CHAPTER 1

INTRODUCTION

1.1 Introduction and Objectives

The objective of this thesis was to develop a procedure for scaling a miniature prismatic, revolute jointed, planar robot. The research sought to:

1. develop a scaleable trajectory planner
2. develop scaling laws for gearmotors with friction
3. develop a control law that would achieve similarity between dissimilar motors

The fields of kinematics, dynamics, dimensional analysis, and automatic controls were called upon during the pursuit of this study. Similitude analysis and the Buckingham Pi theorem were used to nondimensionalize the nonlinear differential motor equations. A modified version of the computed torque method (Craig, 1989) was the control strategy used for controlling the manipulator.

The ultimate goal of this research was to develop unique nondimensional terms that could be used to quickly scale a "prototype" motor from a design "model". These nondimensional terms are analogous to the famous Reynolds Number or Froude Number (White, 1986). The generation of such terms would enable a system designer to develop micro motor applications from a more easily constructable and testable model system. The techniques developed in this research could readily extend to any micro application that uses permanent magnet d.c. motors.

1.2 Motivation and Thesis Contribution

Engineering physical systems usually begins with the design and construction of a representative model system. Models are easier to construct, cost less, and are designed on a scale that can be accommodated by an industrial or university laboratory. In many cases, models are an absolute necessity for prototype systems that are either radically large or small, because data collection at these scales is neither practical nor economically feasible. Scaling the PR manipulator using dimensional analysis was in large part motivated by these traditional reasons. However, the principal reason for pursuing this study was to develop a scaling procedure that would significantly reduce a prototype's design time and reduce the tuning time of its controller. Motivation for pursuing this study also grew from a desire to learn whether it was feasible to scale and control miniature motors selected from low-grade motor stock. Specifically, the study sought to answer whether a prototype system that used inexpensive motors with significant friction terms could be made to match the performance of a larger system that had "better" friction characteristics.

Although dimensional analysis has had a long and productive history in the realm of engineering physics (Bridgeman, 1922; White, 1986), the literature has produced relatively few reports on scaling nonlinear motor friction and applying dimensional analysis to automatic controls. The reports that do exist in the literature offer little instruction or direct design schemes to facilitate the motor selection process faced by a system designer or integrator. Furthermore, a comprehensive approach to scaling a PR micro manipulator appears to be absent altogether in the literature. This work addresses these issues, and offers a set of scaling laws for sizing micro permanent magnet d.c. gearmotors that possess nonlinear friction terms.

1.3 Background: PR Manipulators

The design and construction of robotic manipulators assume numerous configurations in the modern world. By convention and tradition, most robots are modeled as "rigid structures connected by non-compliant prismatic, revoulte or compound joints" (Stoten, 1992). Classifying a robot is determined by its degrees of freedom and by joint description. For example, Figure 1.1 is classified as a two link, two-degree-of-freedom, prismatic, revolute jointed (PR) mechanism (Craig, 1989).

Figure 1.1: PR manipulator

Because the results of this study can be generalized to any planar robot, the question of which mechanical system to use was of marginal importance. Practical limitations guided the selection process, and in general, cost minimization, ease of control, and manufacturability, were the overriding design criteria. For these reasons, the PR manipulator was chosen for this study. Figure 1.2 offers another representation of this mechanism.

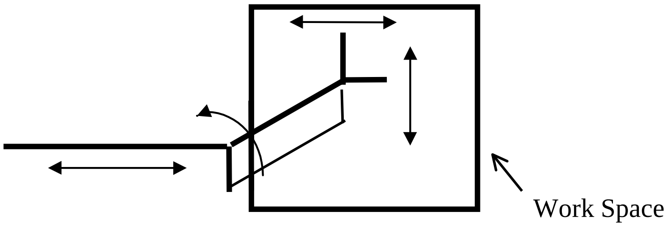


Figure 1.2: PR manipulator with work space

1.4 Background: PR manipulator System Dynamics

Several methods are available for generating a manipulator's dynamical equations. One approach involves forming free body diagrams and applying Newton's second law. However, more expedient means of producing the equations are offered from the Newton-Euler method, and from methods based on Lagrange's equation (Stoten, 1992).

The derivation of the dynamical equations of the PR manipulator using Lagrange's equation is presented in Appendix A. Stoten (1992) presents an algorithm for determining any manipulator's dynamics by using this energy method. It is stated here for quick reference:

1) Determine the absolute velocity of each link.
2) Determine the total kinetic energy T, and potential energy, U in the machine. Form the Lagrangian:

$$L = T - U \tag{1.1}$$

3) Use the results of (1.1) in Lagrange's equation.

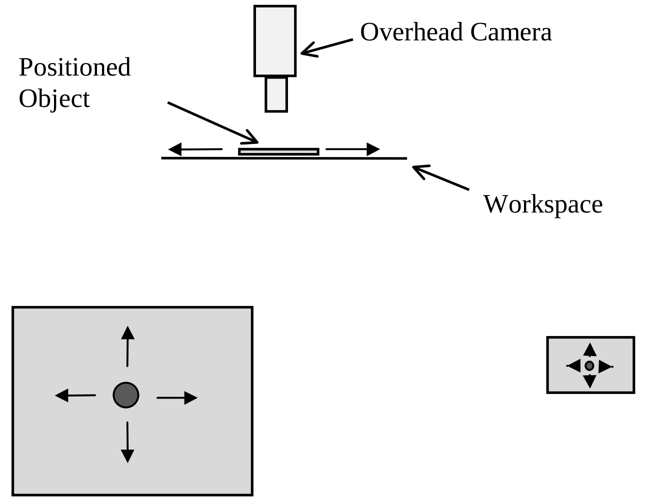
$$\frac{d}{dt}\left[\frac{\partial L}{\partial \dot{x}_i}\right] - \frac{\partial L}{\partial x_i} = \tau_i \tag{1.2}$$

where x_i is the generalized co-ordinate of each degree of freedom and τ_i is the generalized external force applied at each co-ordinate x_i .

Appendix A also develops the case where the PR manipulator is coupled to low gearing. In essence, low gearing uncouples the link dynamics so that only the dynamics of the actuator become important. If the actuator is a d.c. PM motor, then internal friction dynamics become particularly important to the control and scaling of a PR manipulator. Dimensional analysis offers assistance for assessing the magnitude of this potential problem in a prototype system.

1.5 Model and Prototype Application and Design Requirements

The application under study requires the PR manipulator to move a user specified (x,y) position setpoint to a fixed position beneath an overhead camera. The model system's workspace is 8 x 10 inches. A smaller prototype system is required to perform a similar motion in a 23 x 35 mm (.9055 x 1.3779 inches) workspace. The basic concepts of this application are illustrated in Figure 1.3.



Model workspace (8 x 10 in) Prototype workspace (23 x 35 mm)

Figure 1.3: PR manipulator application

The prototype system is scaled to the model by taking the ratios of the longest sides of their respective work spaces. The scale factor is:

$$SF = \left(\frac{35\text{ mm}}{25.4\text{ mm}/\text{in.}}\right)\left(\frac{1}{10\text{ in.}}\right) = .1378\text{ in./in.} \tag{1.3}$$

and

$$X_p = SF \cdot X_m \tag{1.4}$$

where X is the setpoint and the subscripts are defined as p=prototype and m=model. Thus, a 1 inch movement in the model's workspace corresponds to a .1378 inch movement in the prototype system.

To test the effectiveness of the scaling laws derived in this thesis, two motion control requirements are imposed. The first specifies that the model and the prototype systems must follow a "S-curve" trajectory path while running without the benefit of feedback control. This requirement illustrates how well the proposed control algorithm compensates for friction at low velocities. The second requirement stipulates that both systems must complete their X-Y trajectory runs in equal time allotments. This constraint motivates a discussion in Chapter 5 on selecting motors that have dissimilar mechanical time constants.

Other design assumptions are as follows:

- the manipulator links are rigid body systems with non-compliant joints.
- the actuator's gear-train is non-compliant.

- backlash in the mechanism is significant, and because of this, all experimental testing is performed in one direction only.
- the same power amplifiers and power supplies must be used for both the model and prototype systems.
- the systems will not operate in a continuous duty environment, therefore, motor temperature is an insignificant design parameter.

Link and motor dimensions have no design restrictions other than the requirement that the prototype components must be smaller than the model's.

1.6 Design and Testing Approach

A model system was constructed of rigid aluminum links attached to a slider mechanism, and was sized to fit to operate within the previously mentioned designated workspace. The link actuators were low-geared PM d.c. motors. Power was delivered by a Darlington style amplifier connected to a bipolar 13.5 volts, 3 amps power supply. An AT class PC installed with one 8 channel 12-bit A/D board and one 2 channel 12-bit D/A board functioned as the controller for the system. The control algorithm was written in Borland 3.1 C for DOS. An off-line identification scheme was used to identify and confirm motor parameters supplied by the manufacturer. The system was tested by commanding the manipulator to move an object with the coordinate position of (x=1 in., y=1 in.) to a fixed position beneath an overhead camera. This reference caused the manipulator's tip to trace a diagonal path; forcing the system's links to simultaneously rotate and translate. A S-curve trajectory planner was incorporated in the controller to allow for low velocity friction testing.

An analytical model was developed for this system and simulated using Matlab and the Matlab companion program, Simulink. Simulations of the model system were compared to experimental test results, and once the model system was well established, a prototype system was designed. Scaling laws were derived to select candidate prototype motors, and a scaleable trajectory planner was developed to scale the motion path established by the model system. Prototype system simulations were conducted and compared to experimental test results. Following the conclusion of the testing, the effectiveness of the scaling laws were assessed and evaluated. The scaling laws were then altered to reflect the insights thus gained.

At first glance, the procedure outlined above for scaling a robotic manipulator may appear beguilingly simple. However, deriving the "correct" or most appropriate dimensionless scaling laws is not a direct process. White (1986) addresses this point:

> "Although dimensional analysis has a firm physical and mathematical foundation, considerable art and skill are needed to use it effectively."

Nondimensionalizing a motor equation with friction can be accomplished in many different ways, and the methods chosen are largely determined by the application and the researcher's interests (Armstrong and Amin, 1996.) As will be illustrated, applying dimensional analysis effectively to motor systems not only requires knowledge of the techniques themselves, but also requires considerable knowledge of the motor's dynamics and electro-mechanical relationships. These points will be further discussed and unveiled throughout this study.

1.7 Thesis Presentation and Terminology

In general, the thesis is essentially divided into two distinct bodies. The first half presents the analytical concepts that form the basis of this work. The second half is devoted to validating these theories. The specific organization of the thesis and chapter descriptions are as follows.

Chapter 2 presents a literature review on the principal subjects treated in this thesis. Reviews and historical summaries are offered on permanent magnet DC motors, friction in servo mechanisms, friction compensation techniques, and dimensional analysis.

Chapter 3 develops scaling laws to size prototype motors. Similitude methods are used to develop a scaleable trajectory planner and a dimensionless motor equation that includes nonlinear friction terms. The results that are generated from the similitude analysis are used to derive the Buckingham Pi terms. The chapter ends by outlining a scaleable control strategy for high precision servo positioning systems.

Chapter 4 presents the simulation scheme used to test the validity of the scaling laws. The Buckingham Pi terms and the nondimensional closed form solutions derived in Chapter 3 are used to select candidate prototype motors. The prototype PR manipulator is numerically simulated using gearmotors that are dissimilar to the model's. Finally, it shown through simulation that the control strategy under study here can successfully scale a prototype PR manipulator that is actuated by motor's that are dissimilar to the model's.

Chapter 5 discusses the model and prototype experimental testing apparatuses. This chapter also presents test results that both confirm the accuracy of simulations and validate the proposed scaling laws. In addition, a section in this chapter is devoted to an off-line identification scheme that identifies key motor parameters such as static and Coulomb friction. The chapter concludes with a reassessment of the Pi terms derived in Chapter 3, and offers an explanation on how the computed torque controller can achieve similarity among systems with dissimilar motors.

Chapter 6 presents a final summary of the thesis' findings and offers recommendations for future research.

The terminology used in this thesis may be confusing to the uninitiated reader. For example, a control engineer defines a model as an analytical representation of a physical process that is under control. Model reference adaptive control (MRAC) is one sense of this usage. Model as defined by dimensional analysis, however, means a physical object that represents a prototype system of different scale. To distinguish between the two different ideas, the thesis presents the dimensional analysis sense of the word as the "model system," and refers to the control sense of the word simply as the "analytical model." It is hoped that the context of the discussion will further clarify any uncertainties concerning the intended usage.