of a typical robot. The merit of this approach was that the mechanism provided an exacting and informative test of the impedance control algorithm. By restricting the apparatus to two degrees of freedom the significant kinematic nonlinearities of a robot were retained but our understanding of the behavior of the system was not occluded by the mechanical and kinematic complexity of six or more degrees of freedom. The relatively high speed and acceleration capability of the apparatus meant that the behavior of the algorithm, especially any tendency to instability, was not obscured by sluggish hardware performance.

## TEST TASK

To test the effectiveness of the impedance controller, a simple task was chosen: the virtual position $x_0$ was brought at constant speed through a circle in the workspace of the apparatus. Then a rigid barrier was placed in the workspace so that its flat front surface intersected that circle. This task provided a comprehensive test of the impedance controller's ability to control the path of the end-point during free motions, to control the interaction forces during constrained motions, and to deal with the transitions between these two parts of the task.

If the algorithm successfully achieves the target dynamic behavior, then the time histories of force and motion should be as shown in figure 2. During free motion the force will be zero and the path of the end-point will describe an arc of a circle. Upon contacting the barrier the end-point should slide smoothly along a chord of the circle defined by the surface of the barrier. At the moment of contact with the barrier there should be a brief impulsive force due to the collision of the end-point inertia with the rigid surface, but immediately afterwards the force should drop to zero. Then, as the virtual point $x_0$ moves inside the surface but the end-point x remains on the surface, the difference between these two should result in an interface force determined by the target impedance. At low speeds, the dominant term will be due to the static component, $K(x_0 - x)$. If the target impedance has linear components, the time profile of the interface force should describe a circle (or a section of an ellipse, depending on the choice of force and time scales).

## EXPERIMENTAL RESULTS

The actual performance of the impedance-controlled apparatus is shown in figure 3. The system remains stable throughout all phases of the task, both constrained and unconstrained. The combination of the environment (the barrier) and the force sensor is quite stiff. The barrier is a concrete block with essentially infinite stiffness; the force sensor stiffness was measured to be 700 lbf/ft. In this instance the effective stiffness of the robot (which is entirely due to the action of the controller) is quite modest, 4.5 lbf/ft. Similar results were obtained for all values of stiffness and viscosity throughout the range which could be achieved with this apparatus. Stable interaction with a rigid constraint was unaffected by the value of the stiffness and/or the viscosity of the robot. Clearly, the restriction that a compliant sensor be used to achieve stable interaction does not apply to this impedance control algorithm.

During the constrained portion of the task the interface force is as predicted from the ideal target behavior. For clarity, this data has not been smoothed or filtered, as can be seen from the high frequency fluctuations (which are due to the force sensor) superimposed on the ideal performance. Thus, within the limitations of this apparatus, the impedance controller achieves good control of interface force during a contact task.

Throughout the entire task, the path of the end-point is as predicted from the ideal target behavior. Again, for clarity, the data are presented without filtering. The apparently random fluctuations are due to noise in the system. For example, as the end-point "wipes" along the barrier, its true path is constrained to be a perfectly straight line. Within the limitations of this apparatus, the impedance controller achieves good control of end-point position. But remember, this is achieved without any inverse kinematic computations.

## WHY USE FORCE FEEDBACK?

It could be argued that given this idealised laboratory-scale apparatus with its torque-controlled actuators and the low friction in the drive-train, good control of the interface force is to be expected whatever control algorithm is used. How much of the observed perfomance can be credited to the impedance control algorithm and how much is due to the apparatus? To examine this, the same test task was performed using the same computational algorithm, but with the force feedback sensors disconnected. The results are shown in figure

4. During the free motion phase of the task, the path control is essentially as before (as it should be). When the end-point collides with the barrier, the system still remains stable and the end-point slides along the constraining surface.

This is an interesting result in its own right; it demonstrates that, given proper design of the hardware components, force feedback is not necessary to achieve stable accomodation of a constraining surface. It confirms an earlier result in which a constrained motion task was successfully performed by an impedance controlled robot without force feedback[15].

However, it is important to clearly distinguish between stability and performance. Although the system is still stable, the performance is considerably poorer. Upon colliding with the barrier, the end-point bounces several times, repeatedly impacting the surface. As a result, the time history of the interface force departs significantly from the ideal. Comparing with the previous figure it is quite clear that the impedance control algorithm accomplishes a significant improvement in performance by making appropriate use of force feedback.

## CONCLUSION

These experimental results clearly demonstrate that impedance control is a practical strategy for performing contact tasks. To achieve stable behavior while wiping a rigid surface it was not necessary to use a sensor more compliant than the robot, as has been reported in prior approaches to this type of task. In fact, changing the effective stiffness of the robot did not influence the stability of the apparatus during constrained motion. This should not be surprising as the analysis presented here showed that for this kind of mechanism, the true action of force feedback is related to the apparent inertia of the system, rather than its stiffness.

The experimental results also show that given an appropriately designed mechanism, stable interaction may be achieved without using force feedback. However, the results also demonstrate that a control algorithm which can make proper use of force feedback (such as the impedance controller presented here) offers some benefits to offset its cost: it yields a substantial improvement in performance.

In practice, contact tasks also involves phases when the robot is not in contact. The implementation presented here demonstrates that impedance control can provide effective control of unconstrained motions. Furthermore, it does so without the need to perform the complex and difficult inverse kinematic calculations.

A key point is that the same controller successfully deals with all parts of the task: the free motion, the constrained motion and the transitions between them. An alternative might be to restructure the controller (e.g. change from path control to force control) when the robot contacts objects in its environment. But this would require the controller to identify the moment of contact and rapidly switch between different modes of control. Using impedance control this is not necessary. Nor is it necessary for the system to use "guarded moves"[5] to make the transition between free and constrained motion. The impact due to collision with the environment does not destabilise the system. Impedance control is a unified approach to robot manipulation. The results presented here demonstrate one of the practical benefits of a unified approach; the same control algorithm is competent in all parts of the task. In this regard, impedance control is simpler than some of the alternative strategies.

Manipulation is fundamentally a process of mechanical interaction. During contact tasks dynamic interaction between a manipulator and its workpiece becomes the dominant factor determining stability and performance. The key idea behind impedance control is the recognition that the true action of a controller on physical hardware is not merely to regulate motion, or force, or stiffness, but to change its apparent dynamic behavior. Consequently, the controller is designed with the objective of changing the dynamic behavior to an appropriately chosen target impedance. The analytical and experimental results presented here demonstrate the practicality of this approach.

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FIGURES

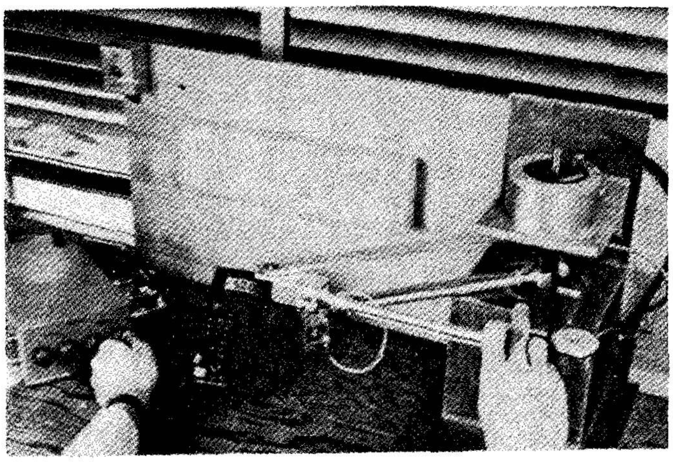

Figure 1. A photograph of the mechanical apparatus used to implement the impedance controller (from reference 12).

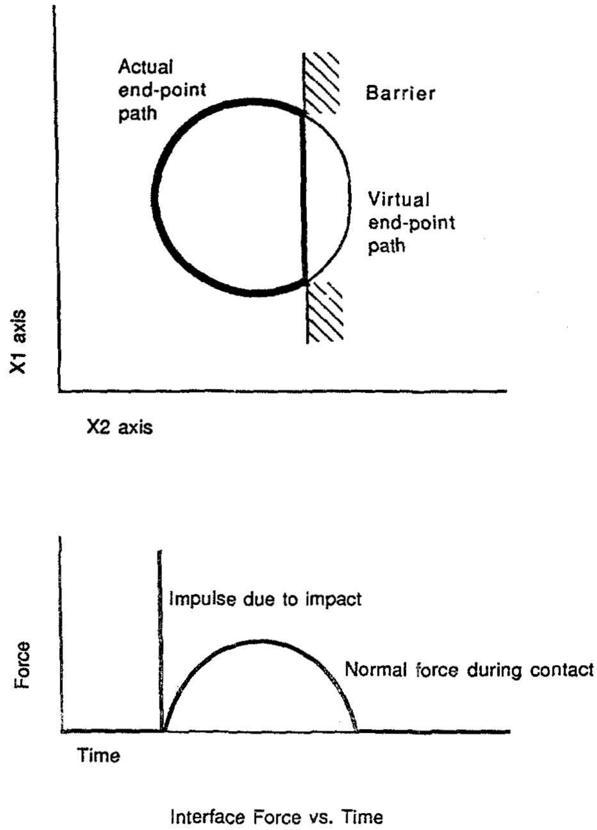


Figure 2. The ideal performance of the impedance controller on the test task. A plan view of the actual path (heavy line) and the virtual path (light line) are shown on the top. The time history of the interface force is shown on the bottom.

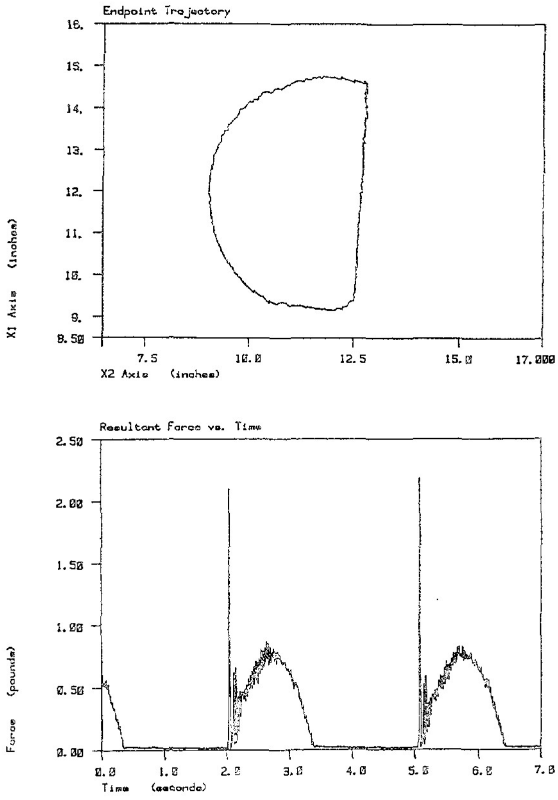


Figure 3. Actual performance of the experimental apparatus on the test task. The path of the end-point is shown on the top. The time history of interface force is shown on the bottom.

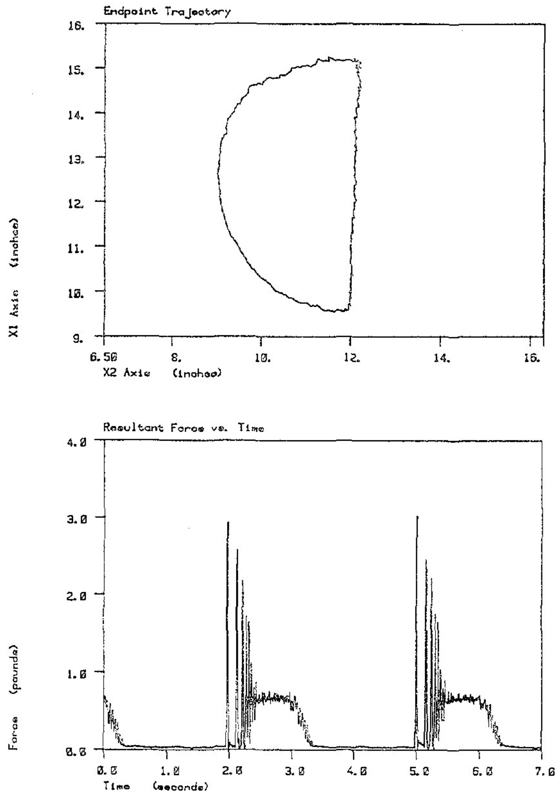


Figure 4. Actual performance of the experimental apparatus on the test task when the force feedback was disconnected. The path of the end-point is shown on the top. The time history of interface force is shown on the bottom.