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# Stability Problems in Contact Tasks

Neville Hogan and Ed Colgate
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

## Introduction

The last several years have witnessed explosive growth in the study of robot force control. The development of successful strategies and implementations for force control is seen as a crucial step in enabling robots to perform tasks, such as deburring, drilling, and parts assembly, which require significant interaction with the environment. The implementation of high-bandwidth, high-accuracy force control, however, has proven to be quite difficult, primarily due to stability problems that occur upon contact with a rigid surface.

Like other types of robot control, a full scale implementation of force control calls for a heirarchical architecture. The breakdown of this heirarchy is a choice of the designer, but it is clearly useful to separate design of the higher levels, which must address task planning and supervision, from design of the lower levels, which must address issues of stability and performance. Much of the force control literature has been divided roughly along these lines.

Paul and Shimano (1976), Mason (1981), and Raibert and Craig (1981) were responsible for much of the early work in planning. In particular, the hybrid position/force control proposed by Raibert and Craig and based upon the theoretical framework of Mason has evolved into a fairly active field of research (Anderson and Spong 1987; Paul 1987; Shin and Lee 1985; Tilley, Cannon, and Kraft 1986; Yabuta, Chona, and Beni 1988). The basic idea behind hybrid control is that the physical constraints of the task should dictate those axes along which force is controlled and those axes along which position is controlled. For instance, in a surface grinding task, force should be controlled normal to the surface, and position tangential to the surface.

Early hybrid schemes implemented force control based upon a kinematic rather than a dynamic description of the robot. More recently, Khatib (1986, 1987) proposed an approach to hybrid control based upon the operational space formulation which accounts for the rigid body dynamics of a robot. Although efforts such as this indicate that the gap between those concerned with higher level issues and those concerned with lower level issues is beginning to close, it remains the case that most of the papers in the area of hybrid control have not addressed the lower level issues of stability or bandwidth in any detail. Yet, stability and high bandwidth are important issues in force control, and are the focus of this survey.

## Contact Stability versus Performance

Whitney (1976) was the first to provide a stability analysis of a force controlled manipulator. He modeled a manipulator as a velocity-input integrator, and assumed that proportional position, velocity, and force feedback were implemented in discrete time. He modeled the environment as a spring and derived the following stability result:

$$0 < TGK_e < 1$$

where $T$ is the sampling rate, $G$ is the force feedback gain, and $K_e$ is the combined stiffness of the sensor and the environment. For fixed $T$, this indicates that a tradeoff exists between $G$ and $K_e$. In other words, high bandwidth force control requires a compliant sensor or environment.

In the years since Whitney published this result, the essential stability tradeoff between force feedback gain and stiffness of the environment[1] has been substantiated many times (Eppinger and Seering 1986, 1987; Hirzinger 1983; Kazerooni 1987; Roberts, Paul, and Hillberry 1985). It is now evident, based on the wealth of literature, that the problem is not tied to a particular geometry, but applies to all robots; moreover, it is now known that the problem transcends the digital implementation, that even for analog control the tradeoff exists (Wlassich 1986). In a recent review, Paul (1987) indicated that the contact problem with a rigid manipulator, rigid sensor, and rigid environment is still unsolved.

[1] The stiffness of the sensor is generally included as part of that of the environment.

Various explanations for contact instability have been offered. Kazerooni (1987) and An (1986) have both shown that the tradeoff may be attributed to unmodeled dynamics. Eppinger and Seering (1986, 1987, 1988) have carried out extensive stability analyses based on a series of increasingly sophisticated single-axis models. They have shown that stability problems arise due to the *non-colocation*[2] of sensors and actuators. There are two important consequences of their observations: first, that it is specifically those dynamic elements (modeled or not) separating the actuator and sensor which are most seriously implicated in contact instability; second, that, even if the robot is exquisitely modeled, high gain force control is a challenging proposition.

Eppinger and Seering (1987) also performed simulations which indicated that the force discontinuity that occurs upon contact with a surface may decrease the range of acceptable gains. However, not all nonlinearities necessarily degrade force control performance; Townsend and Salisbury (1987) have shown that coulomb friction can actually have a stabilizing effect.

Using a Nyquist stability analysis, Colgate and Hogan (1988) have derived the necessary and sufficient conditions for stability in contact with arbitrary passive objects and have shown that contact instability is determined by the impedance of the robot at the point of contact. An important consequence is that contact instability is not an exclusive property of force-feedback controlled systems (1987), but may arise in other controller designs. For example, joint-level position controllers which include integral action will exhibit instability when objects exceeding a certain mass are grasped.

## Dynamic Compensation

Many techniques have been tested in efforts to improve force control fidelity. A number of these techniques involve the use of dynamic compensators (e.g., PID force controllers). Interpreting the literature in this area is complicated by the variety of manipulator models that are used. Although a rigid body description generally serves as the base model, it is frequently assumed that the force control loop is closed *around* some higher-bandwidth inner loop, such as a position (Kazerooni 1987; Roberts, Paul, and Hillberry 1985) or velocity (Haefner,

[2]The importance of non-colocation in the stability of feedback systems was first noted by Gevarter (1970) in the context of flexible space vehicles.

et al. 1986; Stepien, et al. 1987; Whitney 1976) controller. Others, however, have analyzed force feedback in the absence of such inner loops (An 1986; Eppinger and Seering 1986, 1987; Youcef-Toumi and Li 1987). A review of the different control architectures in which force feedback appears is presented by Whitney (1985). De Schutter (1987) has contrasted the use of position, velocity, and acceleration[3] controlled plants. His analysis, however, focuses on performance criteria such as steady state error and accuracy rather than contact stability.

Kazerooni (1987) has shown, for (inner loop) position controlled manipulators, that the gain of any force feedback compensator is inversely proportional to the stiffness of the position servo and to the stiffness of the environment, if stability is to be guaranteed by the multivariable Nyquist criterion. If the position controlled manipulator is non-backdriveable, as is generally the case, and the environment is a rigid surface, the conclusion is that even very low force feedback gains should be sufficient to create contact instability. Roberts, Paul, and Hillberry (1985) experimentally confirmed the tradeoff between servo/environment stiffness and the gain of an integral force controller. They found that low stiffness was necessary to achieve reasonable bandwidth.

Various dynamic compensators—PD, PI, and PID—have been implemented on velocity controlled manipulators with similar results. For instance, Haefner, et al. (1986) implemented a PID force controller for a deburring task. Although they achieved stable control, they found that the bandwidth was too low to be of practical value.

A similar tradeoff exists in the absence of an inner loop control; however, in this case the relative merits of various sorts of dynamic compensation have been more thoroughly investigated. Eppinger and Seering (1987) suggest that compensators which add lead (e.g., PD) should allow larger gains, whereas those which add lag (e.g., PI or slow filters) should have the opposite effect. However, both An (1986) and Youcef-Toumi and Li (1987) have achieved promising results with a first-order lag compensator. This inconsistency can perhaps be resolved by noting that these implementations required that the compensator rolloff occur at very low frequency, which Eppinger and Seering did not necessarily assume.

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[3] In the case of a rigid body manipulator, acceleration control corresponds to the absence of an inner loop control.

Khatib and Burdick (1986) implement force control in the abscence of an inner loop, but also introduce a compensator for the "impact transition" stage when the manipulator first makes contact (typically at non-zero velocity) and chatter is most likely. This compensator, which uses velocity feedback to dissipate energy during the transition, has been shown to create stable impact behavior. Once stable contact has been established, pure proportional force control is implemented; any tradeoff between feedback gain and stability is not discussed.

## Alternative Approaches

A number of other approaches to improved force control exist. For instance, Hogan (1985a, 1985b) has shown that impedance control can be used to control the force exerted on an environment without the need for force feedback. This approach is to implement an endpoint impedance which is a dynamic relationship between motions input by the environment and forces output by the robot. Certain classes of impedances have been shown to guarantee contact stability (Hogan 1988). Hogan (1987) and Wlassich (1986) have also investigated impedance control implementations which make use of force feedback. They have shown that force feedback acts primarily to modulate the inertia of the robot as seen by the environment, and that high gain force feedback does the equivalent of attempting to mask this inertia. One interesting result is that *positive* force feedback (which acts to increase the inertia) was shown to have a strong stabilizing effect on contact. The utility of this result in the context of high bandwidth force control has not yet been demonstrated.

Other approaches to improving force control involve robot design modifications. A number of investigators have suggested the use of passive compliance between the robot and environment (An 1986; De Schutter 1987; Paul and Shimano 1976; Whitney 1976). One example of passive compliance is the use of a remote center compliance (RCC) (Drake 1981), which is well-known as a solution to the peg-in-hole insertion problem. De Schutter (1987) has made the case that passive compliance is essential to reduce impact loads and therefore to increase task execution speeds. Of course, passive compliance is not satisfactory in all applications due to the positioning inaccuracies which may be created. Roberts, Paul, and Hillberry (1985) show that it is possible to compensate for this effect, but their implementation exhibits fairly low bandwidth.

Part of the value of force feedback from a wrist sensor is that, in theory, undesirable effects such as motor cogging and joint friction may be masked. If these effects can be eliminated through design, however, open loop force control becomes a conceivable alternative. Youcef-Toumi and Li (1987) have made the case that, due to the inherently simple dynamics of a direct-drive arm, improved force control may be achieved, possibly in an open loop fashion. Townsend (1988) has designed a cable-driven manipulator which is also intended to exhibit particularly good open loop force control.

Another design alternative is the use of a macro/micro architecture. Sharon, Hogan, and Hardt (1988) have argued that the use of a high bandwidth micro-robot mounted on the end of a standard macro-robot should enable the implementation of higher bandwidth force controllers. Tilley, Cannon, and Kraft (1986) have presented encouraging data with a similar system. Their manipulator is composed of a very fast wrist subsystem mounted on a very flexible arm. An integral force controller at the wrist was shown to exhibit reasonable stability and bandwidth.

## Conclusions

In summary, high bandwidth control of the force exerted on a rigid environment remains elusive. Although stable force controllers have been implemented on a number of different robots with a wealth of different control architectures, performance has been limited in every instance. None of the sundry compensation schemes that have been introduced have achieved notable success from an applications standpoint; however, these studies have continued to improve the basic understanding of those issues which affect the performance of force controlled robots, and have provided direction for ongoing research. Many current efforts are addressing better dynamic modeling of robots as well as better design of robots for force control.

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