A STRATEGIC APPROACH TO ASSESSING NEEDS AND ENGINEERING COST/PERFORMANCE TRADEOFFS FOR INTERNALLY DEVELOPED HIGH PERFORMANCE ASSEMBLY MACHINES

by

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Submitted to the Department of Mechanical Engineering and
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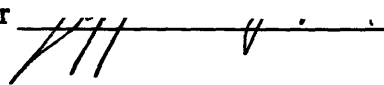in Partial Fulfillment of the Requirements for the Degrees of

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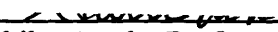## MASTER OF SCIENCE IN MANAGEMENT

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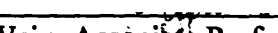May 1994

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Abstract

A case study of two internally developed assembly machines is presented. Based upon this work, a decision framework is proffered for determining strategic ramifications and engineering performance requirements for assembly machines. This is accomplished by examining a firm's core competencies and dividing its manufacturing process into individual tasks. The framework also addresses the make versus buy decision in this context. In the event that a firm elects to develp its own manufacturing equipment, a parametric procedure is described for ascertaining the effect of various components on machine performance. This technique requires the determination of the machine's transfer function which can either be modeled using lumped parameters or experimentally determined. Both procedures are described.

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Chapter 1 - Introduction

Acme Mfg.'s Competitive Situation

The research for this thesis was conducted at a large corporation that wishes to remain anonymous. The company has been disguised as Acme Mfg., a fictitious entity. Acme produces widgets, a high-tech electronics product that requires substantial use of surface mount technology (SMT).

The trend towards ever increasing global competition has forced many manufacturing companies to rethink the way they approach manufacturing. Acme Mfg. Widgets Products Group, WPG, long the global leader in the design and manufacture of widgets recently faced the possibility of being cut-off from critical manufacturing technology. Their current manufacturing process relies heavily upon chip placement machines supplied by external vendors.

The entry of one these suppliers into the widgets market caused great consternation among Acme Mfg.'s top management and a program was initiated to reduce Acme Mfg.'s reliance upon externally supplied proprietary manufacturing technology. As a result of this initiative, Acme Mfg. has embraced an open architecture for its factories and has tried to standardize upon a single technology in any given category. For example, Acme Mfg. has chosen UNIX as the preferred technology in the operating system category. Similarly, they have elected to program in C++ and communicate via Ethernet. Because all of these products are supplied by a large number of vendors, Acme Mfg. believes that competition among vendors will insure technological advancement and

price reduction. It is believed that standardization will reduce complexity and training costs.

In the fields of robotics and chip placement machines, Acme Mfg. could not find a vendor willing to supply a non-proprietary system. Thus standardization meant being at the mercy of a single supplier. The Widgets Products Group felt that they had already done their share of debugging vendors products and wanted to "control their own destiny in the future."[1] Additionally, WPG realized there were a number of material handling tasks that did not require the accuracy provided by the vendor's robots. Unable to find a market mechanism to insure price competitiveness and product effectiveness, Acme Mfg. decided to study the feasibility of building their own robots. The feasibility study included a survey of alternatives to the vendor's robots and a survey of vendors who produced components used in the construction of robots. These surveys confirmed two ideas that Acme Mfg. held. First, there was not an acceptable alternative to the vendor's robots, and second, the cost of the sum of the components was substantially less than the cost of a completed robot. Typically, robot manufacturers only produce the structure and controller while the motors, encoders, bearings, amplifiers, and power supplies are purchased from external suppliers.

Acme Mfg.'s Automation Engineering group had been extremely successful in integrating technologies to produce automated factories. Furthermore, the engineers were very adept at writing the computer coding necessary to create an automated factory. Acme Mfg. felt the construction of a robot entailed the integration of components, the

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[1] Interview by the author with an Acme Mfg employee.

generation of software, and the creation of a structure. In this light, the construction of a robot seemed well within their capabilities.

Although Acme Mfg. was essentially correct in this estimation, they vastly under-estimated the skills required to build a high performance machine from the components. Viewing systems integration as their strength, Acme Mfg. elected to purchase the controller and to build the structure out of aluminum extrusions. The vendor of aluminum extrusions also produces a full line of bolted connectors and machine components for the construction of manufacturing equipment and work stations. The chief virtue of this product line is its "erector set" ease of producing machinery.

Because of Acme Mfg.'s skill in integration, software development, and project management, they were able to produce a working gantry robot in the remarkably short period of 6 months. However, the machine did not fulfill all of Acme Mfg.'s expectations and Acme Mfg. decided to offer the improvement of the gantry robot to MIT as a master's thesis project.

As a fellow in the Leader's for Manufacturing Program, I was assigned the task of improving the performance of this gantry robot. The initial inspection of the machine found the structure to be too compliant. Acme Mfg. had attempted to reduce this compliance by adding corner braces where possible. Although these braces proved somewhat effective, they did not achieve the performance goals that Acme Mfg. desired.

Redesigning the structure to improve rigidity was recommended, but Acme Mfg. wanted to retain the ability to size the machine for different tasks. If possible, Acme Mfg.

wanted to develop a control system to compensate for the compliance in the structure, thus enabling them to retain a scaleable structure.

This thesis introduces a methodology for improving the machine's performance by comparing the incremental changes in performance, caused by changing a single component of the system. This methodology is introduced in chapter 3 and is applied to the Acme Mfg. gantry in chapter 4. Chapter 2 describes the gantry robot in detail.

Although the methodology proved to be moderately successful at improving the performance of the gantry robot, the performance was ultimately limited by a number of factors. Based upon these factors, a second robot was designed considering both the structure and the control system. This machine is described in chapter 5.

Finally, a methodology to assist management in the assessment of their strategic manufacturing needs is proffered in Chapter 6. This methodology provides management a new perspective on the strategic interrelationships between manufacturing and design competencies. The perspective offered can be used to assess manufacturing needs, conduct competitive analyses, find areas of opportunity, uncover weaknesses, and aid in the make versus buy decision. An example of these usages is provided in chapter 7.

Literature Survey

The machine improvement strategy introduced in this paper is based upon prior work in the field of space-structure design. A subset of this field is integrated structure/controller design. The original work in integrated structure/controller design was conducted in order to develop robotic manipulators for the space program, and is characterized by various mathematical optimization techniques. Typically, a model is

used to describe the dynamic behavior of the system, and an analysis is conducted which aims to maximize a performance function while minimizing a cost function. The subject of space-structure design is extensively covered in Eschnauer et. al.[1]. Integrated structure-controller design has been applied to the problem of minimizing the weight of a machine structure subject to modal damping equality constraints and cross-sectional area inequality constraints of the structural members by Khot, Venkayya et. al.[2]. Miller and Shim used a gradient base technique to optimize the sum of structural and control parameters[3]. The problem of obtaining a set of control forces and structural parameters that minimize a specific cost function has been solved by Hale, Lisowski et. al.[4]. An eigenspace optimization technique which simultaneously optimizes over a machine's structural and control parameters has been developed by Bodden and Junkins[5]. A computer-aided procedure has been developed by Rai and Asada that decomposes the sensitivity matrix in order to aid the designer in the selection of an optimal geometry, and has been applied to a flexible arm[6]. A concurrent structure/control design method has been used by Park and Asada to optimize the performance of a high speed two link robot[7].

The methodology proposed herein differs from prior work by focusing on the unit manufacturing costs of the product produced by the machine rather than the cost functions of the machine, and by evaluating the performance of purchased components rather than design parameters.

The strategic assessment methodology proposed is based upon work by Hamel and Prahalad[8] in core competencies of a firm and in resource leverage[9]. A framework for applying these concepts simultaneously to a firm's product offering is described. The framework consists of constructing a three dimensional array based upon a firm's products, design needs, and manufacturing tasks.

Chapter 2 - The Acme Mfg. Gantry Robot

Gantry Description

The Acme Mfg. gantry robot is shown in figure 2.1. As mentioned above, the primary design goal of this machine is to provide Acme Mfg. with a means of quickly constructing automated manufacturing cells. A key feature of the gantry design is its scaleability. This is accomplished through the use of aluminum extrusions and bolted joints. Unfortunately, this asset is also one of the machine's greatest liabilities because the construction technique fails to provide the required rigidity.

As of May 1994, twenty of these machines had been built in five different sizes for conducting five different assembly tasks. These machines share a number of common features. They are capable of generating four degrees of freedom: translations in the x, y, and z directions and rotation about the z axis, which is defined as the theta (θ) axis. Starting at the end effector and working back to the structure, the gantry robot consists of a number of purchased components. The end effector is held by a tool changer that allows the machine to use multiple end effectors. The tool changer, in turn, is connected to a device called a break-away-joint . A break-away-joint shuts down the machine when a collision is detected between the end effector and an unexpected obstacle. This device provides insurance for some very expensive end effector tooling. Unfortunately, the device also adds weight to every axis of motion.

The break-away-joint is connected to a 50:1 harmonic drive that is driven by a brushless DC motor. This motor/transmission pair provides motion about the θ axis and

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Timing Belt

Pulley

Pulley

Connecting Drive Shaft

Timing Belt

Pulley

Pulley

X- axis motor and gearbox

Carriage
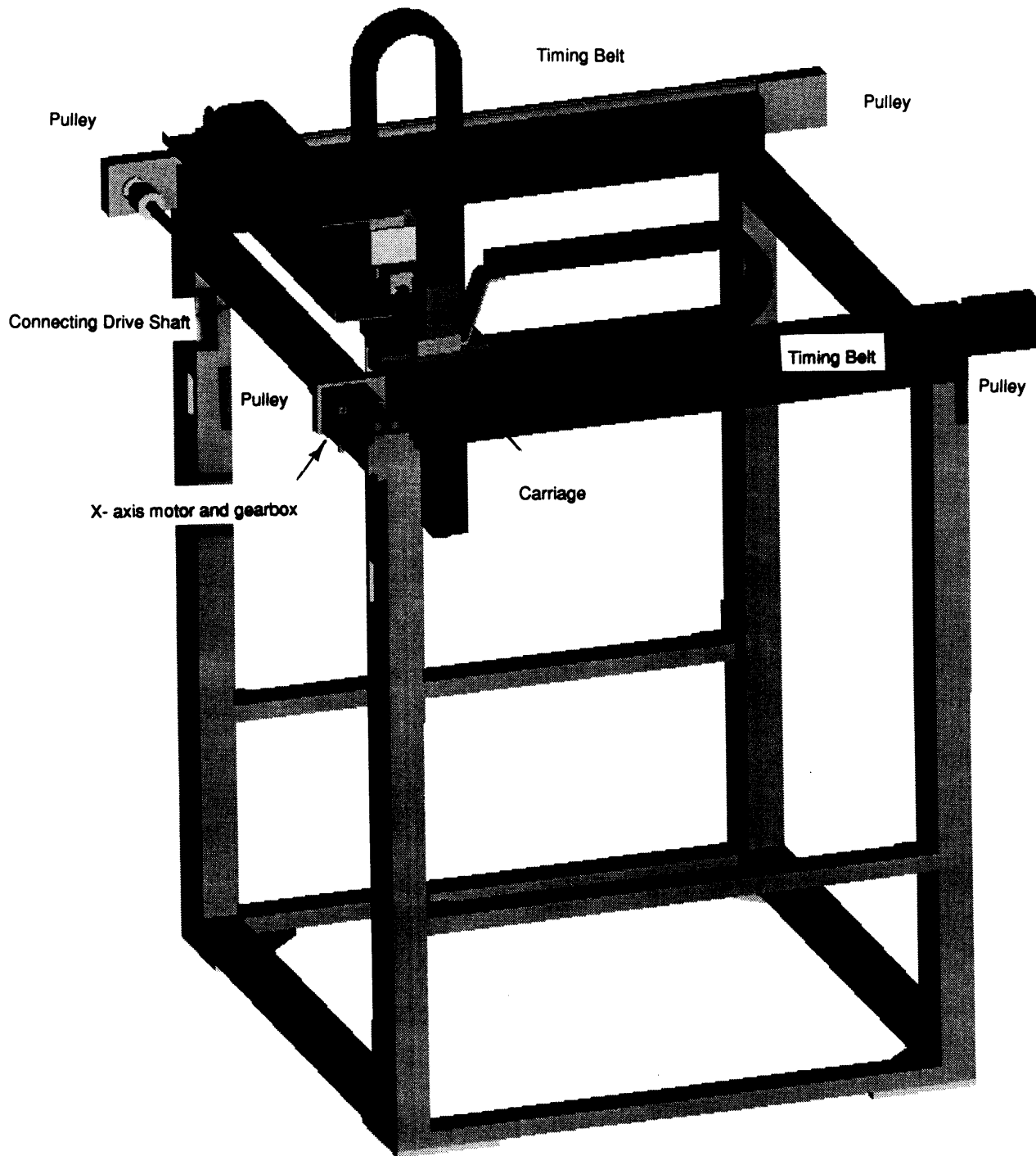
Figure 2.1 - Acme Mfg. Gantry Robot

is used to actuate rotational changes of the end effector. The harmonic drive is mounted at the end of the z-axis aluminum extrusion and the motor and its resolver reside inside of the extrusion. The z-axis is mounted to the y-axis using a recirculating ball linear bearing. The ball bearing slider cars are mounted on the y-axis carriage plate and the ground rail is bolted to the z-axis aluminum extrusion. A pneumatic counter balance is used to support the weight of the z-axis. A brushed permanent magnet DC servo-motor turning a 10:1 gearbox is used to raise and lower the z-axis via a toothed belt and pulley arrangement. Position sensing is handled by a rotary optical encoder mounted on the motor shaft.

The y-axis carriage plate rides on a pair of recirculating ball linear bearings mounted on the top and bottom of the y-axis extrusion. A looped belt is connected to two sides of the carriage plate. The looping is accomplished using an idler pulley and a drive pulley. The drive pulley is driven by a 5:1 gearbox and a brushed permanent magnet DC servo-motor. Position sensing is accomplished by a rotary encoder mounted on the motor shaft and/or a linear encoder mounted along the y-axis aluminum extrusion. The y-axis is a bridge arrangement and is therefore supported on both ends. Each end is bolted to a carriage plate that rides on a recirculating ball linear bearing. These bearings make up the x-axis which also consists of two aluminum extrusions and a pair of looped belts to drive the two carriage plates. A brushed permanent magnet motor driving a 5:1 planetary gear reducer drives one of the drive pulleys which turns a long drive shaft that drives the other drive pulley. The two idler pulleys are not connected. The desired effect of this

arrangement is to maintain orthogonality between the x and y axes during translation of the y-axis.

The x-axis is mounted approximately six feet above the ground, supported by four aluminum extrusions. The four aluminum columns are braced by four horizontal members and a variety of angle braces depending upon the installation requirements. This structure also supports the electrical cabinetry that houses the servo-amplifiers, power supply, transformer, and safety system.

The control scheme consists of a VME bus-based computer that acts as a cell controller, communicating with the factory host via an ethernet card. The cell controller can control two gantry robots and their end effector tooling. The actual servo control is handled by a pair of 4-axis vendor supplied controller cards, one for each gantry. These controllers are only capable of producing trapezoidal trajectories. The control signals are amplified by pulse width modulation amplifiers that operate in torque mode.

Chapter 3 - Development of a Solution Methodology

Problem Statement

Although the initial machines did not meet Acme Mfg.'s design goals for speed and accuracy, the machines successfully performed their intended task. Because the operation took longer than expected, a reduction in cycle time was required to keep pace with the rest of the automated factory. Similarly, the lower than desired accuracy of the machine precluded its use in a number of Acme Mfg.'s manufacturing operations. A solution that required minimal re-design of the existing structure was desired, but the limited programmability of the original controller made a controls solution all but impossible. As a work around, Acme Mfg. elected to experiment with another controller which provided increased programmability.

Solution Methodology

First it must be stated that in order to achieve high performance from an assembly machine, the design must successfully integrate both the structure and control design. The old approach of producing a static and kinematic design of the structure followed by a design of the control system fails to account for the intricate interactions that occur between the structure and the control system.[2] As the speed and accuracy requirements of the machine are raised, these effects becoming increasingly important. Thus, a solution methodology that only addresses the control sub-system of the assembly machine is

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[2] Jahng-Hyon Park and Haruhiko Asada. "Concurrent Design Optimization of Mechanical Structure and Control for High Speed Robots." (Accepted for publication in the *ASME Journal of Dynamic Systems, Measurement, and Control*).

limited in its ability to correct the problem. It should be noted that for any linear third order or higher system, there exists an optimal control solution.

The solution strategy was to model the existing machine using linear elements and then find the optimal control solution. Because the Acme Mfg. engineers had most likely already found or were at least near the optimal controller proportional and velocity gains (K_p and K_v), there was little reason to believe that a mathematical determination of the optimal gains would provide a significant performance improvement. On the other hand, once the mathematical model had been constructed the performance effects of possible component substitutions could be predicted. For example, a stiffer transmission could be tested by changing the model to reflect the new transmission's stiffness and damping characteristics. The basic idea was to find the most cost effective component substitutions that could be made to improve the performance.

This technique differs from a typical parametric design study which would determine the effect of each dynamic parameter upon the desired performance goal. It was decided to perform the analysis for components because many components affected multiple dynamic parameters and because it was much easier to compute the costs. The solution methodology therefore consists of the following steps:

1. Model the plant
2. Model the controller
3. Find the optimal values of K_p and Kv, the values that produce the fastest settling, by using the root locus plot
4. Change a component of the machine
5. Find optimal values of K_p and K_v for the modified machine
6. Repeat steps 4 & 5 for all components under consideration

7. Based upon the real part of the root found in steps 3 or 5, calculate the cycle time for completing the manufacturing operation

8. Based upon the cost of the component, determine which component provides the lowest unit manufacturing cost where the unit manufacturing cost is the annualized cost of the machine divided by annual total production. If the annual total production is unknown, the theoretical capacity of the machine may be substituted. If none of the components improve the unit manufacturing cost, then the current basecase is the optimal set of components.

9. Add this component to the basecase, eliminate all other choices for this component, and repeat steps 3 through 9 for the remaining component choices. Continue until an iteration does not improve the unit manufacturing cost. The basecase of this iteration is the optimal set of components.

Choice of Goals

The design goal for this methodology is to minimize the settling time as cost effectively as possible. The selection of this goal stems from the general underlying goal of all assembly machines, which is to bring two items together and then effect some change in their relationship to each other as cheaply as possible. In other words, the general goal is to effect a relative change in the position and relationship of two items as cheaply as possible. The two items could be a chip and a printed circuit board, the two halves of a housing, or a windshield and an adhesive dispensing nozzle. It is instructive to think of the assembly process as consisting of a positioning step and an operation-at-point step. The positioning step is used to bring about a relative change in position of the two items, and the operation-at-point step effects a change in the relationship between the two items. For example, in the case of the printed circuit board and chip, the position step is the motion required to move the chip from where it was

picked up to its correct location and orientation on the printed circuit. The operation-at point-step is the physical tacking of the chip to the board via the solder paste. The relationship change is from not being attached to being attached. The machine's cycle time is the sum of the times required to complete all of the positioning steps and operation-at-point steps. It is assumed that the operation-at-point step's cycle time is fixed and not affected by the structure or control.

The time a machine takes to complete an operation is inversely proportional to the number of operations a machine can complete in a given amount of time. Thus, the manufacturing costs on a per unit basis decrease as the cycle time decreases. Since this relationship always hold true for a given set of components and there is no cost associated with changing the controller gains, the most efficient operating point for any set of components is the operating point that minimizes cycle time, assuming no changes in machine reliability. For these reasons, the design goal was to minimize settling time as cost effectively as possible.

Settling Time

Most high precision assembly processes consist of a stationary item and a dynamic item. In order to perform the operation, the dynamic item must be accelerated from rest, translated and rotated, and brought to rest in the desired position and orientation. The objective is not raw speed but rather a short cycle time to complete the operation.

In the language of dynamic systems, this goal is referred to as minimizing the settling time. Settling time is defined as "the time required for the response curve to

reach and stay within a range about the final value of size specified by absolute

percentage of the final value (usually 2% or 5%)."[3] A graphical representation is given in

figure 3.1.

Definition of Settling Time
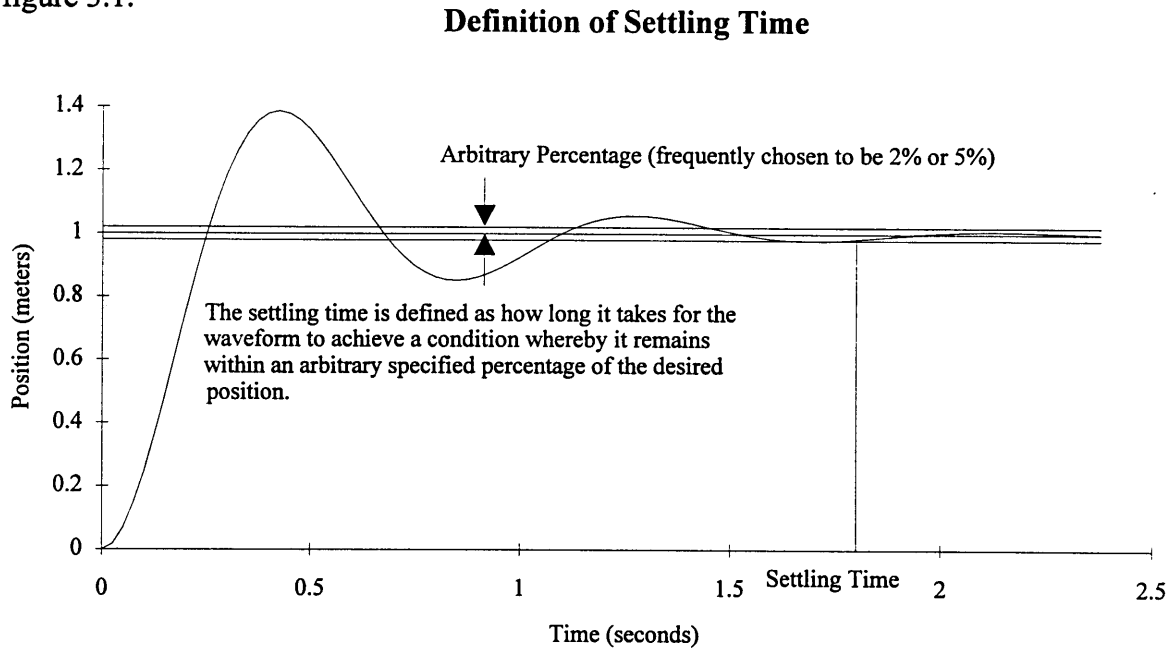
Figure 3.1 - Definition of Settling Time

Complications Introduced by Closed Loop Feedback Systems

The choice of a closed loop feedback control system adds to the complexity of

predicting the settling time because the system can oscillate about the desired final

position as shown in figure 3.1. An introduction to closed loop feedback systems is given

in Appendix 1. It should be noted that these oscillations are a function of the dynamic

parameters of the machine and the gains of the controller.

The closed loop feedback system functions by comparing the actual state of the

system with a reference state and then sending a control command to the actuator that is

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[3]   Katsuhiko Ogata. Modern Control Engineering. (Prentice-Hall, Inc., Englewood Cliffs, New
Jersey, 1990) 266.

proportional to the error -- the difference between the reference state and the actual state. The proportionality constant is referred to as the proportional gain and has units of the signal input to the controller divided by the units of the signal input to the plant. Thus if the signal input to the plant has units of newtons (force) and the feedback and reference signal have units of millimeters, the proportional gain would have units of N/mm. Because the components of the assembly machine are capable of storing energy and there is a very slight delay between when the plant reaches a state and when this state is reported to the controller, the servo system can oscillate. Fortunately, control theory provides a mathematical means to deduce the settling time from a model of the system.

The Root-Locus Plot

The root-locus plot shows a designer the real and imaginary parts of the roots of the system as function of a variable parameter of the system. Based upon the mathematically modeled transfer function of the plant and the controller, a root-locus plot can be constructed by using an arbitrary velocity gain and by arranging the equations in such a way that the proportional gain becomes the variable parameter. The root-locus will then graphically display the real and imaginary parts of the roots of the system's characteristic equation for all values of the proportional gain between zero and infinity. Since the real component of the root is proportional to the settling time of the system, this technique can be used to estimate the settling time. The proportional gain value that produces the fastest settling time is recorded. The velocity gain is then incremented and the process repeated. By using a search algorithm, the values of the proportional gain and velocity gain that minimize the settling time can be determined..

For second order and lower systems, there is no optimal gain setting. A higher proportional gain setting will always improve the performance if the velocity gain is adjusted to maintain the appropriate damping ratio. For third order and higher systems, there exists a gain setting where a number of the poles possess the same real component. If the locus of one set of poles moves towards the imaginary axis as the proportional gain is increased, and the other set of poles moves away from the imaginary axis, then the point where the two have equal real components is the optimal gain setting.

The optimal gain settings for fourth order systems can be determined mathematically. The optimal gain settings for higher order systems require the use of search algorithms. Once the optimal gain settings have been determined, the real component of the dominant poles is recorded.

The technique is now repeated for a different set of components. For example, a different motor could be inserted into the model. If the motor's stator is lighter, it will add less mass to the system's structure. If the motor's rotor inertia is lower, it will add less inertia to the moving part of the system. Of course, if it costs more than the original motor, the improved settling time may not be enough to justify this added cost.

Although this technique is fairly straight forward, a number of complications arise in its use. The proportional gain provided by the root-locus is usually not the value that is entered into the controller as K_p. This occurs because there are a number of other factors that affect the proportional gain of the system. K_p therefore must be derived by dividing
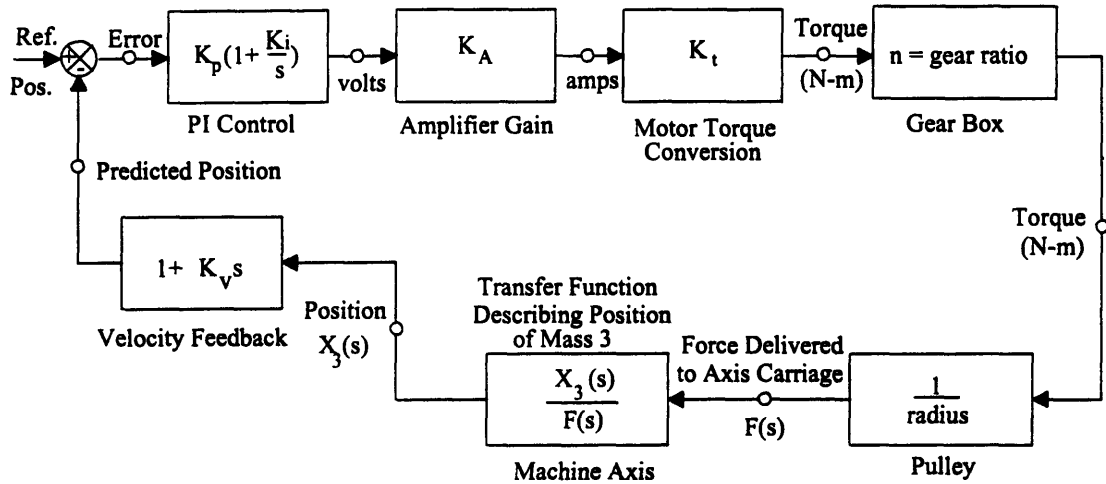
Figure 3.2 - Block Diagram of X-axis Servo System

the optimal gain (from the root locus plot) by the product of the system's other proportional gain terms.

The cycle time derived from the real part of the root also assumes that the system is linear. While this assumption holds for many machines in a limited range, a check must be performed to insure that the system remains within this range. The system is said to saturate when it exceeds its linear operation range.

Calculating K_p and Avoiding Saturation

A diagram of the servo-chain for the Acme Mfg. gantry robot is given in figure 3.2. The controller is the first component to introduce a proportional gain to the system. Ignoring all other controller gains, this gain multiplies the error by K_p which has units of Volts/Length. Since the controller can only produce an output of -10V to + 10V, if the product of K_p and the error exceed this value, the controller will only put out 10V. Thus

the onset of saturation is a function of K_p and the magnitude of the error. In order to determine the error size at the onset of saturation, one must first determine K_p.

The next proportional gain encountered in the system is the amplifier gain which is set at a constant 3Amps/Volt. Continuing through the servo chain, the next gain encountered is the Motor Torque Conversion K_t which converts the input amperage into a torque. For the x-axis motor, $K_t = 1.34$ lb-in/amp. Converting this to MKS units produces .151 N-m/amp. The gear box then multiplies the torque by 5. The pulley converts the torque into a force by dividing the torque by the radius of the pulley which is .02 m. The proportional gain in the controller should therefore be set equal to:

$$K_p = \frac{\text{Optimal Gain from the Root Locus}}{\text{Amplifier Gain} \times \text{Motor Torque Conversion Gain} \times \text{Gearbox Gain} \times \text{Pulley Gain}}$$

The onset of controller saturation can then be determined by dividing 10V by K_p. Whenever, the error exceeds this value, the controller will saturate. Saturation is avoided by specifying a trajectory instead of a final destination.

The controller is not the only component in the system that can saturate; therefore, all components that can saturate must be checked. The PWM amplifier produces two non-linearities due to its two current overload protection circuits. The first one is set at 15 amps to insure that the motor never sees more than 15 amps. Notice that this corresponds with a -5V to 5V operating region of the controller due to the amplifiers 3A/V gain. The second limit is a root mean square limit which insures that the motor does not see high currents for long periods of time. The onset of this circuit is set as a

percentage of the first circuit's limiting value. This circuit then reduces the current delivered to the motor using an exponential functional. When this circuit is set to 50% and the first circuit is set to 15 amps, a constant input signal of 10V produces an output of 15 amps that exponentially decays to 7.5 amps. A constant 2.5V input produces a constant 7.5 amp output. When set this way, the linear operating region of the controller and amplifier is reduced to -2.5V to 2.5V, one fourth the intended operating range. In order for the root locus methodology to accurately predict the settling time, linearity must be insured. As such, the onset of saturation must be divided by 4. Limiting the error to values below this number will insure linear operation.

Calculating Unit Manufacturing Cost

The time required for the machine to complete a move will be approximately equal to 5 times the inverse of the real part of the root, assuming no saturation, regardless of the length of the move. In control theory, the real part of the root is denoted as σ. The settling time can therefore be stated mathematically as : $t_{total} = t_s \cong \frac{5}{\sigma}$

In case of saturation, this formula will not apply. Typically saturation is avoided by generating a trajectory. This technique strives to limit the maximum error signal to a value that is within the linear range of the system. The cycle time for a move that uses a trajectory can conservatively be estimated by summing the theoretical time required to complete the trajectory plus the aforementioned settling time.

$$t_{total} \cong t_s + t_{trajectory} \cong \frac{5}{\sigma} + t_{trajectory}$$

The simplest trajectory to specify is a trapezoidal trajectory. The user specifies the acceleration, maximum velocity, and final destination. The controller then determines

the trajectory. For example, if the acceleration is set to 1 m/sec^2, the maximum velocity to 2 m/sec, and we wish the machine to travel 10m, then the controller will produce the trajectory shown in figure 3.3.

Trapezoidal Trajectory

Maximum Velocity = 2 m/sec

Area Under Curve = 10 meters

Theoretical time to complete move = 7 seconds

Velocity (m/sec)

Time (sec)
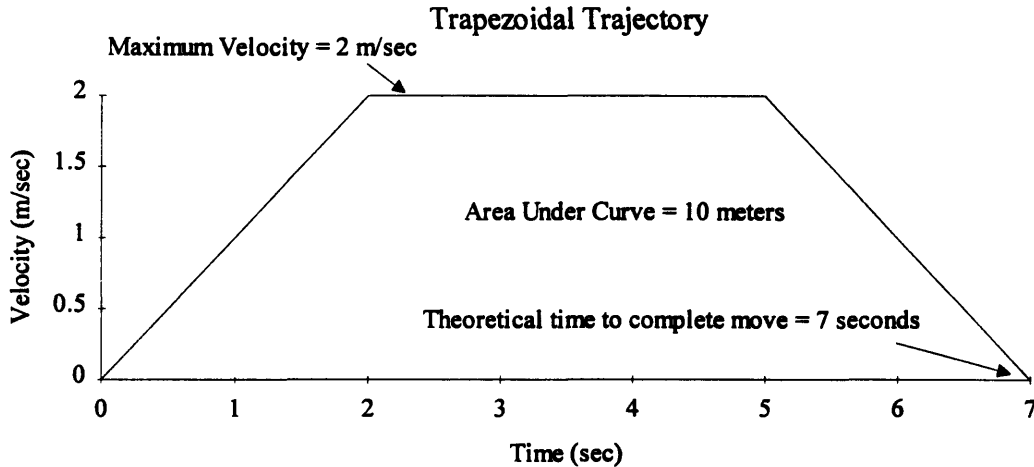
Figure 3.3 - Trapezoidal Trajectory Requiring 7 seconds to move 10 meters

The controller integrates the velocity trajectory to obtain a reference position function that is a function of time. The controller calculates the error as the difference between the planned position evaluated at time t and the actual position at time t. Basically, the machine makes a series of small moves without stopping between successive points and therefore reduces the size of the error signal.

The cycle time of the machine is calculated by summing the time required to complete all of the positioning steps and the operation-at-point steps.

The unit manufacturing costs are calculated based upon the anticipated annual uptime of the machine, the annualized cost of the machine, and the cycle time. For example, if the machine costs $300,000, and is expected to have a life of three years, the

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cost can be converted into an annualized number by finding the uniform series equivalent using the firm's cost of capital. The formula for this is:

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$$

Where A is the uniform series equivalent, P is the present value, n = the number of periods, and i = the interest rate. If the firm's cost of capital is 10%, the resulting annualized cost will be $120,634. Alternatively, straight line depreciation or accelerated depreciation could be used. The machine's theoretical capacity is then determined by dividing the annual uptime by the cycle time. The unit manufacturing cost is then the annualized cost divided by the machine's capacity. A more accurate cost can be determined by dividing the annualized cost by the firm's actual annual production for the machine in question. Care must be exercised if the theoretical capacity of the machine vastly exceeds the expected annual production. Basing design decisions upon the cost divided by capacity number is risky if the capacity and actual production volume are significantly different.

Chapter 4 - Application of the Methodology

Modeling the Plant

The simplest method for modeling an assembly machine is lumped parameter modeling. Lumped parameter modeling breaks the assembly machine into masses, dampers, springs, and actuating forces. Figure 4.1 shows the ideal case.
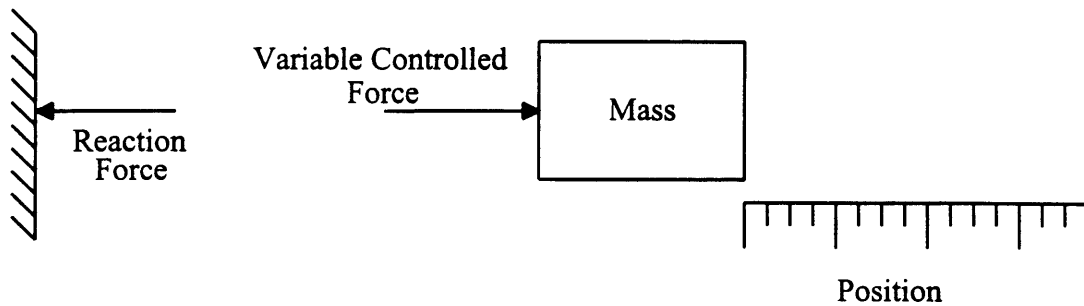
Figure 4.1- Idealized Assembly Machine, Lumped Parameter Model

A variable force controlled by a controller is used to position a mass. The transfer function of this system is a second order equation as discussed in Appendix 1. Actual machines may have some compliance in the transmission. In other words, there is some flexibility between where the force is being generated and where the position is being measured. The lumped parameter model for this condition is displayed in figure 4.2.
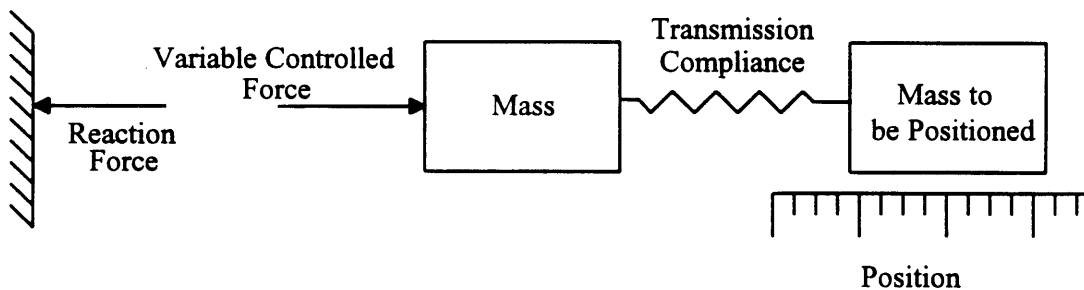
Figure 4.2 - Lumped Parameter Model of a Machine with Transmission Compliance

The machine structure may also be compliant. Because the generation of force requires that an equal and opposite force also be generated, the structure of the machine must transmit this reaction force to the ground. A well designed machine will accomplish this without perceptible movement. A compliant structure is modeled in figure 4.3. A compliant transmission or a compliant structure increases the order of the system to 4.
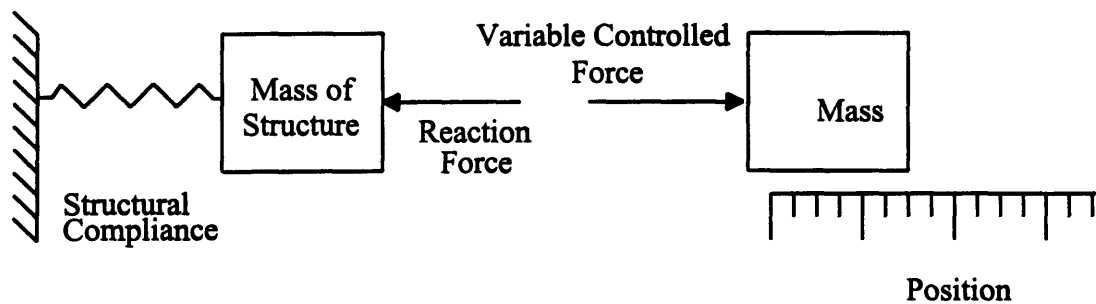
Figure 4.3 - Lumped Parameter Model of a Machine with a Compliant Structure

The combination of both a compliant structure and a compliant transmission results in a sixth order system and is shown in figure 4.4.
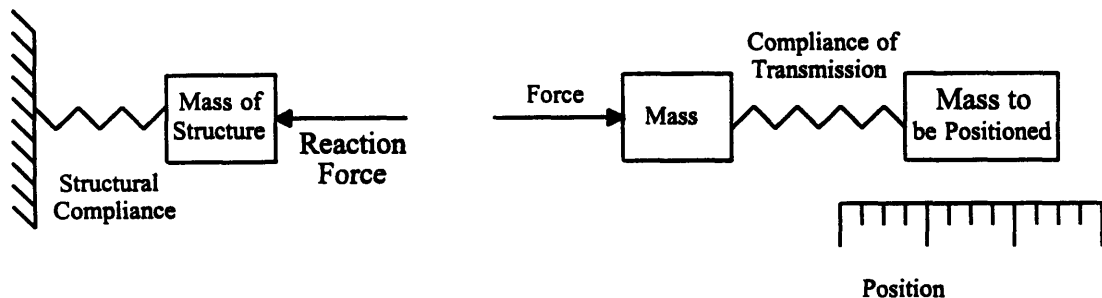
Figure 4.4 - Lumped Parameter Model for a Machine with Compliant Structure and Transmission

The Acme Mfg. Gantry Robot design is at best a 6th order system. The lack of structural rigidity created primarily by the four long columns adds at least two orders to the system. The transmission is plagued by a number of flexible components and a lack

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of symmetry. In the case of the x-axis, the possible sources of compliance in the drive system are the motor shaft, the gear reducer shafts, the gear teeth, the drive shaft, the belt teeth, and the urethane belts. This particular machine is extremely difficult to model because the side nearest to the drive motor and gearbox (the near side) does not encounter the compliance introduced by the torsional twist of the connecting drive shaft that turns the other side (the far side). The net effect is that both sides do not receive the same force input at the same time. The unequal forces cause one carriage to accelerate faster than the other, producing skewing of the y-axis. This skewing motion is exacerbated by the y-axis position of the machine. As the y-axis carriage deviates from the center of the y-axis, one of the x-axis carriages will be carrying a considerably higher percentage of the mass than the other x-axis carriage.

As the y-axis is forced out of an orthogonal orientation relative to the x-axis, the horizontal loading on the linear bearings is increased. This increases the viscous, dynamic and static friction acting in the x direction. From a modeling perspective, the assumption is made that this friction is viscous and the damping is constant. Clearly this assumption does not hold for the gantry robot, but the effect may be within an acceptable degree of error. From a controls perspective, it means that the tuning of the controller gains must be robust enough to tolerate the changes in damping. Frequently, the need to maintain controllability over a wide range of damping results in a lowering of the proportional gain and a longer settling time.

In addition to the variable damping coefficients, the belts cause the spring rates acting on the carriages to vary. This phenomenon occurs because the stiffness of the belt is inversely proportional to its length. Not only are the spring rates variable, but they are also anisotropic. The belt has a finite stiffness when it is loaded in tension but has a very low or zero stiffness when loaded in compression. Looking at the near side carriage, it is apparent upon close inspection that the belt length between the drive pulley and the carriage is always shorter for the piece pulling the carriage towards the motor than for the piece that pulls the carriage away from the motor. As the y-axis traverses the x-axis, one piece of the belt is getting longer -- hence more compliant -- while the other piece is becoming shorter -- hence stiffer. Contrast this behavior with a ballscrew which has equal stiffness in tension and compression. The linear realm of lumped parameter modeling does not provide a means of coping with the variable stiffness or the anisotropy. Clearly, this machine would never appear in a textbook explaining lumped parameter modeling.

In order to model this machine, a number of assumptions were necessary to fit a linear model. These assumptions were:

1. No static or dynamic friction
2. Constant damping terms
3. Constant spring rates

Although these assumptions were clearly overly optimistic, it was hoped that the machine would exhibit quasi-linear behavior for short moves because the belt length changes would be minimized. Also, by conducting tests at the far end of the machine, the two

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pieces of the belt would be as near equal as possible. The lumped parameter model

displayed in figure 4.5 was used to construct a transfer function of the machine's x-axis.

Lumped Parameter Model
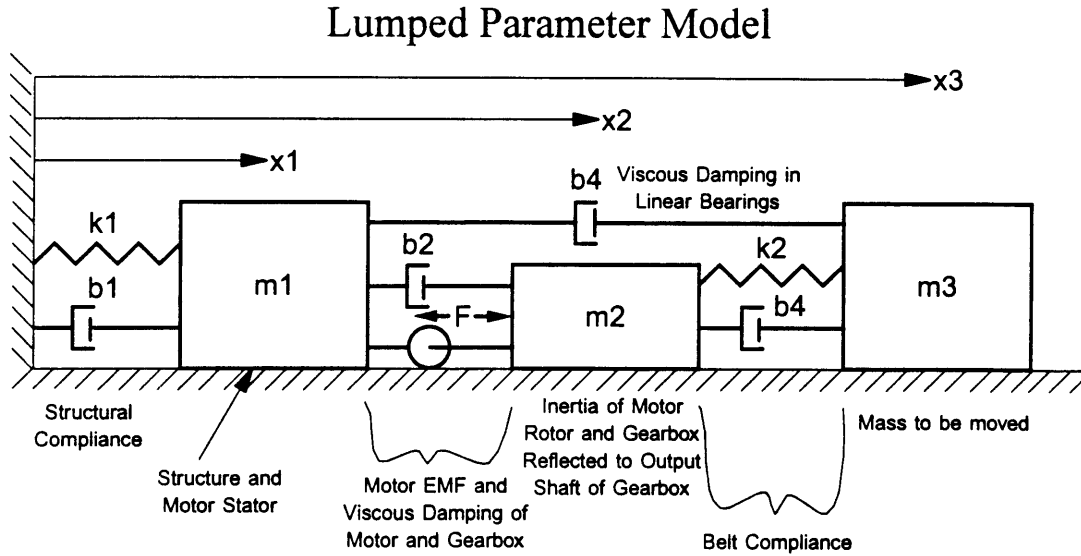
Figure 4.5 - Lumped Parameter Model of Gantry Robot

$$\frac{X_1(s)}{F(s)} = \frac{-m_2 m_3 s^4 - (b_3 m_2 + b_3 m_3 + b_4 m_2)s^3 - (m_2 k_2 + m_3 k_2)s^2}{m_1 m_2 m_3 s^6 + a_1 s^5 + a_2 s^4 + a_3 s^3 + a_4 s^2 + (b_2 k_1 k_2 + b_4 k_1 k_2)s}$$

$$\frac{X_3(s)}{F(s)} = \frac{(b_3 m_1 - b_4 m_2)s^3 + (b_1 b_3 + k_2 m_1)s^2 + (b_1 k_2 + b_3 k_1)s + k_1 k_2}{m_1 m_2 m_3 s^6 + a_1 s^5 + a_2 s^4 + a_3 s^3 + a_4 s^2 + (b_2 k_1 k_2 + b_4 k_1 k_2)s}$$

Where:

$a_1 = b_2 m_1 m_3 + b_3 m_1 m_2 + b_3 m_1 m_3 + b_4 m_1 m_2 + b_1 m_2 m_3 + b_2 m_2 m_3 + b_4 m_2 m_3$

$a_2 = b_2 b_3 m_1 + b_2 b_4 m_1 + b_3 b_4 m_1 + k_2 m_1 m_2 + k_2 m_1 m_3 + b_1 b_2 m_3 + b_1 b_3 m_2 + b_1 b_3 m_3 + b_1 b_4 m_2$
$\quad\quad + b_2 b_3 m_2 + b_2 b_3 m_3 + b_2 b_4 m_2 + b_2 b_4 m_3 + b_3 b_4 m_2 + b_3 b_4 m_3 + k_1 m_2 m_3$

$a_3 = b_2 k_2 m_1 + b_4 k_2 m_1 + b_1 b_2 b_3 + b_1 b_2 b_4 + b_1 b_3 b_4 + b_4 k_2 m_2 + b_1 k_2 m_3 + b_2 k_2 m_2 + b_2 k_2 m_3 +$
$\quad\quad b_4 k_2 m_2 + b_4 k_2 m_3 + b_2 k_1 m_3 + b_3 k_1 m_2 + b_3 k_1 m_3 + b_4 k_1 m_2$

$a_4 = b_1 b_2 k_2 + b_1 b_4 k_2 + b_2 b_3 k_1 + b_2 b_4 k_1 + b_3 b_4 k_1 + k_1 k_2 m_2 + k_1 k_2 m_3$

Figure 4.6 - Transfer Functions for the Structure and Carriage of the Gantry Robot

The transfer functions for mass 1 and mass 3 are shown in figure 4.6.

Identification of the Plant

Once the model has been constructed, the next step is to determine the actual values for the design parameters: b_1, b_2, b_3, b_4, k_1, k_2, m_1, m_2, & m_3. The masses are the easiest to determine, and their masses were identified by weighing the components associated with each of the three masses in the model. The stiffness of the structure, k_1, was identified by using a spring scale to act as a force gauge and a dial indicator to measure the deflection. A number of forces were applied to the structure and the deflections were recorded. The forces were then plotted versus the deflections, a line was fit, and the slope of the line was used as k_1.

The structural damping, b_1, was determined by using the logarithmic decrement method. This method requires the measuring of the structure's response to an impulse. This is accomplished by hitting the structure with a small hammer and then measuring the position of the structure as a function of time. The difference in magnitude of two successive wave forms are used to calculate the damping constant.

The belt stiffness was determined by using an Instron tensile tester to determine the spring constant. It is believed that the value determined in this manner overstates the effective value. This discrepancy arises because the drive belt is rigidly clamped on both sides for tensile testing, whereas in use, only the teeth of the belt engage the drive pulley. The other damping constants were estimated from manufacturers' data.

Modeling the Controller

The compliance in the structure also increased the difficulty of modeling the closed loop feedback. The linear encoder measures the lineal difference between the

structure and the carriage and is therefore feeding back the difference between x_3 and x_1.

To account for this effect, the block diagram is modified to account for the movement of

the base as well as the carriage. In control jargon, the carriage that is moved by the servo

system is referred to as the plant. Hence, its transfer function is labeled $G_p(s)$. The

transfer function for the base is labeled $G_{base}(s)$. The closed loop transfer function is then

solved using block diagram algebra. The resulting closed loop transfer function, $G(s)$, is

given at the bottom of figure 4.7.

Closed Loop Transfer Function
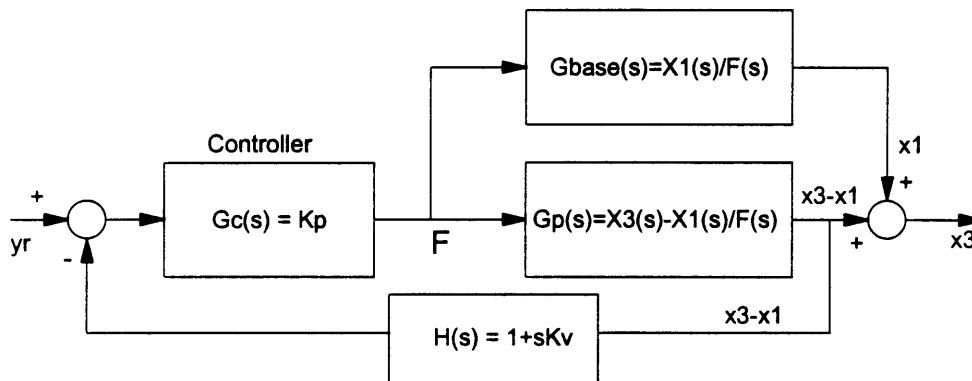
$$G(s) = \frac{X3(s)}{Yr(s)} = \frac{Gc(Gp + Gbase)}{1 + GcGpH}$$

Figure 4.7 - Closed Loop Transfer Function of Gantry Robot

Using the Root Locus to Determine K_p, K_v, and the Settling Time

The resulting transfer function can be converted from the s operator domain to the

time domain by taking the inverse LaPlace Transform of the transfer function as was done

in Appendix 1. This technique produces a series of sine, cosine, and exponential

functions of time that are the system's response to a unit impulse input. This equation

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can be integrated to determine the system's response to a unit step function. The 2% criteria could then be applied to determine the settling time. Fortunately, there is an easier way.

The closed loop poles are the roots of the characteristic equation. Since the characteristic equation changes as the proportional gain is varied, the roots of the characteristic equation change. W.R. Evans invented a graphical technique known as the root locus method that shows the location of the poles in the real-imaginary plane as a function of a parameter of the system. Because the real part of the root is proportional to the settling time of the system, this method may be used to estimate settling times. The further to the left of the imaginary axis the pole is located, the lower the settling time. Poles located on the imaginary axis never damp out and poles located to the right of the axis exhibit oscillations whose magnitude increases as a function of time.

For fourth order and higher systems, there exists at least one combination of proportional gain and velocity gain that results in the four slowest poles being located the same distance from the y-axis. Because two of the poles are headed in the positive direction and two of the poles are headed in the negative direction, the gain values where both pairs are located the same distance from the imaginary axis are the optimal gain values. If either gain is increased or decreased, one of the two pairs of poles will move closer to the imaginary axis and thus yield a less optimal settling time.

Figure 4.8 displays the 6 poles and five zeroes for the lumped parameter model when controlled by the controller shown in figure 4.7. In order to verify the model, in

m1=70.72 m2=14.8 m3=48 b1=700 b2=1000 b3=360 b4=450 k1=4.3e+05 k2=7.9e+04 Kv=0.023

Real Numbers

Imaginary Numbers
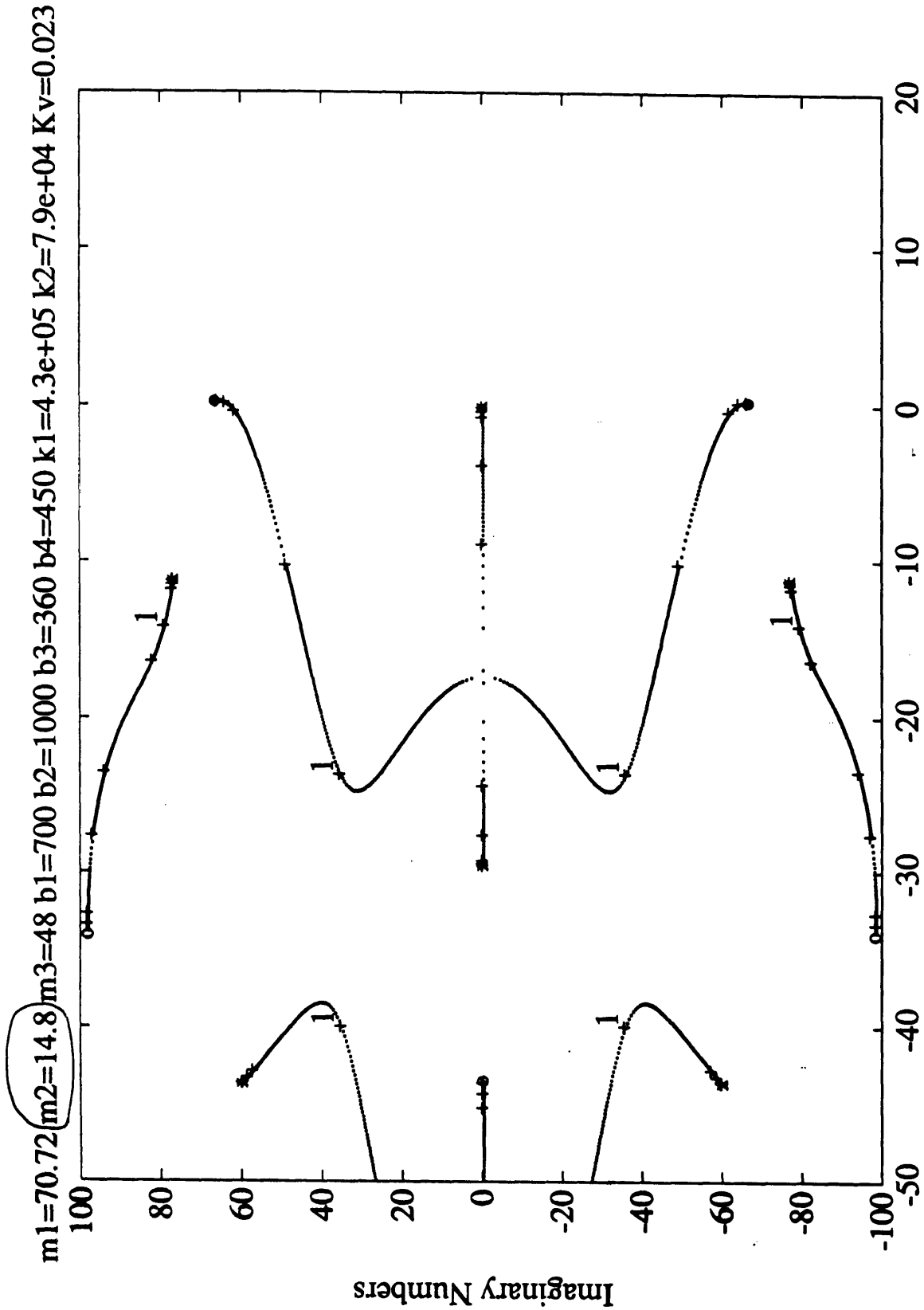
Figure 4.8 - Root Locus of Gantry Lumped Parameter Model

experiment was conducted to compare the lumped parameter model's step response to the step response of the actual robot. The step response of the model is given in figure 4.9 while the actual step response is given in figure 4.10. Numerous attempts were made to improve the correlation between the model and the actual machine. Although the lumped parameter model accurately predicts the overshoot and does a reasonable job of predicting the next two peaks, the settling time is approximately twice that shown in the actual step response of figure 4.10. Additionally, the step response given in figure 4.9 was achieved by doubling the known value of mass 2. The number 2 mass was doubled in an attempt to account for some of the non-linear effects displayed by the machine. The rationale behind the doubling is covered in Appendix II. Because the correct weight for mass 2 gave the correct settling time but incorrect overshoot and the doubling of mass 2 yielded the correct overshoot but the incorrect settling time, it was concluded that non-linear effects severely affected the machine's response.

Based upon this anecdotal evidence, it was concluded that the dynamic friction and other non-linearities were too severe for the assumptions made in the previous section. Due to the difficulty in estimating the design parameters used in the transfer function, it should be noted that the entire transfer function for the machine can be determined experimentally once the machine has been built.

Bode Plots

There are a number of techniques for directly deriving the transfer function from experimental data. The simplest technique is to use a Hewlett-Packard digital signal analyzer with the optional transfer function package. This fairly expensive piece of test

Step Response of Carriage

$m_2 = 29.6$
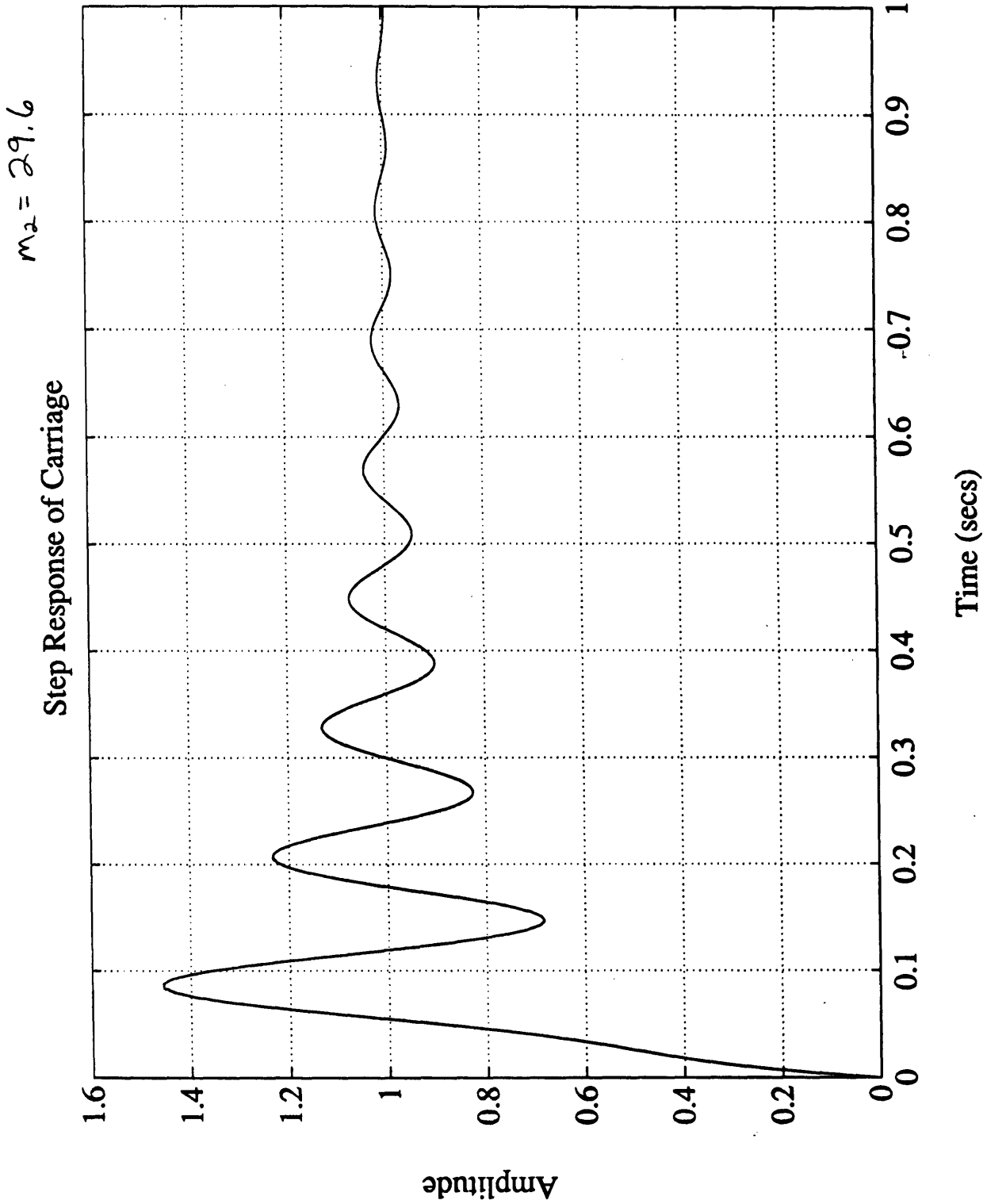
Figure 4.9 - Step Response of Model

Untitled

FAR END

x axis

Time (Seconds)
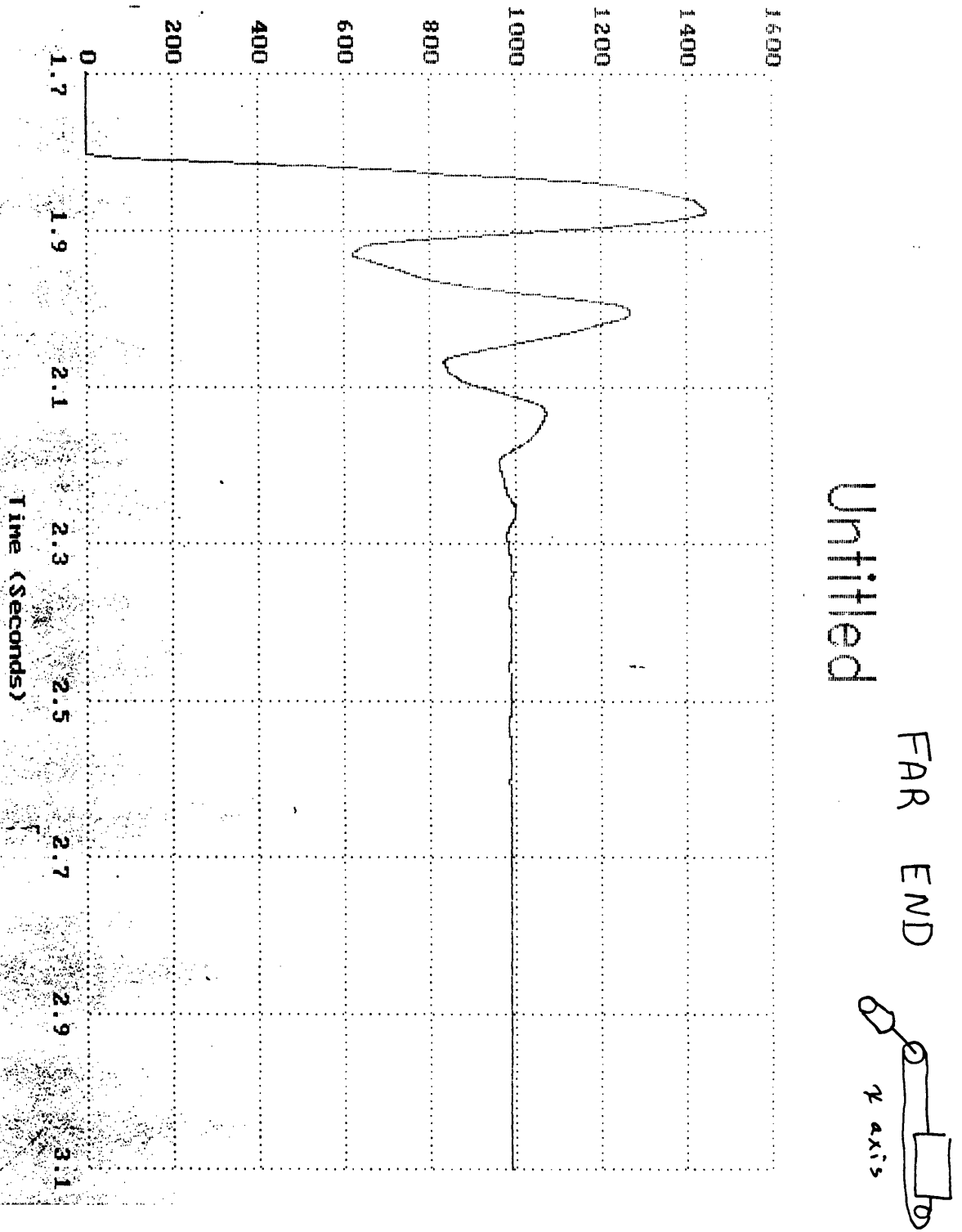
Figure 4.10 - Experimentally Determined Step Response of Gantry Robot, X-axis

gear inputs a signal, records the machine's response, and returns the transfer function. Not having one of these available, a more cost effective technique had to be performed. Two techniques were considered and both were attempted. The first technique is known as a Bode plot. A Bode plot is constructed by inputting a sine wave signal of known magnitude and then measuring the magnitude and phase angle of the machine's response. The ratio of the magnitudes is plotted in decibels against a logarithmic scaling of the frequencies. As such, testing is conducted at logarithmically related frequencies. Due to the limited length of the robot, the lowest frequency that could be tested was 1 Hz and the highest frequency was 20 Hz. Tests were conducted for 1,2,3,4,5,6,7,8,9,10,& 20 Hz and the magnitude ratios are given in figure 4.11. These results are suspect because the low frequency data accounts for the full length of travel in the belts whereas the high frequency data only accounts for a very small travel. The Bode Plot based upon the limited data represents a fourth order system but the 20 Hz point is clearly way off the -80dB/decade slope of the third and fourth orders of the system. A phase angle plot is not given because the recording feature of the controller could not be reliably synchronized with the signal generator. For more on this technique, see Application of Modern Control Theory to a Gantry Robot by Jeff Hamlin and Dan Yeaple.

Block LLS Identifier

A third experimental technique that works well for low order systems is the use of a block linear least squares identifier. This techniques takes derivatives of the experimentally determined data and then determines coefficients of the transfer functions via a LLS fit. The Delta Tau Controller is capable of recording the DAC voltage output

Bode Plot - Amplitude Ratios

Amplitude/3 (Encoder Pulses/Volt) in dB

Frequency (hertz)

-40 dB/decade

-80 dB/decade
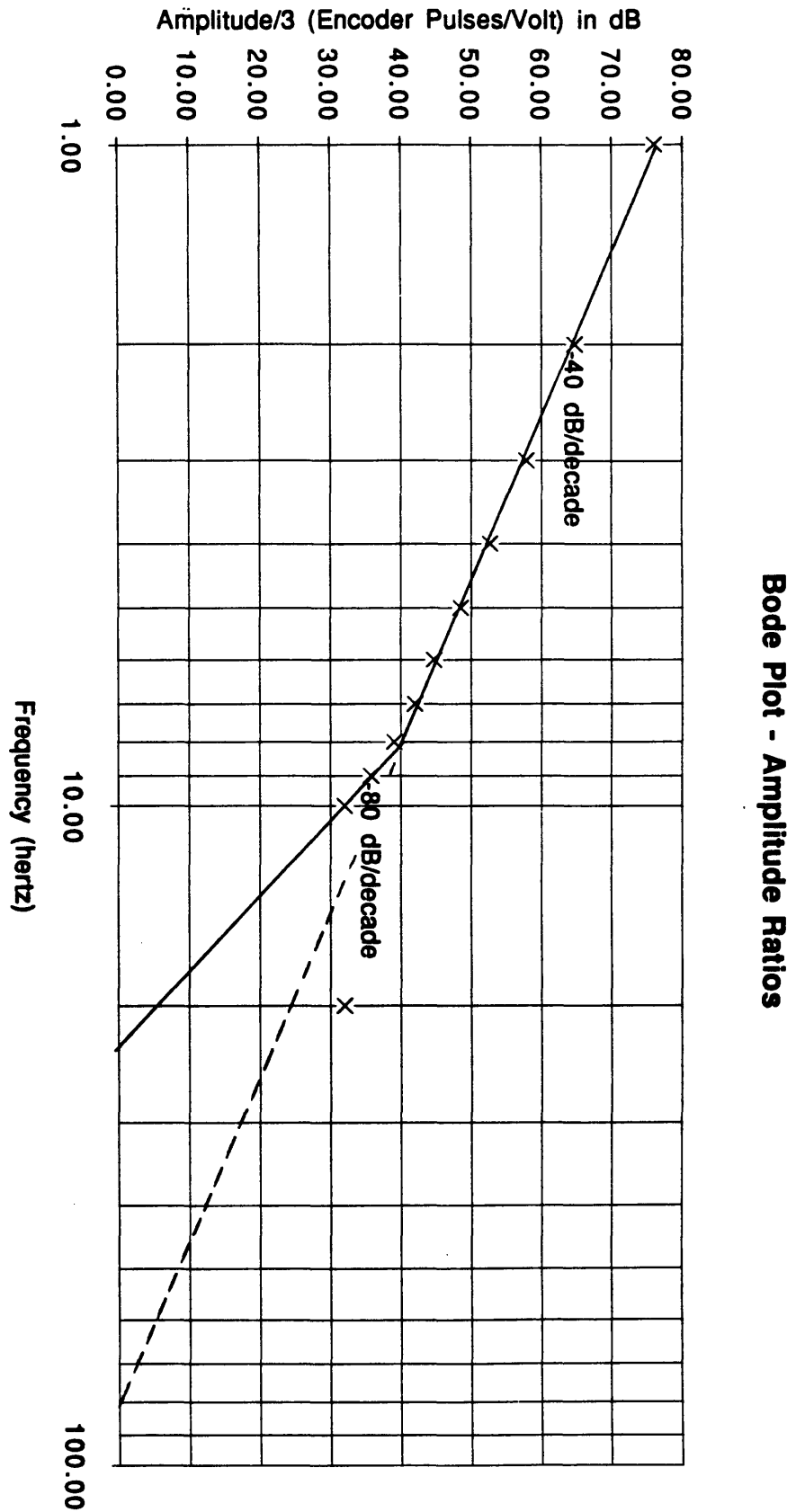
Figure 4.11 - Bode Plot of Gantry Robot, X-axis

to the amplifier and the position of the linear encoder simultaneously. Thus, a move can be performed and the input and output of the system captured every 442 µsec. This data is uploaded via a serial port and can then be transferred to a spreadsheet or other data analysis program. It should also be noted that this technique can be used to determine non-linearities such as dynamic friction.

In order to avoid the noise generated by using finite difference techniques, it is advisable to perform a linear least squares cubic spline fit of the data and then take derivatives of the resulting polynomial equations. This technique works as follows.

First, based upon the number of derivatives that need to be taken an appropriate number of points are picked for fitting a cubic spline. For a second order system, five points are frequently chosen as this number allows the taking of two derivatives if a third order polynomial is fit. By using five points to fit four coefficients, the experimenter can also calculated correlation coefficients to insure that a reasonably good fit has been obtained. The transfer function has the form:

$$G_p(s) = \frac{\text{Output}}{\text{Input}} = \frac{X_3(s)}{Y_r(s)} = \text{e.g.} \quad \frac{...\alpha_2 s^2 + \alpha_1 s + \alpha_0}{...v_4 s^4 + v_3 s^3 + v_2 s^2 + v_1 s +}$$

Re-arranging terms we can write:

$$v_4 \frac{d^4 x_3}{dt^4} + v_3 \frac{d^3 x_3}{dt^3} + v_2 \frac{d^2 x_3}{dt^2} + v_1 \frac{dx_3}{dt} + v_0 x_3 = \alpha_2 \frac{d^2 y_r}{dt^2} + \alpha_1 \frac{dy_r}{dt} + \alpha_0 y_r$$

In order to be able to fit the data to this equation, we must eliminate one of the coefficients. Since the robot is scaleable, this can be accomplished by dividing through by one of the coefficients. It is advisable to divide through by a term that is known. For example if the two masses are known, it would be convenient to divide through by the

fourth derivative's coefficient. Since it is known, the actual values of the other coefficients can be reconstructed.

$$\frac{d^4x_3}{dt^4} = \frac{\alpha_2}{v_4}\frac{d^2y_r}{dt^2} + \frac{\alpha_1}{v_4}\frac{dy_r}{dt} + \frac{\alpha_0y_r}{v_4} - \frac{v_3}{v_4}\frac{d^3x_3}{dt^3} - \frac{v_2}{v_4}\frac{d^2x_3}{dt^2} - \frac{v_1}{v_4}\frac{dx_3}{dt} - \frac{v_0}{v_4}x_3$$

It is recommended that a robust LLS technique such as singular value decomposition factorization or QR factorization. If the experimenter had 1000 data points to begin with, there will now be 1000-4= 996 equations in 7 unknowns.

he weakpoint of this technique is that every derivative amplifies the noise. Based upon the belief that the Acme Mfg. Gantry was a sixth order system, this meant that at least 7 derivatives would have to be taken in order to get a good fit (an extra derivative had to be taken to account for the velocity feedback). Although, there was a limited chance of success for this technique, it was decided to try it anyway. The first attempt gave a correlation coefficient of .998. Unfortunately, two of the coefficients were negative. The technique was repeated on a second set of data. This time the correlation coefficient was .48. It was decided that a controller solution to the problem was not going to produce the desired performance.

Final Results

Due to the fact that a suitable transfer function could not be determined for the machine, the solution methodology was abandoned. However, the new controller did improve the cycle time and accuracy of the machine. The former was improved through filtering the velocity profile of the trajectory. This technique was successful because it eliminated the high frequency constituents from the input. It is believed that the

non-continuous nature of the trapezoidal velocity profile used in the original controller excited a number of the harmonics of the machine's natural frequencies. The performance was further improved by insuring that saturation did not occur. Dual encoder feedback was used to improve the system's stability and allowed the use of a higher proportional gain. This technique used a rotary encoder mounted to the motor shaft for velocity feedback and the linear encoder for position feedback. These modifications reduced the settling time but maximum acceleration and maximum velocity were constrained by the motor's power and the machine's large mass.

The accuracy was improved by using the Delta Tau controller's backlash compensation and leadscrew compensation table features. The latter feature allows the user to specify offsets for the nominal position values of the axis. An offset was specified for every 10 cm. The before and after comparisons are given in figures 4.12 & 4.13. Figure 4.12 is a loosely tuned gantry using the x-axis linear encoder for position and velocity feedback. Note that this is a noncollocated system. This arrangement had an ISO 6σ accuracy of .324 mm and a repeatability of .153 mm.

Figure 4.13 uses the rotary encoder on the motor shaft as the velocity feedback and uses the linear encoder on the x-axis for position feedback. Cables were added to the structure to increase the stiffness. Backlash and leadscrew compensation were enabled using values determined in previous measurements. The controller was tuned for no overshoot and the input trajectory was filtered. It was believed and later proven in many measurements that overshoot reduced the repeatability of the machine. This arrangement
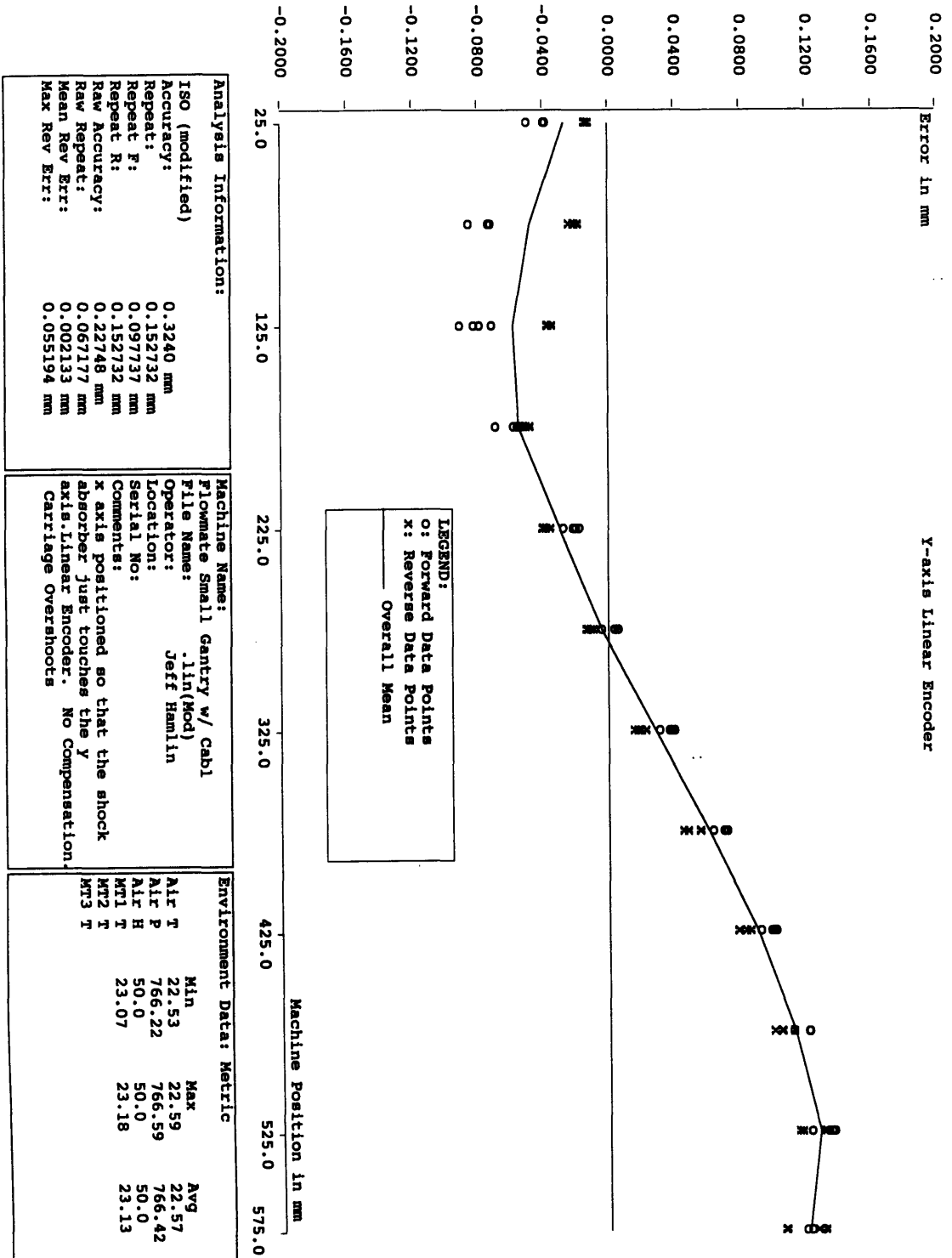
Figure 4.12 - Poorly Tuned Gantry, No Control Compensation

Error in mm

Y-axis Linear Encoder

Machine Position in mm

LEGEND:
o: Forward Data Points
x: Reverse Data Points

⎯⎯⎯ Overall Mean

Analysis Information:

ISO (modified)	
Accuracy:	0.3240 mm
Repeat:	0.152732 mm
Repeat F:	0.097737 mm
Repeat R:	0.152732 mm
Raw Accuracy:	0.22748 mm
Raw Repeat:	0.067177 mm
Mean Rev Err:	0.002133 mm
Max Rev Err:	0.055194 mm

Machine Name:

File Name:	Flowmate Small Gantry w/ Cabl
	.lin(Mod)
Operator:	Jeff Hamlin
Location:	
Serial No:	
Comments:	
x axis positioned so that the shock
absorber just touches the y
axis.Linear Encoder. No Compensation.
Carriage Overshoots

Environment Data: Metric

	Min	Max	Avg
Air T	22.53	22.59	22.57
Air P	766.22	766.59	766.42
Air H	50.0	50.0	50.0
MT1 T	23.07	23.18	23.13
MT2 T			
MT3 T			

Dual Encoder Feedback with Compensation

Error in mm

Machine Position in mm

LEGEND:
o: Forward Data Points
x: Reverse Data Points
—— Overall Mean

Machine Name:

Flowmate Small Gantry		
File Name:	dual2c.lin(Mod)	
Operator:	Jeff Hamlin	
Location:		
Serial No:	Q23098	
Comments:		
Dual Encoder Feedback. Carriage on		
Near Side. Lead Screw Compensation		
Enabled		

Analysis Information:

ISO (modified)		
Accuracy:	0.119811	mm
Repeat:	0.11888	mm
Repeat F:	0.11888	mm
Repeat R:	0.040857	mm
Raw Accuracy:	0.047443	mm
Raw Repeat:	0.045675	mm
Mean Rev Err:	-0.00355	mm
Max Rev Err:	0.03585	mm

Environment Data: Metric

	Min	Max	Avg
Air T	22.03	22.08	22.05
Air P	764.7	765.01	764.86
Air H	50.0	50.0	50.0
MT1 T	22.43	22.51	22.47
MT2 T			
MT3 T			

Figure 4.13 - Finely Tuned Gantry, Stiffened Structure, Dual Encoder Feedback, & Control Compensation

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produced an ISO 6σ accuracy of .120 mm and a repeatability of .119 mm. This corresponds with a 63% improvement in accuracy and a 22% improvement in repeatability. All measurements were performed with a laser interferometer.

Based upon the limitations of the machine and the gap between actual performance and desired performance, it was decided to redesign the machine taking into account the interactions between the structure and the controller.

Chapter 5 - The Second Generation

Lessons Learned

Given a clean sheet of paper, it was decided to enumerate all of the known or suspected problems of the existing gantry robot and to determine possible solutions. This exercise led to the following listing:

Problem	Possible Solutions
Compliant Structure	Use welded joints, use tubing with a higher moment of inertia -- I_{xx} & I_{yy}, use shorter columns
Compliant Transmission	Use direct drive or ballscrew
Anisotropic behavior	Eliminate belts, balance drive system to eliminate skewing, reduce constraints on over-constrained axes, eliminate static friction as much as possible
Slower top speed and lower acceleration than desired	Increase power, decrease mass
Excessive oscillation upon reaching position	Filter input and stiffen structure. Experimentation had shown that first order filtering of the input produces a much smoother actual trajectory. Also cable stiffeners added to the gantry significantly decreased the oscillations of the structure and the carriage.
Gantry was difficult to tune due to a very small window of stability	Use rotary encoders or tachometers on the DC motors so that the system will be collocated. Use dual feedback set-up if better accuracy is required.
Gantry was difficult to install in the factory because the machine had to be assembled around the conveyor belt.	Build the conveyor into the machine.
Accuracy met material handling needs but was insufficient for many assembly tasks	Reduce Abbe error, machine in alignment grooves so that parallel axes will be parallel when assembled, allow adjustability of orthogonality so that the axes can be aligned.

With these ideas in mind, a new design was initiated. It was decided that the original design attempted to accomplish too many different tasks and that it would therefore be advisable to design a machine to accomplish a single task. The single most repeated task in Acme Mfg.'s factory is that of placing electronic components on printed circuit boards and it was decided to build a machine that could accomplish this task. A side benefit of this decision, was the fact that there were numerous types of chip placement machines in factory for the design team to emulate.

Chip Placement Machines

Within the genre of chip placement machines, there are three basic types or levels of equipment. At the top end are the surface-mount component insertion machines better known as chip shooters made by Fuji, Matsushita, and Sanyo. These machines are in the $350,000 to $400,000 range and use a large turret to place multiple components at up to 24,000 SMT components per hour[4]. For common components, these machines are difficult to compete with due to their incredibly high production rates. However, there are a number of components used by Acme Mfg. that these machines cannot place. For these operations, Acme Mfg. uses the other two types of component placement machines. The mid-level consists of purpose built cartesian manipulators that have been integrated with vision systems and fairly sophisticated controllers that are capable of 3,000 to 6,000 components per hour[5]. This level includes machines made by Universal Instruments, Quad Systems Corp., and Zevatech. Although slower than chip-shooters, these machines

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[4]   Wesley R. Iversen. "Component Placement and Insertion Review", Assembly, (Vol. 36, No. 1, January) 14.
[5]   Iversen, "Component Placement and Insertion Review."

have the advantage of being able to place a wider variety of components and at a lower price -- around $200,000. The bottom level is robotic work cells that have been integrated to handle the odd part placement. These work cells can handle everything from 20 mil QFP's to fuses, batteries, and switches. Depending upon the accuracy and speed, these integrated workcells can cost from $70,000 up to $250,000.

The Second Generation

The automation engineers at Acme Mfg. are very skilled at integrating componentry to make robotic workcells. For these reasons, the design team decided to produce a mid-level machine that was capable of placing all of the componentry that could not be placed by a chip shooter. This machine will be referred to as the second generation robot. Since the design team's primary skill was the integration of hardware and software, it was decided to sub-contract the design of the positioning mechanism. Specifications were drawn up and submitted to a number of vendors.

The design team reviewed the vendor's proposals and elected to award the contract to a vendor who proposed a cartesian mechanism that used direct drive linear motors. The x-axis consisted of two parallel linear motors each driving one end of the y-axis. These two parallel motors are called x and x'. Based upon experience with the gantry robot, the design team requested a number of changes to the vendor's proposal. The design team requested the vendor to include a mechanism that would allow the y-axis to pivot relative to one of the x-axis carriages and to pivot and translate relative to the other carriage. This was requested in order to improve the accuracy of the machine by not over-constraining the y-axis and to decouple the two motors. Kinematically

mounting this axis eliminated the variable friction problem encountered in the original gantry where the y-axis was rigidly mounted to the two x-axis carriages. The x and x' carriages are aligned using a proprietary technique. After developing a homing procedure, this technique produced an orthogonality of better than 2 arc sec. Skewing due to the z-axis being off center is countered by using proportional thrust. The controller determines the y position of the machine and then calculates the forces to be delivered by x and x' so that a moment will not be generated about the current centroid of the y axis.

One of the most difficult tasks in constructing the original gantry design was the task of aligning the two linear bearings that made up the x-axis so that the bearings were parallel to each other. It was believed that the lack of parallelism was a contributing factor to the machine's narrow window of stability. The vendor had built a number of machines before that needed parallel axes and showed the team how he was able to insure a reasonable degree of parallelism. This was accomplished by machining an alignment surface into the structure on a very large milling machine. Thus, the accuracy of the parallelism was determined by the milling machine.

A Rigid Structure

Having suffered through a machine with a compliant structure, the design team redesigned the vendor's base. They made it shorter and increased the size of the rectangular tubing. They also increased the bracing. These actions resulted in a very stiff structure, perhaps a little over designed but definitely stiff.

The incorporation of direct drive linear motors eliminated many of the problems of compliant transmissions. Linear motors have a reputation of being extremely expensive and inefficient. The design team was pleasantly surprised with the cost and efficiency improvements that had been made since they last looked at these devices.

The second generation robot was completed in March of 1993 and achieved 10 times the acceleration of the gantry and was 10 times as accurate right out of the box. Due to the proprietary nature of this machine, actual accuracy and performance figures have been withheld.

A Strategic Approach to Assessing Needs and Engineering Cost/Performance Tradeoffs for

Chapter 6 - Manufacturing Strategy - Assessing Automation Needs

The purpose of this chapter is to propose a framework for assessing the strategic benefits and liabilities of a firm's core competencies. This technique may be extended to aid in the make versus buy decision. This methodology was not used on the above referenced robots.

Costs and Benefits

In order to make a well informed make versus buy decision, we felt it important to develop a rational means of dividing the manufacturing operation into its component processes and then quantifying the strategic and economic consequences of each process to the firm. After this division is completed, individual make versus buy decisions are based upon the benefit to cost ratio wherein we identified three types of benefits and two types of cost. The benefits are economic benefits, strategic benefits, and learning benefits. The costs were economic costs and loss of strategic benefits.

The Product Development Process

Our division process is based upon our own model of the product development cycle which is given in figure 6.1. This model is based upon a number of conversion processes that must transpire in order to deliver a new product to the market. The conversion processes are fueled by the profit stream, resulting from the sale of products. The first conversion process is handled by the marketing organization and converts the market's desires into functional requirements. Engineering converts the functional requirements into design needs and then sets out to find solutions to these needs. Design

Figure 6.1 - The Product Development Process

needs differ from functional requirements in that a design need takes into account the full listing of functional requirements. These design needs can typically be defined in a sentence or two. An example of a design need would be the need to attach the product to the user's person. Possible solutions to this problem would be a belt clip or bracelet.

The design solutions are given to manufacturing where each design solution is converted into a manufacturing task. A manufacturing task is the simplest and broadest possible description of what must transpire in order for the actual part to meet the engineering specifications. The task description is intentionally broad in order to give manufacturing the widest possible means of accomplishing the task. Manufacturing tasks are accomplished through manufacturing steps which are physical descriptions of how the part will be acted upon. Manufacturing tasks answer "what" whereas manufacturing steps answer "how". Manufacturing steps by their very nature must be as explicit as possible.

Resource Leverage

In their article, "Strategy as Stretch and Leverage," Prahalad and Hamel describe the need for conserving resources in order to improve resource leverage. They cite Japanese firms have achieved much higher resource efficiency due to their willingness to recycle and reuse technologies.[6] Since higher resource leverage can be achieved by reusing manufacturing steps, manufacturing tasks, and design solutions, the division process has been designed to showcase opportunities for reuse. Re-used manufacturing tasks and steps are highlighted in figure 6.1.

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[6]   Gary Hamel and C. K. Prahalad, "Strategy as Stretch and Leverage", Harvard Business Review, (March/April 1993) 75.

Manufacturing and Engineering Core Competencies

A three dimensional array is constructed to display the strategic relationships between products, engineering core competencies, and manufacturing core competencies. A company's products are placed along one dimension of a three dimensional array. The strategically important functional requirements and their associated design needs/design solutions are then listed on the second dimension of the array. Solutions that are considered to be part of the design core competencies of the firm are listed first and in order of importance to the firm if possible. Thus for Acme Mfg., design solutions that fit into their core competency of wireless communications would all be grouped together on one row and all design solutions that fit into their core competency of semi-conductors would be grouped into a second row. A diagram of the three dimensional array is given in figure 6.2.

A core competency is defined as "the collective learning in the organization, especially the capacity to coordinate diverse production skills and integrate streams of technologies."[7] Furthermore, core competencies must have the following characteristics:

- Provide potential access to a wide variety of markets
- Make a contribution to the customer benefits of the product
- Be difficult for competitors to imitate[8]

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[7] C. K. Prahalad and Gary Hamel. "The Core Competence of the Corporation," Harvard Business Review, (May/June 1990) 79.
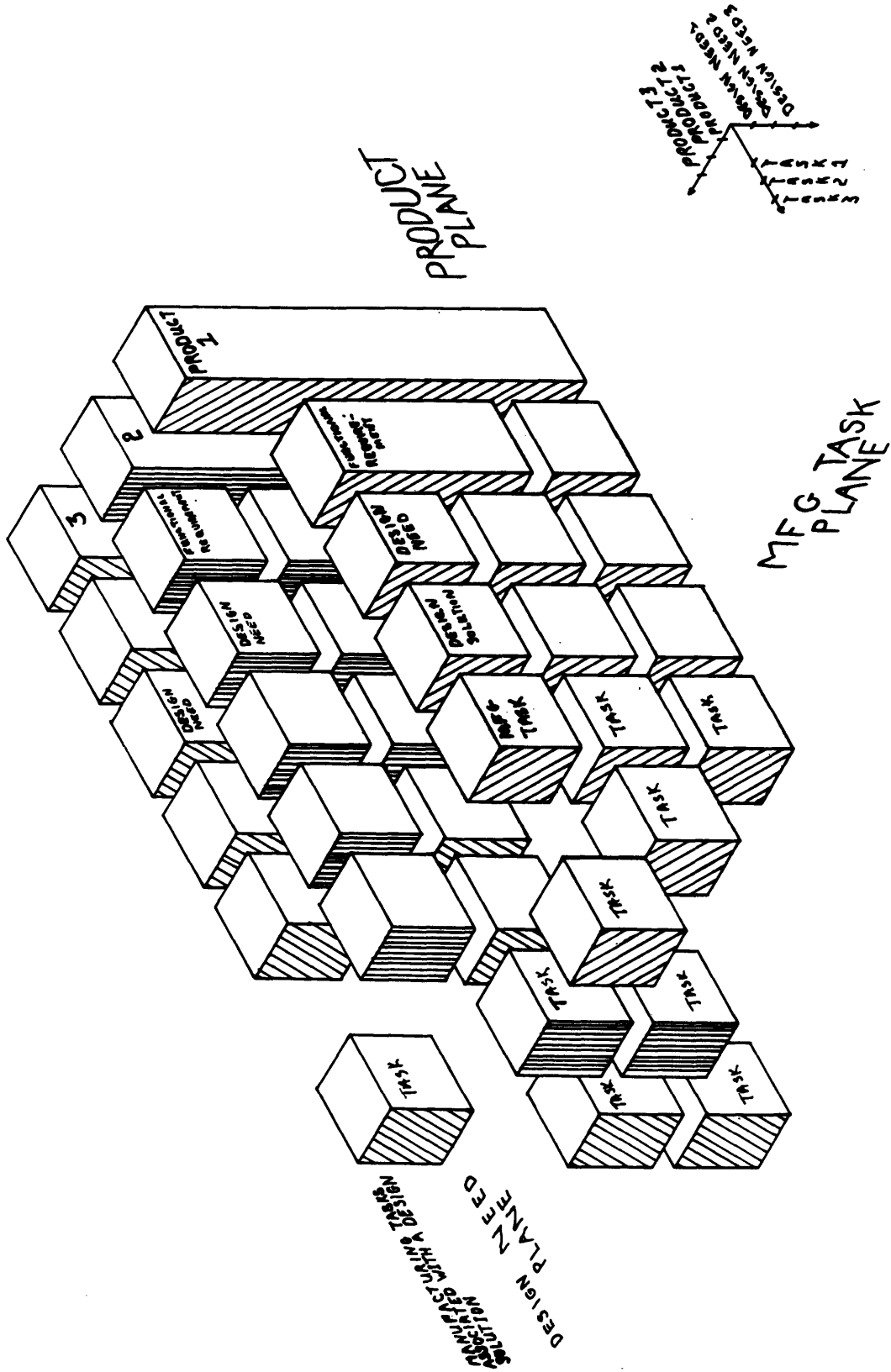[8] Prahalad and Hamel, "The Core Competence of the Corporation."

Figure 6.2 - The Three Dimensional Array

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Using the third dimension of the array, the manufacturing tasks are grouped together and displayed in the order of importance of the manufacturing core competency embodied. The manufacturing steps are laid out in a similar fashion. Upon completion, a three dimensional structure is produced with the intersection between the most important design core competencies and manufacturing core competencies occurring at the top end of the structure.

The following opportunities for better resource utilization will become apparent once the product portfolio has been arranged in this manner.

- Are we using multiple tasks to solve the same design need? If so how can we reuse the best manufacturing task?
- Are we reusing manufacturing steps or does each product produce its own set of steps?
- Are we reusing design core competencies?

In order to achieve balance -- insuring that the "ability to exploit excellence in one area is never imperiled by mediocrity in another" -- a firm must combine: "a strong product development capability; the capacity to produce its products...; and a sufficiently widespread distribution, marketing, and service infrastructure."[9] Hence, we believe that the most strategic manufacturing tasks are those that are used to realize design core competencies. A firm that has strong competencies in the design, manufacture, and marketing/sales/distribution of semiconductors has a stronger strategic position than one

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[9] Prahalad and Hamel, "Strategy as Stretch and Leverage".

that has strong competencies in the design of automobiles, the manufacturing of semi-conductors, and the marketing/sales/distribution of women's fashions.

In order to be successful, the complimentary core competencies do not necessarily have to reside within the firm if a long term strategic partnership can be structured. Thus, a firm with strong competencies in the design and marketing/sales/distribution of semiconductors might fund long term research with a producer of semiconductor manufacturing equipment in return for a period of exclusive use of the equipment developed. This strategy would in effect give the designer of the semi-conductors a virtual core competency in developing manufacturing equipment, even though the actual talent needed to develop the equipment resides outside of the firm.

Make versus Buy

A make versus buy decision can be made by considering the benefits and costs to the firm. We have divided the benefits into three categories in order to try to capture benefits that are difficult to quantify. Chief among the benefits that we are looking for are the long term strategic benefits that accrue to a firm due to the adoption of a particular policy. These benefits are difficult to quantify in monetary terms but our three dimensional array has at least prioritized the benefits and identified opportunities for improvement in other areas.

In terms of manufacturing equipment, the primary strategic objective is to manufacture a product that no other firm can make. Failing this, we would like to be able to manufacture a better product than our competitors, ceteris paribus. Failing this, we

would like to be able to produce our product more economically than our competitors, ceteris paribus.

If we cannot provide any competitive advantages, then the manufacturing equipment that a firm utilizes must at least provide an economic benefit that is better than the status quo. The make versus buy decision is fairly simple in this case. The cost of developing a new machine internally is compared to the cost of sourcing the machine. The lowest cost alternative is selected, if and only if, it provides a cost benefit over the status quo.

The third form of benefits are what we call learning benefits. Basically, these are strategic benefits that have not yet accrued to the company. For example, if Acme Mfg. decides they need a core competency in display technology, their first attempt at producing displays may likely result in a display that is slightly inferior to their Japanese competitors and probably more expensive to produce. However, if they never undertake this first step, they will never be able to compete in the manufacture of displays.

Therefore, we must develop a methodology for capturing the value of learning in order to promote development of core competencies. To this end we would like to suggest that companies view forays into new areas as options to reap strategic benefits at a later date. These options can then be valued using the Black-Scholes formula if the company can determine the expected payoff of developing the competency and the probability of success.[10] By quantifying the value of the option to the firm, a better

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[10]   This idea has been covered by Robert S. Pindyck for making investment decisions. The reader is referred to S. Majd, & R. S. Pindyck, "Time to build, option value and investment decisions." Journal of Financial Economics, (Vol. 18, 1987)7-27.

decision can be made. Failing to recognize the potential strategic benefits of an investment will increase the likelihood that a firm never increases its portfolio of core competencies. Once the economic benefits of the project have been determined and the strategic and learning benefits estimated, the costs must be determined.

The easiest cost to quantity is the economic cost. The cost to the firm should reflect not only the purchase price of the machine but also all transactional costs that are associated with the machine. Internally developed machine's economic costs will have to be estimated based upon the number of hours of effort required to construct the machine. Again, all transactional costs associated with the machine should be included.

Transfer of Core Competencies

When projects are outsourced there is always a transfer of core competencies between the firm and the supplier. Although extremely difficult to quantify, a firm must strive to insure that the net transfer is in its favor. The firm has to realize that it is outsourcing a project because the vendor has a core competency that is superior to the firm's. In effect, the firm captures part of the vendor's core competencies via the outsourcing. This benefit can be further maximized by internalizing or learning the vendor's core competencies. Large U.S. corporations are prone to have a "we are the teacher and you are the student" attitude when dealing with vendors. This is unfortunate because there is a real opportunity to add to the firm's learning during the transaction with the vendor.

On the other hand, the vendor is only too happy to take on the role of student because it insures that the vendor will be the beneficiary in the net transfer of core

competencies. The firm in effect educates the vendor in its core competencies by giving the vendor the blue prints to a new machine. The learning that the vendor receives will help the vendor produce better machines in the long term.

It is critical to understand what the net transfer of core competencies is going to be in an outsourced project. Furthermore, it is essential that the purchasing firm try to minimize the outflow of core competencies and maximize the inflow. We term the loss of core competencies, loss of strategic benefits. Although, these loss of strategic benefits are difficult to quantify, the firm should at least list all potential transfers of core competencies and monitor the degree to which transfer has occurred. In monitoring the net transfer, the firm should be aware that the core competencies lost by the firm do not always appear at the vendor but rather at the firm's competitors which have learned the competency through the vendor.

Modularization

One strategy for coping with this problem is to modularize or compartmentalize competencies so that individual vendors are only privy to tightly compartmentalized pieces of the firms overall core competencies. By architecting a manufacturing operation that relies upon modular pieces the firm can leverage its own resources by not divulging its own core competencies and still reap the technical innovations of its vendors by constructing the organization in such a way that innovation occurs autonomously.[11 & 12]

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[11]   David J. Teece, "Profiting from Technological Innovation: Implications for Integration, Collaboration, Licensing, and Public Policy," Research Policy (Vol. 15, 1986) 285-305.
[12]   Richard N. Langlois and Paul L. Robertson, "Networks and Innovation in a Modular System: Lessons from the Microcomputer and Stereo Component Industries," Research Policy.

An example of a modularized industry is the Stereo Component Industry.[13] The manufacturers in this industry have agreed upon certain interface specification that allow CD player manufacturers to improve their own technology autonomously of amplifier manufacturers. A similar system approach could be architected for a manufacturing operation. To some degree Acme Mfg. has followed this strategy by specifying that all manufacturing equipment must be capable of communicating via ethernet. This minimizes the amount of information about upstream and downstream machines that Acme Mfg. must supply to a vendor providing a machine. As long as the machine can communicate over ethernet, Acme Mfg. can develop the machine's relationship to the rest of the factory without giving this information to the vendor.

Making the Decision

Benefits of the Three Dimensional Array

The primary benefit of the three dimensional array is the relationships between products that are exposed during the construction of the array. If the firm's product offering re-uses a number of manufacturing tasks and design solutions, the array can be very compact for a large number of products. On the other hand, if the array is extremely large and there is very little re-use of technologies, then the constructor should consider defining categories a bit wider to achieve some overlap. Of course, it is possible that a conglomerate would have very little re-use of technologies. Our prognosis is that a "jack of all trades, master of none" firm will fare very poorly in global competition.

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[13]   Langlois and Robertson, "Networks and Innovation in a Modular System..."

The array can also be used to determine which types of products a firm should consider adding to its product portfolio. Products that allow re-use of the firms core competencies have a much higher chance of success than products that have to break new ground.

The array also exposes a company's weaknesses and points that lack balance. A top design core competence that is being constructed using a weak manufacturing competency is a point of lack of balance. A high leverage strategy for the firm is to improve the manufacturing core competency in order to maintain balance and therefore exploit the strength of the design core competency.

Competitive analyses can be conducted by comparing the firms ability to meet functional requirements versus competitors abilities to fulfill these same requirements. By surveying competitors who can meet a significant portion of the functional requirements that the firm currently meets, potential competitors can be monitored before they actually enter the firm's markets. For example, there is some overlap in the functional requirements of a consumer portable AM-FM radio and a pager. A firm that makes AM-FM radios is therefore a potential competitor of a pager manufacturer. This analysis can also be turned around to ferret out weaknesses of the pager manufacturer by asking the question -- What is keeping the pager manufacturer from competing in the AM-FM radio market. The following chapter provides some examples of the use of the array.

Chapter 7 - Applying the Three Dimensional Array

In order to demonstrate how the three dimensional array might be used, we will examine Ericsson's core competencies. Ericsson, is one of the worldwide leaders in wireless communications and telephony. Ericsson has successfully exploited their core competency of wireless communications in a variety of applications. Pagers, two-way radios, and cellular phones are perhaps the most visible products that this core competency has spawned. A firm or a firm and its partners must possess a number of competencies to produce and sell these products. All three products require competencies in wireless communications, semiconductors, display technology, battery technology, and electronic component assembly. Each of these central competencies can then be sub-divided into a design, manufacturing, and marketing/sales/distribution/service competency. Certainly Ericsson does not possess core competencies in all of these areas, but core design competencies in wireless communications and semiconductors; manufacturing strength in electronic assembly and semiconductors; and competencies in marketing/sales/distribution/service make up for deficits in other areas. In an effort to strengthen its wireless core competency, Ericsson entered an 80%/20% joint venture with GE called Ericsson GE Mobile Communications.[14] In order to boost their semiconductor competencies, Ericsson has completed a joint venture with Texas Instruments to manufacture ASICs, application specific integrated circuits, in Kista, Sweden.[15]

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[14] "Ericsson(L.M.) - Re European Support Centre." Regulatory News Service, October 7, 1992.
[15] "Ericsson Orders Applied Materials Systems for New Fab: $10 million Order Covers Wide Range of Advanced Technologies." Business Wire, March 23, 1994.

The stronger a company becomes in a competency, the harder it becomes to improve the company's overall strategic position by improving that competency. Frequently, a much higher leverage policy is to add another competency to the firm's list of competencies, keeping in mind that a firm can typically only possess a handful of core competencies.

A firm can use the Three Dimensional Array to ascertain its strategic place in the market and means of improvement. What follows is not meant to be a complete strategic analysis of Ericsson, but rather an example of how the Three Dimensional Array can be used. The first step is to list the products. For this example, we will examine pagers, two-way radios, and cellular phones. The next step is to list the functional requirements of each product. The goal is to find similarities between the products but care must be taken to insure that the functional requirements are not too broadly defined nor too narrowly defined.

A pager must fulfill four basic requirements. These are the abilities to receive a signal, to decode the signal, to display the signal, and to be transported easily. The importance of the design solutions must be judged relative to a background of competitive offerings. Constructing a lightweight highly portable case is an easy task. The difficulty arises in making a functional unit that can fit inside the case. As such we will eliminate the design of the plastic housing and other simply solved design needs from our analysis. Additionally, a design solution that produces a radio receiver that fits

into a pager housing is more significant than a design solution that produces a radio receiver that fits in closet.

The functional requirement for receiving a signal can be solved in a number of ways, however the design need must be stated in a fashion that encompasses all of the requirements for a successful product. For example, a pager could be designed with a 20 mile long telephone cord on a retractable reel. Although this would solve the functional requirement of receiving a signal, it would fail to satisfy other requirements such as portability, ease of use, etc. Similarly, the use of radio technology would not qualify as a solution if the user of the product had to lug around a 12' satellite dish. Thus, the stated design need and hence its solution must account for all other relevant functional requirements.

Adding a Product to the Three Dimensional Array

Because the pager will utilize radio waves to receive the signal, the design need is a small antenna and a small receiver circuit. Small is achieved in this case by placing as much of the receiver circuit as possible on an application specific integrated circuit, better known as an ASIC, and through the development of a small antenna and filtering circuit. Two primary design competencies were needed to make this solution work. These were competencies in the design of radio frequency circuits and the design of ASIC's. Which is more important, is difficult to assess. Notice that this design need is used in all of the products and by itself does not define a pager. Ericsson's strength is in producing very small RF circuits. Their AXESS wide area pagers are "as small as a business card and are available in numeric and alphanumeric models."[16]

Portable AM transistor radios have existed for years. ASIC technology has recently allowed manufacturers to make AM-FM radios the size of a credit card. So why is Ericsson not a major producer in this field? Simply put, AM-FM radios place different values of relative importance upon competencies than do pagers, two-way radios, and cellular telephones.

Pager service providers own a single frequency and a large antenna. From this facility they broadcast messages to all pager subscribers. A pager would be of very low value if the user had to read everybody else's messages scrolling by like a ticker tape. A far more valuable solution would be a device that alerted the user when a message for that user had been received. The pager performs the task of reading the ticker tape and then alerts the user upon receipt of a message. A circuit known as a decoder is used to decode the incoming signal and watch for messages that are being broadcast for that user. Again, this circuit must be small, portable, and consume little power. These functional requirements, design needs, design solutions, and manufacturing tasks for the pager are plotted on a two dimensional slice of the Three Dimensional Array in figure 7.1. The Three Dimensional Array can be formed by "stacking up" the product slices.

Once the decoder intercepts a message, it must somehow alert the user and then deliver the message. The alert is accomplished through activating an audio transducer, a speaker or beeper, or by activating a vibrator, a small motor with an eccentric weight. This technology, similar to a door bell or telephone bell, is rather mundane and is

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[16] "Wireless World: Ericsson to Distribute AXESS Wide Area Pagers; International Telecom Systems." EDGE on and about AT&T. (Vol. 7, No. 189, March 9, 1992) 12.
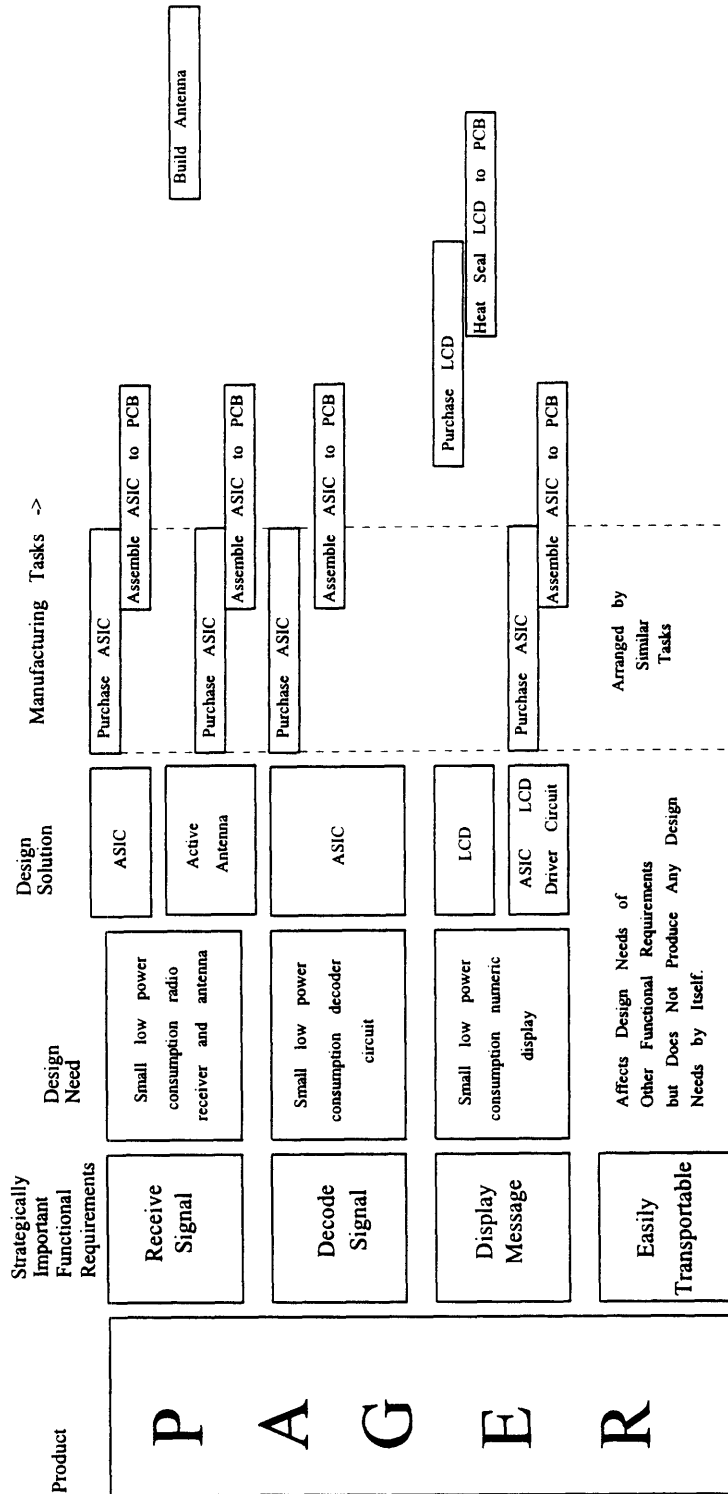
Figure 7.1 - Pager Slice of the Three Dimensional Array

therefore dropped from the analysis. Voice paging, used in the 1970's, has largely been superseded by visual display technology. The decoder circuit delivers the message to the display driver circuit, which converts the message into a visual format that is displayed by an LCD, liquid crystal display.

The combination of the competency to decode and then act upon a signal; the competency to convert that signal into a visually displayable entity; and the competency to design and make ASIC's is used in a number of products. For example, a calculator decodes the input signal from its keyboard, acts upon that input, and then displays the resultant. Similarly, digital watches count the oscillations of a quartz crystal, decode this signal, and then display the result. Ericsson makes neither watches nor calculators.

Product slices for cellular phones and two-way radios are given in figure 7.2 and 7.3. Notice how well Ericsson has re-used their design core competencies and manufacturing core competencies. The reuse of design solutions not only reduces Ericsson's design and engineering costs but also minimizes the technology risk of introducing new products. Similarly, the reuse of manufacturing steps allows the high capital costs of electronics manufacturing to be spread over a number of products thereby reducing the impact of fixed costs on a per unit basis.

Competency Resolution

I will argue that what determines whether a business will be successful in a given product category is the relative importance of competencies to the given product and the degree to which the firm is better equipped to deliver those competencies than its competitor. At first glance, it is hard to make sense of the fact that Ericsson is competent
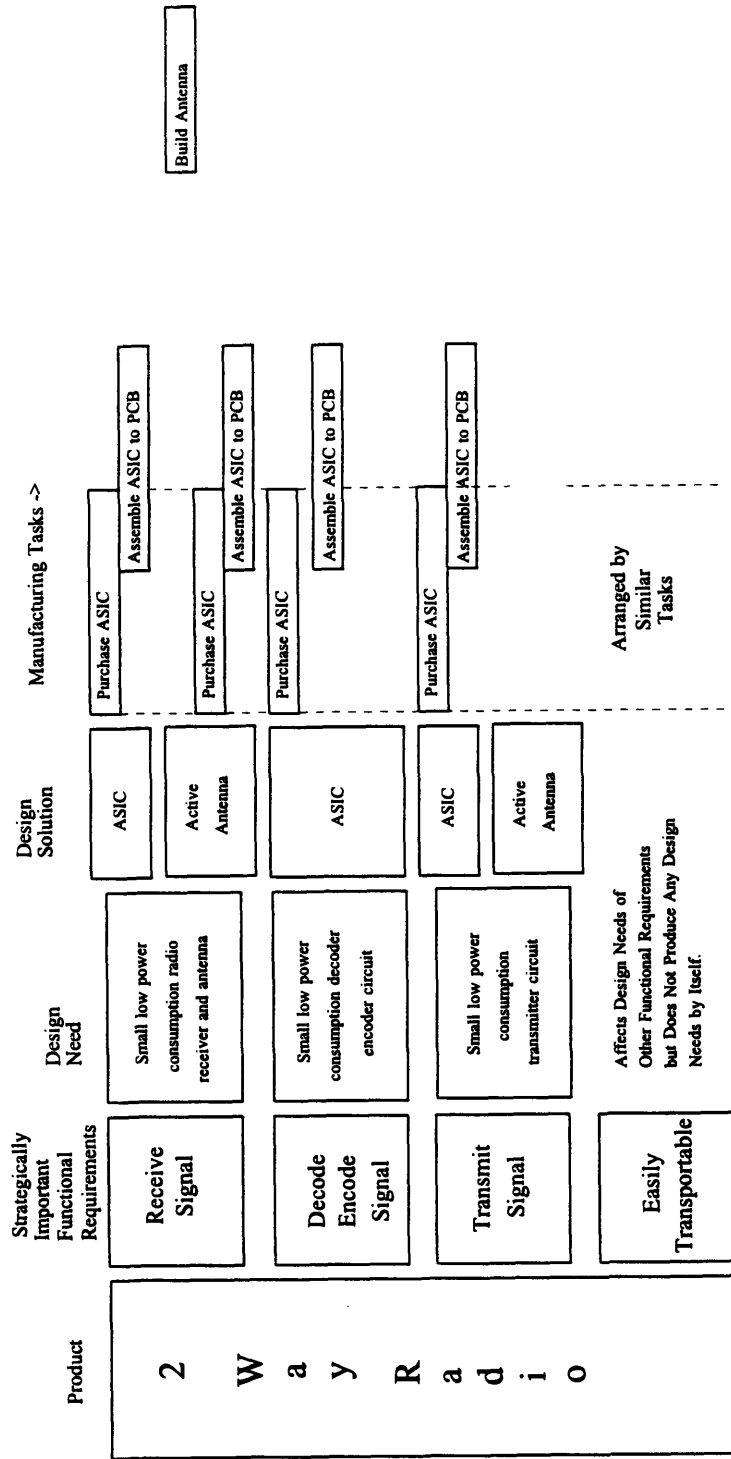
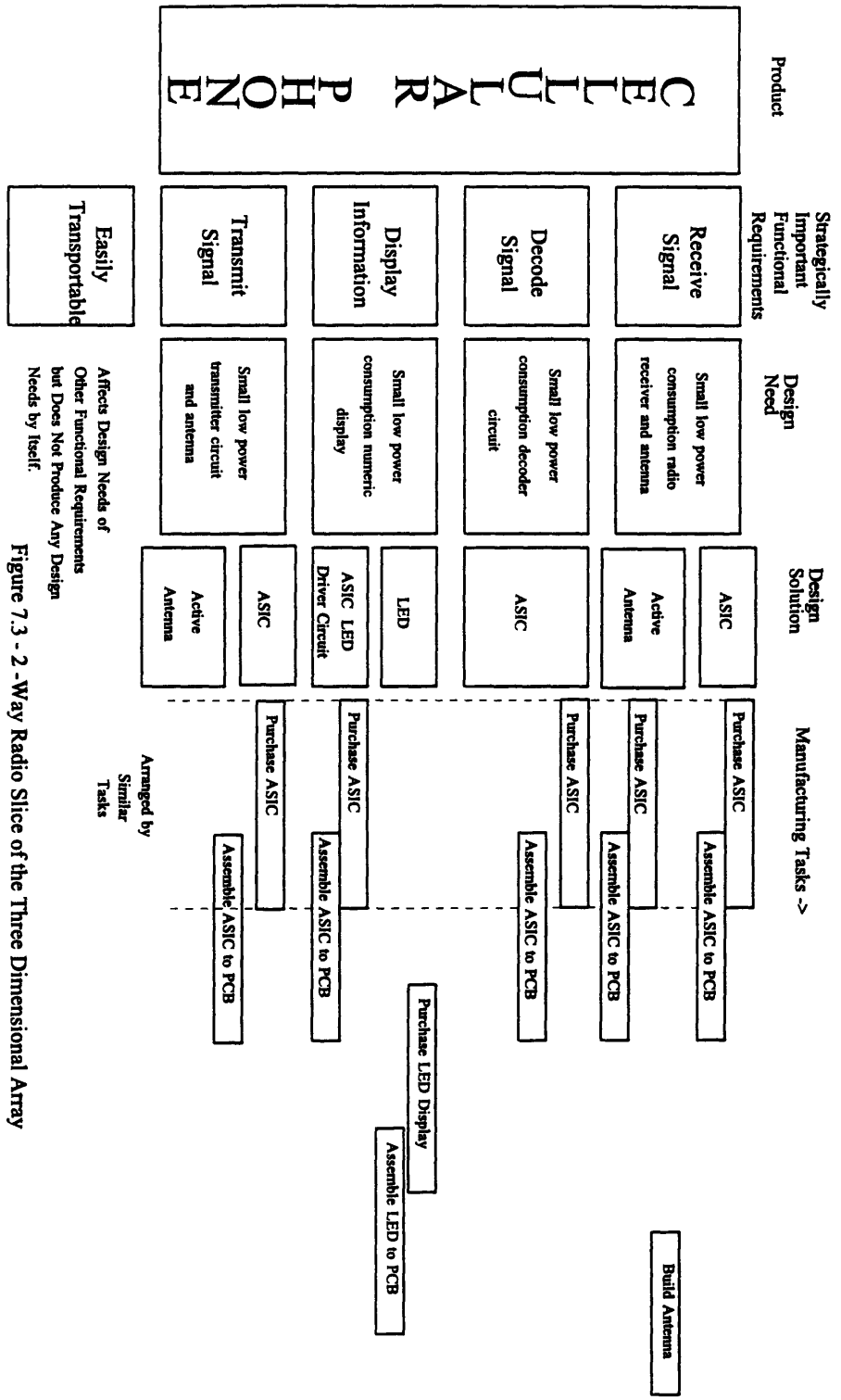Figure 7.2 - Cellular Phone Slice of the Three Dimensional Array

Product

CELLULAR PHONE

Strategically Important Functional Requirements	Design Need	Design Solution	Manufacturing Tasks ->
Receive Signal	Small low power consumption radio receiver and antenna	ASIC	Purchase ASIC — Assemble ASIC to PCB
		Active Antenna	Purchase ASIC — Assemble ASIC to PCB
Decode Signal	Small low power consumption decoder circuit	ASIC	Purchase ASIC — Assemble ASIC to PCB
Display Information	Small low power consumption numeric display	LED	Purchase ASIC — Assemble ASIC to PCB
		ASIC LED Driver Circuit	Purchase ASIC — Assemble ASIC to PCB
Transmit Signal	Small low power transmitter circuit and antenna	ASIC	Purchase ASIC — Assemble ASIC to PCB
		Active Antenna	Purchase ASIC — Assemble ASIC to PCB

Arranged by Similar Tasks

Purchase LED Display — Assemble LED to PCB

Build Antenna

Easily Transportable — Affects Design Needs of Other Functional Requirements but Does Not Produce Any Design Needs by itself.

Figure 7.3 - 2 -Way Radio Slice of the Three Dimensional Array

in applying RF technology and ASIC's but is not competitive in the manufacture of consumer AM-FM radios. On the other hand, what is keeping a radio manufacturer from partnering with a calculator manufacturer? This combination theoretically provides all of the core competencies needed to build a pager. It sounds absurd at first but if one considers GE a manufacturer of light bulbs and consumer radios, Texas Instruments as a manufacturer of calculators, and Ericsson as the glue that brought them together, then you have just that -- a pager manufacturer created by a partnership between a calculator manufacturer and a radio manufacturer.

A good explanation will answer why Ericsson does not make consumer radios and why another calculator/radio partnership has not yet entered the pager market. If we assume that the AM-FM radio producer has a stronger set of low cost manufacturing core competencies than Ericsson, it makes sense that they could be more competitive in this market than Ericsson. If we also assume that the RF design problem for a pager is more difficult to solve than the RF problem for a radio, it makes sense that the radio/calculator partnership would have a tough time competing with Ericsson.

We can then conclude that the relative importance of the RF competency is more important to pagers than radios. Vice-versa we can conclude that low cost manufacturing competencies are relatively more important to AM-FM radios than pagers.

Based upon a strong competitive advantage in RF technology, it is no surprise that Ericsson is also extremely successful in manufacturing and selling two way radios and

cellular phones. Both of these products also place a higher importance upon the RF competency than the manufacturing competency.

The long term implications are that Ericsson must seek out products where its strength in RF technology makes up for its lack of strength in low cost manufacturing. As such we can predict that Ericsson will be a much stronger competitor in products that place a higher relative importance upon wireless technology than products that place a higher relative importance upon low cost manufacturing competencies. By example, we would expect Ericsson to be a very strong competitor in military wireless communications where the emphasis is placed upon RF performance rather than cost. On the other hand, we would expect Ericsson to have more difficulty in a consumer products market like the cordless telephone. This product places more emphasis on low cost than performance when compared to a military two-way radio..

Ericsson can move upstream by improving their technological lead in RF. However, in order to move downstream, they will have to improve their low cost manufacturing competencies to the point where they are on par with Japanese and other Far East consumer electronics manufacturers.

Final Analysis

Because every product that has been mentioned relies upon the core competencies of creating ASIC's and then placing these chips and other electronic components on printed circuit boards, it should be a safe assumption that successful firms in these endeavors either possess these competencies or have other competencies that make-up for any competitive disadvantage in this area. Furthermore, it would seem that a producer of

electronics who also manufactures and sells component placement equipment would have a decided advantage over their competitors. It makes sense that Seiko, Fuji, Sanyo, Hitachi, and Matsushita would want to sell component placement equipment to other firms because this action spreads their development costs over a larger number of machines. It also allows them to capture part of the manufacturing value added of products they themselves do not manufacture. If a key core competency to Seiko's success is manufacturing, it stands to reason that Seiko is not going to fully divulge its source of competitive advantage. I believe that we can therefore assume that these Japanese manufacturers all employ better equipment than they supply to other firms that perform component insertion.

Therefore in order to remain competitive, Ericsson must either develop a stronger low cost manufacturing competency or continue to insure that it can develop products that offer enough of a design/technology advantage over the competitor's offering to offset the difference in manufacturing competencies. Based upon the Three Dimensional Array Analysis, the two tasks that are repeated the most frequently are the purchasing of ASICs and the assembly of these chips to printed circuit boards. Since most of these ASICs are sourced from Ericsson's semi-conductor group, the pager group's ability to impact the cost of these chips is minimal. However, in order to remain competitive, the pager group must be able to procure chips at a competitive price and is therefore strategically reliant upon the semi-conductor group to maintain world class pricing.

The pager group has a tremendous ability to impact the cost of building a pager in the assembly of the ASIC to the PCB task. Because this task is used across the company, a 10% savings in the cost of mounting a component would probably translate into millions of dollars corporate wide. Based upon our limited analysis, the improvement of this core competency seems to be a high leverage policy.

Making the Make versus Buy Decision

In order to decide whether or not Ericsson should make its own component insertion machines, a number of other factors beyond the three dimensional array analysis need to be considered. Looking at the costs and benefits introduced in the previous chapter, we can see that there are huge potentials for learning benefits, strategic benefits, and economic benefits. The three dimensional array shows that improving Ericsson's ability to populate printed circuit boards will have a broad effect on the firm's profits and will also help improve the firm's balance because it improves the manufacturability of one of the firm's key design core competencies. On the other hand the costs are difficult to quantify.

Because the costs are so difficult to quantify, it is advisable that a firm consider the following concepts before trying to estimate the costs. The primary consideration should be whether or not the firm has the capability or is willing to purchase the capability to design and build its own assembly machinery. If these capabilities do not exist and the firm is not willing to hire competent engineers and machinists to design and build the machines, then clearly other alternatives should be pursued.

Because there is a tremendous skill gap between running and maintaining an assembly machine and designing and building these machines, manufacturing managers must carefully assess their staffs capability. Additionally, the design of high performance machines has a decidedly non-linear cost versus performance curve. Norman Augustine states this relation in his law number 15 -- "The last 10 percent of performance generates one-third of the cost and two-thirds of the problems."[17] As such a small deficiency in the engineering design team can translate into large cost overruns. If the firm only requires 90% of the best in class performance benchmark, then the probability of an average engineering team achieving this goal is fairly high. However, if the firm requires 100% or more of the benchmark, then the firm should seriously consider upgrading the engineering design team or purchasing some design tools to improve their capabilities.

Assuming the firm has the engineering talent needed to design high performance assembly machines, the next concept that should be considered is the differential between the strategic benefits and learning benefits of the "make" option versus the net strategic benefits of the "buy" alternative. If there is little or no difference between the two, then the firm should seriously consider the "buy" alternative.

The final analysis is based upon the economic benefits and costs of the alternatives. If the strategic analysis performed above yields little or no net strategic benefits for the "buy" option and the economics of the "make" and "buy" alternatives are similar or favor the "buy" alternative, then the firm should exercise the "buy" alternative. If there is little or no net strategic value to the "buy" alternative but the "buy" alternative

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[17]   Norman Augustine. Augustine's Laws (Penguin Books, New York, New York, 1983) 138.

has favorable economics, then the costs should be reconsidered, keeping in mind that the variances here are usually larger for the "make" alternative than the "buy" alternative. The variances should be weighed against the possible learning benefits and how the potential learning dovetails with the firm's overall business strategy.

If the strategic benefits are high and the economic benefits are high, then the firm should pursue the "make" alternative. If the strategic benefits are high and the economic benefits low, i.e. the cost of the "make" option is higher than the "buy" option, then the learning benefits should be weighed against the possible transfer of core competencies to the vendor. The decision should be made upon this basis.

Chapter 8 - Conclusion

Design Considerations for High Performance Assembly Machines

In order to achieve the full potential of a high performance assembly machine, the designer must integrate the design of the control with the design of the structure. A number of problems with the Acme Mfg. gantry robot could have been avoided if the designers had conducted a dynamic analysis of the structure. Although the structure was designed to limit static deflections in the vertical direction, no analysis was done in the horizontal plane. The reaction force generated by the motor creates a torque on the structure equal to the torque output by the motor and a force on the structure equal to the force delivered to the mass. In the case of the Acme Mfg. gantry robot, the motor's maximum torque was 13.4 lb-in. Because of the gearbox and pulley, this torque is converted into a 52.8 pound force. This is a substantial force for the four columns of the gantry because the loading is transversal not axial. The deflection caused by this loading can be estimated by modeling the column as a cantilevered beam with an end load as shown in figure 8.1.

$$\text{Deflection} = \frac{PL^3}{3EI} \qquad \text{Where } E = \text{Modulus of Elasticity} \\ I = \text{Moment of Inertia of the Cross Section}$$
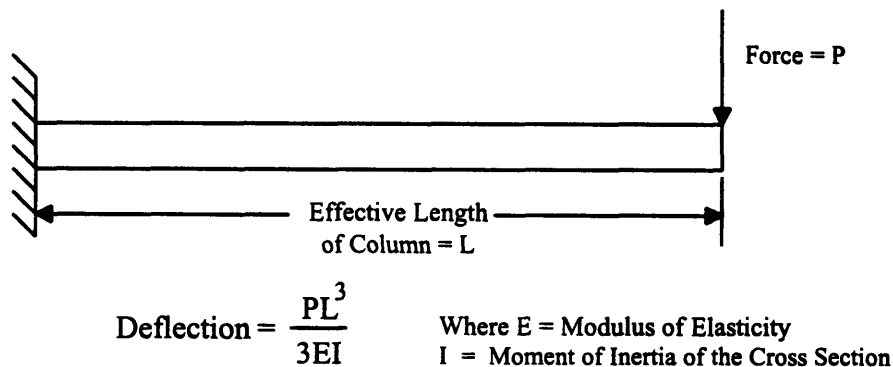
Figure 8.1 - Transverse Loading of a Column, Equivalent Load Case is a
Cantilevered Beam

As stated in chapter 5, the deflection of the structure can be reduced by increasing the stiffness of the columns, decreasing the length of the columns, or decreasing the mass of the carriage. Decreasing the mass of the carriage allows the designer to achieve the same carriage acceleration with a lower input force. The lower input force causes a smaller deflection. Obviously, the high leverage policy is to minimize the length of the column since the cube of the length is proportional to the deflection. The addition of angular braces will decrease the effective length of the columns. Note that the horizontal braces shown in figure 2.1 do nothing to reduce the effective length of the column when it is loaded transversally. The effect of the reaction torque caused by the motor also needs to be considered when calculating the actual deflection.

The gantry's unsymmetric drivetrain for the x-axis also caused a number of problems. The designer of high performance assembly machines should strive for a symmetric delivery of force to both the x and x' carriages. A T-shaped gearbox could have been mounted half way between the x and x' guide rails. Two equal length drive shafts could then have been employed to turn the drive pulleys. This arrangement would insure that both carriages experience the same transport delay and would eliminate skewing caused by unequal drive forces. However, it would not eliminate skewing caused by the movement of the y-axis centroid along the y-axis. In order to eliminate this type of skewing, the designer must produce a system that is capable of delivering different forces to the x and x' carriage.

The belt drives of the x and x' carriages create a number of problems that cannot be solved with a simple PID controller. The large changes in stiffness coupled with the anisotropic nature of the belts do not have an optimal set of controller gains but instead have position dependent optimal gains. A controller using gain scheduling or adaptive control could conceivably be designed to combat this problem. The added complexity is most likely not warranted and therefore the use of belts should be avoided whenever possible. One exception to this recommendation would be a belt used to connect two rotating shafts. In this case the stiffness of the belt is constant and the stiffnesses acting upon the shafts are isotropic.

Even though a number of problems could have been avoided by considering all of the forces acting upon the gantry, only a dynamic analysis could have predicted the settling time. A very stiff structure will have a low deflection but a low structural deflection does not necessarily translate into a low settling time. Since the general goal of all assembly machines is to effect a relative change in the position and relationship of two items as cheaply as possible, the cost imparted by the assembly machine to the manufactured part is of prime consideration.

On Costs and Strategic Considerations

This cost may be considered in two different contexts. The first context is the cycle time of the machine. The solution methodology employed herein strives to minimize the cycle time of the machine by predicting the settling time of the positioning steps. By optimizing the selection of components to the structure, a designer can realize the best possible off-the-shelf solution to the design problem. A higher performance level

will require a space/structure design so that not only the componentry is optimized but also the structure.

Decreasing the cycle time decreases the amount of the machine's cost that is associated with each unit of production. Unit manufacturing costs can also be decreased by reducing the cost of the machine. The other context, as far as the costs imparted to the product produced are concerned, is therefore the actual cost of the assembly machine. Because high performance assembly machines often provide firms with strategic advantages that lead to the ability to charge higher prices, we feel that firms should consider not only the cost of the machine but also the incremental revenues that accrue to the firm because of the assembly machine. We have developed the three dimensional array analysis to aid in the determination of these strategic benefits and to assist managers in the make versus buy decision.

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Appendix 1

What follows is a brief introduction to control theory to demonstrate the non-intuitive behavior of closed loop feedback systems. For more information, the reader should consult Ogata's *Modern Control Engineering* or another text on control theory. The simplest positioning case is a mass that is moved by a force without any static friction, dynamic friction, or viscous friction. A diagram is given at right:
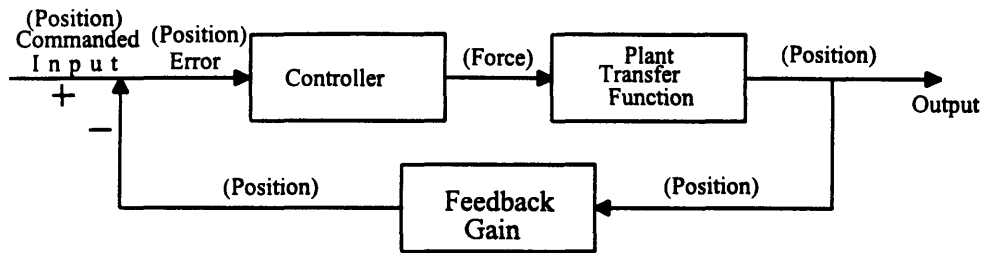
Force → | Mass |

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┌ ┬ ┬ ┬ ┬ ┬ ┬ ┬ ┬ ┬ ┬ ┬ ┬ ┬ ┬ ┬ ┬ ┬ ┐
0                   .5
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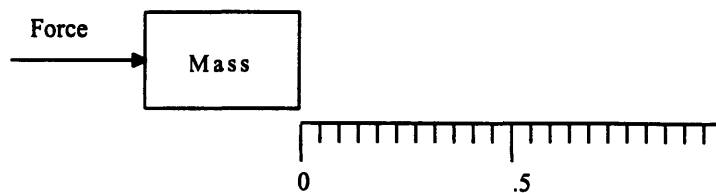
A controller can be designed to regulate the force based upon the position of the leading edge of the mass. The controller will compare the actual position of the mass with the commanded or desired position of the mass and then deliver a force that is proportional to the error, the difference between the commanded position and the actual position. The proportionality constant which converts the error to a force is known as the proportional gain. Most control systems allow a user to adjust or tune this gain to achieve a desired response. Because the proportional gain is adjustable, it is frequently listed as a variable -- K_p. For the above example, K_p will have units of Force/Length.

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Assuming that the system is currently located at position 0 and a desired position of 1 foot is input to the controller, the controller will calculate the error (error = desired position - actual position or 1 - 0 = 1), multiply the error by the proportional gain K_p and deliver this force to the mass. Thus if K_p is set to be 10 pounds/foot, a 10 lb force will be delivered to the mass.

A number of positioning systems involve electric motors and it is therefore highly recommended that control calculations be performed using the MKS system in order that the units of volts and amperes can work with units of mass, time, and length without using conversion factors. Rather than perform the conversions, let's change the example. The mass is a 1 kg mass, the desired movement is 1 meter, and K_p = 10 newtons/meter. Notice that when the mass reaches .5 meters, the error signal is reduced to 1-.5 = .5 meters and the resulting force applied to the mass will be .5 m * 10 N/m = 5 N. Similarly, when the mass reaches .75 m, the error will be .25 m and the resulting force will be 2.5 N. Finally, when the mass reaches 1 m, the error is 0 m and the resulting force applied is 0 N.

This type of control system can be represented using a block diagram. The block diagram contains the controller, the transfer function of the plant, and the feedback loop and any gain associated with the feedback. The plant is the object to be controlled and its transfer function is a mathematical representation of the relationship between the input to the plant and the corresponding output.

Signals listed in parentheses refer to the above example. Notice that the controller converts a position signal into a force signal.

The general equation is given by:

$$\Sigma F = ma$$

For our example the only force acting on the mass is F and the equation therefore becomes

$$F = ma$$

Since the acceleration is the second derivative of the position, we can write:

$$F = m\frac{d^2x}{dt^2} \quad \text{or} \quad F = m\ddot{x}$$

The transfer function is the output divided by the input and in the example above will have units of position/force because a force is input to the plant and results in a change of position. A commonly used technique for solving differential equations is the LaPlace Transform and it is therefore convenient to express the transfer function in terms of its LaPlace Transform. Taking the LaPlace Transform yields:
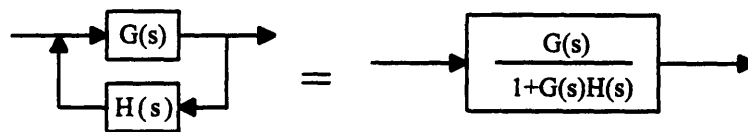
$$F(s) = ms^2X(s)$$

Where F(s) is the LaPlace transform of the input to the plant and X(s) is the LaPlace transform of the output. The LaPlace transform of the transfer function G(s) is therefore equal to X(s)/F(s) and is found to be:
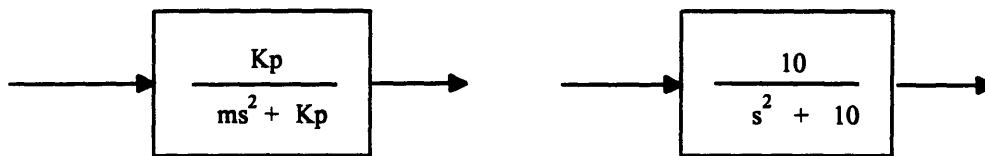
$$G(s) = \frac{X(s)}{F(s)} = \frac{1}{ms^2}$$

Substituting the LaPlace transform values into the block diagram, we obtain:

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$$\xrightarrow{\hspace{1cm}} \boxed{Kp} \xrightarrow{\hspace{1cm}} \boxed{\dfrac{1}{ms^2}} \xrightarrow{\hspace{1cm}}$$

$$\boxed{1}$$
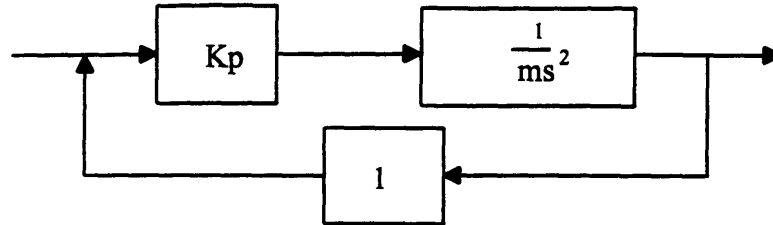
Using block diagram algebra, the closed loop transfer function can then be ascertained

using the relationship:

$$\boxed{G(s)} \quad = \quad \boxed{\dfrac{G(s)}{1+G(s)H(s)}}$$

$$\boxed{H(s)}$$

Which leads to:

$$\boxed{\dfrac{Kp}{ms^2 + Kp}} \qquad\qquad \boxed{\dfrac{10}{s^2 + 10}}$$

Suddenly changing the input to the controller from 0 meters to 1 meter

corresponds to an input of a unit step function which has a LaPlace Transform of 1/s.

Remembering that a transfer function is the mathematical relationship between the input

and the output, the output can be obtained by multiplying the input by the transfer

function. To obtain the closed loop response of the system to an input, the LaPlace

Transform of the input is multiplied by the system's closed loop transfer function. The

output is then:

$$\frac{10}{s(s^2 + 10)}$$

By using the inverse LaPlace transform, the above equation can then be solved for time. This is accomplished by using the partial fraction expansion method.

$$\frac{10}{s(s^2 + 10)} = \frac{a_1}{s} + \frac{a_2s + a_3}{(s^2 + 10)}$$

For the left side and the right side to have the same denominator, we would multiply the numerator and the denominator of the first term on the right side by the denominator of the second term. Similarly the numerator and denominator of the second term on the right side would be multiplied by the denominator of the first term.

$$\frac{10}{s(s^2 + 10)} = \frac{a_1(s^2 + 10)}{s(s^2 + 10)} + \frac{(a_2s + a_3)(s)}{(s^2 + 10)(s)}$$

Therefore we can solve for a1, a2, & a3 by equating the left and right side numerators.

$$10 = a_1(s^2 + 10) + (a_2s + a_3)s$$

or

$$10 = a_1s^2 + 10a_1 + a_2s^2 + a_3s$$

Equating like factors of s produces 3 equations in 3 unknowns.

$$10 = 10a_1; \quad 0 = a_3s; \quad 0 = a_1s^2 + a_2s^2$$

Thus

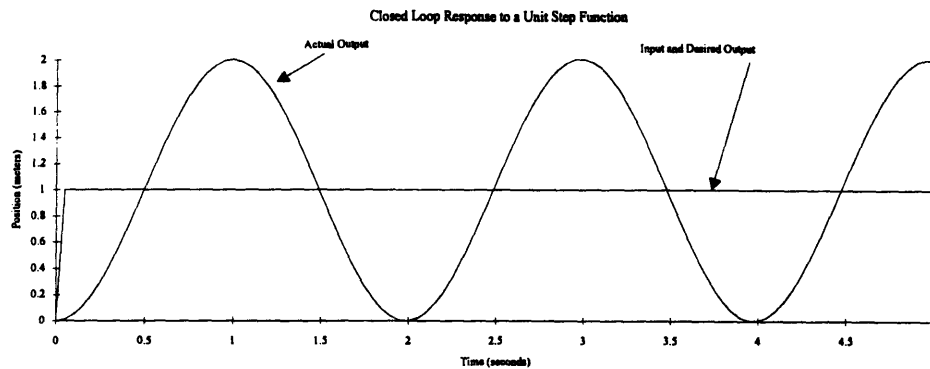$$a_1 = 1; \quad a_3 = 0; \quad a_2 = -1$$

This produces

$$\frac{10}{s(s^2 + 10)} = \frac{1}{s} - \frac{s}{s^2 + 10}$$

A LaPlace Transform table can then be used to determine the answer as a function of time:

$$\text{Output} = 1 - \cos(\sqrt{10}\, t)$$

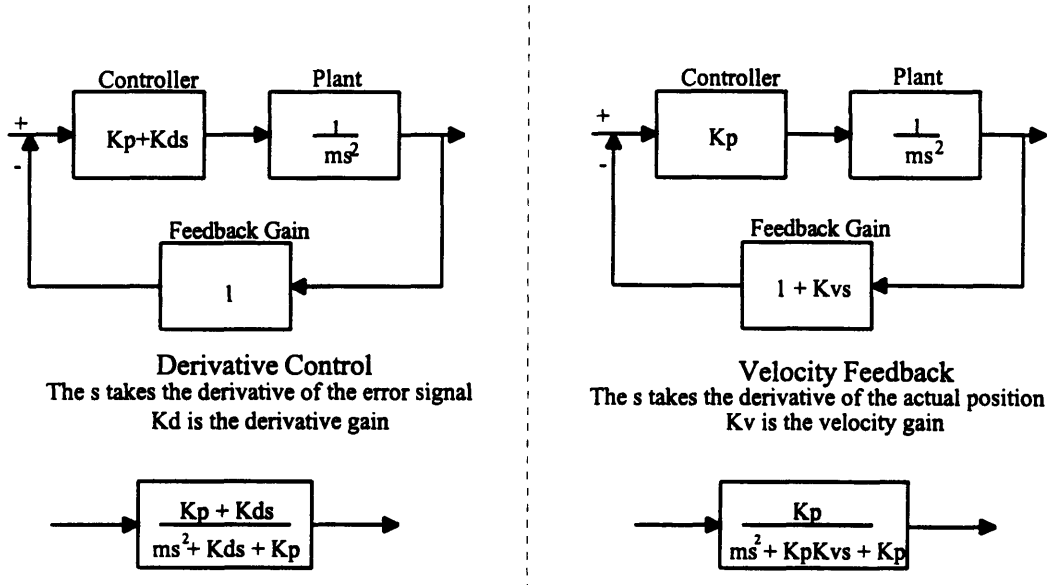The response of the system to the unit step input is shown in the following graph.

It is probably not what the reader expected and is definitely not the desired response.

Closed Loop Response to a Unit Step Function

This phenomenon occurs because the mass stores energy. When the mass reaches 1 meter, no force is applied to the mass. Prior to this, the force has always been pushing on the mass in the positive direction. As such, the mass reaches it maximizes velocity at exactly the point where we want it to stop. A body at rest tends to stay at rest and a body in motion tends to stay in motion. As the mass passes the 1 meter point, the controller begins to generate a negative force that stops the mass and then pushes it back towards the 1 meter point. Again, the mass reaches the 1 meter mark and just as it attains its maximum negative velocity. This continues forever. Fortunately, there is a technique to deal with this behavior.

One way to add damping to the system is to have the controller keep track of the velocity of the mass. The velocity can be derived from the position sensor by taking the derivative. A separate sensor such as a tachometer can also be used. Another way to add damping to the system is to take the derivative of the error signal. The former technique is known as velocity feedback while the latter technique is termed derivative control. The two produce similar but different results. The velocity feedback technique has a higher

relative stability than derivative control but derivative control can more accurately follow

a ramp input. A number of control manufacturers implement velocity feedback in their

designs but call it derivative control. The difference in the controllers are shown below.

Derivative Control
The s takes the derivative of the error signal
Kd is the derivative gain

Velocity Feedback
The s takes the derivative of the actual position
Kv is the velocity gain

By again multiplying the closed loop transfer function by the unit step function and using partial fraction expansion the following is obtained for the velocity feedback system:

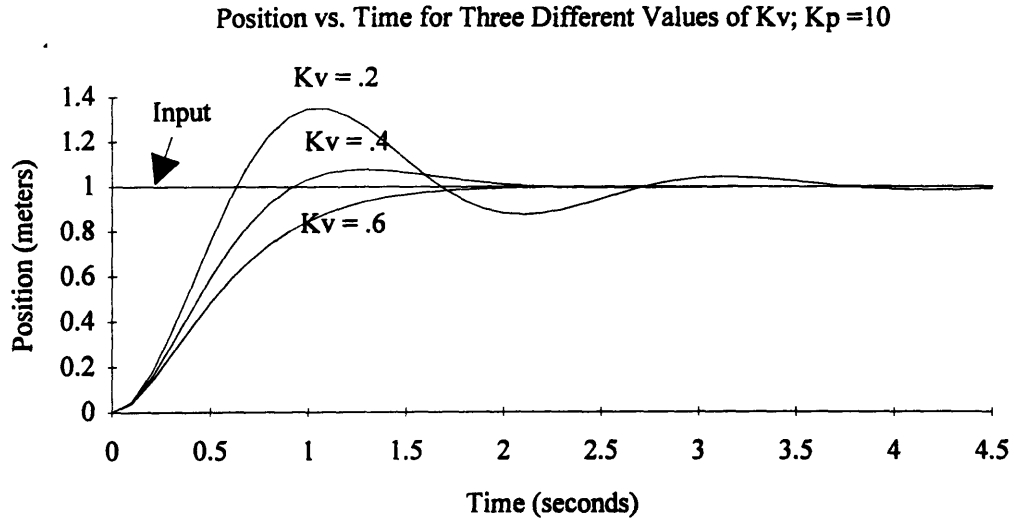$$\text{Output} = C(s) = \frac{K_p}{s(ms^2 + K_p K_v s + K_p)}$$

Fortunately, this is a common function and the inverse LaPlace Transform can be taken directly out of a table. For convenience, we make the following definitions:

$$\omega_n^2 = \frac{K_p}{m}; \quad \zeta = \frac{K_v}{2}\sqrt{\frac{K_p}{m}}; \quad \omega_d = \omega_n\sqrt{1-\zeta^2}$$

The LaPlace Transform is therefore:

$$1 - \frac{e^{-\zeta\omega_n t}}{\sqrt{1-\zeta^2}}\sin\left[\omega_d t + \tan^{-1}\left(\frac{\sqrt{1-\zeta^2}}{\zeta}\right)\right] \quad t \geq 0 \text{ and } 0 \leq \zeta \leq 1$$

Using K_p=10 and K_v= .2, .4, & .6 yields the following response:

Position vs. Time for Three Different Values of Kv; Kp =10

Notice that it takes about 2 seconds for the mass to come to rest at the position 1 meter if K_v = .4 or .6 and takes longer if K_v = .2. The time it takes for the mass to reach its position is known as the settling time, and can be improved by increasing the gain or decreasing the mass and then adjusting the velocity gain K_v accordingly. The effect of changing the proportional gain K_p to 50 is shown on the following page:

Position vs. Time for Three Different Values of Kv; Kp =10
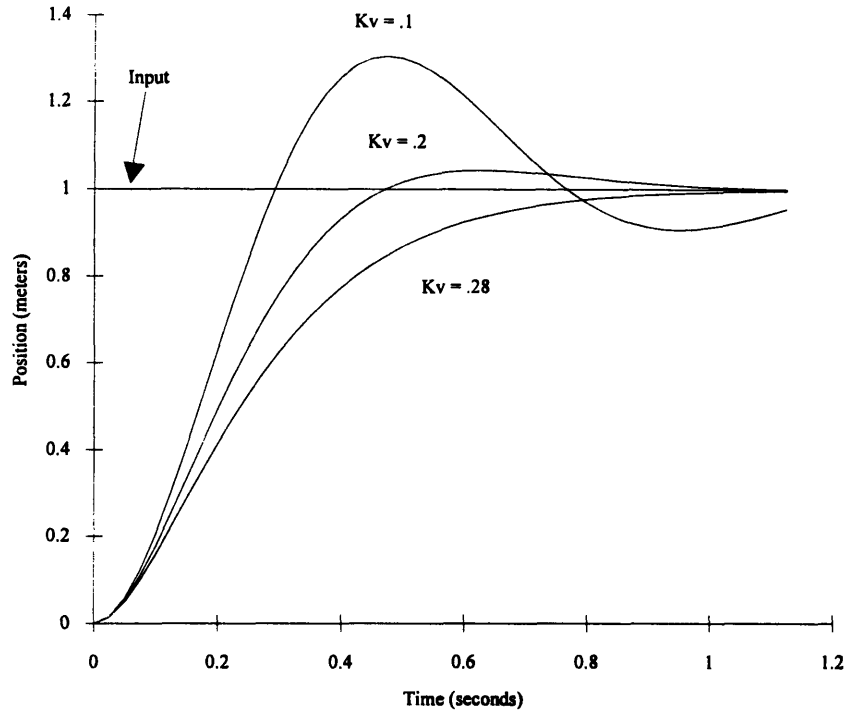
It is preferable where possible to reduce the mass rather than increasing the gain. Increasing the gain requires more power to be delivered to the system. Additionally, increasing the gain can excite structural natural frequencies that may lead to instability.

Appendix II

Doubling the value of the second mass helps the linear model account for the dynamic

friction. However, it does not account for the fact that the dynamic friction helps to stop

the mass. Thus, it makes sense that the actual step response damps out quicker than the

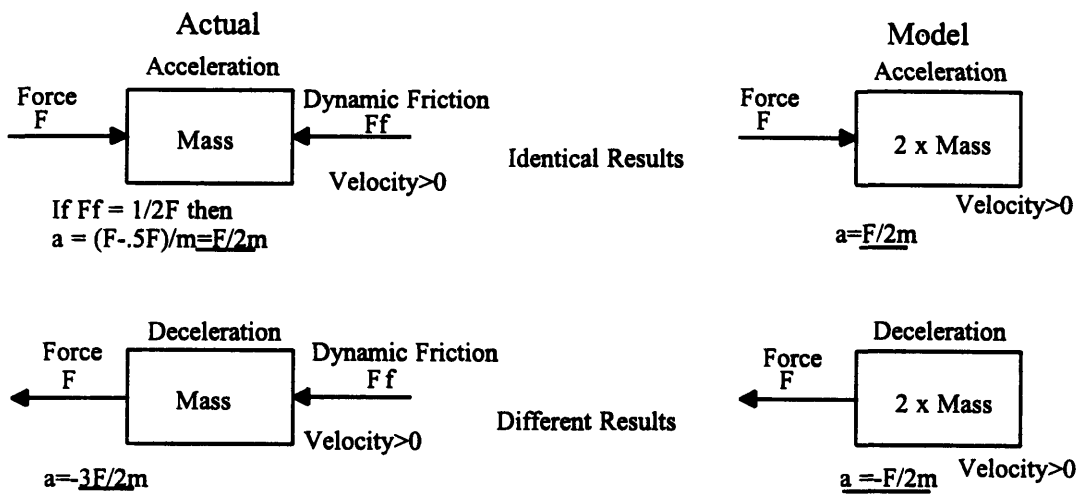model. An explanation is diagrammed below in figure II.1.

Actual

Acceleration

Force
F → | Mass | Dynamic Friction
Ff
Velocity>0

Identical Results

If Ff = 1/2F then
a = (F-.5F)/m=F/2m

Model

Acceleration

Force
F → | 2 x Mass |
Velocity>0

a=F/2m

Deceleration

Force
F ← | Mass | Dynamic Friction
Ff
Velocity>0

Different Results

a=-3F/2m

Deceleration

Force
F ← | 2 x Mass |
Velocity>0

a =-F/2m   Velocity>0

Figure II.1 - Linear Modeling Approximation of Dynamic Friction