Chapter 1

Introduction

1.1 Statement of Purpose

This thesis addresses the control of dynamically interacting systems. Interest in this problem arises in the study of manipulation. One of the major difficulties currently facing those in the field of robotics is controlling the dynamic interaction of a robot with its workpiece. This problem has engendered several approaches to robot control, such as "force control" [89] and "impedance control" [36], which have met with varying degrees of success. However, despite these approaches, basic understanding of the interaction of controlled systems—such as manipulators—with dynamic environments remains weak.

The primary goal of this thesis is to develop tools for analysis of the interactive behavior of controlled systems. These tools are intended to be sufficiently general to apply to any linear control system. Their utility will be experimentally examined.

The second goal is to better, through application of these tools, the understanding of those approaches to robot control which address interaction. Several existing approaches, as well as several proposed here, will be examined.

The strategy for realizing these two goals involves investigation of control systems' driving point impedances (see Section 1.5). A final goal is to demonstrate that the focus
on impedance rather than transfer functions, which lie at the heart of servo control theory, is the correct approach to the interaction problem. The distinction between interaction and servo problems will be illustrated with examples located throughout the text.

1.2 Background

The approach taken to the realization of the goals above is the application of an eclectic set of concepts and theoretical tools. The purpose of this section is to provide a brief introduction to the influential background topics, with emphasis on their relevance to the thesis goals.

1.2.1 Physical Systems Modeling

Physical systems modeling techniques, such as bond graphing [65], provide a means of analyzing the behavior of complex dynamic systems based upon an understanding of one, the dynamic behavior of the system components, and two, the energetic interaction (connection) of these components. This thesis is a systems approach to the study of manipulation (see Section 1.3.1), where the system of interest is composed of the manipulator coupled to some dynamic environment. The study of this system can be addressed with the techniques of physical systems modeling; however, there is a complication, which is that one of the components is feedback-controlled.

Because feedback is the use of measures of system states to modulate a source, one reasonable approach is to develop a model of the complete system (manipulator plus environment), and subsequently analyze the effect of adding feedback. This, however, is not the approach taken here. Primarily because a manipulator may be expected to interact with a diverse set of environments (e.g., tools), it would be convenient to treat
it as a component of the overall system\textsuperscript{1}.

Such an approach is not without its perils. Much of the power of bond graphing, for instance, lies in its parsimony. Only nine symbols \((0, 1, S_\alpha, S_f, GY, TF, I, C, R)\) are typically used in bond graph models, yet these symbols are sufficient to describe the behavior of nearly all physical systems. The choice not to represent explicitly the presence of feedback will result in system components which cannot necessarily be described by these symbols alone. Thus, the increased complexity of such an approach is a concern.

Nevertheless, this route has been taken because it is felt that both a \textit{modular} treatment of a controlled manipulator, and access to the insights and theoretical results (e.g., Tellegen's theorem) of the study of physical systems, would prove quite powerful.

\subsection*{1.2.2 Physical Equivalence}

A related concept which is also of great influence is Hogan's postulate of "physical equivalence" \cite{36}:

"Any controlled system will consist of 'hardware' components (e.g., sensors, actuators, and structures) combined with controlling 'software' (e.g., neural networks, brains, or computers). A unified approach to both the design of the controller and the physical hardware can be developed by postulating that, taken together, the hardware and software is still a physical system in the same sense that the hardware alone is."

The potential value of this postulate is twofold: first, in the design of controllers for physical systems, one need not consider any controllers which will result in behavior

\textsuperscript{1}The use of feedback controlled components in the design of complex systems is actually quite common—consider the ubiquitous op-amp. Devices such as the op-amp, however, make use of high input impedance and low output impedance connections to limit energetic interaction (and don't always succeed); mechanical devices generally exhibit more significant energy exchange.
that cannot be described as that of an equivalent physical system; second, it should be possible to use physical systems modeling techniques to describe controlled systems. Thus, this postulate suggests that the approach described in the previous section is not altogether unreasonable.

The coupled stability analysis in Chapter 3, and, to a greater extent, the concept of a "passive physical equivalent" introduced in Chapter 6, attempt to exploit this concept. Throughout this thesis, feedback—whether it is introduced for servo control or for interaction control—is treated as an operation which has the effect of changing the physical behavior of the plant.

1.2.3 Control Theory and Network Analysis

The mathematical techniques of control theory and (electrical) network analysis and synthesis are used throughout this thesis. The proofs in Chapter 3 are based on Nyquist stability theory and root locus. The mathematical statements of passivity presented in Chapter 2 may all be found in the network analysis literature, and network synthesis concepts are the basis of the passive physical equivalent analysis in Chapter 6.

Although network analysis may be considered a subset of physical systems theory, it is focused to a much greater extent on the analysis of models rather than the modeling of systems. Because of this focus, many powerful mathematical results are available, some of which play a large role in this thesis.
1.3 Context

1.3.1 Manipulation

The context of this thesis is the study and design of manipulators. The study of manipulation, both human and machine, provides a strong incentive for understanding the control of interacting systems. As Hogan has often reasoned [37]:

"By any reasonable definition, manipulation of an object implies mechanical interaction with that object."

The human arm, for instance, is a manipulator with capabilities that include well-behaved interaction with an extremely diverse set of environments. Its repertoire includes the abilities to employ eating utensils, to perform complex dynamic tasks such as catching or throwing a ball, and to perform kinematically constrained tasks such as sanding a surface or opening a drawer.

This tiny selection of tasks in fact encompasses a far broader range than that achievable by a mechanical manipulator controlled with state of the art servo (i.e., command following) techniques. Most successful industrial applications of robots have been in non-contact applications such as welding or spray-painting, or in simple pick-and-place operations. Yet, the bulk of industrial operations to which a robot might be applied require significant work transfer. These operations include parts assembly and various material removal processes. In the future, cooperation with other robots may also be included. In such a case, the conventional position servo strategy of making the robot much stiffer than the environment (to ‘reject’ environmental disturbances) is bound to encounter difficulties—the environment may be just another, perhaps identical, robot.

In the next section, an approach to manipulator control which explicitly considers interaction with the environment is described.
1.3.2 Impedance Control

The concept of active control of a manipulator's interactive behavior is formally treated as an aspect of "impedance control" [34,35,36]. Impedance control is an approach to manipulation which is based on the assertion that it is not sufficient to control some vector of port variables such as positions, velocities, or forces, but that it is also necessary to control the dynamic relations among the port variables, such as impedances and admittances. In particular, impedance control makes the reasonable assumption that most "environments" a manipulator will interact with are admittances (i.e., kinematic constraints or mass-like objects), and that to be causally consistent, the port behavior of the manipulator should be that of an impedance. To illustrate, a single-axis manipulator connected to an environment with admittance causality may be represented by the bond graph in Figure 1.1. The job of the impedance controller is to modulate both \( v_0 \), the "virtual trajectory" of the manipulator [36], and \( Z \), the manipulator impedance. The reader should note that the use of a bond graph to represent an impedance controlled manipulator is an application of the postulate of physical equivalence.

Hogan has shown that a large class of nonlinear, multi-axis manipulators may be represented by the structure in Figure 1.1. He has also provided a few illustrations of impedance controller designs (see Section 4.1). The benefits of these designs are well documented [39,33]. The design methods offered do not, however, apply to a broad range of manipulators. Indeed, impedance control is intended to provide an approach to understanding manipulation rather than a prescription for designing controllers.

The design and implementation of impedance controllers is, however, an active area of research. Some of the current topics of interest are planning impedances [5,26,27], designing impedance controllers in the face of modeling errors and/or complex models [22,30,44,45,55], and applications to force control [40,92]. The latter two topics will be briefly introduced in the following two sections, and then reviewed in more depth in
Chapters 4, 7, and 8, as they are important background for this thesis.

The work presented in this thesis may be classed as impedance control as the focus is on interaction with a dynamic environment. This work, however, departs philosophically from impedance control in two ways: manipulators are modeled as admittances, not impedances, and the basis of the theoretical developments is a concern for the stability rather than the causal consistency of a manipulator which interacts with its environment.

The reason for these departures is the difficulty associated with modeling the coupling of dynamic systems, particularly when both systems would, if modeled independently, be assigned the same causality (see, for instance, [37]). Most manipulators and many environments are probably best modeled as admittances, thus the difficulty. Two readily apparent approaches to this problem are one, to model the manipulator as an impedance, and attempt to design controllers which make it behave as an impedance, as there is nothing that can be done about the environment; and two, to avoid the issue by considering the stability of the coupled system which, at least in the linear case, does not require consideration of causality. Other methods, such as endowing the junction between the two systems with appropriate dynamic behavior, may also be used, but tend to lead to stiff system models, which are difficult to analyze. The second approach lends itself most neatly to the application of network analysis, and is therefore used
here. Because this thesis does not focus on the manipulator impedance—as opposed to the admittance—the controller designs are frequently referred to as “interaction controllers”.

1.3.3 Departures from the Ideal

Despite the desirable properties that an impedance controller would have if it could be designed, it is not always easy or even possible to implement a particular impedance. A major part of the reason for this is that real hardware exhibits various non-ideal behaviors, such as actuator, transmission, and sensor dynamics. The implementations suggested by Hogan have all been for robots with rigid links and without any of these additional dynamic effects.

Recently, efforts have been made to examine the effects of various non-idealities on the performance of impedance controllers. Kazerooni [44] has developed an approach to the design of impedance controllers which treats a linearized manipulator model with first-order actuator dynamics; Spong [74] has developed an impedance controller which is intended to perform well in the face of joint flexibilities; Fasse [22] has examined the robustness of impedance controllers to various modeling errors. More recently, Kazerooni [45] has developed an approach to the design of impedance controllers which will work with almost completely unstructured models.

This thesis takes a step back from these sundry design efforts in an attempt to establish quantitative design criteria which any of these implementations must meet if it is to be successful. Thus, Chapters 3–7 focus on the development and application of analytical techniques; these techniques are restricted to linear systems, but not to particular manipulator models or controller designs. Chapter 8 returns to consider the design of interaction controllers in light of what is learned from the analysis.
1.3.4 Force Control

Force control of robotic manipulators is analyzed in detail (see Chapter 7) as it is a research topic that is currently receiving tremendous attention in the literature. Force control is a type of interaction control as it presumes that the manipulator is attempting to exert a controlled force on some object (generally, a stiff surface as in, for instance, a deburring application).

Force control is also interesting in that it demonstrates how demanding interactive tasks can be. As described in Chapter 7, many implementations of force control (using force feedback) result in a violent chattering behavior upon contact with the workpiece; implementations which do not exhibit this behavior generally suffer from low bandwidth.

An analysis of force control, which treats the problem as one of interaction control, is presented. New insights into the difficulty with force control are generated, and novel suggestions for improved control are offered.

1.4 An Approach to the Control of Interaction

In this section an approach to the design of interaction controllers is presented. Design specifications are described and contrasted with those of a servo, and the structure of the closed loop interaction controller is presented in a fashion suited to the application of network analysis.

1.4.1 A Heirarchy of Design Specifications

To begin, consider a servo controller, which is meant to be synonymous with a "command following" or "tracking" controller. Specifications for a servo controller may be
stated in virtually any manner the designer chooses, but generally include some subset of those shown in Figure 1.2. The hierarchy of specifications is also generally as shown. Nominal stability is, of course, an absolute requirement, while tradeoffs are required for the other specifications. Classical control focuses on nominal stability, command following, and disturbance rejection. Many of the techniques of modern control provide guarantees of nominal stability, while command following and disturbance rejection are weighed against various measures of robustness. Much of the current effort in control theory is focused on robustness and sensitivity issues.

The design specifications for an interaction controller are somewhat different. The hierarchical structure is shown in Figure 1.3. Stability of the isolated system remains paramount; however, as the manipulator is expected to interact extensively with its environment, coupled stability is nearly as important. Coupled stability may, however, be traded against performance; a manipulator need not be capable of interacting stably with every conceivable environment, just those which it is likely to encounter. Interactive behavior has been added to the performance specifications as stability is clearly an
insufficient requirement; a reasonable behavior is also needed. The other requirements are essentially as before.

Although methods for the design of interaction controllers can be expected to develop more rapidly than methods for the design of servo controllers have evolved, they are currently in an infant state. Recently, Kazerooni has begun to apply various techniques of modern control to the design of impedance controllers, but many of his results, which will be reviewed herein, suffer poor behavior at the level of coupled stability or interactive behavior. In Chapters 8 and 9, the relation of interaction control to recent activity in control theory is considered further. The bulk of the analysis, however, will have a classical control flavor, and will concentrate primarily on coupled stability, and secondarily interactive behavior. The intent is to develop analytical tools which provide the same sort of insight to the design of interaction controllers that stand-by
techniques such as root locus and Bode plots do for servo controllers.

The sets of design specifications should indicate that, at least in conception, interaction control differs from servo control. Several examples located throughout the thesis serve to bolster the argument that this is more than a matter of philosophy, that different designs and behavior result.

1.4.2 Structure of Interaction Controllers

The structure of the complete system to be studied in this thesis is shown in Figure 1.4. It consists of an active system (the manipulator) with \( m \) states, \( n \) control ports, and \( p \) interaction ports (generally, \( m \geq n \geq p \), connected at the appropriate ports to a controller and a passive environment (see Section 3.1 for an explanation of the restriction to passive environments).

It is assumed that the control can be divided into a state-dependent part and a state-independent part, that is, that the control vector \( u \) may be expressed as \( u = h + r \), where \( h \) is the output of a compensator whose inputs are the states of the active system, and \( r \) represents the state-dependent control, which itself may be the output of a dynamic system. The complete system may now be reconfigured as shown in Figure 1.5.

As an aside, it should be noted that many of the interaction controller designs that will be presented assume that a measure of the inputs to the manipulator from the
environment is available. In point of fact, such a measure is a measure of sensor state, and the sensor is part of the active system, so that the structure in Figure 1.5 applies.

Finally, a change of viewpoint will be made. The combination of the active system and state-dependent control will be viewed as a controlled network, as shown in Figure 1.6. The value of this viewpoint is that it indicates that the wealth of literature and experience in the area of network analysis and synthesis may be applied to the problem of controlling interaction. This will be quite important in Chapters 3, 6, and 7.
1.5 Terminology

The terminology in this thesis reflects a rather mixed heritage. The disciplines of classical control, physical systems modeling, and network analysis all provide important background, but also contribute distinct dialects to common subject areas. This section, therefore, is intended to be as much thesaurus as glossary.

All of the examples in this thesis treat the behavior of physical systems. The physical system of interest, in the absence of control, is referred to as a system, network, or plant. It is generally the case that there is control, possibly via feedback, over the behavior of the system.

A system communicates with its environment at ports. The environment is simply another physical system, but generally not one over which there is control. A port is a physical location where two systems exchange energy. It is characterized by two variables, such as force and velocity, whose product is the power flow into the system through that port. For an electrical system, any two terminals constitute a port.

A 1-port is a system with one interaction port. A two-terminal network is an example of a 1-port. An n-port is a system with n interaction ports.

The two power variables associated with any port are generally termed effort and flow variables. Forces, torques, and voltages, for instance, are types of efforts. Translational and angular velocities and currents are types of flows. The term force will generally refer to a force-torque vector. The term velocity will generally refer to a translational velocity-angular velocity vector.

The dynamic relationship between power variables at a port is, in general, called an impedance. More specifically, the impedance maps a flow input to an effort output, while the admittance maps an effort input to a flow output. It should be clear from context whether "impedance" is being used in a general or specific sense. For n-ports,
impedances and admittances are generalized to map vectors of inputs to vectors of outputs. The terms driving point impedance and driving point admittance are equivalent to "impedance" and "admittance".

Although the terms "impedance" and "admittance" are commonly restricted to linear systems, they may be applied to nonlinear systems as well. They are causal dynamic operators which map an input time function \( u(t) \) onto an output time function \( y(t) \) such that the present value of the output \( y(t) \) may depend on the entire past history of the input \( u(t - \tau) \) for \( 0 < \tau < \infty \), and such that \( u'(t)y(t) \) is the instantaneous power flow into the system [65].

A transfer function is distinct from an impedance in that it relates arbitrary inputs and outputs found at arbitrary locations. Transfer functions generally relate controlled outputs to reference inputs. A servo controller attempts to make such a transfer function equal to unity within a specified bandwidth. A good servo controller also attempts to 'reject' disturbances to the closed loop system.

The term interactive behavior is used loosely throughout the thesis until Chapter 8, where it is defined in terms of a frequency domain specification. In general, however, interactive behavior simply refers to the system's response to environmental disturbances.

The term "physical equivalence" was defined in Section 1.2.2. A physical system which has the same behavior as a controlled system, at least as viewed at some port, is termed a realization. The passive physical equivalents described in Chapter 6 are realizations.
1.6 Summary of Remaining Chapters

Chapter 2 serves as a primer in *passivity*. The intuitive notion and mathematical statements of passivity play an important role throughout the thesis. In Chapter 3, a necessary and sufficient condition for the stability of a linear control system coupled to an arbitrary passive environment is derived. This analysis lays the theoretical groundwork for the remainder of the thesis. Graphical tests for "coupled stability", based on the Nyquist and root locus constructions, are presented. Several examples of the application of the coupled stability criterion are described in Chapter 4. Some of the examples apply to a two-link manipulator. In Chapter 5, experiments performed with a two-link manipulator are described. The experiments demonstrate the utility of the analytical tools developed in Chapter 3, and corroborate the analyses presented in Chapter 4.

In Chapter 6, "passive physical equivalents" and "uncontrollable elements" are introduced. These are tools for the analysis of a control system's interactive behavior based upon the generation of an equivalent structured model. In Chapter 7, these tools are used to analyze the behavior of various force feedback controlled robot models. Suggestions for improved force control are also made. In Chapter 8, attention is focused on methods of implementing desired interactive behavior. Three methods are described, and examples are analyzed. Some conclusions are drawn with regard to the effectiveness of these methods, and the importance of the inherent dynamics of the plant is discussed. In Chapter 9, the results of the thesis are summarized. The relevance of these results to areas other than manipulation is discussed, and directions for future research are suggested.