Design and Prototype Fabrication of a Manipulator for Semiconductor Test Equipment

by

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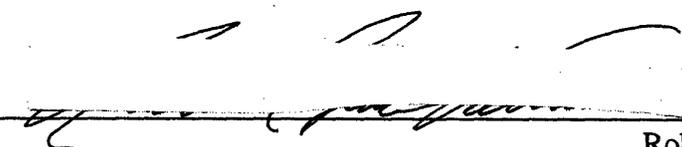
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Abstract

This thesis describes a product development project that was part of the New Products Program in the Department of Mechanical Engineering at the Massachusetts Institute of Technology. The project focused on the development of the Universal Manipulator, an inexpensive, seven degree of freedom, pendant/manual controlled manipulator to position semiconductor test equipment. The Universal Manipulator was developed jointly with Teradyne, Inc., one of the world's leading manufacturers of semiconductor test equipment. Teradyne employees were responsible for the initial design specifications and subsequent design reviews. Graduate students within the Precision Engineering Research Group were responsible for the conceptual design, detailed design, and prototype fabrication. This thesis introduces why a new manipulator was needed, summarizes the project management, provides a thorough overview of the alpha prototype, and introduces the beta prototype.

Thesis Supervisor: Alexander H. Slocum
Title: Alex and Brit d'Arbeloff Associate Professor
                            Mechanical Engineering Department

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I acknowledge Alex for his ceaseless creativity and enthusiasm, Rick for his management insight, the entire design team for late hours and hard work, and Debie for unloading the Kaydon bearings.

I thank God for being blessed with the capacity to question, learn, explore, and create.

I thank my family for their loving thoughts and for forgiving me when I forget.

I thank Elizabeth for her compassion, encouragement, and devotion.

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I thank the design team: Carsten, Dave, Rolland, and Sep.

I thank Alex for giving me the opportunity to design.

*"Do not say that you're afraid to trust your mind because you know so little. Are you safer in surrendering to mystics and discarding the little that you know? Live and act within the limit of your knowledge and keep expanding it to the limit of your life. Accept the fact that you are not omniscient, but playing a zombie will not give you omniscience--that your mind is fallible, but becoming mindless will not make you infallible--that an error made on your own is safer than ten truths accepted on faith, because the first leaves you the means to correct it, but the second destroys your capacity to distinguish truth from error. In place of your dream of an omniscient automation, accept the fact that any knowledge man acquires is acquired by his own will and effort, and that **that** is his distinction in the universe, **that** is his nature, his morality, his glory."*

Ayn Rand, **Atlas Shrugged**

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"The machine, the frozen form of a living intelligence is the power that expands the potential of your life by raising the productivity of your time."

Ayn Rand, **Atlas Shrugged**

1. Introduction to the Thesis

This thesis describes a product development project that was part of the New Products Program in the Department of Mechanical Engineering at the Massachusetts Institute of Technology. The project focused on the development of the Universal Manipulator, an inexpensive, seven degree of freedom, pendant/manual controlled manipulator to position semiconductor test equipment. The Universal Manipulator was developed for Teradyne, Inc., one of the world's leading manufacturers of semiconductor test equipment. The project consisted of designing and fabricating an alpha prototype and subsequently designing and fabricating two beta prototypes. The thesis introduces why the Universal Manipulator was needed, describes how the project was managed, provides a thorough overview of the alpha prototype, and introduces the beta prototypes.

A small team of graduate students from the Precision Engineering Research Group (PERG), directed by Dr. Alexander H. Slocum, was responsible for the design and prototype fabrication. The Precision Engineering Research Group is a member of MIT's Laboratory for Manufacturing and Productivity (LMP). Teradyne employees were responsible for the initial design specifications and subsequent design reviews. After the beta prototypes were delivered, Teradyne was responsible for additional design modifications and preparing for production. The project required extensive effort from

other people including employees from Aesop, Inc. and several machine shops. The author has attempted to recognize all contributing individuals and companies.

Chapter 1 of the thesis introduces the Universal Manipulator project by beginning with the semiconductor and semiconductor equipment industries and narrowing to Teradyne's need for a new manipulator to position semiconductor test equipment. The semiconductor test process and the associated test equipment are introduced, and particular mechanical issues with the testing process and equipment are explained. The chapter concludes with a conceptual solution to Teradyne's mechanical issues, of which the new Universal Manipulator is a subset.

1.1 The Semiconductor and Semiconductor Manufacturing Equipment Industries

The semiconductor industry has revolutionized the world with their ability to rapidly *develop* and *apply* new technology. For that reason, the boom of the semiconductor industry has been referred to as the second industrial revolution. As the world becomes dependent upon electronics, manufacturers of integrated circuits deliver increasingly powerful products with improved quality and reliability. To accomplish this, the industry continuously improves by developing new integrated circuits and by improving manufacturing quality with new manufacturing equipment and processes.

The history of the semiconductor industry tells the story of international competition between Europe, the United States, and Japan. Malerba describes why the Europeans lost their semiconductor industry to the United States (U.S.) when the U.S.

invested extensively in defense related technologies[1]. More familiar to Americans, however, is the loss of our semiconductor industry to Japanese manufacturers during the 1980s. Angel explains how the U.S. market share in the semiconductor industry shrunk from 58% to 37% while Japan's grew from 26% to 49%[2]. Angel attributes the loss in market share to many factors, but chiefly problems with "low yields"[3] and problems with matching market demand and production capabilities. Semiconductor manufacturing facilities in the U.S. were designed for large production rates, and as a result it was difficult to produce quality products when demand was low.

In addition to low yields and production problems, Angel also attributes the Japanese market take-over to Japan's effective long-term relationships with their equipment suppliers. U.S. manufacturers elected to not form long term relationships because they preferred to selectively jump from supplier to supplier depending on which had the best technology at the moment. In addition, U.S. manufacturers often forwarded some of the cost of their fluctuating market demand to their equipment suppliers in the form of canceled or reduced orders on new manufacturing equipment. In contrast, the Japanese formed strong relationships with equipment suppliers, sponsoring investments in new technologies and strengthening the Japanese semiconductor equipment industry. In 1990, the *Tokyo Business Today* published that between 1983 and 1989 the U.S.

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[1] Malerba, Franco. *The Semiconductor Business*. Frances Pinter Publishers. London. 1985.

[2] Angel, David P. *Restructuring for Innovation, The Remaking of the U.S. Semiconductor Industry*. The Guilford Press. New York, New York. 1994.

[3] The term "low yields" is used to indicate that the percentage of acceptable dies or chips is a small percentage of the total manufactured.

market share of semiconductor equipment had dwindled from 62% to 41% while the Japanese share had increased from 28% to 48%[2].

Many economic forecasters predicted the loss of the semiconductor industry to Japan, but instead, U.S. manufacturers revitalized by structuring themselves for innovation[2] and applying Total Quality Management (TQM) techniques[4]. In 1994, the U.S. semiconductor industry lead the $101.88 billion worldwide semiconductor market with a 32.9% market share compared to Japan's 28.9% market share[5,6]. To accomplish this dramatic reversal, U.S. manufacturers focused their attention on production and quality issues, including relationships with their equipment suppliers.

The semiconductor industry's rapid pace of technological innovation significantly impacted the semiconductor equipment manufacturers. To maintain the pace of semiconductor manufacturers, equipment suppliers were forced to be fast and innovative. The short product life cycles were beneficial, however, because semiconductor manufacturers regularly invested in new equipment to produce their latest integrated circuits.

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[4] Shiba, Shoji, Alan Graham, and David Walden. *A New American TQM, Four Practical Revolutions in Management.* Productivity Press and the Center for Quality Management. Portland, Oregon and Cambridge, Massachusetts. 1993.

[5] Bulkley, Ann E. "Strong Chip Sales Spark Capital Equipment Investment". Economic Indicator Column. *Semiconductor International.* August, 1995.

[6] W. Europe and Korea/ROW were close behind with 19.4% and 18.8%, respectively.

1.1.1 Overview of Integrated Circuit Manufacturing

The details of the semiconductor manufacturing process are described in several sources[7,8,9]. The general process is condensed and illustrated by the flow chart in Figure 1.1. The manufacturing process begins with silica sand and ends with an integrated circuit. The first phase of processing is wafer preparation. Silica sand, which contains about 1% impurities, is refined through chemical reactions to obtain ultrapure polycrystalline silicon. The polycrystalline silicon is melted and recrystallized (often referred to as "growing") into a rod of single-crystal silicon using either the Czochralski or float zone techniques. The silicon crystal rod is ground round to an 8" diameter, and the rotational orientation of the crystal is determined. Then the crystal rod is sliced into thin wafers[10]. Each wafer receives a mirror-like finish by polishing the wafer to the proper surface quality.

The next phase in the manufacturing process, wafer processing, generates a rectangular array of "dies" on the surface of the wafer. Each die is an intricate topographical structure of device regions, interconnections, and pads which will become the heart of an integrated circuit. In Figure 1.1, the wafer processing stage is broken into

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[7] Gise, Peter E. and Richard Blanchard. *Semiconductor and Integrated Circuit Fabrication Techniques.* Reston Publishing Company, Inc.. Reston, Virginia. 1979. MIT Library: TK7871.85.G49 (1979)

[8] Wolf, S. and Tauber, R. *Silicon Processing for the VLSI Era Volume 1: Process Technology.* Lattice Press. Sunset Beach, CA. 1986.

[9] Wolf, S. and Tauber, R. *Silicon Processing for the VLSI Era, Volume 2: Manufacturing Technology.* Lattice Press. Sunset Beach, CA. 1986.

[10] Currently, wafers are 200 millimeters in diameter and about .7 millimeters thick. The industry is beginning to switch to a new standard diameter of 300 millimeters, but this will take several years to complete.

three iterative steps: surface conditioning, photolithography, and etching or lift-off. With

each iteration, a layer of patterned material is built-up on the surface of the die until the

topography is complete.
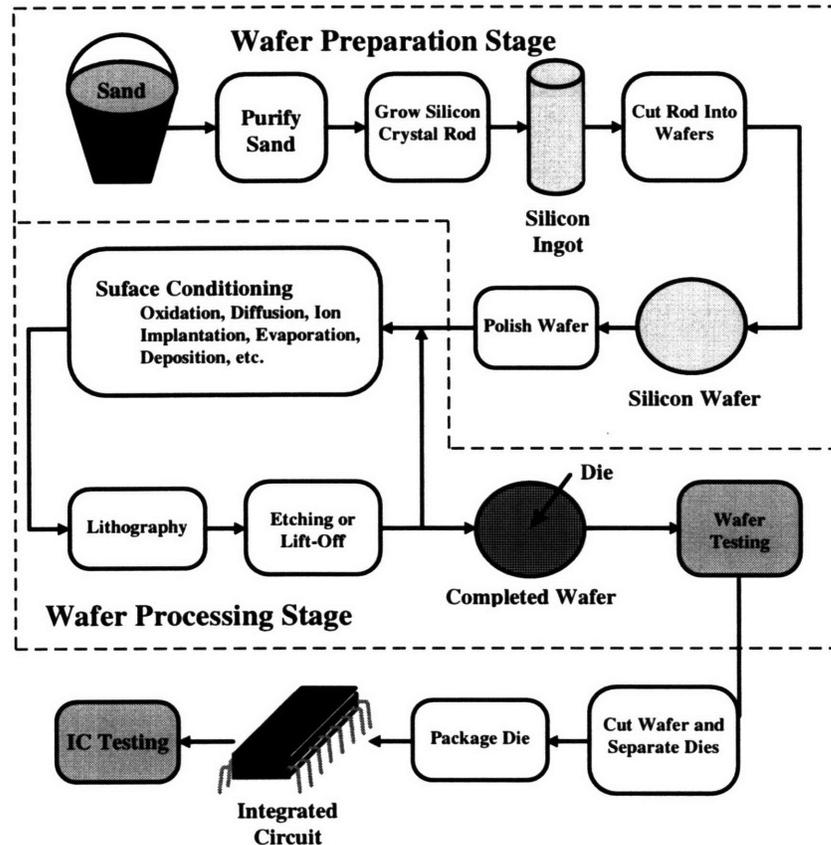
Figure 1.1: Flowchart of the Integrated Circuit Manufacturing Process[11]

The most common surface conditioning processes are diffusion, ion implantation,

thermal oxidation, vapor deposition, and cleaning. Diffusion uses concentration gradients

at high temperatures to form the p-n junctions by introducing impurities or dopants in gas,

liquid, or solid form into the silicon. Ion implantation, another method of introducing

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[11] This figure was adapted from a figure in Chapter 1 of *Silicon Processing for the VLSI Era Volume 1: Process Technology* by Wolf and Tauber, Lattic Press, 1986.

dopants, is becoming increasingly more common because of its superiority over the diffusion process. Thermal oxidation is the process of generating a protective coat of silicon oxide (SiO_2) on the surface of the die. Vapor deposition is a process for applying a thin film (.5 - 20 μm) of varying materials onto the die.

After surface conditioning is complete, the die is subjected to photolithography. The first step in photolithography is coating the wafer with a thin film of photoresist. Radiation in the form of ultraviolet light, electrons, or x-rays is applied to the photoresist through a mask with a pattern of opaque and transparent areas. In the subsequent developing process, the areas exposed to the radiation are generally made soluble in a specific solvent. Following development, the exposed regions can then be removed with etching[12]. The entire process replicates the pattern of the mask on the surface of the dies. The iterative loop of surface conditioning, photolithography and etching continues until the topography on the die's surface is complete.

After the wafer processing stage, each die on the wafer is tested. The wafer is then cut into individual dies, and the dies which passed the tests are generally encapsulated within a black ceramic package. After packaging, each integrated circuit is usually tested a final time prior to shipping.

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[12] Lithography can also be used with a process known as "lift-off" to add material to the die.
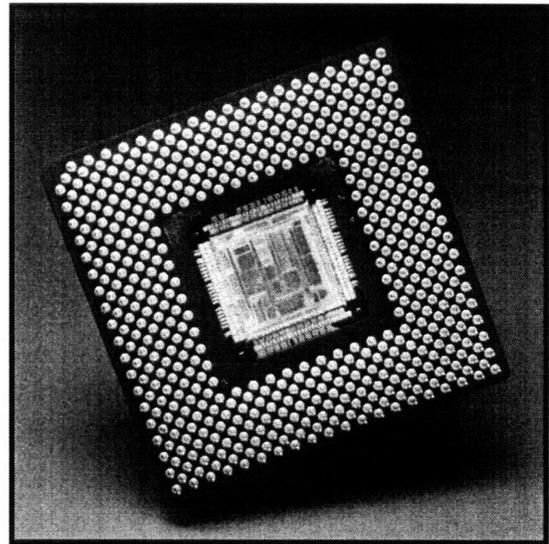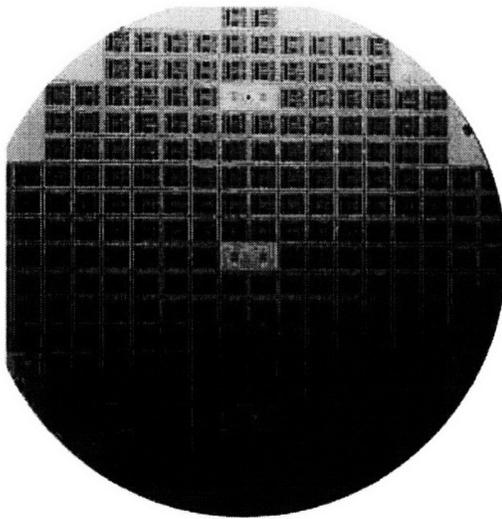
Figure 1.2: Uncut Silicon Wafer (Left) and Packaged Integrated Circuit (Right)

1.1.2 Ensuring Quality and Reliability in Integrated Circuits

In today's world, almost everything is dependent upon the performance of integrated circuits. They are used in nearly every electronic device, and they are becoming increasingly popular in mechanical systems as controllers. Integrated circuits are commonly used with little regard for their inherent reliability and quality of performance. How is it that integrated circuits appear to operate continuously without failing? This phenomenon is the result of the failure rate characteristics of electrical devices and effective testing during the manufacturing process.

Figure 1.3 illustrates a common model of the failure rate (probability of failure) of electronic devices as a function of time when operated under design conditions (temperature, voltage, and current). Electronic devices exhibit a high probability of failure near the beginning of their life (commonly referred to as "infant mortality"), but the failure rate eventually reaches a low and nearly constant value. This failure rate

model is much different than the degradation exhibited by mechanical components in which the failure rate continually increases with time. Once an electrical device has passed the infant mortality stage, it generally operates indefinitely with a low probability of failure[13].

Hazard Rate
$\lambda(t)$

Dead on arrival (DOA) failures which tested OK but were later discovered as non-functional because of an *event-dependent* situation such as handling damage or other insults which made them fail before the use clock started.

Device operating failure which occurred during early operation of the device. The failure rate is time dependent and described by the Weibull infant mortality model.

Steady-state failure rate from random events described by the exponential failure model.

Operating Time

0

Infant Mortality

10^4 hours
~1 year +

Steady-State Operation

Figure 1.3: Failure Rate Model for Electrical Components[14]

The second reason for the quality and reliability of integrated circuits is effective testing during the manufacturing process and the testing of the device prior to shipment. Semiconductors are typically tested at two periods in the manufacturing process as shown in Figure 1.1. Semiconductor manufacturers have discovered that there is a significant economic advantage for testing dies prior to cutting the silicon wafer and packaging because money is not wasted on packaging defective dies. Another set of tests are

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[13] Electrical devices are often accelerated through the infant mortality phase with a process known as "burn-in" in which the device is subjected to high operating temperatures.

[14] Barringer, Paul. "Reliability Engineering Principles". Barringer & Associates. Humble, Texas. 1994.

performed on the integrated circuit after they have been packaged and prior to shipment. These tests insure that the devices are functional and beyond their infant mortality stage. Together, the failure rate characteristics described above and effective testing during production, nearly eliminate all defective integrated circuits and insure reliable electronic devices.

1.2 Teradyne's Business and Products

In the late 1950s, Nick DeWolf observed a need in the semiconductor industry for a device capable of testing diodes during production. In 1960, DeWolf joined with Alex d'Arbeloff[15] and formed Teradyne, Inc. in Boston Massachusetts to fulfill this market need. Teradyne went public in 1970, and has been traded on the New York Stock Exchange since 1979. Today, Teradyne describes their business as "the creative application of systems technology to practical problems in the design, manufacture, and servicing of electronics" [16]. Teradyne's products include test systems for semiconductors, test systems for circuit-boards, test systems for telecommunications, and backplane connection systems. Teradyne designs, manufactures, sales, and services these systems throughout the United States, Europe, and Asia's Pacific Rim.

Teradyne's semiconductor test systems are designed by two separate divisions, the Industrial/Consumer Division (ICD) in Boston, Massachusetts, and the Semiconductor

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[15] Alex d'Arbeloff remains in the company as Chairman of the Board and President. Nick DeWolf is no longer associated with the company.

[16] Teradyne's Annual Report to Shareholders. 1994.

Test Division (STD) in Agoura Hills, California. ICD is responsible for test systems related to linear and mixed-signal integrated circuits, and STD is responsible for test systems related to VLSI and memory integrated circuits. Teradyne's customers use the test systems to increase product performance, improve product quality, shorten time to market, enhance manufacturability, conserve labor costs, and increase production yields. Prices for Teradyne's test systems range from less than $100,000 to $5 million or more[17].
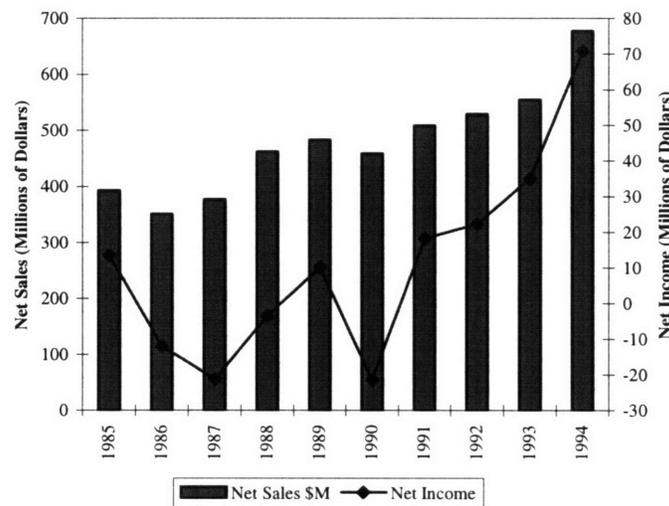
Figure 1.4: Teradyne Net Sales and Net Income Since 1985[16]

Teradyne managed to survive the hard times experienced by U.S. semiconductor equipment manufacturers during the 1980s. Through the leadership of d'Arbeloff and other managers, Teradyne initiated Total Quality Management (TQM) techniques in 1990. Since that time, Teradyne has experienced four straight years of increased sales as shown in Figure 1.4, including a record year in 1994. Semiconductor manufacturers

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[17] Teradyne's 10-K SEC filing contained in Teradyne's 1994 Annual Report to Shareholders.

spent two years increasing their production capacity and suddenly discovered a lack of test capacity. Record sales were recorded by Teradyne during 1994's fourth quarter in all of their products, including VLSI logic, memory, and linear/mixed-signal[16].

The highly technical nature of Teradyne's products requires a large engineering and development effort[18]. Teradyne's engineering and development expenditures for new and improved products were approximately $62.0 million in 1992, $62.4 million in 1993, and $70.4 million in 1994. These recent engineering expenditures resulted in the release of four new test systems with more to arrive in early 1996[17,19].

1.3 The Semiconductor Test Equipment

Teradyne's test systems typically contain four pieces of equipment: a testhead, a mainframe computer, a workstation computer controller, and a manipulator. Figure 1.5 shows a photograph of Teradyne's J971 VLSI Test System. The testhead is packed with circuit boards which are responsible for the initial analog signal processing when a die is tested. The results of the testhead's signal processing are then forwarded to the mainframe for further processing as digital signals. A large cable bundle contains the power cables and the intermediate signals wires.

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[18] Traditionally, these expenditures have focused on electrical engineering issues, but recently an increased share has been invested in solving mechanical problems that are addressed in Section 1.4 of this chapter.

[19] STD introduced three new test systems in 1994, one new system to the J971 product line, and two new systems to the J921 product line. In 1995, ICD released the A565 test system. Both ICD and STD are expected to release new product lines in early 1996.
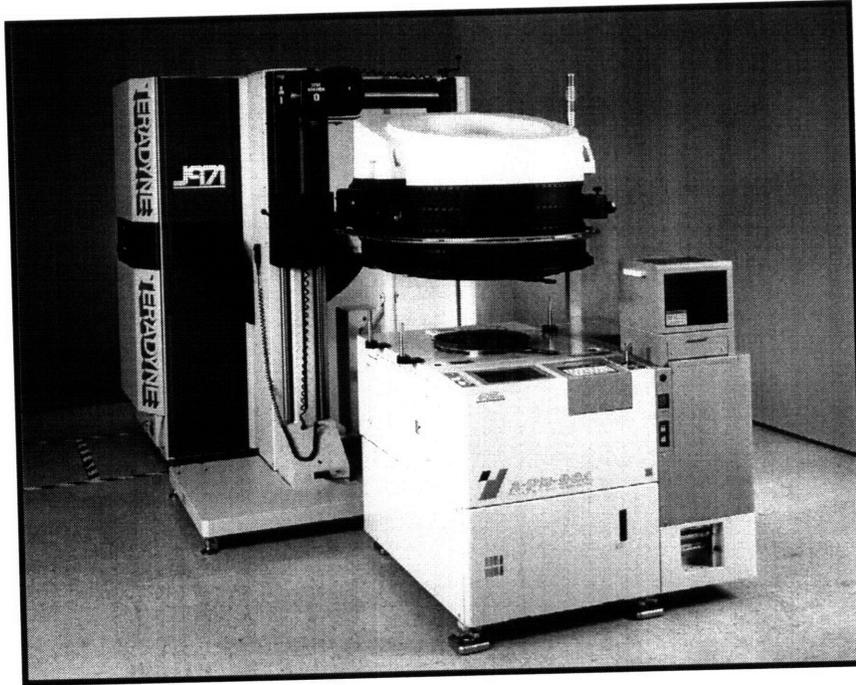
Figure 1.5: Teradyne J971 Test System with RAM Manipulator

1.3.1 Teradyne's Magnum Testhead and Cable Bundle

Teradyne's STD and ICD divisions sale about nine different test systems which are available in a variety of testhead, mainframe, and cable configurations. The new Universal Manipulator was initially designed to be used with STD's Magnum testhead, illustrated in Figure 1.6. It is anticipated that the Universal Manipulator will later be adapted for use with Teradyne's other testheads.

TOP VIEW OF TESTHEAD AND CABLE

ø 33.50

38.25

SIDE VIEW OF TESTHEAD AND CABLE

21.00

BOTTOM VIEW OF TESTHEAD AND CABLE

ø 11.00

ø 28.00

CABLE BUNDLE

CABLE EXIT

MOUNT TO MANIPULATOR

CAST ALUMINUM FRAME

ISOMETRIC VIEWS OF TESTHEAD AND CABLE

DUT PLANE
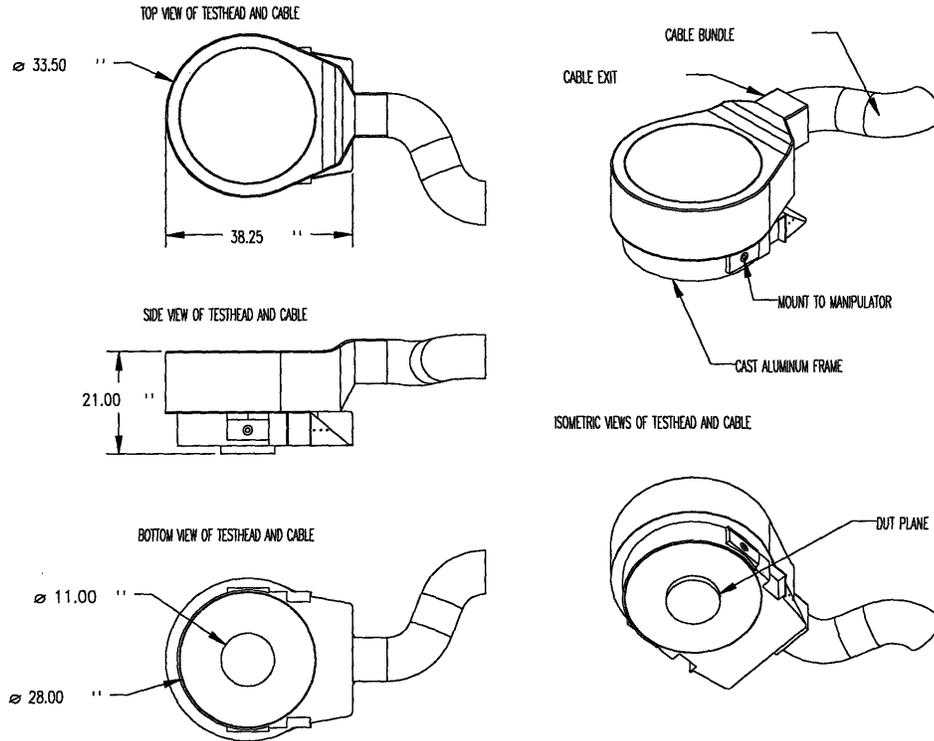
Figure 1.6: Illustration of STD's Magnum Testhead and Cable Bundle

The Magnum testhead, STD's newest testhead, weighs approximately 900 pounds, is 83.8 cm (33 in.) in diameter and 53.3 cm (21 in.) tall. The structure of the testhead is provided by an aluminum casting. The cable bundle used with the Magnum testhead weighs approximately 1560 N (350 lbs), has a cross-sectional area of about 323 cm^2 (50 $in.^2$), and is about 2.29 m (7.5 ft.) long[20]. The circuit boards within the testhead are cooled by coolant water supplied from the mainframe through flexible hoses included within the Magnum's cable bundle.

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[20] The cable bundle for the Magnum testhead played a significant role in the specifications of the Universal Manipulator because it subjected the testhead and manipulator to large external forces and torques.

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1.3.2 Testhead Manipulators

Teradyne's testheads are supported by manipulators which position and orient the testhead relative to probers or handlers. Probers and handlers are described in Section 1.3.3. Four types of manipulators were common prior to the development of the Universal Manipulator:

1. the RAM manipulator, sold by Teradyne's' ICD and STD divisions,
2. mainframe-mounted manipulators, sold by Teradyne's ICD division,
3. the in^2 manipulator, sold by inTEST, and
4. a hinged manipulator, sold by Electroglass.

Traditionally, manipulators moved the testhead with assistance from a person pushing or pulling the testhead, by driving the testhead with motors controlled by a hand-held pendant, or by a combination of the two methods.

Both STD and ICD commonly sold the RAM manipulator, shown in the Figure 1.5, with their test systems. The RAM manipulator used human power and a motor to move the testhead with seven degrees of freedom[21]:

1. Swing positioning about the manipulator column,
2. Up/down positioning in the vertical direction,
3. In/out positioning in the x-direction,
4. Side-to-side positioning in the y-direction,
5. Twist rotation about the x-axis,
6. Tumble rotation about the y-axis, and

---

[21] The testhead has seven degrees of freedom, three position, three orientation, and a redundant degree of freedom provided by the swing motion. Swing is often used by operators to move the testhead to the service position.

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7. Theta rotation about the z-axis.

The only powered motion on the RAM manipulator was the twist rotation about the x-axis. All of the remaining motions were powered by a human operator pushing or pulling on the testhead. Counterweights balanced the weight of the testhead so that a human could lift or lower the testhead by hand to accomplish up/down positioning in the vertical direction. The testhead cable was held by a cable support on the manipulator's vertical column and a gas spring behind the column.

In addition to the RAM manipulator, ICD sold a manipulator that attached to the mainframe computer and was supported by the mainframe computer's structure. This style of manipulator is shown in Figure 1.7. The mainframe-mounted manipulator provided motions similar to the RAM manipulator.

Other companies sold third-party manipulators as alternatives to Teradyne's manipulators. Two of the leading competitors were the in^2 manipulator from inTEST Corporation shown in Figure 1.8 and the simple one degree-of-freedom, hinged manipulator sold by Electroglass which is shown in Figure 1.9.
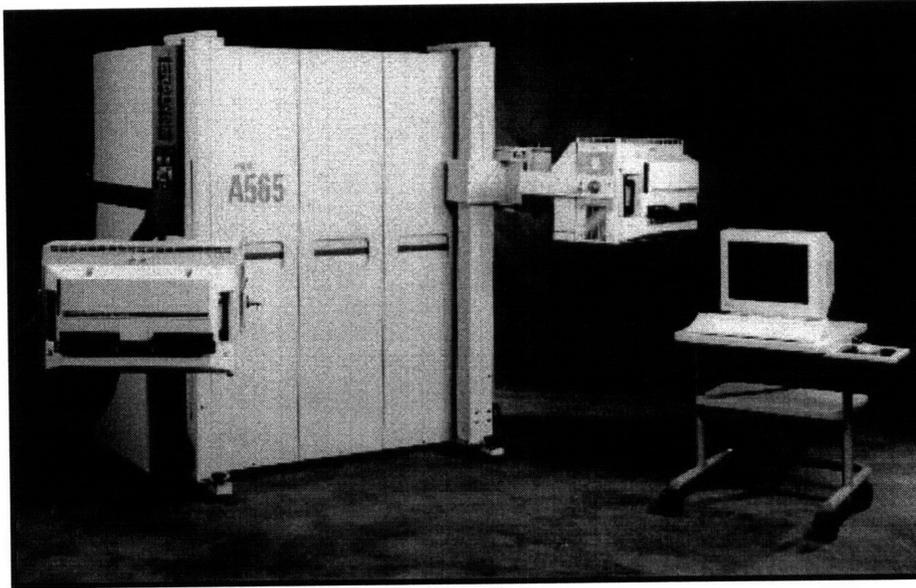
Figure 1.7: ICD's Mainframe-Mounted Manipulator
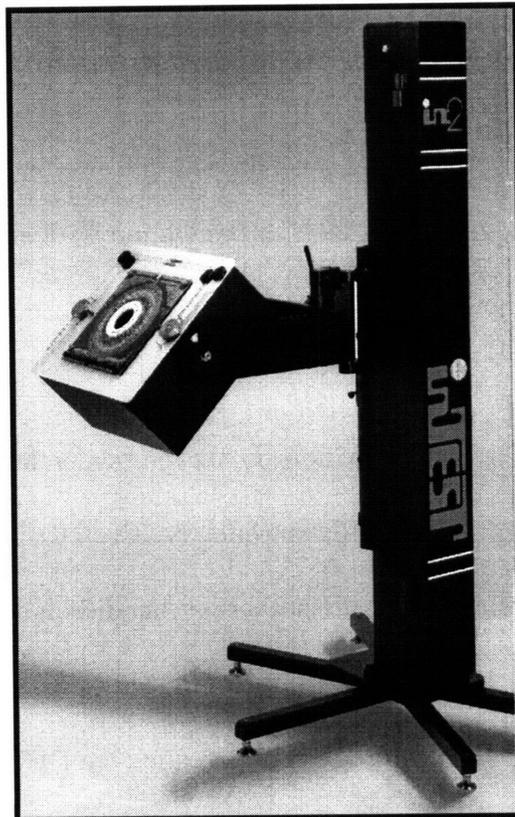
Figure 1.8: The in^2 Manipulator from inTEST Corporation
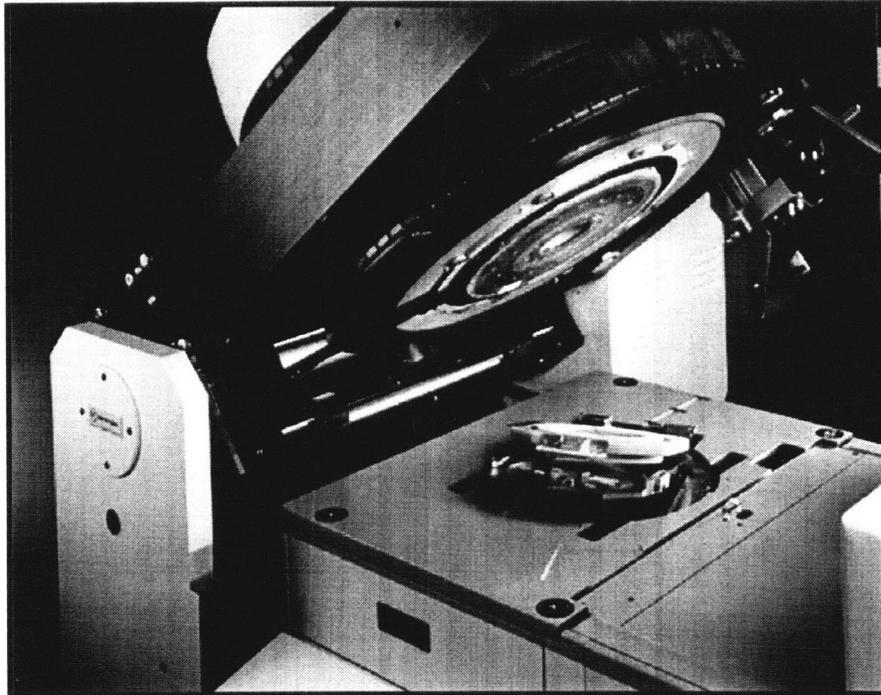
Figure 1.9: Hinged Manipulator from Electroglass

1.3.3 Probers and Handlers

Teradyne's test equipment is used in production with either a prober or a handler. A prober positions an uncut silicon wafer beneath a testhead, and a handler positions a packaged IC beneath a testhead. Probers and handlers are stationary machines which internally move the wafer or IC. A hole in the prober or handler allows the testhead electronics to be connected to the silicon wafer or IC. The process of positioning and orienting the testhead relative to the prober or handler is commonly referred to as "docking" the testhead. The wafer or IC being tested is called the Device Under Test (DUT), and the plane where the testing occurs is called the DUT plane.

Probers are generally capable of positioning and orienting a wafer with three position degrees of freedom and a rotation degree of freedom for alignment. Probers and

handlers are manufactured by different equipment suppliers, and as a result, almost every prober or handler has a unique design. Some probers and handlers position the wafer or IC horizontally facing upwards toward the ceiling. Other probers and handlers position the wafer or IC horizontally but facing downward towards the floor. Still others position the wafer or IC so that it is vertically oriented or at a 55° angle to the floor. Figure 1.10 shows a photograph of a dual setup with two probers.
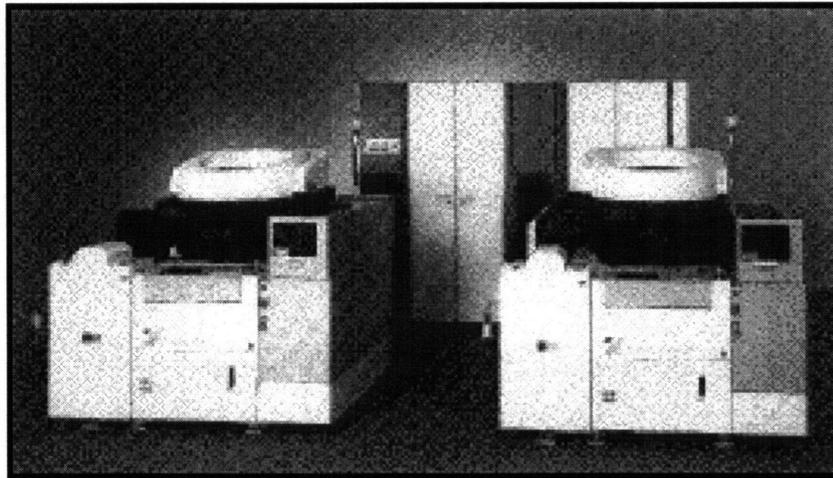
Figure 1.10: Photograph of a Floor Plan Arrangement with Two Probers

The electrical connections between the testhead electronics and the die or IC being tested within the prober or handler is made by the testhead interface. A typical interface is illustrated in Figure 1.11. Alagheband[22] described the components within the interface and their role in the docking of testheads to probers and handlers.

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[22] Alagheband, A. "Teradyne: A Kinematic Interface for Semiconductor Test Equipment". A case study published by MIT's Laboratory for Manufacturing and Productivity. 1995.

Figure 1.11: Photograph of a Typical Testhead/Prober Interface

1.4 Mechanical Issues in the Testing Process

Alex d'Arbeloff, Chief Executive Officer of Teradyne, described the history of the integrated circuit testing process with the following analogy:

> If you drop a frog into a pot of boiling water, it will immediately jump out, but if you drop it in cool water and gradually turn up the heat it will remain.[22]

When semiconductors and integrated circuits were first produced, tests were performed by technicians using probe needles to measure voltages and current. From this history, the semiconductor industry became trapped into moving the test equipment to the DUT rather than moving the DUT to the test equipment. Moving the test equipment was not a problem twenty years ago, but this is no longer true. As integrated circuits become more powerful, they require more complex testing equipment. The test equipment must be faster and more accurate than the devices being tested, yet be made with existing

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technology. As a result, test systems are enormous with huge testheads and cable bundles. This size problem compounds with the variety of probers and handlers available and their respective floor plan arrangements. It is ironic that as the devices being tested became more complex, they became smaller, but the test equipment became larger and heavier.

As the size and weight of test equipment increased, mechanical issues in the test process became evident which had been neglected for many years. One issue encountered was the size of the manipulator required to lift and move the large testheads. The load capacity of the RAM manipulator became a serious issue when Teradyne's STD division began to design the Magnum testhead which is described in Section 1.3.1. It was determined that the RAM manipulator was not strong enough to handle the Magnum testhead. The large cable bundles were also becoming an issue because the external forces applied to the testhead and manipulator pulled the testhead and created linear forces and rotational torques. In addition the wires in the cable bundle became damaged due to the tension forces in the cable as the bundle flexed while the testhead was moved.

Problems with repeatability and accuracy were also becoming issues, because the number pads that the probe needles had to touch were increasing while the size of the pads and distance between neighboring pads decreased. As a result, the testhead needed to be positioned and oriented relative to the prober or handler with greater accuracy. Repeatability was necessary because users wanted the testhead to repeatedly go to the same location after moving the testhead and servicing the interface.

Another mechanical issue was that as the probe needles contacted the pads, they often scraped and damaged the surface of the die. Scraping occurred because the motion of the testhead was not perpendicular to the pads during the docking process.

All of these mechanical issues were causing significant increases in the time to dock a testhead to a prober or handler and reducing the quality of the testing process. Semiconductor manufacturers were quickly becoming frustrated with test equipment performance. Teradyne's management also realized that these issues would only become worse as integrated circuits continued to become faster and more powerful.

In summary, Teradyne needed to resolve the following issues to improve the quality of the testing process, reduce the docking time, and satisfy their customers:

1. a stronger manipulator to support future testheads and cable bundles,
2. an improved method for supporting the cable bundle,
3. reduce the bending and flexing of the wires inside the cable bundle,
4. increase the accuracy in the docking process,
5. increase the repeatability between docking processes,
6. increase manipulator manufacturability,
7. ensure that the final travel of the interface needles is normal to the die surface, and
8. a single manipulator that could be used with all probers and handlers by Teradyne's STD and ICD divisions.

1.5 Conceptual Solution to Teradyne's Mechanical Issues

In response to Teradyne's mechanical issues, Dr. Alexander H. Slocum, Associate Professor of Mechanical Engineering at MIT and the Director of the Precision

Engineering Research Group (PERG), proposed a solution to Alex d'Arbeloff: design a new manipulator and design a new testhead interface based on a kinematic coupling.

Kinematic couplings have been used for years in the precision engineering community for repeatably positioning and orienting two objects relative to each other. Methods for designing kinematic couplings were provided by Slocum[23,24,25], and Slocum and Donmez[26] demonstrated that kinematic couplings can have repeatability on the order of 0.3 μm in the machine tool industry. More recently, Van Doren's doctoral thesis[27] described the use of kinematic couplings in the semiconductor equipment manufacturing industry with a specific application to wafer handling robots for lithography. Teradyne's new kinematic coupling interface was designed by Michael Chiu, a doctoral student in the Precision Engineering Research Group, and described by Alagheband[22].

The kinematic coupling solution, conceptually illustrated in Figure 1.12, uses three grooves mounted on the prober or handler and three balls mounted on the testhead. When the testhead is docked, the three testhead balls rest in the three grooves mounted on the prober or handler such that contact occurs at only six points, two points between each

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[23] Slocum, A. "Kinematic Couplings for Precision Fixturing - Part I: Formulation of Design Parameters". *Precision Engineering: Journal of the ASPE*. Vol. 10, No. 2, April 1988, pp. 85-91.

[24] Slocum, A. *Precision Machine Design*, Prentice Hall, 1992.

[25] Slocum, A. "Design of Three-Groove Kinematic Couplings". *Precision Engineering: Journal of the ASPE*. Jan. 1992.

[26] Slocum, A and Donmez, M. "Kinematic Couplings for Precision Fixturing - Part II: Experimental Determination of Repeatability and Stiffness". *Precision Engineering: Journal of the ASPE*. Vol. 10, No. 3, July 1988, pp. 115-122.

ball and groove. Thus, the kinematic coupling repeatably and accurately constrains all six

degrees of freedom of the testhead relative to the prober or handler.
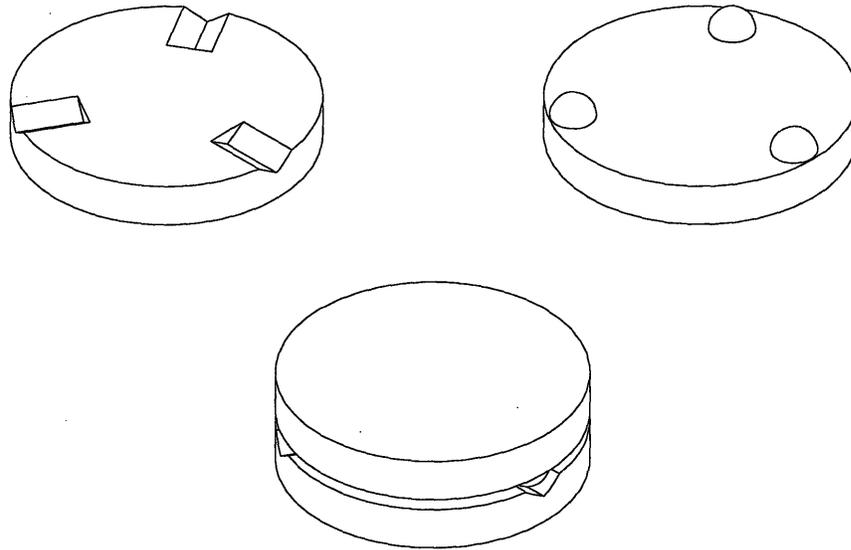
Figure 1.12: Illustration of a Kinematic Coupling

Kinematic couplings normally depend upon the gravitational force to pull the

coupling's balls into the grooves. Unfortunately, testheads are often docked to probers

and handlers in orientations where the gravitational force may not be capable of pulling

the balls into the grooves. Thus, Chiu's interface design depends upon an actuated

coupling capable of pulling the balls into the grooves. To minimize the actuation force

needed in the interface coupling, it was specified that the Universal Manipulator should

be capable of supporting the testhead in a compliance mode. The compliance mode

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[27] Van Doren, M *Precision Machine Design for the Semiconductor Equipment Manufacturing Industry.*
Ph.D. Thesis. Massachusetts Institute of Technology. 1995.

would allow the testhead to be moved within a limited range with an actuation force of less than 155 N (35 lbs).

The solution proposed by Slocum resolves the mechanical issues described in Section 1.4. The new manipulator would be designed to handle larger and heavier testheads, it would be operable with all of the probers and handlers in each floor plan arrangement, and it would be inexpensive. The new kinematic coupling interface would increase accuracy and repeatability. The kinematic interface would also reduce die scrubbing by insuring that the last 760 μm (.030 in) of travel was normal to the die. Figure 1.13 illustrates the conceptual solution of a new manipulator combined with a kinematic coupling.
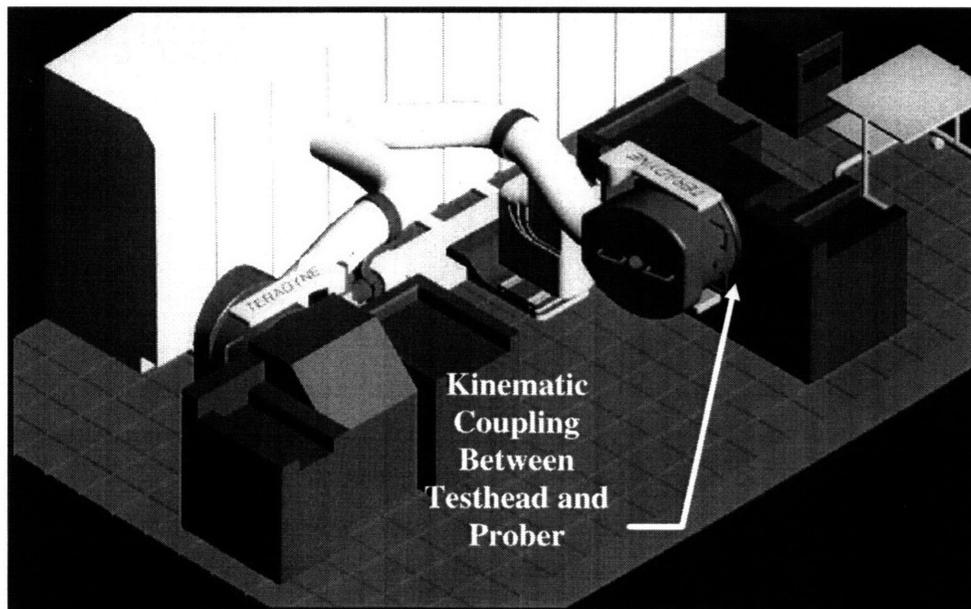
Figure 1.13: Conceptual Solution to Teradyne's Mechanical Issues: A Kinematic Coupling Interface and the Universal Manipulator

1.6 Remaining Topics in Thesis

This thesis describes the development of Teradyne's new Universal Manipulator, the manipulator designed in response to Slocum's conceptual solution to Teradyne's mechanical issues. The project began in the spring of 1994 and should culminate with the market release of the manipulator during 1996. The thesis reflects on the management of the project as well as describing some of the design and manufacturing details.

Chapter 2 describes the Universal Manipulator project in terms of concurrent engineering and conventional product development management. Attention is given to the how the joint project between Teradyne and MIT was planned, structured, and scheduled.

Chapter 3 describes the design of the Universal Manipulator at the alpha prototype stage, and then describes the manufacture and assembly of the alpha prototype. This chapter also summarizes the design issues that remained unresolved at the completion of the alpha prototype.

Chapter 4 concludes the thesis by summarizing the accomplishments of the Universal Manipulator project and the anticipated success of the Universal Manipulator and kinematic coupling interface in the marketplace.

2. The Universal Manipulator Project

The design of the Universal Manipulator was intended to be a concurrent engineering project in which the designers worked closely with Teradyne and the manipulator manufacturer. This chapter describes the Universal Manipulator project in light of concurrent engineering, and attempts to summarize the benefits that were experienced due to the increased integration.

Chapter 2 begins with an overview of concurrent engineering, focusing on the principles and modern tools for implementation. The following sections present the details of the Universal Manipulator project in terms of the design team, resources, schedule, budget, and deliverables. A subsequent discussion focuses on how the project was effectively concurrent and how the project concurrency could have been improved.

2.1 Overview and Principles of Concurrent Engineering

Product development is a complex process involving many disciplines such as industrial design, design engineering, manufacturing engineering, marketing, and sales. Over recent years, extensive effort was invested to determine how companies can develop higher quality products faster and cheaper. Overwhelmingly, academia and industry pointed to concurrent engineering as one solution.

Concurrent engineering (CE) describes a design process in which all aspects of the product life cycle, from product conception to product disposal, are considered

simultaneously. Figure 2.1 illustrates how the marketing, design, manufacturing, and sales disciplines might be scheduled within a CE project. The arrows in the illustration represent information flow between the disciplines. For instance, marketing might develop new product ideas and then forward them to design engineering. Design engineering would then develop design concepts and forward them back to marketing for customer review and to manufacturing for production review. While marketing and manufacturing review the designs, the design engineering continually progresses. Every discipline is attempting to work in parallel with the most recent design information. It is important to observe that the scheduled activities generally overlap and that information is transferred often and iteratively.

Marketing

Design Engineering

Manufacturing Engineering

Sales

Time
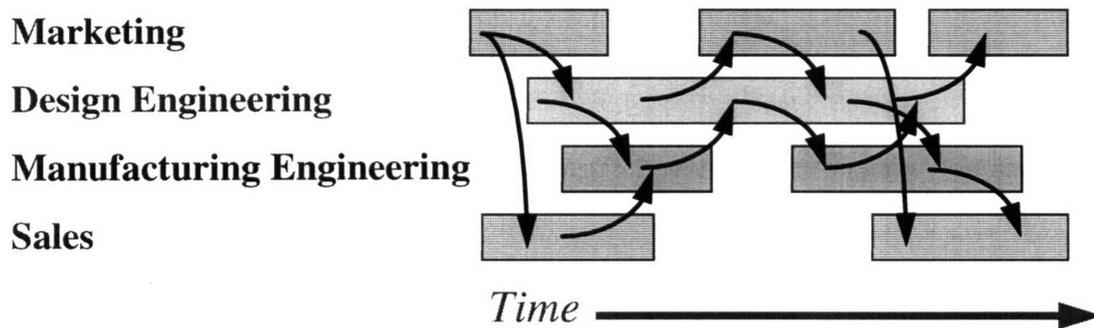
Figure 2.1: Illustration of Concurrent Engineering in Product Development

Concurrent engineering is dramatically different than the conventional design process in which information is transferred between disciplines sequentially as illustrated in Figure 2.2. This sequential information transfer is often referred to as "over-the-wall" because there is typically very little integration, and the information receivers are generally left to resolve any problems. Concurrent engineering is beneficial because most

of the costs associated with a product are defined during the early design stages. It becomes increasingly expensive to make design changes as the product progresses from design towards production.
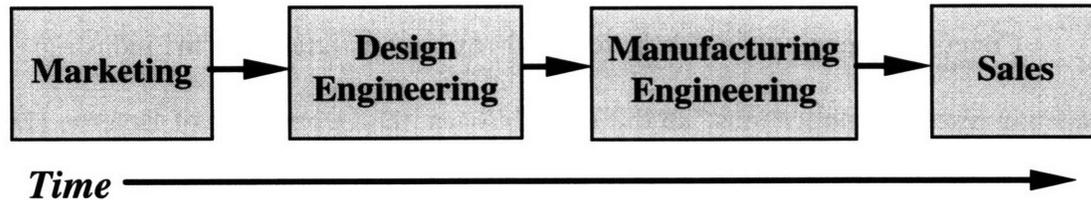
Figure 2.2: Illustration of Conventional Scheduling in Product Development

Several books have been published that focus on the product development process and concurrent engineering. Ulrich and Eppinger[1] published a thorough book on the product development process. Nevins and Whitney[2] wrote a book which addresses the concurrent design of the product and the product's production process. Clausing published a book on total quality development[3], and Phadke has published a book on designing products that are robust to changes in design and manufacturing[4]. In addition, many books exist on general management of engineering design projects[5,6,7]. These

[1] Ulrich, K.T. and S.D. Eppinger. *Product Design and Development*. McGraw-Hill, Inc. New York. 1995.

[2] Nevins, J.L., and D.L. Whitney. *Concurrent Design of Products and Processes*. McGraw-Hill. New York. 1989.

[3] Clausing, Don. *Total Quality Development*. ASME Press. 1994.

[4] Phadke, Madhav S. *Quality Engineering Using Robust Design*. Prentice-Hall. Englewood Cliffs, New Jersey. 1989.

[5] Hales, Crispin. *Managing Engineering Design*. Co-published by Longman Scientific & Technical in England and John Wiley & Sons in the United States. 1993.

[6] Bronikowski, Raymond. J. *Managing the Engineering Design Function*. Van Nostrand Reinhold Company. New York, New York. 1986.

general books focus on fundamentals such as selecting financially sound projects, defining project objectives, scheduling projects, organizational issues, project supervision, and the design process.

Concurrent engineering has received extensive attention in industrial and academic research publications. In the United States, the Department of Defense (DoD) and the Defense Advanced Research Projects Agency (DARPA) have funded extensive concurrent engineering research in academia. The DARPA Initiative on Concurrent Engineering (DICE) was initiated in 1988 to encourage concurrent engineering in the US military and industrial base. Many large companies such as Hewlett-Packard, Motorola, AT&T, Texas Instruments, Chrysler, and IBM have all recognized the advantages of concurrent engineering[8]. Research publications on concurrent engineering have addressed topics such as:

1. effective scheduling of project tasks,
2. product data modeling,
3. information systems and databases,
4. computer-aided engineering (CAE) systems,
5. cost estimation and cost models, and
6. design team communication and interaction.

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[7] Cross, Nigel. *Engineering Design Methods: Strategies for Product Design.* John Wiley & Sons. New York, New York. 1994.

[8] Jo, Hyeon H., Hamid R. Parsaei, and William G. Sullivan. "Principles of Concurrent Engineering". *Concurrent Engineering, Contemporary Issues and Modern Design Tools.* Chapman & Hall. New York. 1993.

2.2 Implementing Concurrent Engineering

The goal of considering the entire product life cycle during the design stage is a difficult task. To help accomplish this goal, industry and academia have developed many tools for performing concurrent engineering. The primary tools can be grouped into five categories:

1. multi-disciplinary teams,
2. design for 'X' philosophies,
3. computer aided engineering (CAE) systems,
4. information management systems, and
5. product cost estimation.

The most successful tool in concurrent engineering is probably the multi-disciplinary design team. When large companies implement concurrent engineering, a product development team is formed that generally consists of members that represent each of the product's life-cycle issues. For instance, a team might be formed that consists of design engineers, manufacturing engineers, quality control, marketing, sales, and maintenance. The team is often responsible for the entire product development process, beginning with determining the customer's needs and continuing through to production. The experience and knowledge base of a multi-disciplinary team helps companies develop products that are more likely to meet customer needs, have exceptional quality, and are less expensive to manufacture.

The design for 'X' philosophies in which 'X' may stand for manufacturability, assembly, reliability, recyclability, disassembly, etc. are common to nearly every concurrent engineering effort. These philosophies help designers focus attention on the

wide variety of life-cycle issues. Common tools for implementing DFX philosophies include multi-disciplinary teams, general rule-based approaches that are applicable to a broad range of design problems, and expert systems that address a narrow range of design problems. A common rule-based approach is the Boothroyd-Dewhurst Design for Assembly process[9,10,11].

An essential ingredient in concurrent engineering is the computer-aided engineering (CAE) system. A computer aided design (CAD) system is the pillar of any CAE system. The capabilities of modern CAD vary greatly. Simple and inexpensive CAD systems help designers create two-dimensional drawings of parts. More complex and expensive CAD systems allow designers to create "virtual" prototypes of the entire product. Virtual prototypes are created by forming three-dimensional solid models of the product's components and then assembling them together to form the entire product. The solid models and virtual prototypes can be used for analysis and manufacturing as well as generating drawings.

The CAD software industry has provided an extensive range of software for analyzing the CAD system solid models and virtual prototypes. For instance, a designer can perform a kinematic analysis to determine position, velocity, acceleration, and forces on dynamic assemblies or use finite element analysis (FEA) software to determine the

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[9] Boothroyd, D. *Design for Assembly Handbook*. Boothroyd Dewhurst, Wakefield, RI. 1985.

[10] Boothroyd, G. and P. Dewhurst. *Product Design for Assembly*. Boothroyd Dewhurst, Inc. Wakefield, RI. 1987.

stresses, strains, deflections, modes, and natural frequencies within a part subjected to complex loading.

Information management becomes an increasingly difficult task as the design process becomes more concurrent because information is transferred more often. To help manage the information burden, several systems now include database software with their CAD systems. These databases help track revisions to solid models and drawing changes.

CAD systems are also being integrated with more advanced data systems called document management (DM) or product data management (PDM). DM and PDM software packages help companies control information and workflow by integrating data from the design, production, and service support. PDM software helps integrate distributed data sources within companies. PDM aims to give access to the company's product data to many users simultaneously[12,13].

Another class of useful tools are cost estimation methods. With these methods, designers begin estimating the cost of the product early in the design stages and refine the estimate as the product progresses towards production. This allows designers to include the effects on product cost when comparing design alternatives. Cost estimation is a difficult task, however, because it is often difficult to acquire accurate cost estimates for

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[11] Boothroyd, G. and P. Dewhurst. "Product Design for Manufacture and Assembly". *Design for Manufacture: Strategies, Principles, and Techniques*. Addison-Wesley Publishing Company. 1991.

[12] "Engineering Drives Document Management". *Machine Design*. June 15, 1995. p. 77-78.

custom parts. For cost estimation to be effective, designers must be well integrated with the product manufacturer(s).

2.3 The Universal Manipulator Project

The Universal Manipulator project was performed *jointly* between Teradyne, Inc. and a design team from the Precision Engineering Research Group at MIT's Laboratory for Manufacturing and Productivity. The project was part of the New Products Program which aims to train students in product development by designing and prototyping real products for real companies.

The academic product development scenario is quite different than the product development process within large companies. It is similar, however, to the process in small companies, start-up companies, and consulting firms. For instance, the Universal Manipulator project was performed with a lean design team and without contributions from an internal manufacturing department. In addition, it was accomplished with a flat management structure, excited and dedicated team members, long and irregular work hours, and a design team that was geographically distributed. For these reasons, the project is an interesting case study in concurrent engineering outside large corporations.

2.3.1 Organization of the Universal Manipulator Project

Figure 2.3 illustrates the organizational structure of the Universal Manipulator project. The project was overseen at the highest management level by Alex d'Arbeloff,

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[13] Manji, James F. "Making PDM Pay". *Machine Design.* June 15, 1995. p. 81-84.

Teradyne's Chief Executive Officer. Dennis Legal was the manager in charge of the project, while Simon Longson and his group at Teradyne's STD division in Agoura Hills, California, were directly responsible for the project. The mechanical design specifications were written by Art Lecolst, a mechanical designer in Simon Longson's group. In addition, Art worked extensively with the MIT design team throughout much of the detailed design and prototype fabrication. Dr. Alex Slocum and a team of graduate students in the Precision Engineering Research Group at MIT were responsible for the conceptual design, detailed design, and fabrication of the manipulator prototypes. The MIT design team is outlined in Section 2.3.4. Aesop Inc. managed the project schedule, cost estimates of the manipulator, and the purchasing of the prototype parts.

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                    │ Universal Manipulator Design Project │
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                          ┌──────────────────────┐
                          │     Alex d'Arbeloff   │
                          │ Chief Executive Officer│
                          │     Teradyne, Inc.    │
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                                      │
                          ┌──────────────────────┐
                          │     Dennis Legal      │
                          │     STD Division      │
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│  Simon Longson   │  │ Dr. Alexander H. Slocum│  │  Richard Slocum III  │
│  STD Division    │  │ Precision Engineering │  │     Aesop, Inc.      │
│  Teradyne, Inc.  │  │    Research Group     │  │                      │
│                  │  │         MIT           │  │                      │
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│   Art Lecolst    │  │  Graduate Students   │
│ Mechanical Designer│ │ Precision Engineering│
│  STD Division    │  │   Research Group     │
│  Teradyne, Inc.  │  │        MIT           │
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Figure 2.3: Organizational Structure of the Universal Manipulator Project

2.3.2 The Project Goals and Deliverables

The goal of the Universal Manipulator project, as established by Teradyne's management, was "to develop a new manipulator that had performance equal to or better than the RAM manipulator at equal to or less cost". This goal slightly addressed the performance issues associated with the RAM manipulator which are highlighted in Chapter 1, but it also demonstrated that Teradyne's management expected that the market would be unwilling to pay for a more expensive manipulator, even if it offered better performance. At the time of the design project, Teradyne stated that they could purchase a completely manufactured RAM manipulator from the supplier for around $15,000, and so the goal for the Universal Manipulator was also $15,000. It was later determined that the price of a RAM manipulator was near $20,000.

The MIT design team was responsible for delivering a detailed design for the Universal Manipulator. The design would include a detailed drawing package of the manipulator parts and a bill of materials for the custom and off-the-shelf components. In addition to the drawing package, MIT would supply two prototype manipulators to Teradyne. One of the prototypes would be delivered to Teradyne's STD division in Agoura Hills, California, and the other prototype would be delivered to Teradyne's ICD division in Boston, Massachusetts. These two prototypes are now referred to as the beta prototypes. Each division would test the prototypes, and then Teradyne would revise the design prior to production.

2.3.3 The Project Schedule

An important detail in product development projects is the development of the project schedule. A project schedule is important for many reasons, including estimating the development time, determining necessary resources, and organizing tasks among team members. Project schedules are also useful to the designer(s) because they force the designer(s) to anticipate future activities and to develop a systematic plan to design the product.

When preparing a product development schedule, it is important to realize that product development schedules are inherently more inaccurate than some other types of schedules such as a construction schedules. This is because there is greater uncertainty associated with the tasks in a design schedule, especially if the product is revolutionary rather than evolutionary. This is because the designer(s) must resolve a greater number of unknowns, and the time to resolve these unknowns is uncertain. This does not imply that schedules are useless for design projects. The team should simply be aware that the schedule will likely evolve and be revised several times.

The project schedule for the Universal Manipulator was initially prepared by Richard Slocum and Dr. Alexander Slocum. The complete schedule is included in Appendix B. Section B.2 contains the project schedule in Gantt chart format, and Section B.3 contains the schedule in PERT chart format. The major milestones and the corresponding start dates are summarized in Table 1. The prototypes referred to in these milestones refer the beta prototypes.

Table 1: Initial Project Schedule, Milestones and Start Dates

Milestone	Start Date
Conceptual Design Refinement Phase	July 23, 1994
Detailed Design Phase	August 29, 1994
Prototype Construction	December 28, 1994
Prototype Assembly	March 30, 1995
Prototype Complete	May 18, 1995

Unfortunately, the initial project schedule was not met, and during mid April, the schedule changed dramatically due to the problem with the alpha prototype's layout. This problem is discussed in Section 4 of Chapter 3. The layout problem meant that nearly the entire manipulator needed to be redesigned. During the beta redesign, the remaining unresolved design issues listed in Section 4 of Chapter 3 would be addressed.

For the beta redesign, a new schedule was prepared by Vallance, Kiani, and Hochmuth. The principle milestones within this schedule are summarized in Table 2. The complete beta redesign schedule is included in Appendix B. Section B.4 contains the schedule in Gantt chart format, and Section B.5 contains the schedule in PERT format.

Table 2: Beta Redesign Project Schedule, Milestones and Start Dates

Milestone	Start Date
Layout Design	April 21, 1995
Construct Detailed Solid Models	April 25, 1995
Motion and Assembly Studies	May 5, 1995
Begin Detailed Drawings	May 12, 1995
Release Drawings to Manufacturer	May 24, 1995
Prototypes Complete	June 27, 1995

The initial project schedule and the beta redesign schedule used two different scheduling approaches. The initial project schedule was planned so that when the details of one assembly were completed, its drawings proceeded directly to the manufacturer.

Then, the next subassembly would be designed. This approach, illustrated in Figure 2.4, overlaps the design and prototype fabrication tasks.
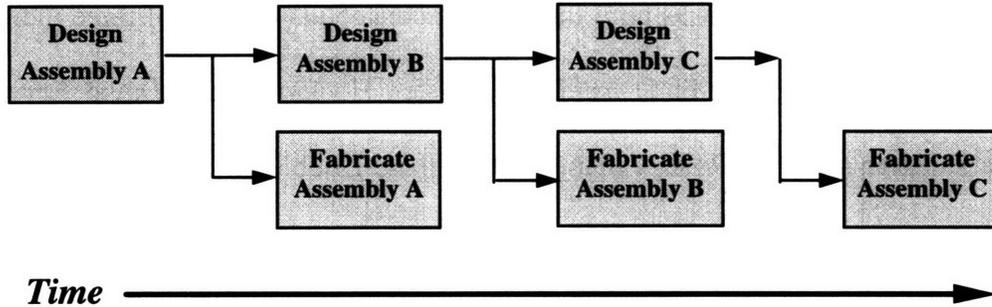
Figure 2.4: Approach Used for the Initial Project Schedule

The approach to the beta redesign schedule is shown in Figure 2.5. With this approach, the design tasks were completed prior to the prototype fabrication. This allowed the design team to complete the entire design and incorporate all of the details prior to releasing drawings. This scheduling approach looks similar to the sequential design process shown in Figure 2.2, but it is important to realize that the prototype fabrication should be considered a design task and not a manufacturing task. Hence, this scheduling approach does not contradict the concurrent engineering philosophy.
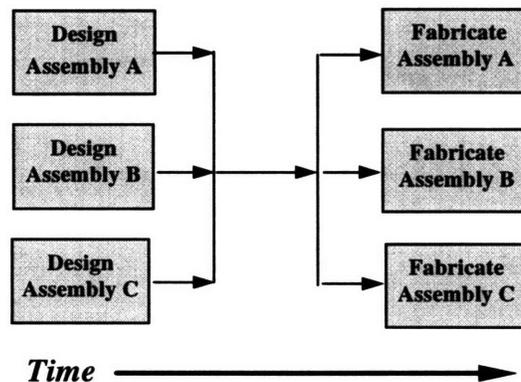
Figure 2.5: Approach Used for the Beta Redesign Schedule

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2.3.4 The Design Team

The design team that participated in the Universal Manipulator project evolved several times. The project was born through the conceptual designs of three individuals, Dr. Alex Slocum and two Ph.D. students, Carsten Hochmuth and David Levy. Two Master's degree students, Ryan Vallance and Rolland Doubleday, joined the design team at the beginning of the 1994 fall semester. Late in the fall semester, Dave Levy exited the design team. In the beginning of the 1995 spring semester, a new Ph.D. student, Sepehr Kiani was added to the design team. Figure 2.6, Figure 2.7, and Figure 2.8 show the MIT design teams during the conceptual design phase, the detailed design phase of the alpha prototype, and the detailed design phase of the two beta prototypes.

Each change in the design team impacted the project in a unique fashion, but as might be expected, the addition of students had a positive impact while the loss of students hurt the project. In general, the loss of team members, meant that information about the history of the design was lost and that team manpower was reduced. The addition of new team members brought a wider experience base to the team and fresh ideas. Once the dynamics associated with the team changes settled, the designers truly integrated into an effective design team.

Conceptual Design Phase
April 1995 - August 1995

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                    │  Teradyne Manipulator│
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│ Dr. Alex H. Slocum│ │ Carsten Hochmuth│ │   Dave Levy      │
│ Associate Professor│ │  Ph.D. Student  │ │  Ph.D. Student   │
│ of Mechanical      │ │                 │ │                  │
│ Engineering        │ │                 │ │                  │
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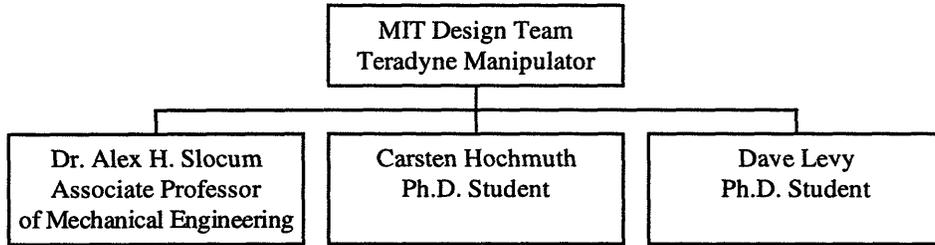
Figure 2.6: MIT Design Team During the Conceptual Design Phase

Detail Design -- Alpha Phase

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                         │  Teradyne Manipulator│
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│ Dr. Alex H. Slocum│ │ Mechanical Design│      │ Electrical and Control│
│ Associate Professor│ │     Group        │      │   Systems Group       │
│ of Mechanical      │ │                  │      │                       │
│ Engineering        │ │                  │      │                       │
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   │  Ph.D. Student  │ │Ph.D.Student│ │ S.M. Student │ │  S.M. Student    │
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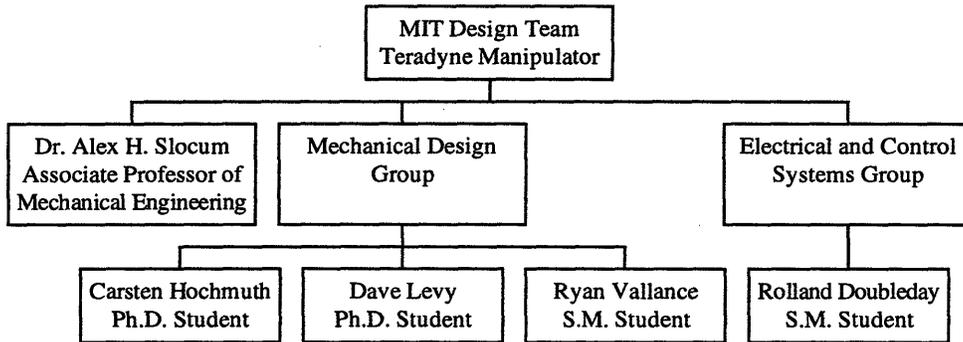
Figure 2.7: MIT Design Team During the Detail Design of the Alpha Manipulator

Detail Design -- Beta Phase

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                         │  MIT Design Team     │
                         │  Universal Manipulator│
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│ Dr. Alex H. Slocum│ │ Mechanical Design│      │ Electrical and Control│
│ Associate Professor│ │     Group        │      │   Systems Group       │
│ of Mechanical      │ │                  │      │                       │
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   │ Carsten Hochmuth│ │Sepehr Kiani│ │ Ryan Vallance│ │ Rolland Doubleday│
   │  Ph.D. Student  │ │Ph.D.Student│ │ S.M. Student │ │  S.M. Student    │
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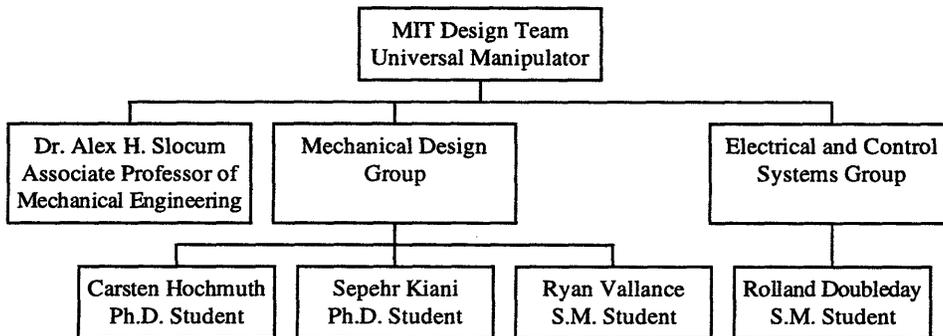
Figure 2.8: MIT Design Team During the Detail Design of the Beta Manipulator

2.3.5 The Design Tools

The design team was fortunate to use Pro/Engineer software from Parametric Technologies, Inc. as the CAD solid modeling software. Pro/E allows designers to create solid models of parts on a feature level. A designer can specify that a protrusion will be made by sketching the cross section of the protrusion and then specifying the extrusion distance. The designer can also create assemblies by establishing position relationships between multiple parts. For instance, a designer can specify that Part A is to be mated to Part B so that their axes are aligned and their surfaces are in contact.
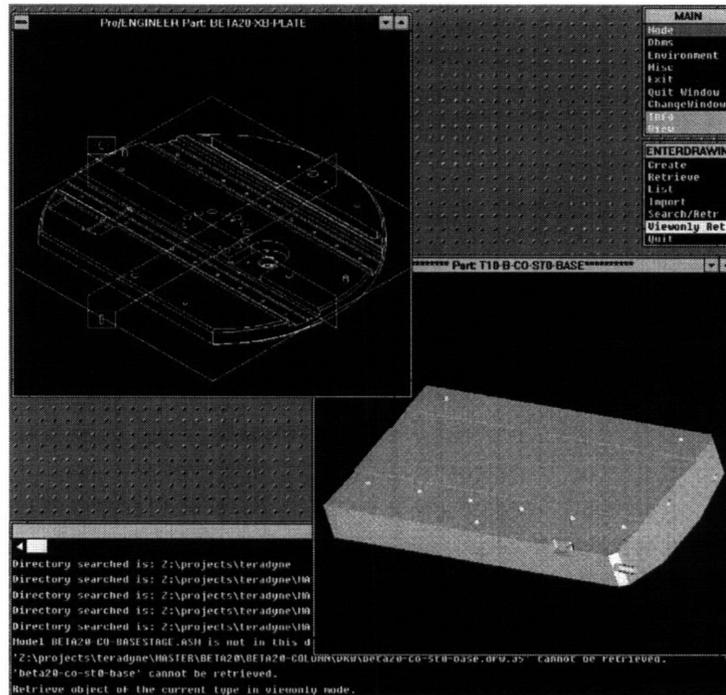
Figure 2.9: Pro/Engineer CAD Software from Parametric Technologies

Assemblies are one of the most powerful tools in solid modeling because they permit the designer to actually perceive how the individual components within a design

will fit together. The process of creating parts and then assembling them into a complete solid model representation of the product is often referred to as "virtual prototyping".

Once parts and assemblies are created in Pro/Engineer, drawings are made simply by selecting particular views of a part and then locating the views on the drawing sheet. The process of making drawings is simple but extremely time intensive, primarily because detailed drawings require manufacturing dimensions rather than the dimensions that are used to create the solid model. For instance, manufacturing datums need to be established and then dimensions often need to be given with respect to the manufacturing datums.

Another benefit of Pro/Engineer is that the solid models, assemblies, and drawings are associative. This means that a change in either of these items is propagated to the others. For instance, if the designer changes a dimension in the solid model, that dimensions is automatically propagated to the assembly and the drawing. This allows designers to work confidently in the more intuitive part and assembly modes and know that the drawings will accurately reflect the current status of the design.

Pro/Engineer also helps designers determine critical engineering parameters such as centers of gravity, moments of inertia, tipping angles, and transformations between coordinate systems. Assemblies can also be set up relationally so that parts may be moved with respect to each other to perform motion studies and check for interference in different positions.

At the beginning of the project, Pro/Engineer was used primarily by Carsten Hochmuth on a DEC Alpha workstation or an SGI Indigo[2] workstation. During the detailed design of the beta prototype manipulators, Sepehr Kiani and Ryan Vallance also used Pro/Engineer extensively. When this occurred, the design team quickly realized that a local area network (LAN) was necessary so that all three designers could work on the manipulator and share the same solid models. Therefore, Kiani established a LAN that connected the DEC Alpha workstation, a Sun workstation, and a MIPS-based workstation. The DEC Alpha served the Pro/Engineer files to the Sun and MIPS machines.
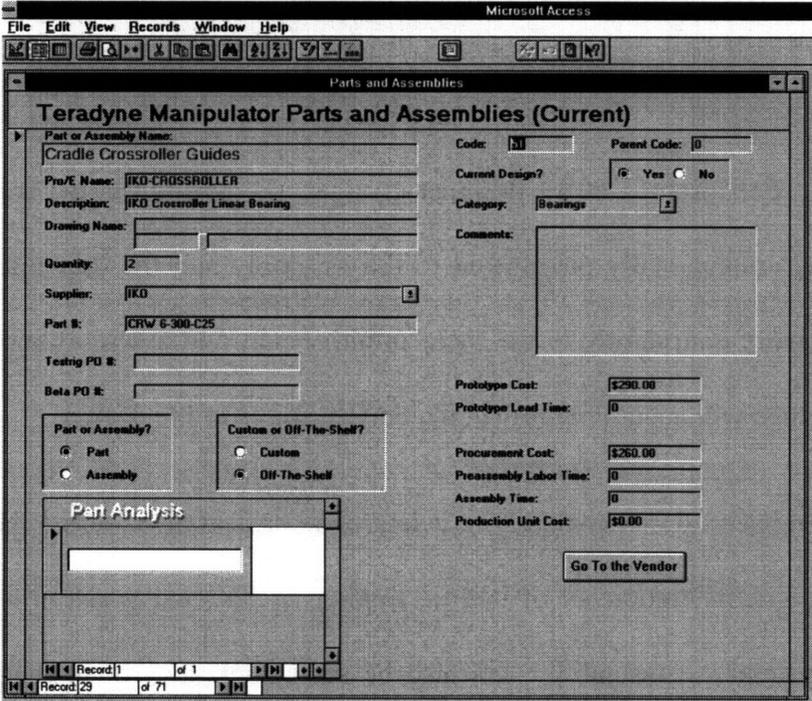
Figure 2.10: Microsoft Access Relational Database for Tracking Design Information

The design team also recognized that a product data management (PDM) system would also be useful to track the bill of materials, cost information, manufacturing information, vendor and supplier information, drawing releases, etc. Vallance began using a simple relational database in File Maker Pro, and the database was later expanded and converted to Microsoft Access when the LAN was established. Figure 2.10 shows a screen snapshot of the Parts and Assemblies form in the Access database. An additional feature that was added by Kiani after converting to Access was the capability of embedding a spreadsheet analysis into the database. This helped the team document common analyses such as sizing motors and power transmission equipment because the analyses could be linked with the respective parts.

2.3.6 Relationships with Vendors and Manufacturers

The MIT design team depended heavily upon commercial vendors and manufacturers to design custom parts, purchase parts rapidly, and manufacture parts for the prototypes. In the small design team environment, close relationships with vendors and local manufacturers are extremely valuable. Design teams need to be able to purchase parts rapidly for prototyping, whether the parts are off-the-shelf from local vendors, custom parts from vendors, or parts manufactured by local job shops.

The limited human resources of the MIT design team forced the team to take advantage of the design capabilities of commercial vendors. For instance, the beta prototype of the Universal Manipulator used a custom turntable bearing manufactured by Kaydon, Inc. Initially, the bearing was a standard off-the-shelf bearing, but after meeting with representatives from Kaydon, the MIT designers outlined the specifications for a

new custom bearing. Kaydon designed the bearing according to the specifications, and this allowed the same bearing to be used in two locations on the manipulator. Kaydon's internal design services helped the design team integrate part functions without increasing the work load on the MIT design team.

A close relationship with Thomson Industries was also beneficial to the design process. The Universal Manipulator used Thomson linear bushings and several linear ball bearings. Unfortunately, Thomson's purchasing lead times were often quite long because every linear bearing rail is made after the order has been placed. A pre-established relationship with Thomson allowed the design team to purchase prototype parts and have them expedited to meet the demanding project schedule.

In addition to the lead time advantages, Thomson provided the design team with the very first size 16 SuperSmart Twin Pillow Block Linear Bushings ever sold and prior to being available in the marketplace. After the fabrication of the beta prototypes, Thomson's ball screw designers even designed a custom, telescoping ballscrew to replace the more expensive telescoping ballscrew designed by the MIT team. Several other vendors, including Bison Motors, Ball Screws & Actuators, Peterson, and SMC Pneumatics also provided substantial assistance with parts for the manipulators.

The fabrication of the custom parts in the prototype manipulators were manufactured by several New England companies. The design team found that each of these companies provided valuable insight about the manufacturing issues. Iron Dragon, a steel fabricator, and Bow Industries, a job shop, both located near Concord, New

Hampshire, manufactured the parts for the alpha prototype. Perry Technologies in Canton Center, Connecticut, and Renaissance Design in New Hampshire, manufactured several miscellaneous parts for the alpha prototype and the beta prototypes. The majority of the custom parts for the two beta prototype manipulators were manufactured by Moore-Producto and James Ippolito & Co., both in Bridgeport, Connecticut.

2.4 Discussion of the Universal Manipulator Project

This section is an anecdotal discussion of some of the Universal Manipulator project. The section describes areas in which the project was successful and areas in which it was less successful. Special attention is given to the design process, the design team, the computer-aided engineering software, designing for manufacturability, and prototyping.

2.4.1 The Design Process

Slocum describes the design process as the mental process of combining nuggets of information together to form a whole. The collection of nuggets can be pictured, as shown in Figure 2.11, as a multi-dimensional space where at least three of the dimensions are wisdom, knowledge, and imagination[14]. As a designer gains experience and learns new technologies, this multi-dimensional space is filled with new nuggets. The design

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[14] Slocum, Alexander H. *Precision Machine Design*. Prentice-Hall, Inc. 1992.

process is then systematically or randomly searching this space for a solution[15]. Once a solution is found, discipline is required to complete the details.
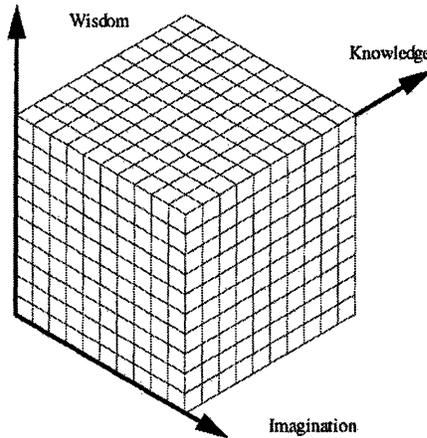
Figure 2.11: Multi-dimensional Design Space Described by Slocum[14]

Another lesson well learned is that it pays to consider the details of a design as early as possible. As an example, the design team chose to postpone the selection of drive components until the detailed design phase. This proved to be a design issue, because there was very little room to package motors and brakes. The manipulator originally used an ACME threaded, telescoping screw, to power the up/down motion, but the friction in the screw required a large motor to obtain Teradyne's speed requirements. Unfortunately, the motor could not be adequately packaged within the design, and it was far too expensive. As a result, the ACME screw was replaced with a telescoping ballscrew which reduced the friction and the size of the motor.

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[15] One should be careful in concluding that someone's design process is random because what appears to be random to others is often systematic to the person searching the design space.

In addition to paying close attention to the details, the designers learned to not artificially constrain manufacturing alternatives. For instance, from the beginning of the project, the Universal Manipulator was designed to take advantage of standard structural steel shapes to make the manufacturing processes near net-shape. This was a sound approach during the alpha phase when the shapes of most custom parts were simple. However, the parts' shapes became more complex during the beta phase, and many of the parts required significant machining. Later, the team realized that it would be advantages to make some of the parts and assemblies into castings either to reduce cost or to simplify the assembly process.

Meeting the needs of the customers was a difficult task during the Universal Manipulator project. The Universal Manipulator needed to be compatible with a wide variety of probers and handlers as well as their different floor plan arrangements. Unfortunately, the MIT team was not familiar with all of the details of each prober and handler arrangement. The design team had to depend heavily upon the manipulator specification and upon the knowledge of Teradyne employees. Unfortunately, both the MIT design team and Teradyne employees missed a major design flaw; the manipulator would not work with a particular floor plan arrangement. As a result, the alpha design was abandoned, and the team redesigned nearly the entire manipulator during the beta phase. This situation might have been avoided if project schedule time had permitted the MIT team to study each of the prober/handler arrangements or if the design could have been automatically subjected to an exhaustive motion study using the virtual prototype.

A valuable design process which the MIT team was successful in implementing was a method for estimating the production cost of the Universal Manipulator. Richard Slocum developed a procedure for estimating the cost of the Universal Manipulator, and implemented the procedure in a spreadsheet. The estimate included all of the components in the bill of materials as well as estimates for the assembly costs and wiring costs. The price estimate was scaled for different manufacturing quantities.

Determining the itemized costs for the spreadsheet procedure was a large task. All of the vendors and suppliers had to provide estimates for the parts at different quantities, and all of the custom parts had to be scaled for manufacturing quantity based on a general rule of thumb. It would be advantageous to have the price estimation procedure linked with product data management system so that the estimate could evolve as the design changed. For the cost estimation process to be really accurate, the designers need to be closely integrated with the manufacturer(s).

2.4.2 The Design Team and Communication

During design, it is extremely valuable for each team member to be familiar with all of the design issues. This permits the team to function with minimal dependency on a single team member. This is somewhat contradictory to the conventional multi-disciplinary team approach where tasks are often split among disciplines. Regular communication enhances the extent to which each team member is aware of the design issues. It is generally more beneficial for the designers to interact and discuss each issue rather than reading or writing a report. The MIT team found it useful for each of the

designers to share the same office so that they could easily communicate about design issues and work together around the workstations.

Because of the geographic separation, communication between the MIT design team and Teradyne's STD division was occasionally sporadic. The communication gap was similar to a phase shift in which the MIT design team was shifted ahead of the Teradyne division. As a result, the design communication was often a status or update in which the MIT team was explaining the latest design ideas or discussing how a design issue had been resolved. This form of communication was inefficient and prevented Teradyne's design people from becoming integrated into the design process.

2.4.3 Computer Aided Engineering System

Pro/Engineer CAD software, from Parametric Technologies, Inc., was an extremely useful concurrent engineering tool. By using the solid models and assemblies, the design team could accurately represent the manipulator design and determine important engineering parameters. The associative links between drawings and solid models were infinitely valuable when revising the design and making minor changes.

Unfortunately, Teradyne used another CAD software package. This was initially a minor issue, but became more important during the detailed design phases and as the design moved towards production. Since the MIT and Teradyne teams used different software, it was difficult for the designers to communicate without producing drawings. This creates a time burden on the designers when the design could be progressing by using the more intuitive solid models.

In addition, Teradyne found it useful to create two-dimensional models in their CAD software from MIT's drawings. This two-dimensional model was very useful for checking layouts, but occasionally, the designers had to sort through several dimensions to determine why there was a difference between the MIT's and Teradyne's models. It would have been easier and more efficient if MIT and Teradyne had shared a common CAD database.

As the design moved towards production, the conflict in CAD systems became more of an issue. The problem was that the entire design of the manipulator lived at MIT and was based on the Pro/Engineer data. There was not an efficient and inexpensive method for transferring the design into Teradyne's CAD system.

One of the most mundane tasks in the design process is managing the product's bill of materials (BOM). A bill of materials lists the quantities of individual parts and assemblies contained in a product and is, in general, a combination of off-the-shelf and custom parts. The BOM of the universal manipulator contained well over a hundred parts, some purchased and some custom. During the fabrication of the prototypes, the MIT design team discovered that a product data management system was necessary. For this reason, a relational database was designed in Microsoft Access to track the Universal Manipulator's BOM. Ideally, the database would have been integrated with Pro/Engineer so that they shared a common database or were associatively linked.

The MIT design team found that having networked workstations was extremely valuable. This allowed the designers to share the same Pro/Engineer files by centralizing

the data files for the Universal Manipulator on a single server. This eliminated the need for managing multiple copies of the same files and reduced the probability of losing design revisions.

2.4.4 Design for Manufacturability

Design for manufacturability is a DF'X' philosophy in which the designers focus on reducing the production cost, meeting the production rate goals, and meeting the tolerances required to insure product performance. The most valuable tool in DFM is a design team that has sufficient experience in the manufacturing process that will be used in the product. For the prototype versions of the Universal Manipulator, the processes were primarily torch cutting, welding, blanchard grinding, and machining. Subtractive manufacturing processes such as machining are highly dependent upon the tools and processes available to the manufacturer. For this reason, the manufacturer needs to be selected early in the design process. This permits the design team to work with the manufacturer to sort through manufacturing alternatives and determine optimal designs.

Unfortunately, the selection of the Universal Manipulator's manufacturer was a long process. This was unfortunate because the designers could have been integrated with the manufacturers, and the manufacturer could have gained valuable experience in building the alpha and beta prototypes. Instead, the design team had to depend primarily upon their manufacturing experience and local job shop manufacturers. During the fabrication of the alpha prototypes, the design team was fortunate to have established relationships with Iron Dragon and Bow Industries, and this helped the team design parts that were manufacturable. During the fabrication of the beta prototypes, the design team

did not have adequate access to the manufacturer, and the process was more sequential than concurrent.

2.4.5 Prototyping

The final aspect of the project to be discussed is the prototyping process. During the Universal Manipulator project, the MIT team was responsible for delivering two prototypes to Teradyne. However, the decision was made early in the project to build a "testrig" to measure forces resulting from the large cable bundle. The testrig would move the cable through motions similar to the conceptual design of the Universal Manipulator, and the reaction forces and torques on the manipulator could be measured. In the interest of accelerating the project, the team decided to build the testrig as similar to the actual design as possible.

As it turned out, the "testrig" was so similar to the actual design that it was referred to as the alpha prototype[16]. The fabrication of the alpha prototype began before the manipulator design was completed. As a result, when parts were received from Iron Dragon or Bow Industries, they often did not assemble correctly because the design had been revised between fabrication of two of the parts. This forced the MIT team to spend valuable time resolving the assembly problems and increasing the performance of the alpha prototype. Clausing describes this problem as "hardware swamp"[17]. Although the design team profited from the experience of building actual hardware, the project would

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[16] Throughout this thesis, the testrig is referred to as the alpha prototype.

have progressed quicker if the team had taken better advantage of the "virtual prototyping" within Pro/Engineer to ensure motion requirements, analyze assembly procedures, and address details such as wire routing, alignment of components, bolt placement, and bearing selection.

2.5 Summary

This chapter described the Universal Manipulator project in terms of its organization, schedule, resources, and design team. The project was discussed in terms of concurrent engineering and how the project benefited from improved integration. Specific attention was given to the design process, design team communication, the computer aided engineering system, design for manufacturability, and prototyping.

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[17] Clausing, Don. *Total Quality Development*. ASME Press. New York. 1994.

3. The Design and Fabrication of the Alpha Prototype

The detailed design and fabrication of the Universal Manipulator alpha prototype occurred during the fall of 1994 and the spring of 1995. The detailed design included the completion of the machine layout, determining the exact geometry and dimensions of the structural components, and selecting off-the-shelf components such as motors, ballscrews, and bearings. The fabrication of the prototype included delivering the detailed drawings to the manufacturers for all custom parts, modifying part designs due to manufacturing constraints, and assembling the prototype. This chapter describes the design of the alpha prototype, the custom and off-the-shelf parts, the fabrication and assembly of the alpha prototype, and the design issues that remained unresolved after the alpha prototype was completed.

3.1 The Design of the Alpha Prototype

The alpha prototype was originally referred to as the "test rig" because the team intended to use the prototype to test the manipulator concept and to measure the cable forces and torques resulting from the testhead cable bundle. The design team later decided that the "testrig" should resemble the actual design as closely as possible, and so the "testrig" evolved into the alpha prototype. The alpha prototype incorporated many of the novel design features associated with the concept of the Universal Manipulator, including a telescoping column assembly, powered motions, and a twistarm with the cable bundle in a fixed position.

The alpha design was divided into five primary subassemblies referred to as the baseplate, crossbase, column, twistarm, and cradle subassemblies. Figure 3.1 shows an isometric drawing of the alpha prototype and the approximate boundaries between these subassemblies. Table 1 summarizes the motions, bearings, and principal structural components within each of the subassemblies.
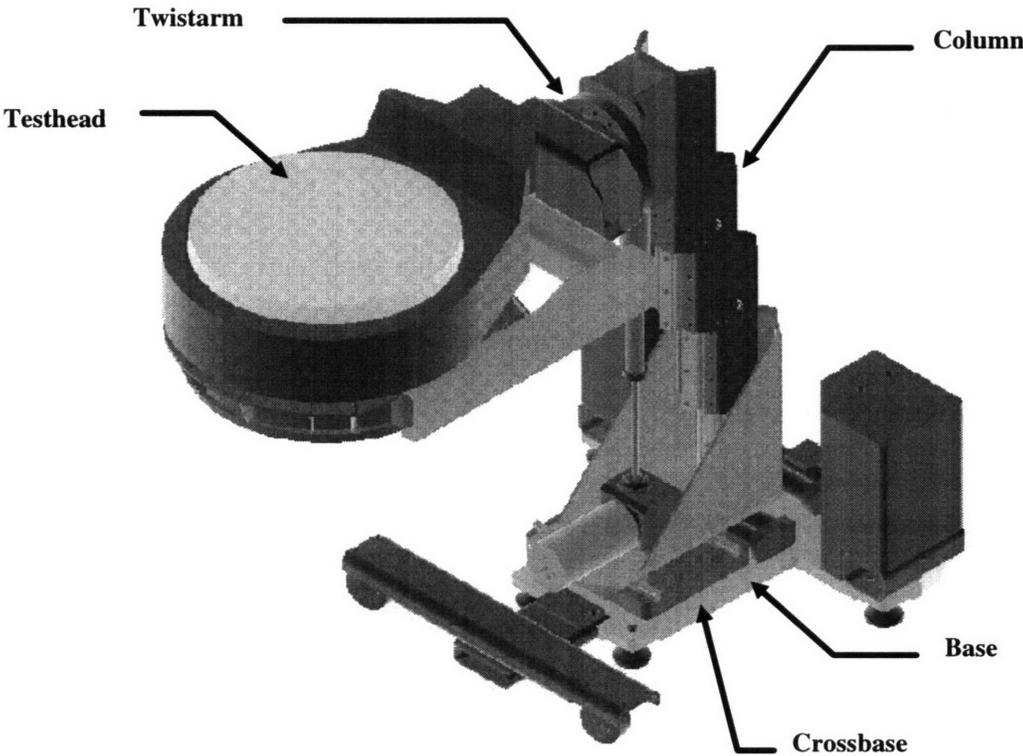
Figure 3.1: The Alpha Prototype and Primary Subassemblies

Table 3: Primary Subassemblies in the Alpha Prototype of the Universal Manipulator

Name	Motions	Bearings	Structure
Base subassembly	Swing motion	Kaydon turntable bearing	Baseplate, caster assemblies, counterweights
Cross-base subassembly	Side-to-side motion	Thomson linear ball bearing system	Crossbase plate
Column subassembly	Up/down motion	Thomson linear ball bearing system	Column-baseplate, stage 0, stage 1, stage 2, last stage, screw assembly
Twistarm subassembly	Twist motion	Kaydon turntable bearing	Twistarm tube, ring and pinion gears
Cradle subassembly	In/out, theta, and tumble motions	IKO crossed roller linear ways, plain spherical bearings	Cradle crossbeam, cradle arms, slide plates

3.1.1 The Base Subassembly

The functions of the base subassembly included supporting the entire manipulator, transporting the manipulator to different locations, lowering or raising the manipulator to the correct height above the cleanroom floor, and providing the swing motion. The components in the base subassembly, shown in Figure 3.2, included the manipulator baseplate, the front and rear caster assemblies, the leveling feet, and the manipulator counterweights.

The manipulator baseplate was designed in the shape of a "T". This would allow a prober or handler to set in the left or right pocket of the "T", and the side-to-side motion could slide the manipulator column assembly towards the prober or handler. With this layout, the manipulator could dock the testhead to probers or handlers in the DUT left and DUT right configurations and satisfy the infinite plane specification.

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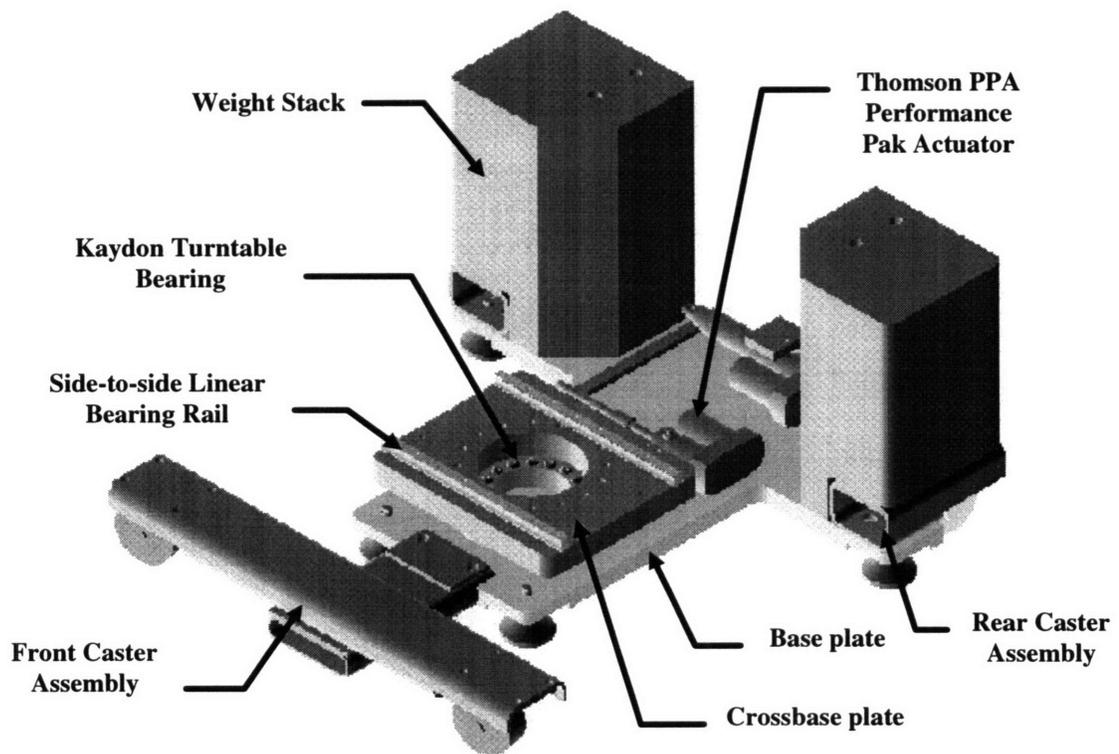
Figure 3.2: Base and Crossbase Subassemblies in the Alpha Prototype

The manipulator's four leveling feet screwed from the bottom-side of the baseplate into four tapped holes at the extreme corners of the "T" shape. The selected leveling feet were made with a threaded rod and a plastic tilt pad. Combined with recessed pockets in the bottom side of the baseplate, the threaded rods on the leveling feet allowed the distance between the baseplate and the cleanroom floor to be adjusted. The leveling feet were positioned so that the manipulator had a 15 degree tipping angle.

The base subassembly contained a front caster assembly and two rear caster assemblies. The caster assemblies provided elevated surfaces for bolting the casters, and this allowed the casters to be taller than the top surface of the baseplate, even at the nominal operating height. The front caster assembly consisted of a steel weldment and

two swivel casters, and the rear caster assemblies consisted of a section of steel tube and a single non-swivel caster. All four of the casters were forged steel. The front caster assembly bolted to the front of the manipulator baseplate, and the two rear caster assemblies bolted to the top surface at the rear corners of the baseplate. This allowed the caster assemblies to be removed once the manipulator had been positioned in the appropriate location within the cleanroom.

The swing motion of the manipulator was provided by a Kaydon MTO-145 turntable bearing. Figure 3.3 shows a section view of the bearing, the dimensions of the MTO-145, and the bearing load capacity. This bearing supported the moment from the cantilevered testhead because it was a four-point contact ball bearing. The turntable bearing was also selected because it did not require a large and expensive bearing bore. The Kaydon bearing bolted directly to the top surface of the manipulator baseplate and the bottom surface of the crossbase plate. The alpha prototype did not have a brake or adjustable hard stops at the end of travel on the swing motion.
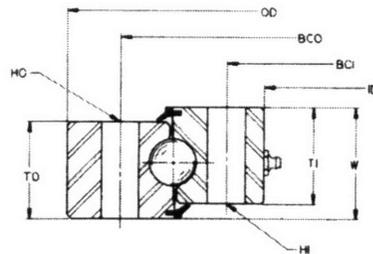
Model No.	Kaydon P/N	Reference No.	Outline Dimensions (Inches)				Mounting Holes					Approx. Wt. (Lbs.)	Reference Moment Load Rating Ft. Lbs.
			OD	ID	W	TO/TI	BCO	BCI	No. Holes Inner	Outer	Hole Dia. HI/HO		
MTO-145	13102	T7-9P1	11.811	5.709	1.968	1.732	10.630	6.890	16	16	.562	37	26,000

Figure 3.3: Kaydon MTO-145 Four-Point Contact Ball Bearing

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To support the torque due to the cantilevered testhead, the alpha prototype used a stack of stationary weights positioned on the back edge of the baseplate. The moment from the cantilevered testhead required approximately 6,672 N (1500 lbs) of counterweights. The counterweights were designed to be cut from 2.54 cm (1 in.) thick steel plate, in two different shapes. The smaller shape was designed to stack beside the rear caster assemblies, and the larger shape was designed to stack on top of the smaller shaped plates and a rear caster assembly. A single large plate weighed approximately 40 lbs, and single small plate weighed about 20 lbs. Thus, a 53.4 cm (21 in.) tall stack of weights was necessary on each corner of the manipulator baseplate.

3.1.2 The Crossbase Subassembly

The crossbase subassembly, shown in Figure 3.2, attached to the top of the base subassembly by bolting the crossbase plate to the inner race of the swing motion's Kaydon bearing. Hence, the crossbase and base subassemblies shared responsibility for the swing motion of the manipulator. The crossbase subassembly also shared responsibility with the column subassembly for the side-to-side motion, because the side-to-side linear bearing rails mounted on top of the crossbase plate.

The side-to-side linear motion was supported with Thomson Accuglide linear ball bearings, shown in Figure 3.4. Two size 25 linear rails and four size 25 carriages were selected. The dimensions and load capacity for the size 25 bearings are shown in Figure 3.5. These bearings were sized based on an estimated moment from the cantilevered testhead of 6,780 N m (60,000 lb-in.) and a load of about 10,230 N (2300 lbs) due to the weight of the column, twistarm, cradle, and testhead. The testhead moment created a

force couple on the side-to-side linear bearings. With the rails spaced 28.83 cm (11.35 in.) apart, this resulted in a compressive load of 23,520 N (5,286 lbs) on the front bearings and an equal tensile load on the rear bearings. Superposing the compressive force from the weight on the bearings resulted in a compressive load of 28,630 N (6440 lbs) on the front bearings and a tension load of 18,400 N (4,140 lbs) on the rear carriage. It is important to note that because the crossbase plate rotates above the swing motion, the front bearing rail is always loaded in compression and the rear rail is always loaded in tension.
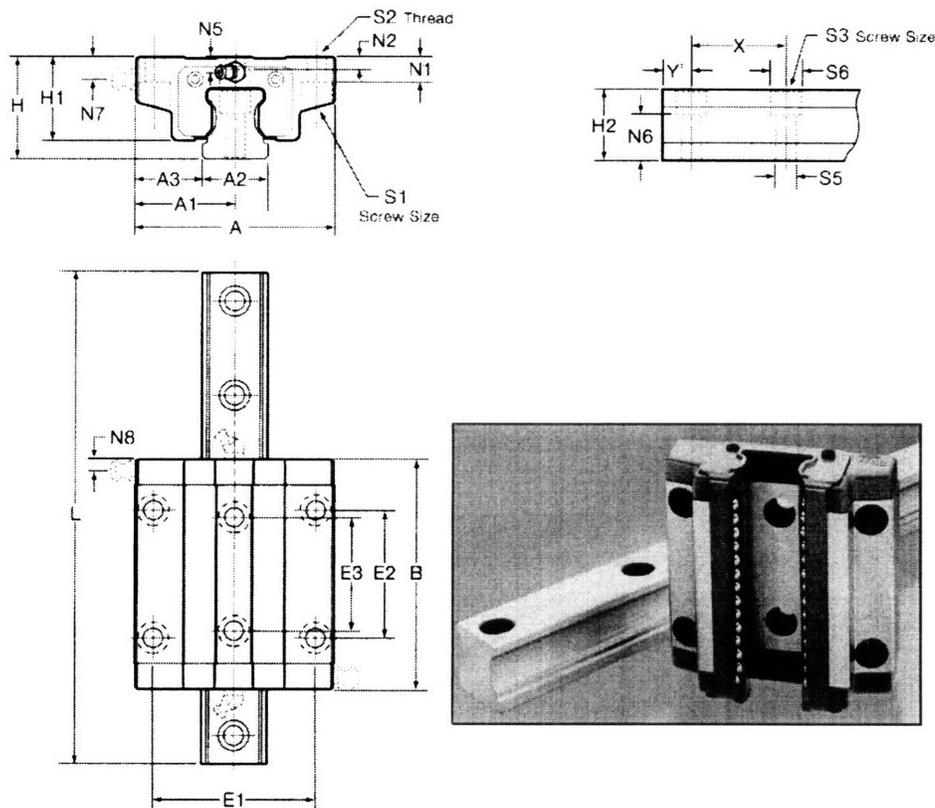
Figure 3.4: Thomson Accuglide Linear Ball Bearings

	(mm)															
Size	A	A1	A2	A3	H	H1	H2	B	E1	E2	E3	S1	S2	S3	S5	S6
25	70	35	23	23,5	36	29,5	24,5	86	57	45	40	M6	M8	M6	7	10,7

	(mm)								LOAD CAPACITY N (lbf)		MOMENT CAPACITY Nm (lbf-ft)				MASS Carriage Rail	
Size	N1	N2	N5	N6	N7	N8	X	Lmax†	C(@100km)	Co	Mp,My	Mpo,Myo	Mr	Mro	kg	kg/m
25	9	4,5	5	16	8	5,5	60	3 000	16 000 (3,600)	28 000 (6,290)	76 (56)	195 (145)	225 (165)	400 (295)	0,75	3,2

Figure 3.5: Thomson Accuglide Size 25 Linear Ball Bearings, Dimensions and Load Capacity

A reference edge was designed into the crossbase plate for aligning the two bearing rails and ensuring parallelism and straightness. The rails were 457 mm (18.0 in.) long and provided a side-to-side travel length of 14.0 cm (5.50 in.). The travel length allowed the manipulator to be moved to the far left or far right of the side-to-side travel range and have the DUT plane of the testhead comply with the infinite plane design specification.

The side-to-side motion in the alpha prototype was originally intended to be actuated by a PPA Performance Pak Actuator from Thomson Saginaw. As shown in Figure 3.6, the PPA actuators integrated a DC motor, spur gear transmission, and ballscrew into a single off-the-shelf unit. An integral brake prevented the ballscrew from backdriving, and a slip clutch prevented the motor from overloading. PPA actuators are typically supported with a trunion mount and then connected to the object to be driven with a simple pin joint. The actuators were available with two different spur gear reducers. With one of the reducers, the actuator was rated for a 3340 N (750 lbs) load at a speed of 0.028 m/s (1.1 in./s), and with the other reducer, it was rated for a 6670 N (1500

lbs) load at a speed of 0.010 m/s (0.4 in./s). For the side-to-side motion, the high speed

PPA actuator with a 20 cm (8.0 in.) stroke was selected.
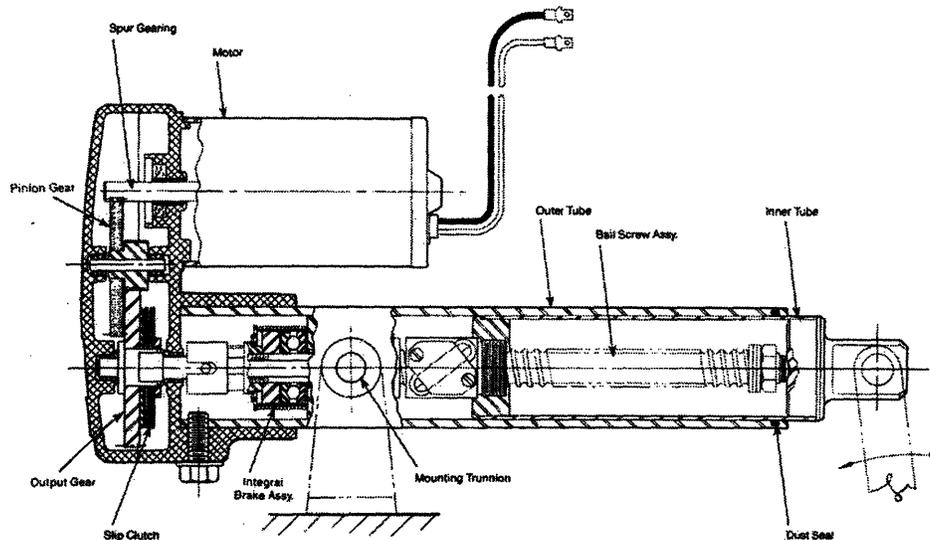
Figure 3.6: Thomson PPA Performance Pak Actuators

The PPA actuators were later eliminated and replaced with a custom drive

assembly consisting of a stepper motor, ballscrew, and mounting hardware. This drive

assembly was identical to the drive assembly used to power the in/out and theta motions

in the cradle. A photograph of the drive assembly is shown in Figure 3.25. This change

was beneficial because it reduced the cost of the manipulator by eliminating the need for

expensive control amplifiers. A model 23D204 stepper motor, shown in Figure 3.7, and

the corresponding controller from Anaheim Automation were selected. Doubleday

described the control system design for the stepper motors[18].

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[18] Doubleday, Rolland L. *A Control System for a Testhead Manipulator.* S.M. Thesis. Massachusetts
Institute of Technology. May, 1995.
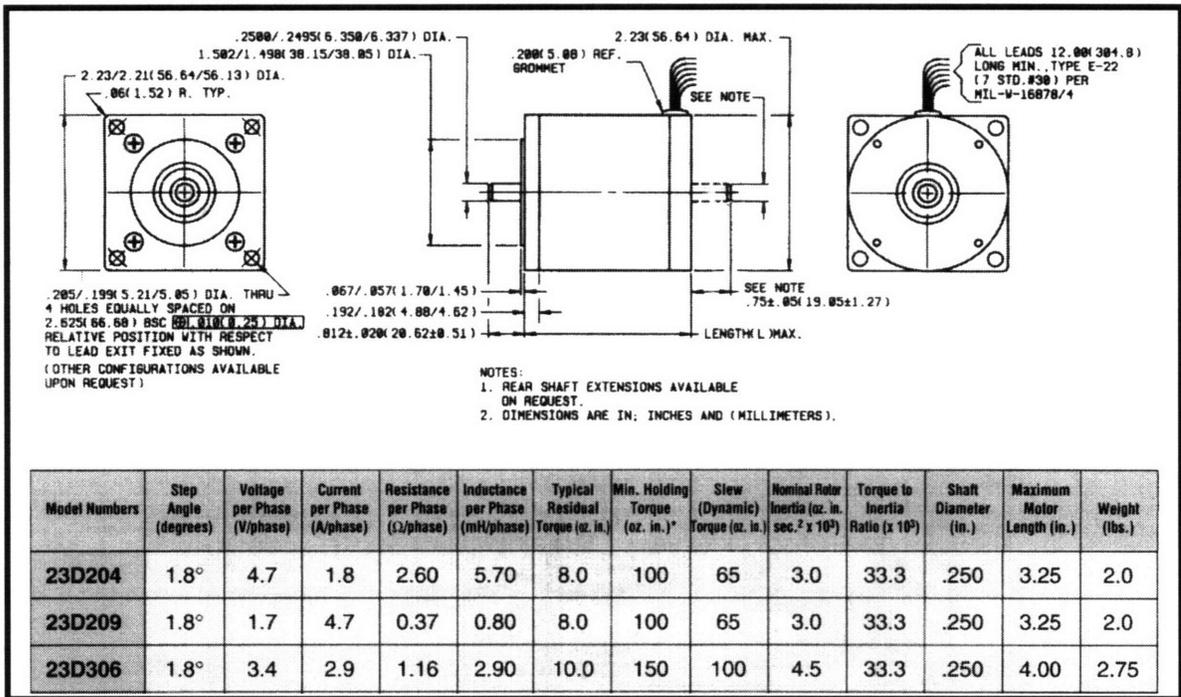
Figure 3.7: 23D204 Anaheim Automation Stepper Motor

Model Numbers	Step Angle (degrees)	Voltage per Phase (V/phase)	Current per Phase (A/phase)	Resistance per Phase (Ω/phase)	Inductance per Phase (mH/phase)	Typical Residual Torque (oz. in.)	Min. Holding Torque (oz. in.)*	Slew (Dynamic) Torque (oz. in.)*	Nominal Rotor Inertia (oz. in. sec.² x 10³)	Torque to Inertia Ratio (x 10³)	Shaft Diameter (in.)	Maximum Motor Length (in.)	Weight (lbs.)
23D204	1.8°	4.7	1.8	2.60	5.70	8.0	100	65	3.0	33.3	.250	3.25	2.0
23D209	1.8°	1.7	4.7	0.37	0.80	8.0	100	65	3.0	33.3	.250	3.25	2.0
23D306	1.8°	3.4	2.9	1.16	2.90	10.0	150	100	4.5	33.3	.250	4.00	2.75

SCREW SIZE					STANDARD BALL NUTS										FLANGE
See Pages 5-6 For Matching Screws		Ball Nut Part No.	Type See Below	No. of Circuits	CAPACITY		DIMENSIONS					BALL SIZE & QUAN.		TORQUE	Fits Flange Part No. Page 28
					Dynamic Load for 10⁶ Inches Life (Lbs.)*	Max Static Load (Lbs.)	Outside Dia. D	Radius Over Tube R	Overall Length L	Mounting Thread Size T	Thread Length TL	Nominal Diameter †	Quantity (±5%)	To Raise 1 Pound	
Nom. Dia.	Lead														
3/8	.125	RB-10-2	1	1	150	1,300	.750	.460	1.00	.664-32	.250	1/16	62	.021 Lbs. in.	R10-3
		R-11-2		2	300	2,600			1.875				124		R10-3
		•RB-15-2		1	25	230			1.00				62		•R15-3
		•R-16-2		2	50	460			1.875				124		•R15-3

Figure 3.8: 3/8 in. Ballscrew from Ball Screws and Actuators, Inc.

A rolled ballscrew and ball nut, shown in Figure 3.8, transmitted the motor power to the column baseplate. The ballscrew was manufactured by Ball Screws and Actuators Co., and the screw was 0.953 cm (.375 in.) in diameter with a lead of 3.18 mm (0.125 in.). The ball nut attached to the column baseplate, and the stepper motor attached to the rear of the crossbase plate.

A Lenze model 14.436.04.2.0 clutch coupling without hand release was used to provide a static braking torque of 0.475 N m (4.2 lb-in.) on the side-to-side ballscrew. The dimensions and power ratings of the clutch are shown in Figure 3.9, and a drawing is shown in Figure 3.10. The clutch coupling was a fail-safe design in which the friction surface was normally engaged by a spring preload. The clutch was disengaged by applying power to an internal solenoid. The clutch coupling attached to the rear end of the shaft in the Anaheim Automation stepper motor. Doubleday described the control system and logic for operating the clutch coupling[18].

Size	Rated torque lb-ft	Watts W	Max. air gap inch	Max. adjustm. distance inch	Min. Rotor thickn. inch	n_{max} RPM	WK^2 lb-ft^2 x 10^{-3}	m lbs
04	0.35	10	0.016	0.06	0.10	5000	0.031	0.49

Inch/metr.																			
size	b	b_1	d H7	d_l	d_2	d_3	d_4	d_5	d_6	d_7	h	h_1	h_2	h_3	h_4	h_5	l	l_1	air gap
04	1.811	–	1/4	4 x 0.138	1.89	2.165	1.654	0.591	0.433	–	1.378	1.26	0.118	–	–	–	0.354	15.748	0.006
04	46	–	6,7	4 x 3.5	48	55	42	15	11	–	35	32	3	–	–	–	9	400	0.15

Figure 3.9: Dimension and Ratings for Lenze Model 14.436.04.2.0 Clutch Coupling
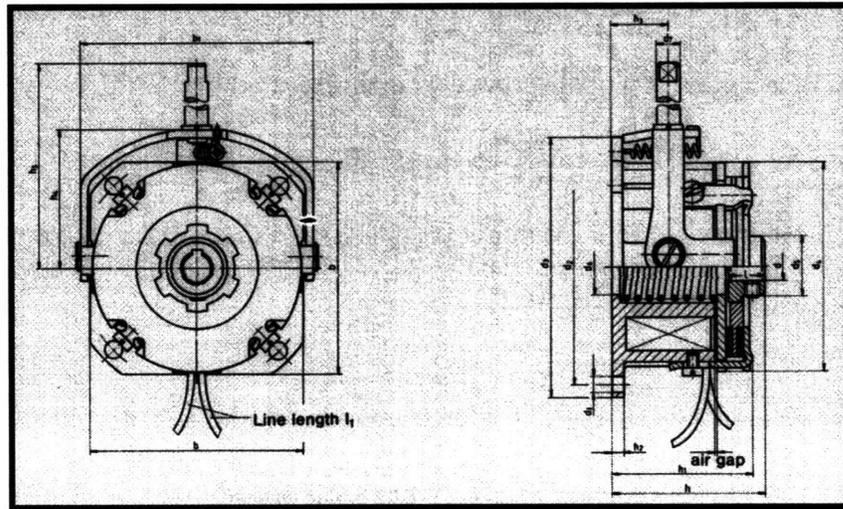
Figure 3.10: Drawing of Lenze Model 14.436.04.2.0 Clutch Coupling

3.1.3 The Column Subassembly

The column subassembly was responsible for the up/down motion of the testhead. The column needed an actuator that was capable of lifting a vertical load of about 10,200 N (2300 lbs) due to the weight of the testhead and upper portion of the manipulator. In addition, the column had to support the moment of approximately 6,780 N m (60,000 lb-in.) due to the cantilevered testhead. The critical design specification for the conceptual design of the column was that the subassembly needed to provide the up/down travel while maintaining a fixed distance between the top of the column and the centerline of twist motion. This would insure that the cable bundle could always be twisted over the top of the column subassembly.

To satisfy this specification, a novel design for the column subassembly was necessary. A typical, fixed-height column could not achieve this specification because the distance between the top of the column and the twist motion center-line would vary

with the position in the up/down motion. Thus, a telescoping column design was selected. The twistarm assembly could then be bolted to the column at a specified distance from the top of the column subassembly. This distance would remain the same throughout the up/down travel so that the cable bundle could always be twisted over the top of the column assembly.

The structural members of the column subassembly included the column baseplate and the telescoping stages. The carriages from the side-to-side motion's linear ball bearings were attached to the bottom surface of the column baseplate. The first of the telescoping stages was stationary and referred to as stage 0. The remaining stages, referred to as stage 1, stage 2, and the last stage, were not stationary. As the up/down motion was actuated, the column stages would sequentially be lifted by the up/down actuator. The last stage lifted off of the column baseplate's top surface first, followed by stage 2 and stage 1, respectively. The twistarm subassembly attached to the front surface of the last stage.

Each of the telescoping stages was designed to be fabricated by brake-bending a 3/4 in. thick plate. The bend in the plates increased the plate's moment of inertia to help support the bending moment from the cantilevered testhead. Stage 0 was welded to the column baseplate at the bottom edge of the bent plate, and it was reinforced with gussets that were welded on the left and right sides of the column baseplate. The last stage was initially designed as a weldment formed from one of the brake-bent plates and a 15.2 cm X 15.2 cm (6.0 in. X 6.0 in.) structural steel tube welded to the front of the brake-bent

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plate. A plate with a machined hole for attaching the up/down actuator was welded to the bottom of the last stage.

The linear bearings for the up/down motion were grouped into three sets, each set composed of a Thomson Accuglide Size 45 linear rail and two Accuglide linear ball bearing carriages. Figure 3.4 shows a drawing of the rails and carriages, and Figure 3.11 shows the corresponding dimensions and load capacities for the Size 45 bearings. The linear rails were bolted to the front surfaces of the bent plates, and the corresponding carriages were bolted to the rear surfaces of the bent plates. Similar to the side-to-side motion, a reference edge was machined into the plates to insure that the rails were aligned. The carriages were spaced apart to convert the bending moment created by the cantilevered testhead to a force couple that would load the top carriage in tension and the bottom carriage in compression. The spacing between the carriages was 15.0 cm (5.91 in.), and so the moment created a tensile load of 45,400 N (10,200 lbs) on the upper carriage and an equal compressive force on the lower carriage.

(mm)														
Size	A	A1	A2	A3	H	H1	H2	B	E1	E2	E3	S1	S2	S3	S5	S6
45	120	60	45	37,5	60	50	40	139	100	80	60	M10	M12	M12	14	20

(mm)								LOAD CAPACITY N (lbf)		MOMENT CAPACITY Nm (lbf-ft)				MASS Carriage Rail	
Size	N1	N2	N5	N6	N7	N8	X	Lmax'	C(@100km)	Co	Mp,My	Mpo,Myo	Mr	Mro	kg	kg/m
45	15	8	7,4	24	14	9,5	105	3 000	48 000 (10,800)	76 000 (17,100)	430 (315)	900 (665)	1 325 (975)	2 070 (1,530)	3,40	10,5

Figure 3.11: Thomson Accuglide Size 45 Linear Ball Bearings, Dimensions and Load Capacity Correspond to Figure 3.4

The initial column design used a 3-stage, telescoping, ACME threaded screw as the actuator. Figure 3.12 shows a conceptual drawing of the assembly, including the steel

ACME screw and the bronze nuts. This screw assembly was designed by Dave Levy, and

the prototype was manufactured by Horspool and Romine in Oakland, California.

Hardstops

4 " diam
8/inch lead
screw

2.5" diam
8/inch lead
screw

5/8" diam
8/inch lead
screw

17"

2000 lb
mass

bronze nut with 1.375" OD

bronze nut with 3.25" OD

bronze nut with 4.75" OD

Nut length
TBD

drive point
(with spline or equivilent)
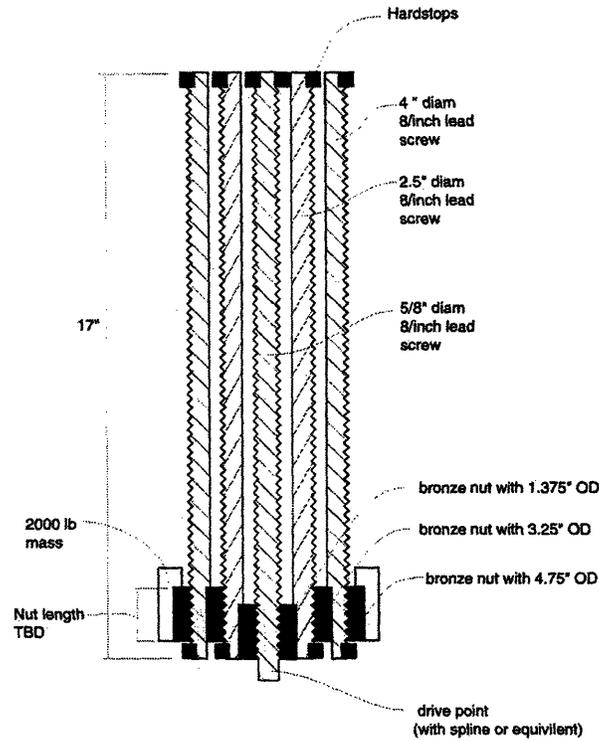
Figure 3.12: Conceptual Drawing of the Up/Down ACME Screw[19]

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[19] The dimensions in this drawing were not the actual dimensions of the prototype ACME screw assembly.
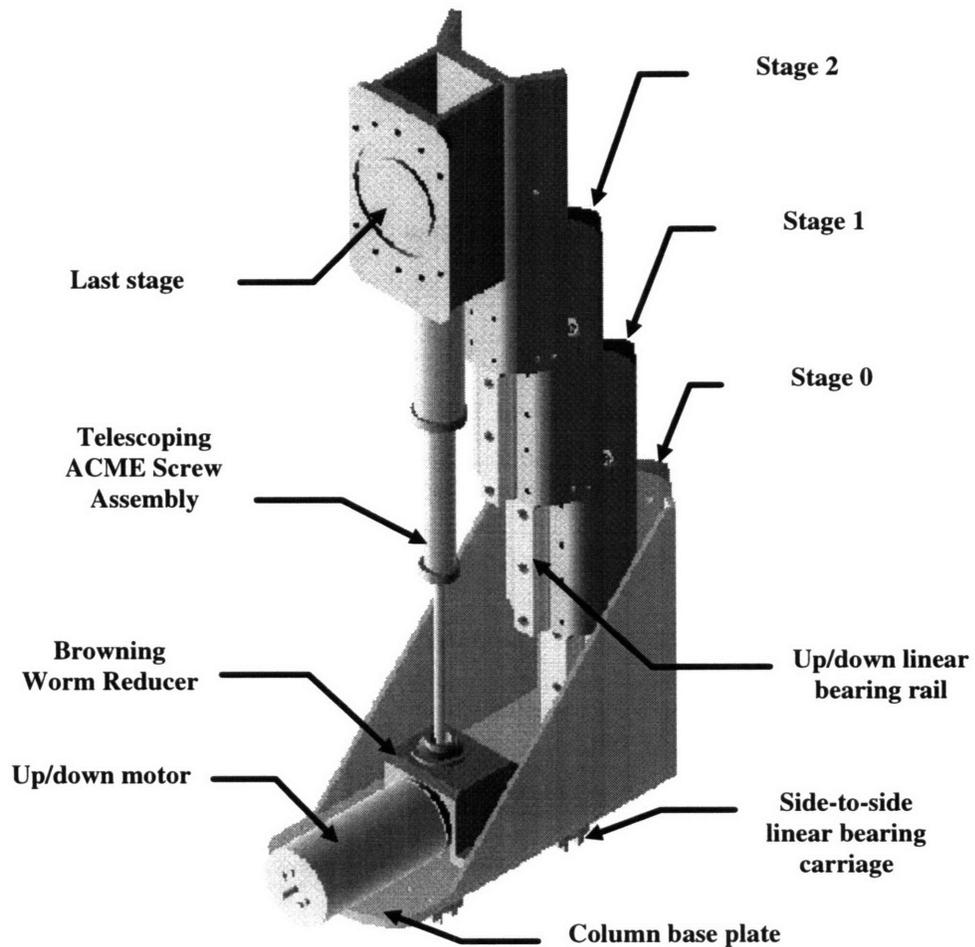
Figure 3.13: Column Subassembly with the Telescoping ACME Screw Extended

The ACME screw was to be driven by a DC motor with a Browning model R206Q56-L gearbox as the reducer. The gearbox, shown in Figure 3.14, contained a worm reducer with a 60:1 ratio. It was mounted on the top side of the column baseplate, and had a hollow shaft for inserting the bottom of the smallest screw in the telescoping ACME assembly.
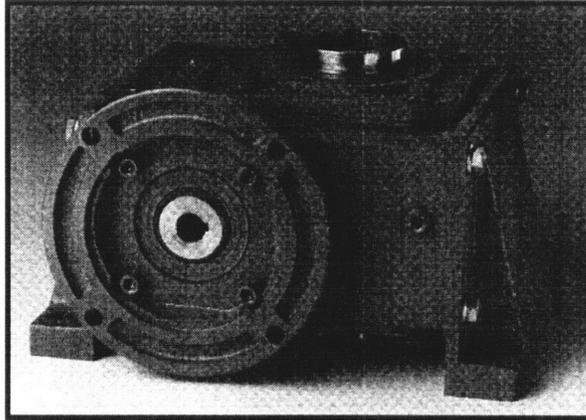
Figure 3.14: Browning R206Q56-L Worm Gear Reducer

After testing the ACME screw on the alpha prototype, it was determined that the friction loads in the ACME screw and worm gearbox were unacceptably large. The motor necessary to drive the screw at specified speed could not be packaged in the space at the front of the manipulator column.

The ACME screw design was therefore replaced with a new telescoping ball screw. To reduce the cost of the new ballscrew, it was designed with two stages rather than three. Unfortunately, this increased the height of the column subassembly, and that meant that the cable bundle would need to be located further from the twist axis to clear the top of the column.

Unlike the ACME screw design, the large diameter stage of the ballscrew was positioned at the bottom of the column and the small diameter ballscrew was positioned at the top of the column. Although this had no real affect on the structural loading of the ballscrew or manipulator, this design was aesthetically preferred because the manipulator appeared to be better supported.

The new telescoping ballscrew design meant that the last stage had to be redesigned. The new last stage consisted of a hollow, 8 in. X 12 in. structural steel tube. The tube was closed at the top with a removable plate that contained a bearing bore for the ballscrew bearing. The ballscrew was supported at the bottom by attaching large diameter nut to a stationary tube that was bolted to the top surface of the column baseplate. This layout was beneficial because the column stages could now be lowered and left in position while the top plate could be removed to access the drive motor and ballscrew assembly for maintenance. Figure 3.15 shows a photograph of the alpha prototype with the telescoping ballscrew assembly.

Figure 3.15: Photograph of Alpha Prototype with Telescoping Ballscrew

The ballscrew assembly was driven from the top by a Bison 300 DC, 1/4 HP, 137 RPM motor. A photograph of the motor is shown in Figure 3.16, and the dimensions are shown in Figure 3.17. The motor was mounted so that its axis was parallel to the ballscrew and concealed within a newly designed last stage. An Inertial Dynamics, model 1904-2621, fail-safe brake that was rated for a static torque of 1.7 N m (15 lb-in.) was attached to the rear end of the motor shaft.
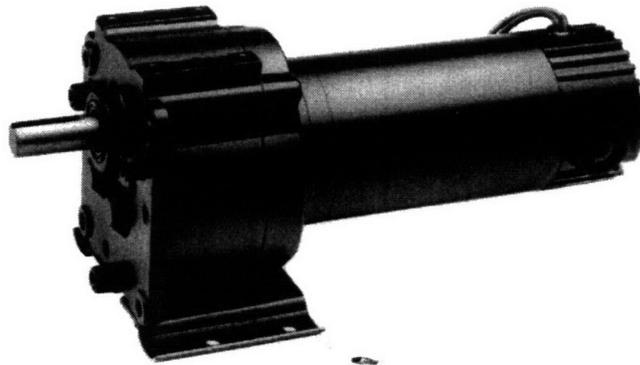
Figure 3.16: Photograph of the Bison 300 DC Gearmotor
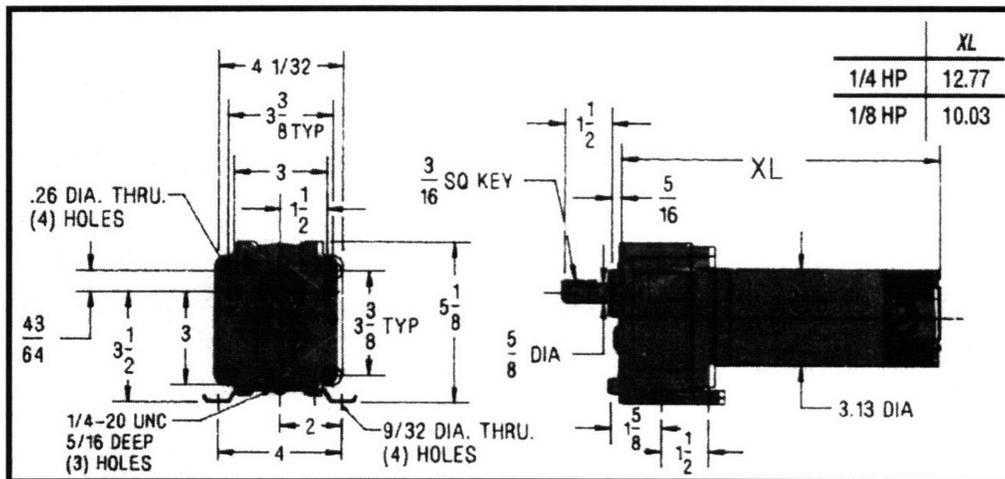
Figure 3.17: Dimensions of the Bison 300 DC Gearmotor

Power from the Bison motor was initially transmitted to the ballscrew through a spur gear transmission with a ratio of near 1:1. The gears were mounted above the top plate of the column's last stage. The spur gears were later switched to a 3/8 in. standard roller chain transmission to reduce the impact of incompatible tolerances stacking through the telescoping stages and through the ballscrew assembly.

3.1.4 The Twistarm Subassembly

The primary function of the twistarm subassembly, shown in Figure 3.18, was to provide the twist motion of the testhead. The motion was provided by a Kaydon MTO-145 turntable bearing, identical to the Kaydon bearing used for the swing motion. The Kaydon bearing is shown in Figure 3.3. The structure of the twistarm subassembly was formed by a hollow steel tube with a round extension on the rear side. The Kaydon bearing bolted to the back side of the tube and depended upon a shoulder on the round extension for alignment. The crossbeam of the cradle subassembly bolted to the front of the twistarm tube.

The twist motion was driven by a model 4064, 42A-GB PM DC gearmotor from Bodine. A photograph of the motor is shown in Figure 3.19, and a dimensioned drawing is shown in Figure 3.20. The Bodine motor mounted within the hollow twistarm tube. A custom designed pinion with a hollow shaft was slid over the motor shaft, keyed, and clamped in place. The pinion engaged with a stationary, external ring gear that mounted around the perimeter of the Kaydon bearing's outer race. The Bodine motor drove the pinion around the ring gear to provide the twist motion. The selected Bodine motor was rated for a torque of 33.9 N m (300 lb-in.) at a speed of 13 RPM. The motor could obtain

a maximum torque of 54.2 N m (480 lb-in.). Combined with the 13:1 ratio from the pinion and ring gear, the motor provided a twist torque of up to 705 N m (6,240 lb-in.). A brake was not required on the twist motion because the Bodine gearmotor used a non-backdrivable worm reducer to obtain the rated low speed and high torque.
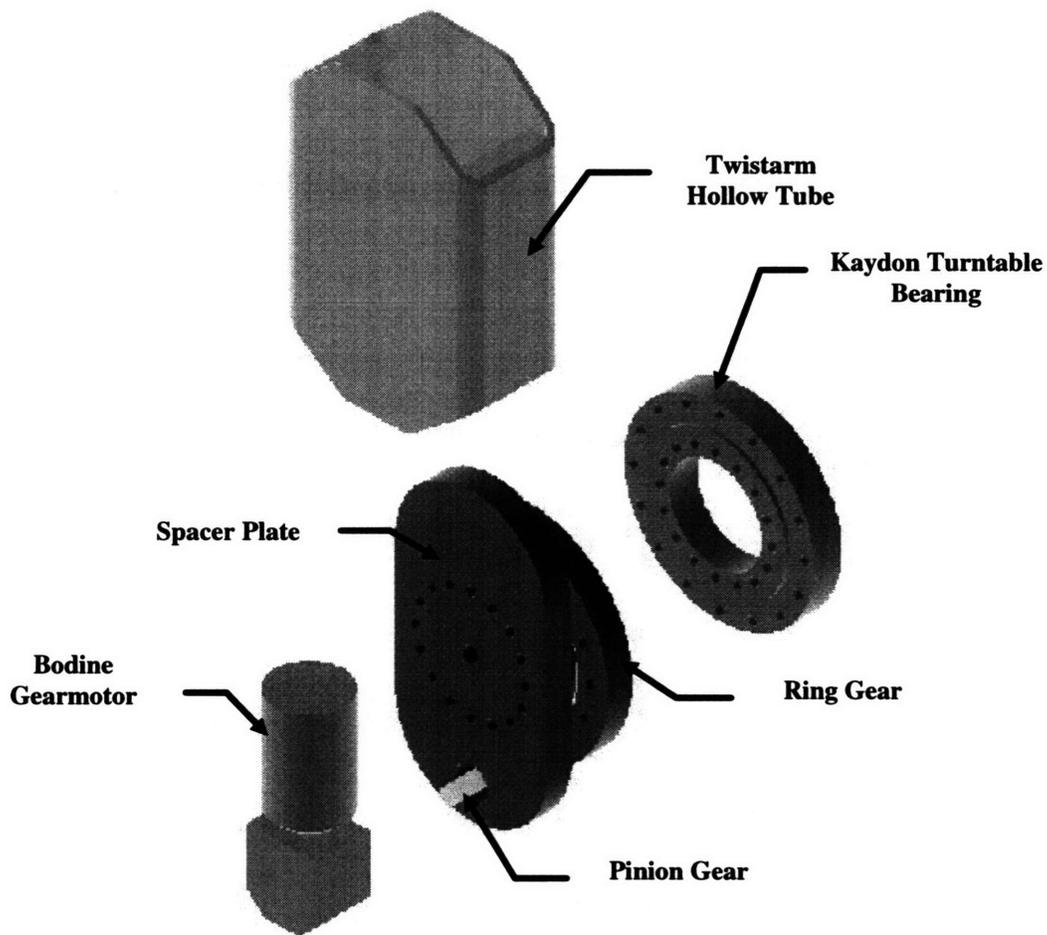
Figure 3.18: Exploded View of the Twistarm Subassembly
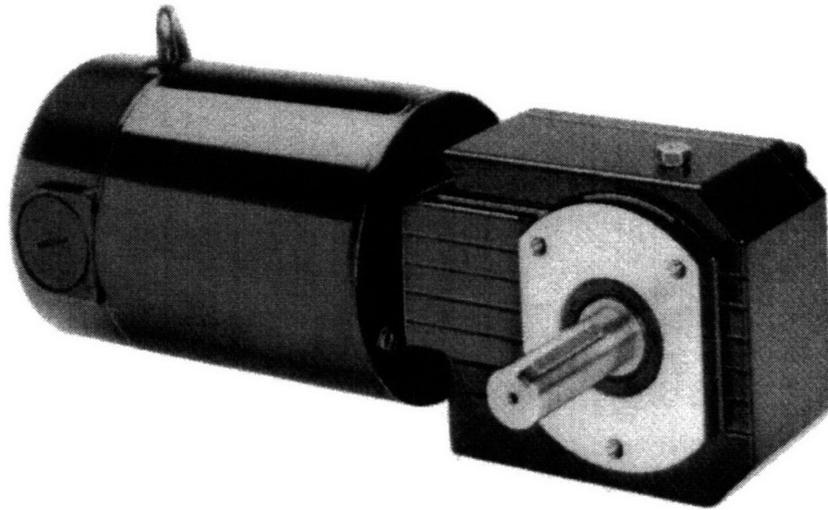
Figure 3.19: Photograph of the Bodine 42A-GB PM DC Gearmotor

| Bodine Data | | Output | | | Motor | Input | | | Obtainable Torque |
Model No.	Type	Rpm	Rated Torque Lb-in.	Ratio	Hp	V	FF	Amps	Lb-in.
130VDC, FF=1.0 Continuous Duty									
4066	42A5BEPM-GB	8.6	250	280	1/4	130	1.0	1.8	400
4064		13	300	190					480
4062		21	270	120					432
4060		42	180	60					288
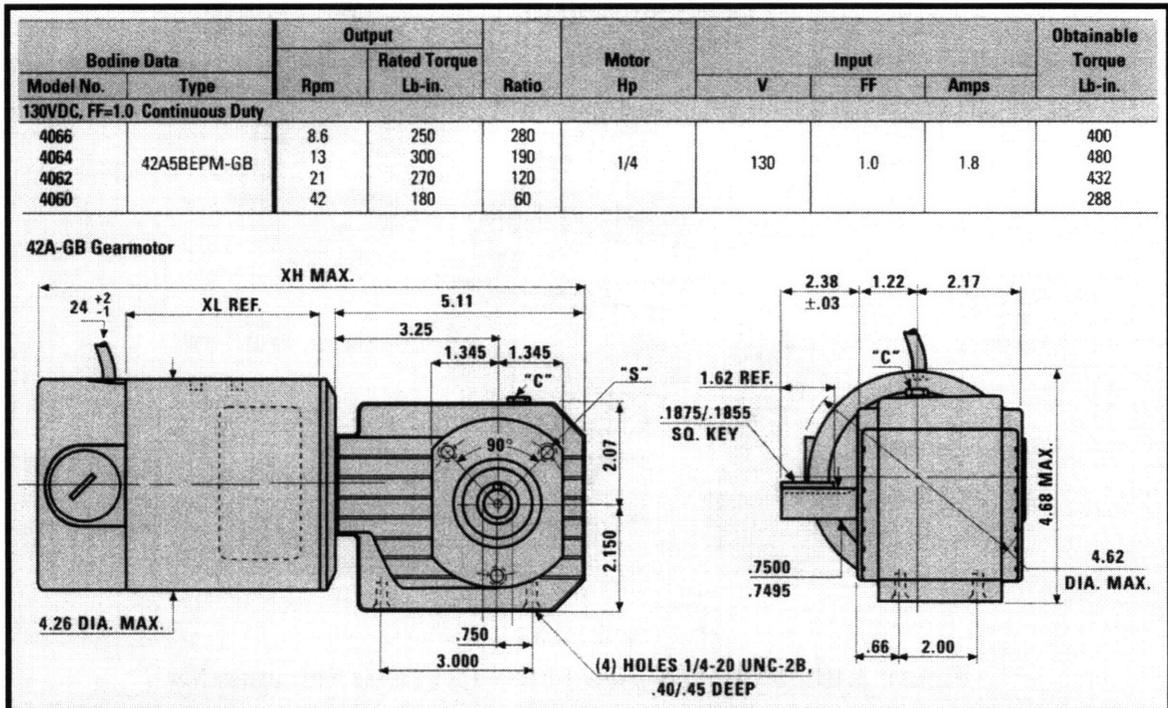
Figure 3.20: Dimensions of the Bodine 42A-GB PM DC Gearmotor

3.1.5 The Cradle Subassembly

The primary functions of the cradle subassembly, shown in Figure 3.21, were to provide the in/out motion, theta motion, and the tumble motion. The structure of the cradle subassembly consisted of the cradle crossbeam, left and right cradle arms, and left and right slide plates. The cradle crossbeam bolted to the front of the twistam tube. The crossbeam was designed to be made by welding a 1/2 in. thick plate onto a 5 in. X 5 in. structural steel tube. The plate increased the size of the crossbeam so that it would fit directly into the cradle arms. Each cradle arm was designed to be made by machining a 6 in. X 3 1/2 in. structural steel MC channel. The testhead was positioned within the cradle and was attached to the moving slide plates.
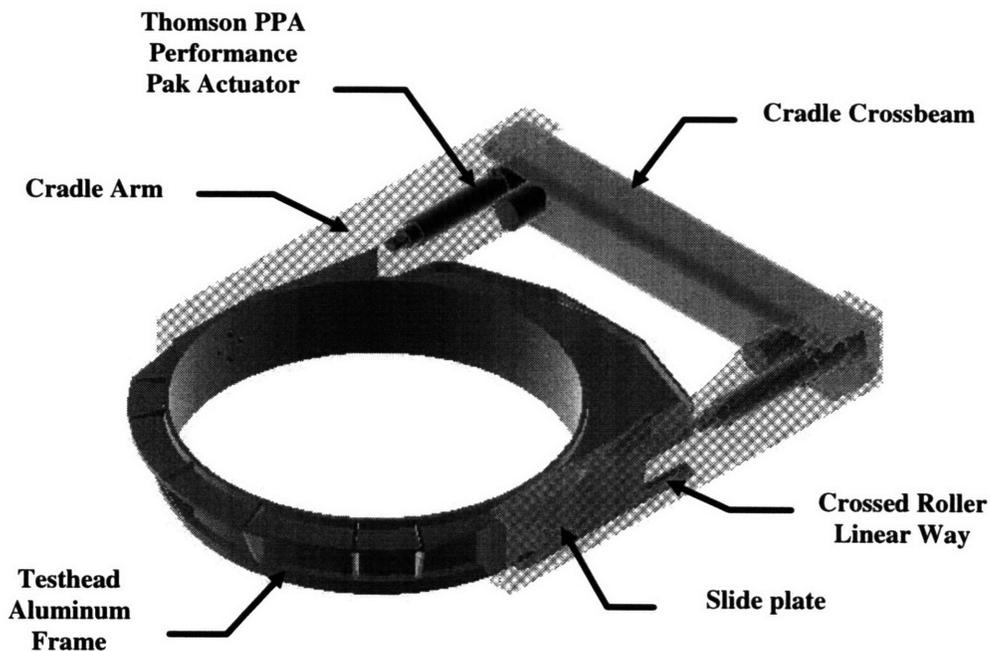
Figure 3.21: Cradle Subassembly

The in/out and theta motions shared common actuators and bearings. This was achieved by using two pairs of crossed roller linear ways, one pair in each cradle arm. Figure 3.22 shows the rolling elements, cage, and ways of a typical crossed roller linear way. Figure 3.23 and Figure 3.24 show a drawing, the dimensions, and load capacity of the selected IKO CRW 6-300 crossed roller linear ways. In each cradle arm, a slide plate was mounted between a pair of the IKO crossed roller linear guides. The in/out motion was provided by driving the slide plates in the same direction, and the theta motion was provided by driving the slide plates in opposite directions. Doubleday described the controller and logic for operating the in/out and theta motions using the same actuators and bearings[18].
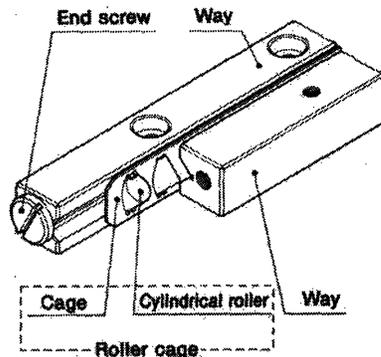
Figure 3.22: Illustration of a Typical Crossed Roller Linear Way
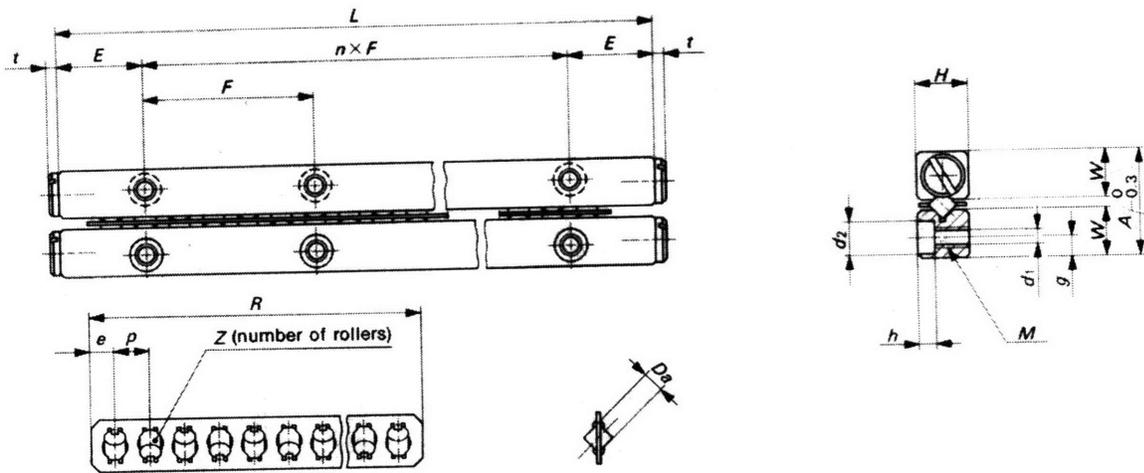
Figure 3.23: Drawing of the IKO CRW 6-300 Crossed Roller Linear Ways

Model number	Weight		Main dimensions				Nominal dimensions mm				
	Way[1] kg/m	Roller[2] cage g	A	H	L (n×F)	E	Da	R	Z	p	
							Roller Cage dimensions				
CRW 6- 300	1.57	20.3	31	15	300 (5× 50)	25	6	246	27	9	

Mounting dimensions								Basic dynamic load rating Cu [3] kgf	Basic static load rating Cou [3] kgf	Allowable load Fu [3] kgf	Model number
e	W	g	M	d_1	d_2	h	t				
6	14	6	M6	5.3	9.5	5.2	3	270	230	78	**CRW 6- 300**

Figure 3.24: Dimensions and Load Capacity of the IKO CRW 6-300 Crossed Roller Linear Ways

Similar to the side-to-side motion described in Section 0, the in/out and theta motions were originally intended to be driven with the Thomson PPA Performance Pak Actuators shown in Figure 3.6. This concept was later converted to the same custom drive assembly used to power the side-to-side motion. This drive assembly is described in Section 3.1.2, and Figure 3.25 shows a photograph of the drive assembly mounted in the left cradle arm.

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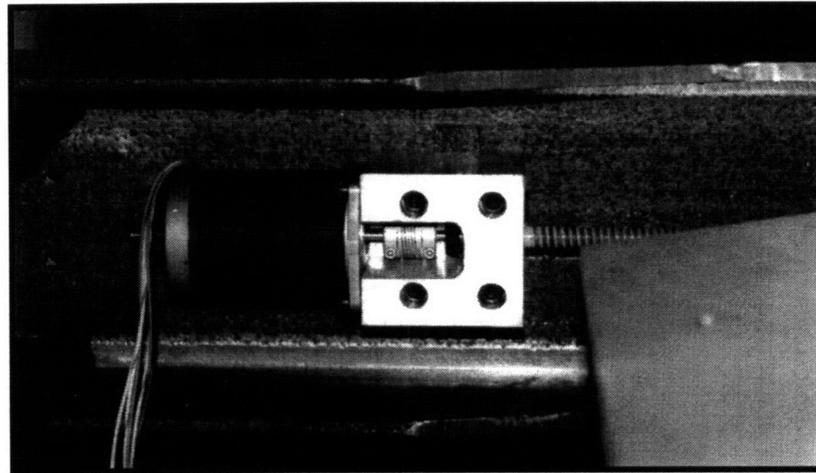
Figure 3.25: Drive Assembly in Alpha Prototype's Left Cradle Arm

The tumble and theta motions were provided by Torrington 6SF10 plain spherical bearings, shown in Figure 3.26, that were mounted within bearing bores in the slide plates. The spherical bearings had a maximum tilt angle of 6 degrees. The Frankenstein bolt which was mounted on the side of the testhead extended through the spherical bearing and was held in place by a snap ring.
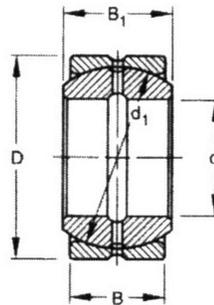
Bearing Number	Bore d		Outside Diameter D		Inner Ring Width B_1		Outer Ring Width B		Spherical Diameter d_1 (ref.)		Radial Clearance* (unmounted) inches		millimeters		Load Ratings Radial Limit Load Rating	Dynamic Radial Load Rating
	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	min.	max.	min.	max	lbf	lbf
5SF8	0.5000	12.700	0.8750	22.225	0.437	11.10	0.375	9.52	0.719	18.26	0.004	0.008	0.10	0.20	8330	2690
6SF10	0.6250	15.875	1.0625	26.988	0.547	13.89	0.469	11.91	0.899	22.83	0.004	0.008	0.10	0.20	13000	4200

Figure 3.26: Torrington 6SF10 Plain Spherical Bearing

3.2 The Fabrication of the Alpha Prototype

Nearly the entire alpha prototype was designed to be fabricated from standard structural steel shapes to minimize cost. Hence, nearly all of the parts could be fabricated with steel weldments and/or a little machining. The majority of the custom parts in the alpha prototype were fabricated by two companies, Bow Industries and Iron Dragon, both located near Concord, New Hampshire. Iron Dragon was responsible for steel fabrication and most of the raw materials. Bow Industries was responsible for the machining work. Bill Miskoe of Iron Dragon and Paul Preble of Bow Industries were valuable resources to our team because they helped insure that our custom parts were manufacturable. Perry Technologies, in Canton Center, Connecticut, made the custom ring and pinion gears for the twist motion.

The manufacturing of the parts followed in parallel with the detailed design. When the details of each major subassembly were completed, the drawings were delivered to Iron Dragon and Bow Industries for discussion. After discussion, any necessary revisions to the part drawings were made, and the parts were then fabricated. The turn-around time was generally about four to five weeks for most of the parts. While the parts for one subassembly were being manufactured, the detailed design of the next subassembly was completed.

The manipulator baseplate was manufactured by torch cutting 1 1/2 in. thick steel plate to the approximate shape of the "T". Torch cutting was capable of holding a straightness tolerance of about +/- 1/8 in. The bottom and top surfaces of the baseplate were blanchard ground to provide flat surfaces for fixturing and attaching the Kaydon

turntable bearing. The stationary counterweights were made by torch cutting the appropriate shape from a 1 in. thick steel plate. To minimize cost, the edges of the counterweights were not machined. The crossbase plate was cut and machined from 2 in. thick steel plate with all of the necessary bolt holes for the Kaydon and side-to-side linear rails machined in place.

The next major structural component, the weldment of the column-baseplate and stage 0 plate, was formed from one of the brake-bent, 3/4 in. plates welded at a right angle to a 3/4 in. thick baseplate. The 3/4 in. brake bent plate was machined prior to welding so that the setup would be the same for all of the bent plates. A welded strut connected the brake-bent plate to the base plate on each side to provide stiffness to support the torque due to the cantilevered testhead. Once these pieces were welded together, the holes and reference edges in the column baseplate were machined. Each telescoping stage plate was formed from one of the brake-bent, 3/4 in. thick plates and post machining.

The last stage of the column assembly was made by cutting an 8 in. X 12 in. structural steel tube to length and welding it to the front of another brake-bent plate. The top edges and front surface of the tube were machined to provide flat faces for attaching the twistarm's Kaydon bearing and the top plate.

The twistarm tube was fabricated by welding a round extension on the back side of a 6 in. X 12 in. tube. A circular shoulder was machined onto the round extension to provide a reference for aligning the twistarm to the Kaydon turntable bearing. This

alignment was necessary to insure that the pinion and ring gears were aligned. A shallow bearing bore was machined for the bearing that supported the twistarm pinion into the back surface of the twistarm tube. A pattern of tapped holes for attaching the cradle crossbeam was included on the front surface of the twistarm tube.

The cradle crossbeam was fabricated by welding a 3/4 in. plate on the top surface of a 5 in. X 5 in. structural steel tube. The plate was then machined to control the distance between the top and bottom surfaces of the crossbeam so that the fit within the cradle arms could be tightly controlled. This also prevented the cradle arms from being offset from each other.

The cradle arms were machined from 6 in. X 3 1/2 in. structural steel, MC channels. Reference edges for the IKO crossed roller linear guides were machined into the front of the channels, and the channel flanges were machined at the rear ends to accommodate the cradle crossbeam.

3.3 The Assembly of the Alpha Prototype

After custom parts were completed by Iron Dragon and Bow Industries and after the off-the-shelf parts were received from the vendors, they were assembled in the Precision Engineering Research Group's laboratory. It was often necessary to make modifications to the custom parts in the Laboratory for Manufacturing and Productivity's machine shop. Figure 3.27 shows a photograph of the alpha prototype after completing the entire assembly process.
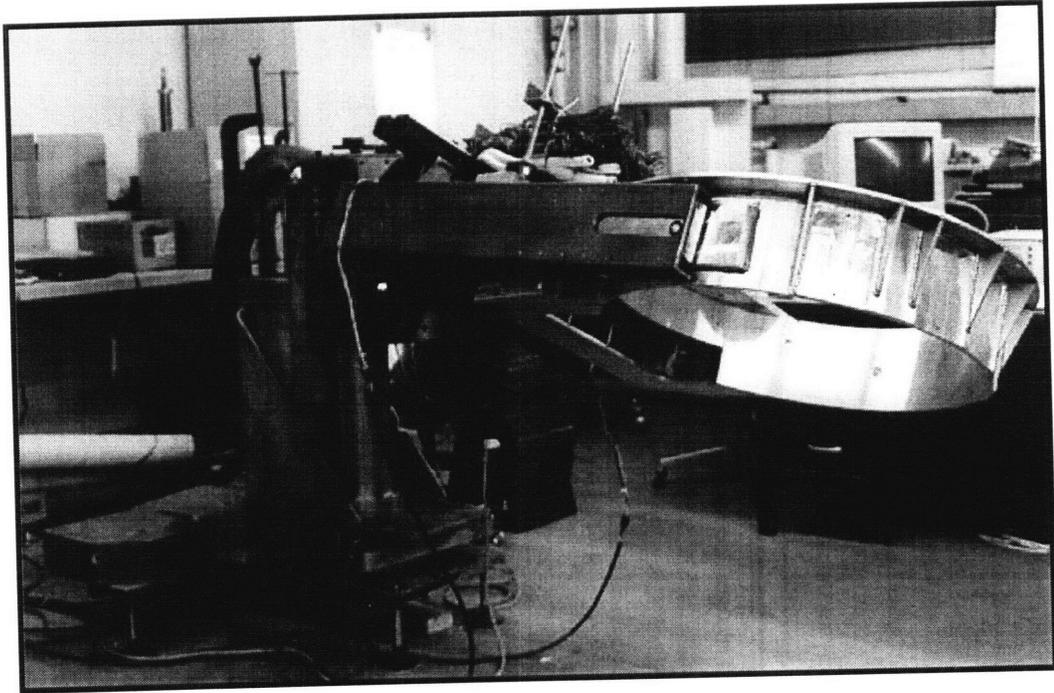
Figure 3.27: Photograph of the Assembled Alpha Prototype

The assembly of the alpha prototype was often difficult. This was primarily due to two reasons. The first reason was because of the way in which the design and manufacturing were performed concurrently. For instance, as soon as the detailed design of the base assembly was completed, the drawings were delivered for manufacture. Then, the team began the detailed design of the crossbase assembly. This type of project schedule was optimized for speed, but it left no overlapping time between the major subassemblies to insure that they would assemble correctly. The position of the ACME screw was a good example of the problems that can occur under this type of project schedule. Because the Browning gearbox was bolted to the top of the column baseplate, the positions of the bolt holes were designed prior to the details of how the ACME screw would mount in the last stage. When it was time to assemble the column, the mounting holes in the column baseplate were not properly located.

The second reason that the prototype was difficult to assemble was because the design team did not adequately consider design for assembly issues. For instance, the assembly process for the telescoping stages in the column was extremely difficult. The stage 0 Thomson linear rail was bolted to the front of the stage 0 bent plate. This rail was aligned by pulling the rail against a vertical reference edge that was machined in the bent plate. The carriages for this rail were then attached to the back of the stage 1 plate with screws that had to be put in from the back side of the plate. This made it extremely difficult to align the bearings and be able to bolt the carriages in place.

3.4 Unresolved Design Issues

After the completion of the alpha prototype, the designers were aware of several issues that needed to be addressed during the design of the beta prototype. Some of the issues became obvious during the fabrication of the alpha prototype, while others had simply remained unresolved due to the compressed development schedule. This section will summarize the most important issues and list the secondary issues.

The most important unresolved design issue was discovered on April 13,1995, while observing the alpha prototype. It was observed that the alpha design would not work with a common floor plan arrangement because a collision would occur between the manipulator column and a prober or handler. The collision would occur when the manipulator was set up in the floor plan arrangement where a prober or handler was located in the pocket of the "T" shape in the manipulator baseplate. When the manipulator was swung into a new position for servicing the DUT or docking, the rear end of the column would collide with the corner of the prober or handler. It was decided

that this collision was unacceptable and that it would be resolved by redesigning the entire manipulator layout during the beta design phase. Figure 3.28 shows a photograph of the alpha prototype in the position where the collision would have occurred. It can be seen that the rear of the column subassembly extends beyond the perimeter of the column baseplate.
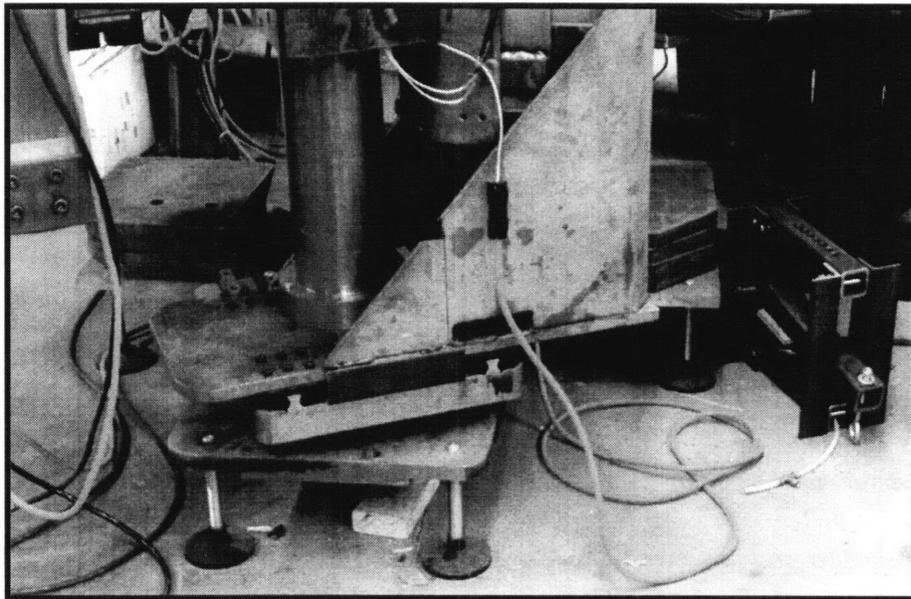
Figure 3.28: Photograph of Alpha Prototype in Collision Position

The second most important issue was that the beta design needed to implement compliance in all of the degrees of freedom except swing. The compliance would be necessary for the manipulator to work effectively with the kinematic coupling interface being designed by Michael Chiu, a doctoral student in the Precision Engineering Research Group that was employed by Teradyne's ICD division in Boston. The compliance in the manipulator would allow the testhead to move a specified range with a maximum force of 35 lbs. Compliance would insure that the kinematic coupling

interface could be actuated without having to overcome the weight of the testhead, the inertia of the manipulator, or the cable forces.

The remaining issues that were unresolved after the alpha design of the Universal Manipulator are listed below:

- Eliminate the front and rear caster assemblies by attaching casters directly to baseplate,
- Incorporate a static brake for the swing motion,
- Incorporate adjustable hard stops for the swing motion,
- Incorporate hard stops at the end of the side-to-side travel,
- Improve the assembly process for the telescoping stages in the column subassembly,
- Design hard stops for the telescoping stages,
- Design a method for smooth transition between the stages of the telescoping ballscrew,
- Select a different bearing for the telescoping ballscrew,
- Improve the assembly process for the twistarm subassembly,
- Select larger stepper motors for the in/out and theta motions,
- Incorporate limit switches on the side-to-side, up/down, twist, in/out, theta, and tumble motions,
- Design a method for adjusting the nominal testhead tumble position, and
- Design the cable support.

3.5 Summary

This chapter described the alpha prototype of the Universal Manipulator. An overview of the detailed design was presented by outlining the principal components within the major subassemblies of the manipulator. The prototype fabrication was briefly presented by describing the manufacturing processes for the primary structural components and the assembly of the entire manipulator. The chapter concluded with the major design issues that remained unresolved at the completion of the alpha prototype.

4. Conclusion

This thesis described the design and prototype fabrication of the Universal Manipulator's alpha prototype. The manipulator was designed jointly by a team of graduate students within the Precision Engineering Research Group and employees at Teradyne's STD and ICD divisions in Agoura Hills, California, and Boston, Massachusetts. Teradyne intends to sell the Universal Manipulator as an integral component in their semiconductor test systems. These test systems generally consist of a mainframe computer, a testhead, and a manipulator. The testhead contains analog circuitry for testing silicon wafers and/or integrated circuits. The wafers or circuits are held and positioned by either prober or handler machines, and Teradyne's testheads are positioned with respect to the probers or handlers using a manipulator.

As integrated circuits became more intricate and complex, the test equipment grew in size. As a result, mechanical issues such as the required size of the manipulator, accuracy and repeatability in positioning the testhead relative to the probers or handlers, and the wide variety of test equipment significantly reduced the quality of the testing process. In response to these issues, Dr. Alexander H. Slocum proposed to Teradyne's CEO, Mr. Alex d'Arbeloff, that Teradyne's old manipulator be replaced and that the new manipulator be integrated with a kinematic coupling interface. The kinematic coupling interface would solve the accuracy and repeatability issues, and the new manipulator would be stronger and work with all floorplan arrangements of probers and handlers.

The development of the Universal Manipulator began during the spring of 1994. During the project, the MIT team did the conceptual design, detailed design, and prototype fabrication of the Universal Manipulator's alpha prototype and subsequently designed and fabricated two beta prototypes. This thesis described the design and prototype fabrication of the alpha prototype which was completed during the spring of 1995.

The redesign of the Universal Manipulator during the beta prototype phase was necessary to resolve the remaining design issues which had not been resolved by the end of the alpha prototype phase. The beta prototype phase began during April of 1995, and the two beta prototypes were fabricated by September, 1995. Figure 4.1 shows a photograph of an assembled beta prototype.
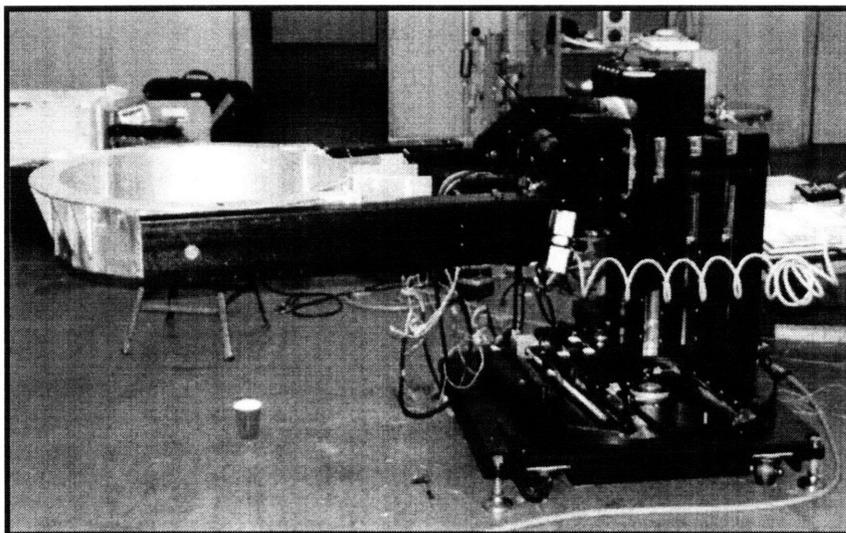
Figure 4.1: Photograph of Assembled Beta Prototype

The two beta prototypes were delivered to Teradyne's STD and ICD divisions for testing and design revisions, and the MIT team transferred the design information such as

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detailed drawings and bill of materials. Teradyne's designers continued the project with final design revisions. The project should culminate with the market release of the Universal Manipulator during 1996.

Appendix A: Universal Manipulator Specification

A.1 Introduction

Appendix A contains the design specification for the Universal Manipulator. The specification was prepared by Art Lecolst, a mechanical designer at Teradyne's STD division in Agoura Hills, California.

A.2 Design Specification

Universal manipulator specification

1.0- Introduction:
    1.1- This specification describes the overall performance for a manipulator
        to be used for holding and moving a 973 test head to interface with all
        commercially available handlers and probers. See Equip list Para 25.0

    1.2- This design shall also accomodate a 971 type round head, an A570, A580 and
        the Hydra head. This may require new arm/cradle assembly(s) to be designed so
        as to "not" impact air flow for these series test heads.

    1.3- A glossary has been provided in sect 26.0 in order to clarify special
        Teradyne terminology.

2.0- Environmental:
    2.1- Operating environment
        2.1.1- Temperature: 68 to 86F (20 to 30C)
        2.1.2- Altitude: 6000 ft (1828 m)
    2.2- Shipping environment
        2.2.1- Temperature: 32 to 120F (0 to 49C)
        2.2.2- Pressurization: 2000 feet (610 m)
    2.3- Abnormal conditions   50 to 140 F (10 to 60C)

    2.4- Weight and size:

Parameter	Max value	Min value	Comments
Test head dia	30" [762]	28" [711.2]	See new casting design
Test head weight	900lb[409Kg]	300 lb[136Kg]	Including cables up to the manipulator cable support.

    2.5 Cable length

	Max	Min	Exposed between T.H and M/P
973	102" [2590]	98" [2337]	
971 (round)	94" [2387]	90" [2286]	
A570, A580	90" [2286]	84" [2133]	
Hydra	To be determined		

    2.6- Cable weight

		Exposed cable	
256 channels	45 lb [20.4Kg]		
512 "	75 lb [34Kg]	"	"
768 "	105 lb [47.6Kg]	"	"
1024 "	135 lb [61.2Kg]	"	"

    2.7- Meet clean room requirements for class 100.

3.0- Set-up:
    3.1- Unit shall be designed to minimize installation time. Maximum allowable shall
        be 2 hours.

Universal manipulator specification

3.2- Change-over
   Peripheral change-over time shall not exceed 45 minutes, excluding
   moving the peripheral.

4.0- Symmetry:
   4.1- The manipulator design shall allow the test head DUT plane to maintain
      an infinite plane clearance of 2.00 [50.8] min to any manipulator (including
      cable supports) structure for a distance of 55 [1397] inches in all directions
      (except the floor) with the DUT in any of the following positions.

   DUT up or zero   DUT right or 90   DUT down or 180   DUT left or 270
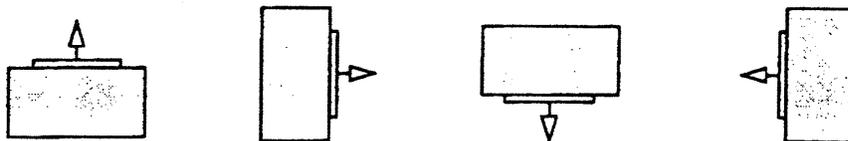
      The design shall also allow the cable bundle to enter from either side
      (and or over the top) of the manipulator base/column assembly.

5.0- Motions
   5.1- All motions shall be easy to accomplish and in a safe manner by one
      operator with a minimum amount of training. The force required to achieve
      any motion (not power assisted) shall comply with human safety standards
      and be within the ability of an average operator.
      5.1.1- Any motion that is power assisted, shall have built-in safegaurds for
            assurance that "no" personal injury or damage to equipment can
            occur. See open issues list on last page.

   5.2- The motions to be designed in, are as follows and are divided into 2 categories.
      5.2.1- Category 1:
         Coarse or large motion ranges used for positioning/orienting the test head to
         support docking with various peripheral equipment, within different
         floorplans.
               Up/down.........(vertical)   See Para 5.4
               Twist...........(rotation)   "   "   5.5
               Swing...........(move away)   "   "   5.6

      5.2.2- Category 2:
         Fine or small motion ranges for assurance that docking (in all axes and
         planes) can be accurately and repeatably achieved (with a minimum amount of
         force) at any test head position mentioned in category 1.
               Side to side....(lateral)   See para 5.7
               In/out..........(horizontal   "   "   5.8
               Theta   "   "   5.9
               Tumble   "   "   5.10

Universal manipulator specification

5.3- All motions shall have locks that can be independently operated. These locks can be power assisted or manual but must be positive locking in nature, easily reached and activated by an operator without the use of any tools.

5.4- Up/down: (Category 1)
This motion shall allow the test head to accomodate all commercially available handlers and probers. See approved handler and prober list para 25.0. As a minimum, the DUT shall be capable of being positioned (from the floor) at the following positions or any point in between.

DUT position	Max height	Min height
Facing up	50.00 inches	30.00 inches
Facing down	47.00 inches	27.00 inches
Facing right	45.00 inches	25.00 inches
Facing left	45.00 inches	25.00 inches

UP

50.00
30.00

47.00
27.00

DOWN

45.00
25.00

RIGHT

LEFT
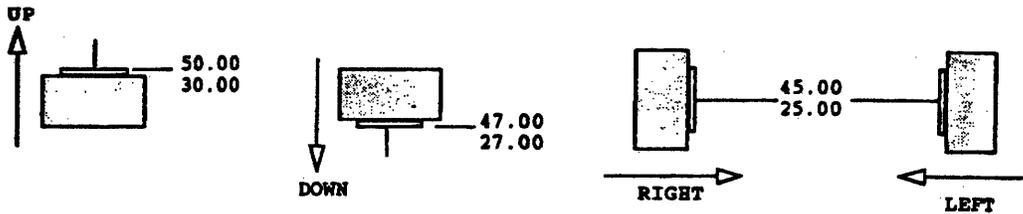
5.5- Twist: (Category 1)
This motion is to be power assisted. Time to complete one full cycle of this motion shall not exceed one minute. The purpose of this motion is to present the DUT at different angles for interfacing to various handlers and probers. This motion shall be available regardless of all other motion positions.

5.5.1- This motion shall operate in two modes.
Mode 1- Allowing the DUT position to face- "up" (horiz), "90 degrees vertical right" and "down" (horiz), or at any inclined angle in between.

UP

RIGHT
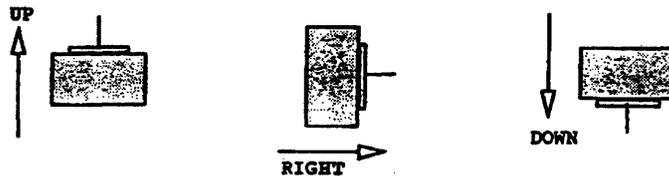
DOWN

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Mode 2- Allowing the DUT position to face- "up" (horiz), "90 degrees
vertical left" and "down" (horiz), or at any inclined
angle in between.

UP

LEFT

DOWN
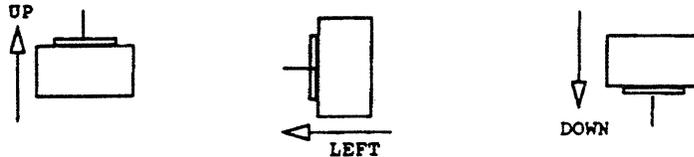
5.5.2- When operating in mode 1, there shall be stops to prevent the
test head from twisting or traveling over into mode 2 or DUT left.
When operating in mode 2, there shall be stops to prevent the test
head from twisting or traveling over into mode 1 or DUT right.
These can be adjustable (positive setting) type designed stops
that can be set at 5 degrees beyond the DUT "up" or "down"
positions for either mode 1 or 2 giving each mode a total travel
of 190 degrees. The 5 degrees on either side of the twist travel
compensates for tolerance build-up in docking to handler/probers.

5.5.3- This motion shall provide for a window of "free play". This free
play shall be measured at the perimeter (edge) of the test head
as +/- .25" [6.35 or a .50" [12.7] total window.

+/_.25   +/_.25
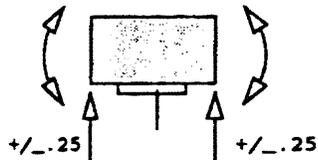
5.5.4- There is to be a degree increment indicator positioned on/along the twist
point axis showing at least 5 degree (preferrably 1 degree) graduations.
This shall be easily viewed by an operator.

5.5.5- Infinite plane shall be maintained at any given angle of test
head rotation.

5.6- Swing: (Category 1)
For purposes of clocking this motion, a "zero" position will be established
with the test head directly positioned in front of the manipulator column.
A motion of 95 degrees clockwise or left and 95 degrees counter clockwise or
right shall be provided.
Infinite plane (See Para 5.5.5) shall be maintained within this 190 degree
swing window. A lock is to be provided such that the test head can be
locked at any position within this 190 degree swing window. Adjustable stops
are to be provided to set swing travel limits. Force required to activate this
motion (unlocked) shall not exceed 15 lbs [6.81Kg] in either direction. Both

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degree positions (and anywhere in between) can be considered working positions.

Clockwise or left

Counter Clockwise or right
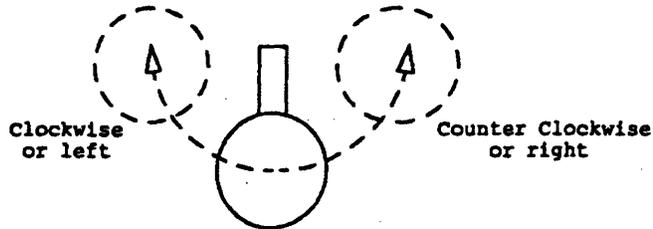
5.7- Side to side: (Category 2)
The total travel from side to side will be dictated by the design, but must allow the DUT plane to travel beyond any manip structure by at least 2.00" [50.80] thus creating an infinite plane. This infinite plane shall extend in all directions (parallel to the DUT surface) at least 55.00 [1397] excluding the floor. This motion shall be available in any "swing" or "twist" motion position. A positional lock (within the travel limits) is to be provided as part of this motion. Force to activate this motion shall not exceed 35 lbs [15.89Kg] in either direction.
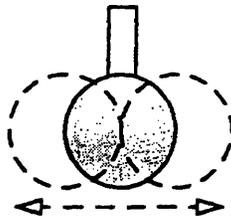
5.8- In/out: (Category 2)
A minimum of 4.00" [101.6] (+/- 2.00 [50.8] from nominal) total travel shall be available for purposes of aligning the test head. This travel is to be available within any "swing" or "twist" motion position. A positional lock (within the 4.00" travel limit) is to be provided as part of this motion. Force required to activate this motion shall not exceed 35 lbs [15.89 Kg] in either direction.

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5.9- Theta: (Category 2)

The purpose of this motion is to allow the aligning of the test head
"X" "Y" axis with the handler/prober "X" "Y" axis at final dock.
The manipulator shall provide a "True Theta" 4 degree window (+/- 2
degrees from nominal "X" "Y") and shall be adjustable. It shall manitain
true position for the test head center within .010 thru the range of motion.
This adjustment mechanism shall provide for ease of control, smooth operating,
and a fine pitch movement. There shall be a degree increment indicator with
1/2 degree graduations. This indicator is to have a "zero" or nominal
position and 2 degrees of markings on either side which shall be easily
viewed by an operator.
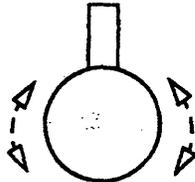
5.9.1- It is preferred, but not required, that the X-Z plane (theta) be
coincident with the test head center of gravity rather than the
geometric center.

5.10- Tumble: (Category 2)

The purpose of this motion is to allow the DUT plane to become planar
with the docking surface on handler/probers. The manipulator shall
provide a 4 degree window, (+/- 2 degrees from nominal or "true level
of the arm cradle"). This mechanism shall be "adjustable" and/or "free
floating" with a lock for each mode . The mechanism shall provide for ease
of control, smooth operating, and a fine pitch movement. There shall be a
degree increment indicator with 1/2 degree graduations. This indicator is
to have a "zero" or nominal position with 2 degrees of markings on either
side of zero which shall be easily viewed by an operator.

Cables
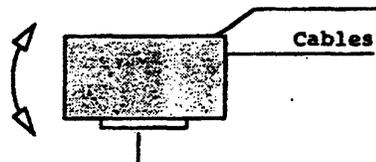
5.10.1- It is preferred, but not required, that the X axis (tumble) be
coincident with the test head center of gravity.

5.11- Motion positioning memory:

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To be determined, see open issues on last page

6.0- Brakes:

6.1- A safety measure must be in place on the up/down motion to guard
against a catastrophic failure or sudden rapid motion of the test
head. This safety measure must ensure that an "immediate automatic"
lock/brake will be invoked preventing movement of the test head if
such an occurance takes place.

6.2- All motions are to have lock/brake capability that can be either
manual or power assisted unless otherwise specified in this document.
In the case of power assisted locks/brakes, if a power failure
occurs, all locks/brakes will "Fail Safe" ie, to the locked position. Any
and all power assisted locks/brakes must have an overide system and
a tool shall be provided for such.

6.3- There may be a requirement to have locking/braking occur in a
sequential manner. Teradyne will address this issue and advise.

7.0- Cable management

7.1- Cable routing shall be such that it requires minimum cable length,
to allow test head movement within the manipulator range of motion
without straining the cable bundle beyond its service length.

7.2- The cable bundle may enter from either side, and/or the top of the
manipulator column and shall be sufficently supported such that it
will not contact the column during motion movements. This may require
more than one support system. This support(s) shall be an integral
part of the manipulator itself and accomodate either a left/right or
top entry.

7.3- The cable support(s) shall be designed such that the cable bundle
has minimum influence on manipulator and test head motions. The
support(s) shall allow for free, non-damaging twist of the cable
bundle when the test head is twisted thru its range of motion. It
shall not allow the cable bundle and/or individual wires to be
subjected to an inside bend radius of less than 6" [152.4]. This
design shall also allow for easy upgrade (adding cables) with a minimum
amount of dis-assembly.

7.4- The cable support system(s) shall allow for various size and weight
cable bundles and shall not interfere with handler/probers.

7.5- The support system(s) shall accomodate 2 liquid cooling lines that lie
adjacent to the cable bundle and 2 pneumatic lines that will lie within
the cable bundle.

7.6- The cable support system(s) shall be designed such that there are no sharp
corners or edges exposed to the cable bundle, misc lines and or the
system operator.

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7.7- The cable bundle exits the mainframe at a height of 40.00" [1016mm] from the floor.

7.8- There shall be safeguards such that "no" rapid movement of cable bundles (liquid and pneumatic lines) or support systems can occur. If the support is power assisted, it shall continue to support the cable bundle in the event of a power failure.

8.0- Performance differentiation;

8.1- From the docked position, a complete undock, moving the test head to the service or manual position, and back to the docked position shall take no longer than 5 minutes. This excludes any service performed while in the service or manual position.

8.2- Individual motion repeatibility (departing from and returning to a given location) shall be +/- XXX resulting in 99% repeatability. This repeatability is guaranteed after initial alignment or set-up. See open issues list on last page.

9.0- OTHER FEATURES:

9.1- Testhead Mounting To The Manipulator:

9.1.1- The mounting of a complete arm/cradle assembly to the test head, shall induce "no" stress to the test head itself.

9.1.2- For 971 test head applications, the manipulator structure around the testhead shall not restrict airflow and shall allow ample for replacement of the air filters (see reference document 396-375-00)

9.2- Stand Alone/ Attachable:

9.2.1- Manipulator shall be able to stand alone with a 900 lbs testhead (including cable bundle) for any given position outlined within this spec.

9.3- The AC power cord must be a harmonized 15 foot long cord, and shall provide a "Reversed IEC 320 #TF1" connector as the end termination.

9.4- Labels On The Manipulator: (See Para 9.5.1)

9.4.1- All labels shall conform to international standards where possible.

9.4.1- Operational: All operator controls on the manipulator shall be clearly labeled with function (ie: Emergency Stop, Vertical Lock, etc) and direction for operation (ie: ON|OFF, UP|DOWN, IN|OUT,

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LOCK|UNLOCK, RUN|STOP, etc). Operational labels may be in the
form of words, arrows or symbols.

9.4.3- Functional labels, generally in the form of scales and pointers,
shall be fixed to the manipulator to reference and indicate the
position, rotation, tumble, theta and head weight compensation.

9.4.4- Electrical labels shall conform with international standards.
These labels will generally take the form of 'icon' type images for
identification.

9.4.5- Operator safety, procedural and warning labels shall be affixed
to the manipulator as necessary. Location of safety labels must
be documented by the vendor.

9.4.6- A small nameplate with serial number shall be mounted on the rear
of the main structure near the top of manipulator. Teradyne P/N
395-533-00 must be visible on the serial number nameplate.

9.5- Documentation
9.5.1- The manipulator supplier shall provide and maintain current
documentation as to type, quantity and location of all supplier
installed labels.

10.0- Aesthetics:
10.1- The manipulator shall be painted using only Teradyne color chips
no. 003 and no. 009 as detailed in Teradyne control document
CD-0009. Teradyne may authorize a water based paint as a substitute
for 003 & 009.

11.0- Unusual or Unexpected Noise:
11.1- Teradyne will review, and may grant variances, in the cases of
unusual or unexpected sounds occurring in the course of normal
manipulator operation.

11.2- The conditions for the consideration of a variance are as follows
11.2.1- The source of the sound must be precisely identified and deemed to be
non-detrimental.
11.2.2- A written report stating all relevant facts must accompany a variance
request.
11.2.3- Teradyne reserves the right to deny.

11.3- Unusual or unexpected noise may be, but not limited to, squeaking,
grinding, brake noise, excessive motor noise, etc.

.2.0- Instruction Manual:
12.1- Every manipulator shall come with an complete operational user's
manual showing various motions with pictures and illustrations to
inform the users. The manual shall include installation, use and

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set up procedure for the manipulator on the test floor.

12.2- The instructions manual must be provided by the manipulator manufacturer and approved by Teradyne.

13.0- Floor Space:
13.1- Refer to Para 25.0 for the preferred floor plan to support various handlers and probers for the specified allowable cable length.

14.0- Movability/Leveling:
14.1- Manipulator shall provide casters (2 swivel type in front, 2 fixed type in rear) to ease the movement prior to final installation. Minimum caster diameter is 4 inches (101.6 mm).

14.2- Leveling feet (4) shall be supplied to accommodate for various floors conditions and types. The force per area on the pad of each leveling foot shall not exceed 132 Lbf/sq. inch (59.9 Kg/sq. mm). These leveling feet shall have a built-in safety net, such that during a leveling operation, the leveling foot "cannot" be accidentaly unscrewed causing an unexpected tip.

14.3- The manipulator with testhead attached shall be movable in a safe manner within a localized area only. The manipulator height measured from the floor and on the casters shall not exceed 78 inches (1981).

15.0- Shipping:
15.1- The manipulator will be shipped completely assembled (except for the cradle arms) in an enclosed wooden crate with ramp. The cradle arms shall be safely supported within the crate by either shipping banding or bubble plastic bag.

15.2- Counter weights (if applicable) must be packaged in boxes where the weight of the box (including weights) does not exceed 40 lbs [18.2Kg] . Weights are to be finished such that they will be rust proof.

15.3- At no time shall motion locks built into the manipulator be used to support, hold or lock any movement during shipment.

16.0- Safety Requirements:
16.1- The manipulator shall meet following Teradyne Safety Specs.
1. Electrical Product Safety Standard 2.5
2. Mechanical Product Safety Standard 2.6
3. Documentation Product Safety Standard 2.7
4. Marking Product Safety Standard 2.8

16.2- The manipulator shall meet EN 60-950 and EN 60- 204-1 and shall be certified by independent agency such as TUV stating that it meets the EN requirements.

16.3- All metal parts within the manipulator structure shall be grounded and a grounding stud(s) shall be provided to connect a ground wire to

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an outside unit. The location and dimension of the grounding stud(s) is contingent on Teradyne's approval.

16.4- The manipulator shall be able to tilt at any 15 degree angle with the test head at any position within its range of motion without losing its balance at full weight.

16.5- All plastic parts material must meet the UL 94-V0 flammability rating.

16.6- The manipulator must be designed and built to provide a minimum 3:1 factor of safety - ratio of irreversible destructive load on a member, structure or mechanism and the maximum possible working load of 900 lbs (409 Kg). Failure of any part shall not cause a safety hazard. The factor of safety must be certified by the manufacturer, based on a one time destructive test.

16.7- At final shipment (with test head and cables) the manipulator shall allow the test head and cradle arms to be disconnected from the main portion of the manipulator, at the rear side of the cradle arms or front face of the twist shaft.

17.0- Electrical Grounding Points:
   17.1- It is required that the base assembly have 2 tapped holes (1 on each corner of the rear surface) to accommodate ground wires. These shall be 10-32 thd X .50 [12.7] deep with a cleared away area (of paint or finish) of .75 [19.05] dia to insure grounding.

   17.2- For aesthectic reasons, no grounding wires shall be visible.

   17.3- All electrical grounding hardware shall be stainless steel.

18.0- Oils & Hydraulics:
   18.0- The use of oils and lubricants shall be minimized.

   18.1- The use of hydraulic fluid is strictly forbidden.

19.0 Clean Room Compatibility:
   19.1- All materials shall be in accordance with clean room standards Class 100

   19.2- All moving/sliding mechanisms shall be in accordance with clean room standards Class 100.

20.0- Reference documents:
   20.1- Quality & Workmanship Standards:
      20.1.1- Manipulator must conform to the following:
         1. Mechanical Manufacturing Workmanship Standards 822-197-00
         2. Electrical Product Safety Standard 2.5
         3. Mechanical Product Safety Standard 2.6
         4. Documentation Product Safety Standard 2.7
         5. Marking Product Safety Standard 2.8

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6. Mechanical Parts Standard 551-180-01
7. Torque SPEC - Electrical Connectors 551-180-05
8. EN 60-204 part 1
9. EN 60-950

21.0- Floor plan & Reference:

22.0- Quality assurance criteria
  22.1- Detailed Manufacturing Instruction:

   22.1.1- The vendor must have available Detailed Manufacturing
          Instructions for each sub-assembly and final assembly. Teradyne's
          Quality Assurance personnel must have access to these documents.

  22.2- Assembly Traveler Check List:
   22.2.1- The vendor must have a traveler check list by S/N for each
          manipulator. This should be kept on a history file, and made
          available if required by Teradyne personnel at any time. The
          vendor assembly process must be inspected and certified by
          Teradyne.

  22.3- Assembly Drawings:
   22.3.1- After design is approved by Engineering, the vendor must
          provide assy drawings and electrical diagrams that will be
          controlled as part of Teradyne's documentation. Vendor shall
          not change any design features or aesthetics without Teradyne
          Engineering ECO approval.

   22.3.2- Any approved change shall be reflected on assy drawings and
          updated in the vendor dedicated check list. Vendor to maintain
          an approved document control system.

23.0- Loose Hardware:
  23.1- Any hardware shipped loose from the vendor shall be packaged
         separately and be accompanied by a bill of material and drawing that
         clearly indicates an assembly procedure and location for all loose hardware.

24.0- Inspection criteria:
  24.1- Check List Guide Line:

  1. LIMITS FOR ALL MOVEMENTS AND SET UP:

   THE MANIPULATOR SHALL BE INSPECTED UNDER 900 LBS. OF SIMULATED LOAD
ON A LEVELED BASE. ALSO INSPECT AMOUNT OF MOVEMENT PER THIS SPEC
         A. Z DIRECTION / IN-OUT ....
            CRITERIA: 35 LBS [15.9Kg] MAX. EACH DIRECTION

         B. X DIRECTION / SIDE TO SIDE...........
            CRITERIA: 35 LBS [15.9Kg]. MAX. EACH DIRECTION

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C. Y DIRECTION / VERTICAL ....
   CRITERIA: 35 LBS [15.9Kg] MAX. EACH DIRECTION

D. SWING (LEFT - RIGHT)................
1. LIMITS FOR ALL MOVEMENTS AND SET UP:

THE MANIPULATOR SHALL BE INSPECTED UNDER 900 LBS. OF SIMULATED LOA
1. LIMITS FOR ALL MOVEMENTS AND SET UP:

THE MANIPULATOR SHALL BE INSPECTED UNDER 900 LBS. OF SIMULATED LOAD
ON A LEVELED BASE. ALSO INSPECT AMOUNT OF MOVEMENT PER THIS SPEC
   A. Z DIRECTION / IN-OUT ....
      CRITERIA: 35 LBS [15.9Kg] MAX. EACH DIRECTION

   B. X DIRECTION / SIDE TO SIDE...........
      CRITERIA: 35 LBS [15.9Kg]. MAX. EACH DIRECTION

   C. Y DIRECTION / VERTICAL ....
      CRITERIA: 35 LBS [15.9Kg] MAX. EACH DIRECTION

   D. SWING (LEFT - RIGHT)................
1. LIMITS FOR ALL MOVEMENTS AND SET UP:

THE MANIPULATOR SHALL BE INSPECTED UNDER 900 LBS. OF SIMULATED LOAD
ON A LEVELED BASE. ALSO INSPECT AMOUNT OF MOVEMENT PER THIS SPEC
   A. Z DIRECTION / IN-OUT ....
      CRITERIA: 35 LBS [15.9Kg] MAX. EACH DIRECTION

   B. X DIRECTION / SIDE TO SIDE...........
      CRITERIA: 35 LBS [15.9Kg]. MAX. EACH DIRECTION

   C. Y DIRECTION / VERTICAL ....
      CRITERIA: 35 LBS [15.9Kg] MAX. EACH DIRECTION

   D. SWING (LEFT - RIGHT)................
      CRITERIA: 15 LBS [6.8Kg] MAX. EACH DIRECTION

   E. ROTATION..............................
      CRITERIA: LESS THAN 1 MIN. FOR 185 DEGREE MOTION.

   F. THETA FREE MOTION ....
      CRITERIA: 15 LBS [6.8Kg] MAX. EACH DIRECTIOND
ON A LEVELED BASE. ALSO INSPECT AMOUNT OF MOVEMENT PER THIS SPEC
   A. Z DIRECTION / IN-OUT ....
      CRITERIA: 35 LBS [15.9Kg] MAX. EACH DIRECTION

   B. X DIRECTION / SIDE TO SIDE...........
      CRITERIA: 35 LBS [15.9Kg]. MAX. EACH DIRECTION

   C. Y DIRECTION / VERTICAL ....
      CRITERIA: 35 LBS [15.9Kg] MAX. EACH DIRECTION

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D. SWING (LEFT - RIGHT)..................
   CRITERIA: 15 LBS [6.8Kg] MAX. EACH DIRECTION

E. ROTATION...............................
   CRITERIA: LESS THAN 1 MIN. FOR 185 DEGREE MOTION.

   F. THETA FREE MOTION ....
      CRITERIA: 15 LBS [6.8Kg] MAX. EACH DIRECTION

G. ARM SAG...............................
   CRITERIA: SHALL NOT EXCEED .060 [1.52] ALONG
             THE LENGTH OF THE ARM

2. ALL BOLTS, NUTS, SCREWS TORQUED TO SPEC.....
3. SAFETY BRAKE FUNCTIONAL......................
4. SAFETY COVERS INSTALLED.....................
5. POWER CORD LOCATION CORRECT.................
6. ALL LOCKING KNOBS ARE IN PLACE/INSTALLED AND SECURE.........
7. GROUND CABLE LOCATION IS CORRECT AND FREE OF PAINT PER SPEC
8. PAINT COLOR MATCHES TERADYNE PAINT CHIP NO.003 AND 009
9. LIMIT SWITCHES ARE FUNCTIONAL................
10. ALL LOCKING MECHANISMS LOCK..................
    CRITERIA: 15 LBS [6.8Kg] MAX. EACH DIRECTION

E. ROTATION...............................
   CRITERIA: LESS THAN 1 MIN. FOR 185 DEGREE MOTION.

   F. THETA FREE MOTION ....
      CRITERIA: 15 LBS [6.8Kg] MAX. EACH DIRECTION

G. ARM SAG...............................
   CRITERIA: SHALL NOT EXCEED .060 [1.52] ALONG
             THE LENGTH OF THE ARM

2. ALL BOLTS, NUTS, SCREWS TORQUED TO SPEC.....
3. SAFETY BRAKE FUNCTIONAL......................
4. SAFETY COVERS INSTALLED.....................
5. POWER CORD LOCATION CORRECT.................
6. ALL LOCKING KNOBS ARE IN PLACE/INSTALLED AND SECURE.........
7. GROUND CABLE LOCATION IS CORRECT AND FREE OF PAINT PER SPEC
8. PAINT COLOR MATCHES TERADYNE PAINT CHIP NO.003 AND 009
9. LIMIT SWITCHES ARE FUNCTIONAL................
10. ALL LOCKING MECHANISMS LOCK..................
11. INSTRUCTION MANUAL IS INCLUDED..............
12. THERE ARE NO BURRS, CHIPS, CRACKS, SCRATCHES, PITS, NODULES OR OTHER
    IMPERFECTIONS.........
13. IDENTIFICATION LABELS AND WEIGHT DISTRIBUTION LABEL ARE INCLUDED AND
    IN CORRECT LOCATION...
14. ALL GROUNDING HARDWARE IS STAINLESS STEEL....
15. ELECTRICAL WIRING IS ROUTED CORRECTLY........
16. GOOD GENERAL WORKMANSHIP AND CLEANLINESS.....
17. ALL OPERATOR SAFETY LABELS ARE VISIBLE AND CORRECT LOCATION

Universal manipulator specification

18. ASSY TRAVELER CHECK LIST ON FILE.............

25.0- Listing of peripherals of which to dock and Teradyne location files
  25.1- Probers (Wafer test)

Mfgr	Model	Teradyne assigned file
Electroglas	2001	396-429-00
"	2010	" " -01
"	3001	" " -02 (*)
"	4060	" " -06
"	4080	" " -07 ✓
"	4080 PPC	" " -11 ✓ PPC= probe card changer
"	4085	" " -09
KLA	1007	" " -03
"	1200	" " -04
"	1220	" " -05 ✓
TEL	80S*	" " -09 ⎤ SAME
"	80W**	" " -10 ✓ ⎦
TSK	APM-90	395-448-00

 * Same as KLA 1200
 ** Same as KLA 1220

25.2- Handlers (Final package test)

Mfgrs	Model	Teradyne assigned file
Aseco		396-430-
Daymarc		" " -
Delta-flex		" " -00 ✓
Delta-flex	Dual	" " -01
JLSI	8090	" " - ✓
MCT		" " -
Symtek	VP 5000	" " -03 ✓
"	MP 408	" " -04
Synax		" " -
Mirea		" " -
Sony		" " -

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Universal manipulator specification

26.0- Glossary

Cable bundle---- Electrical wires connecting from the mainframe to the test head.
This bundle is large (approx 9" [228.6] dia) and heavy which will
need support at some point(s) between the mainframe and test head.
Cable bundle size may vary depending on tet head configuration.

Handlers------- Peripherial equipment which present devices to the test head for
"Final Package Test". Handlers are usually large (bulky) pieces of
equipment that get rolled up to the test head. Many shapes and sizes
require various test head positions/angles to achieve docking.

Infinite Plane-- An imaginary plane (that exists parallel to the DUT board) in all
directions for a given distance.

Probers-------- Peripherial equipment that presents wafers to the test head for
"Pre-package Test". Probers are large heavy pieces of equipment that
are generally stationary with the test head position overhead,
DUT down when docked.

Open Issues;

A- Para 5.11-
The subject of accuracy for the up-down motion on initial set-ups and repeat
dockings is of concern. Is there need to encode the travel of the up down
motion and to what resolution is required.

B- ICD has recieved customer requests to dis-able or lock up the free play that
is built into the twist motion once the initial set-up is complete. It is
believed that this takes out any operator subjectivity.

C- ICD has requested that the tumble motion control be centrally located or at
least be interchangable from one side to the other.

D- Section 8.2 location tolerance to be determined.

Appendix B: Project Schedules

B.1 Introduction

This appendix contains the project schedules that were created during the Universal Manipulator project. Section B.2 contains the Gantt chart for the initial schedule that was developed by Richard Slocum and Alex Slocum. Section B.2 contains the PERT chart corresponding to the Gantt chart in Section B.2. Section B.3 contains the GANTT chart for the beta redesign schedule, and Section B.4 contains the PERT chart corresponding to the Gantt chart in Section B.3. The beta redesign schedule was created by Carsten Hochmuth, Sepehr Kiani, and Ryan Vallance on April 13, 1995, after the discovery of the collision problem with the alpha design.

B.2 Initial Project Schedule, Gantt Chart

Initial Project Schedule

ID	Task Name	Duration	Start	Finish
1	Develop modular design components; report	8d	6/1/94	6/8/94
2	Design Review at Teradyne/Boston	1d	6/28/94	6/28/94
3	Present recommended Conceptual Design	1d	7/18/94	7/18/94
4	Teradyne Inform Aesop of design approval	5d	7/19/94	7/23/94
5	Phase 2: Conceptual Design Refinement	37d	7/23/94	8/28/94
6	Begin Conceptual Design Refinement	0d	7/23/94	7/23/94
7	Eng. Analysis: Bearing/ Struct. Loads	10d	7/24/94	8/2/94
8	Design Mechanical Interface to Exist Machine	8d	7/24/94	7/31/94
9	Develop Variational Solid Model	3d	7/24/94	7/26/94
10	Human Interface Design	5d	7/25/94	7/29/94
11	MTO and Cost Estimate	4d	7/25/94	7/28/94
12	Check manipulator motions against desired	4d	7/27/94	7/30/94
13	Final Aesop Design Review	3d	8/6/94	8/8/94
14	Revise Project Plan	1d	8/11/94	8/11/94
15	Build Mock-Up	5d	8/11/94	8/15/94
16	Design Review at Teradyne	1d	8/22/94	8/22/94
17	Teradyne Review/Decision Cycle	7d	8/23/94	8/29/94
18	Phase 3: Detail Design	87d	8/28/94	11/22/94
19	Begi Detailed Design	0d	8/29/94	8/29/94
20	Conceptual Design Refinement Complete	0d	8/29/94	8/29/94
21	Detailed Human Interface Design	2d	8/30/94	8/31/94
22	Engineering Calculation Check	10d	8/30/94	9/8/94

Initial Project Schedule

ID	Task Name	Duration	Start	Finish
23	Electronic System Design	2d	8/30/94	8/31/94
24	Create Detail Design Drawings	30d	8/30/94	9/28/94
25	Vendor Identification	3d	9/3/94	9/5/94
26	Manufacturing Pricing	6d	9/12/94	9/17/94
27	Final Design Review and Revisions	7d	12/19/94	12/25/94
28	Detailed Design Complete	0d	12/28/94	12/28/94
29	Phase 4: Prototype Construction	101d	12/28/94	4/7/95
30	Begin Prototype Construction	0d	12/28/94	12/28/94
31	Issue Purchase Orders	10d	12/29/94	1/7/95
32	Shipping time for parts	40d	2/3/95	3/14/95
33	Begin Prototype Assembly	0d	3/30/95	3/30/95
34	Phase 4a: Assemble Prototype	35d	3/30/95	5/3/95
35	Mechanical	7d	3/31/95	4/6/95
36	Electronics	7d	4/11/95	4/17/95
37	Functional Check Out	7d	4/20/95	4/26/95
38	Start-Up and Initial Shake-Down	14d	5/1/95	5/14/95
39	Protypte Assembly Complete	0d	5/18/95	5/18/95

Initial Project Schedule

Jun 26, '94   Jul 3, '94   Jul 10, '94   Jul 17, '94   Jul 24, '94

7/23

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Initial Project Schedule

19, '94			Jun 26, '94							Jul 3, '94							Jul 10, '94							Jul 17, '94							Jul 24, '94							Ju
W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T

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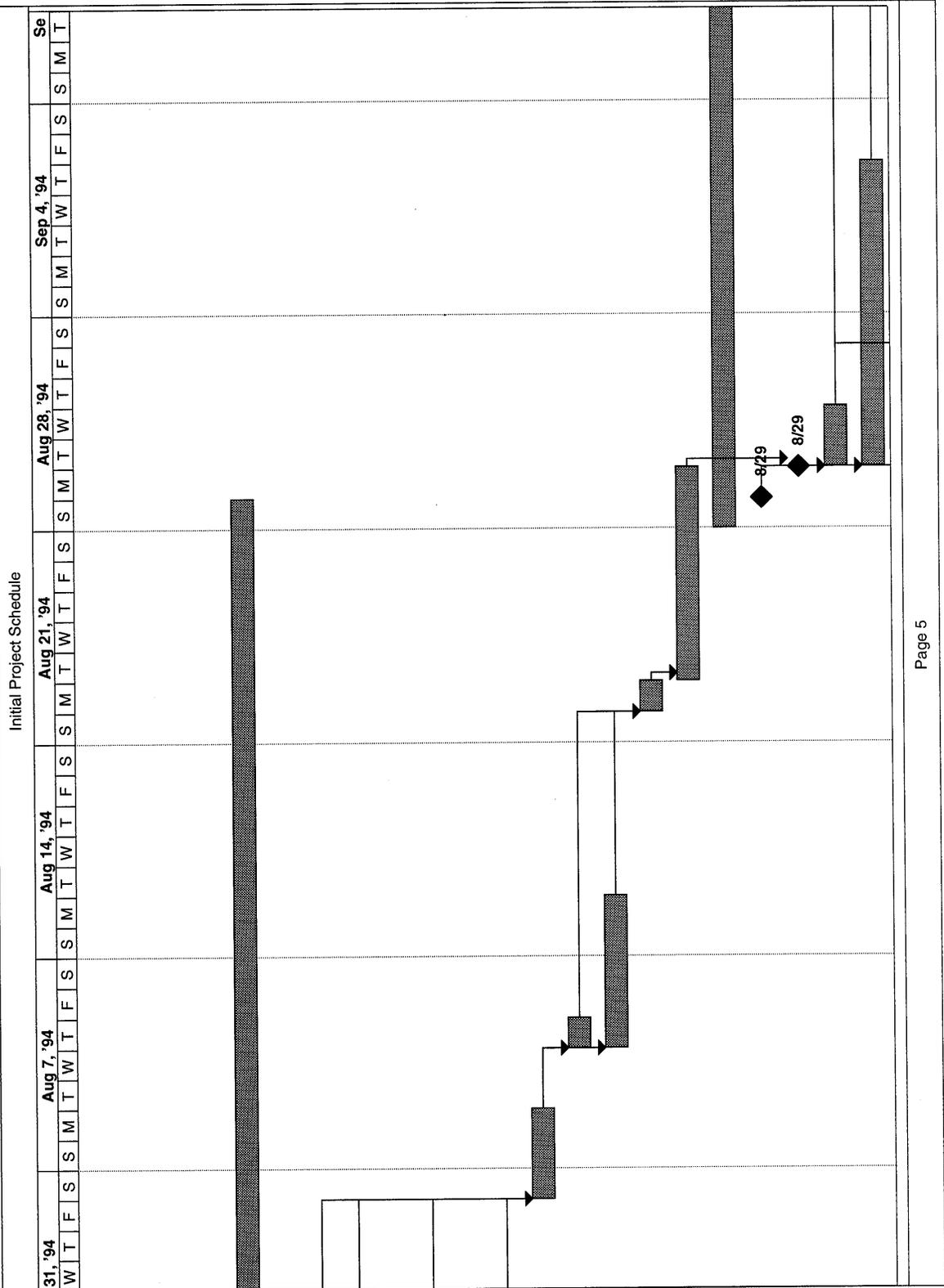
Initial Project Schedule

Initial Project Schedule

31, '94 | Aug 7, '94 | Aug 14, '94 | Aug 21, '94 | Aug 28, '94 | Sep 4, '94 | Se

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Initial Project Schedule

11, '94			Sep 18, '94							Sep 25, '94							Oct 2, '94							Oct 9, '94							Oct 16, '94							Oc	
W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	M	T

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Initial Project Schedule

| 11, '94 | Sep 18, '94 | Sep 25, '94 | Oct 2, '94 | Oct 9, '94 | Oct 16, '94 | Oc |
| W T F S | S M T W T F S | S M T W T F S | S M T W T F S | S M T W T F S | S M T W T F S | S M T |

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Initial Project Schedule

23, '94			Oct 30, '94							Nov 6, '94							Nov 13, '94							Nov 20, '94							Nov 27, '94							De
W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	M	T

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Initial Project Schedule

23, '94			Oct 30, '94							Nov 6, '94							Nov 13, '94							Nov 20, '94							Nov 27, '94							De
W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T

Initial Project Schedule

	4, '94				Dec 11, '94							Dec 18, '94							Dec 25, '94							Jan 1, '95							Jan 8, '95							Ja	
W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	

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Initial Project Schedule

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Initial Project Schedule

15, '95			Jan 22, '95							Jan 29, '95							Feb 5, '95							Feb 12, '95							Feb 19, '95							Fe	
W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	M	T

Initial Project Schedule

15, '95				Jan 22, '95						Jan 29, '95						Feb 5, '95						Feb 12, '95						Feb 19, '95						Fe
W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T

Initial Project Schedule

	26, '95			Mar 5, '95							Mar 12, '95							Mar 19, '95							Mar 26, '95							Apr 2, '95						A
W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	M	T

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Mar 5, '95   Mar 12, '95   Mar 19, '95   Mar 26, '95   Apr 2, '95

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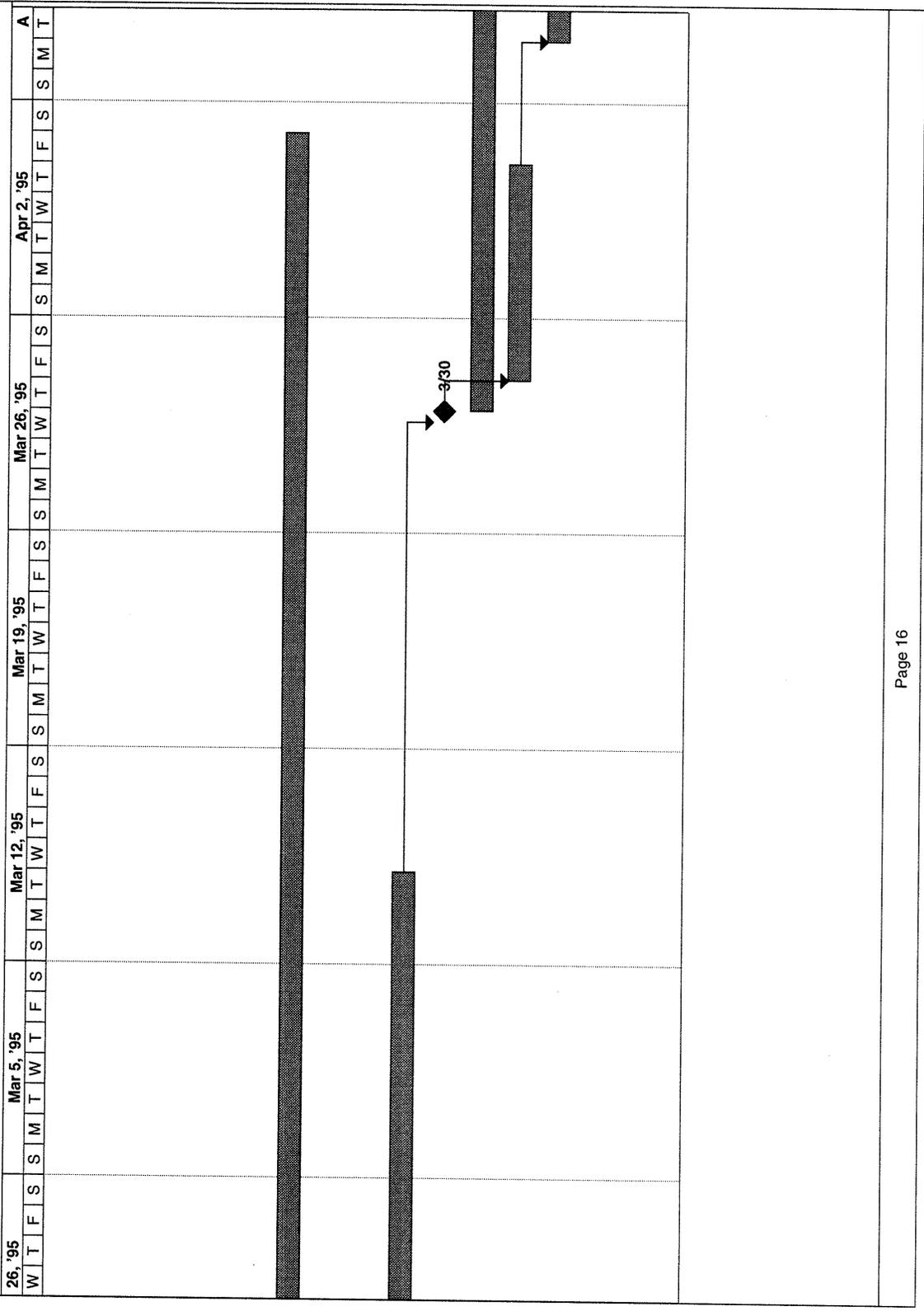
Initial Project Schedule

	r 9, '95			Apr 16, '95						Apr 23, '95						Apr 30, '95						May 7, '95						May 14, '95						Ma
W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T

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Initial Project Schedule

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Initial Project Schedule
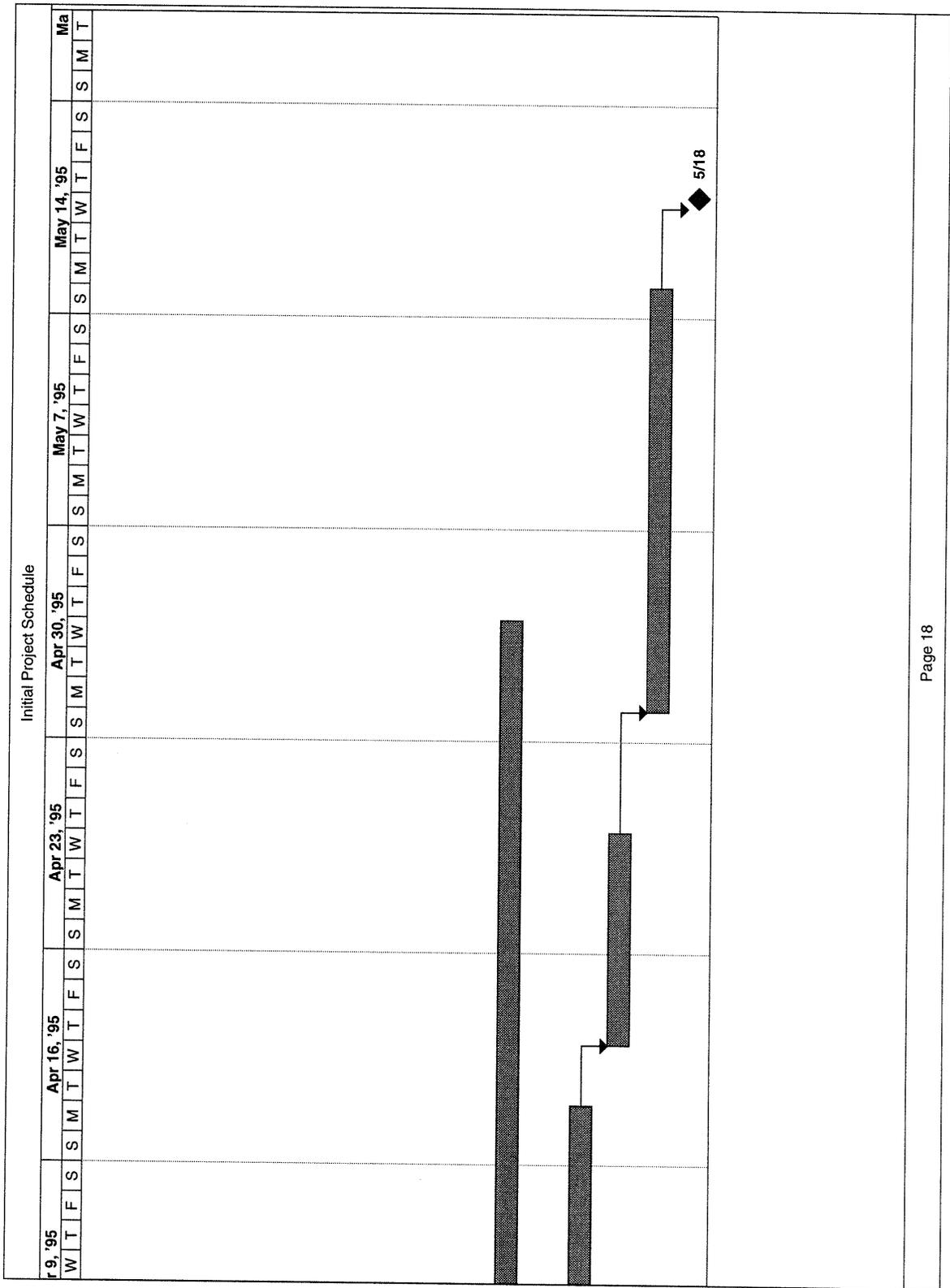
Task	Summary	Rolled Up Progress
Progress	Rolled Up Task	
Milestone	Rolled Up Milestone	

Project: Initial Project Schedule -- Made by
Date: 4/19/96

B.3 Initial Project Schedule, PERT Chart

Develop modular design components; report		
1	8d	
6/1/94		6/8/94

Design Review at Teradyne/Boston		
2	1d	
6/28/94		6/28/94

Present recommended Conceptual Design		
3	1d	
7/18/94		7/18/94

Teradyne Inform Aesop of design approval		
4	5d	
7/19/94		7/23/94

Phase 2: Conceptual Design Refinement		
5	37d	
7/23/94		8/28/94

Begin Conceptual Design Refinement		
6	0d	
7/23/94		7/23/94

Human Interface Desig		
10	5d	
7/25/94		7/29/94

MTO and Cost Estimat		
11	4d	
7/25/94		7/28/94

Eng. Analysis: Bearing Struct. Loads		
7	10d	
7/24/94		8/2/94

Develop Variational So Model		
9	3d	
7/24/94		7/26/94

Design Mechanical Interface to Exist Mach		
8	8d	
7/24/94		7/31/94

Initial Project Schedule, PERT Chart

Design Review at Teradyne		
16	1d	
8/22/94		8/22/94

Revise Project Plan		
14	1d	
8/11/94		8/11/94

Build Mock-Up		
15	5d	
8/11/94		8/15/94

Final Aesop Design Review		
13	3d	
8/6/94		8/8/94

Check manipulator motions against desired		
12	4d	
7/27/94		7/30/94

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Phase 3: Detail Design		
18	87d	11/22/94
8/28/94		

Begi Detailed Design		
19	0d	8/29/94
8/29/94		

Detailed Hun Design		
21		8/30/94

Engineering Cal Check		
22	10	9/8
8/30/94		

Electronic System [		
23	2d	8/31/9
8/30/94		

Create Detail Design Drawings		
24	30d	9/28/94
8/30/94		

Teradyne Review/Decision Cycle		
17	7d	8/29/94
8/23/94		

Conceptual Design Refinement Complete		
20	0d	8/29/94
8/29/94		

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Initial Project Schedule, PERT Chart

Phase 4: Prototype Construction
| 29 | 101d | 4/7/95 |
| 12/28/94 | | |

Begin Prototype Construction
| 30 | 0d | 12/28/94 |
| 12/28/94 | | |

Issue
| 31 | | 12/29| |
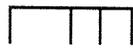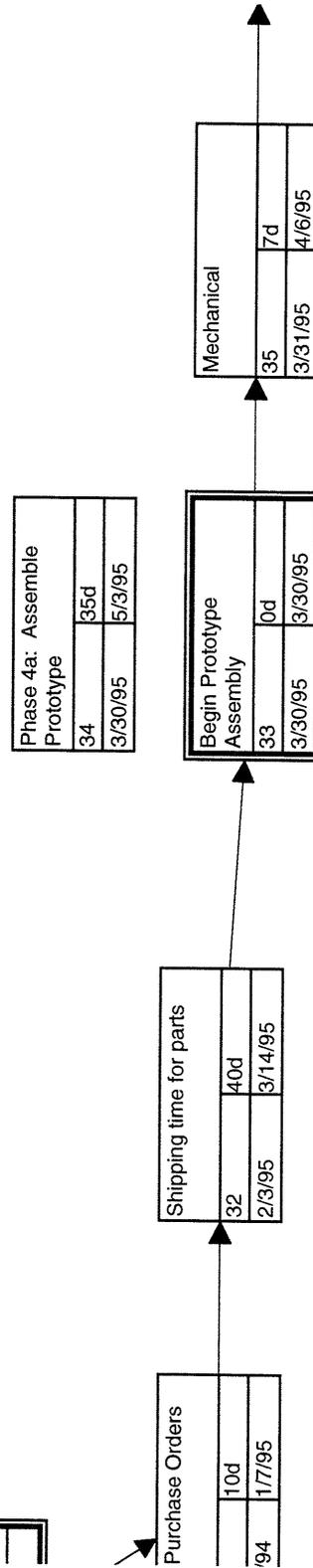
Detailed Design Complete
| 28 | 0d | 12/28/94 |
| 12/28/94 | | |

Vendor Identification
| 25 | 3d | 9/5/94 |
| 9/3/94 | | |

Manufacturing Pricing
| 26 | 6d | 9/17/94 |
| 9/12/94 | | |

Final Design Review and Revisions
| 27 | 7d | 12/25/94 |
| 12/19/94 | | |

nan Interface
| | 2d | 8/31/94 |

culation
| | d | /94 |

Design
| | | 4 |

Purchase Orders			Shipping time for parts			Phase 4a: Assemble Prototype			Mechanical		
10d			32	40d		34	35d			7d	
'94	1/7/95		2/3/95	3/14/95		3/30/95	5/3/95		35		4/6/95
									3/31/95		

Begin Prototype Assembly		
33	0d	
3/30/95	3/30/95	

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Initial Project Schedule, PERT Chart

Electronics		
36	7d	4/17/95
4/11/95		

Functional Check Out		
37	7d	4/26/95
4/20/95		

Start-Up and Initial Shake-Down		
38	14d	5/14/95
5/1/95		

Protypte Assembly Complete		
39	0d	5/18/95
5/18/95		
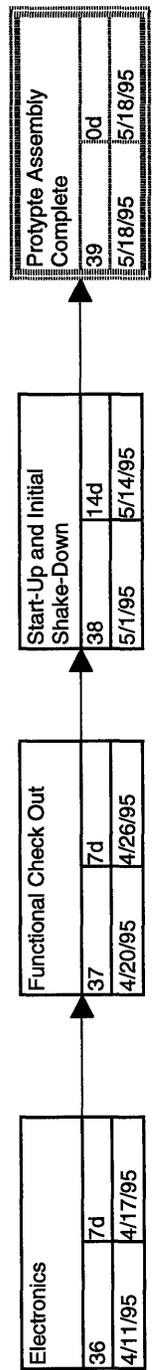
Critical | Milestone | Subproject

Noncritical | Summary | Marked

Name	
ID	Duration
Start	Finish

Project: Initial Project Schedule -- Mac
Date: 4/19/96

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B.4 Beta Redesign Schedule, Gantt Chart

ID	Task Name	Start	Finish
1	Complete Alpha Assembly	4/13/95	4/21/95
2	Teradyne Visit	4/19/95	4/21/95
3	Alpha Prototype Completed	4/21/95	4/21/95
4	Layout Design	4/13/95	4/25/95
5	Layout Design Freeze	4/25/95	4/25/95
6	Order Long-lead items	4/27/95	4/28/95
7	Order Short-lead Items	5/22/95	5/23/95
8	Detail Modeling	5/1/95	5/5/95
9	Solid Modeling Completed	5/5/95	5/5/95
10	Motion Studies	5/8/95	5/12/95
11	Assembly Studies	5/8/95	5/12/95
12	Motion and Assembly Studies Completed	5/12/95	5/12/95
13	Detail Drawings	5/13/95	5/16/95
14	MIT Drawing Review	5/17/95	5/18/95
15	Print Final Drawings	5/19/95	5/22/95
16	Vendor Review at MIT	5/23/95	5/24/95
17	Teradyne Visit	5/23/95	5/24/95
18	Beta Drawings Released	5/24/95	5/24/95
19	Prototype Fabrication	5/25/95	6/20/95
20	Assemble Beta Prototype	6/21/95	6/27/95
21	Beta Prototypes Assembled	6/27/95	6/27/95
22	Ship Betas to Teradyne	6/28/95	6/28/95
23	Completed	6/28/95	6/28/95

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Project: Post-Interference Schedule
Date: 4/19/96

Task		Rolled Up Task	
Critical Task		Rolled Up Critical Task	
Progress		Rolled Up Milestone	◇
Milestone	◆	Rolled Up Progress	
Summary			

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B.5 Beta Redesign Schedule, PERT Chart

Teradyne Visit		
2	3d	4/21/95
4/19/95		

Complete Alpha Assembly		
1	7d	4/21/95
4/13/95		

Layout Design		
4	9d	4/25/95
4/13/95		

Alpha Prototype Completed		
3	0d	4/21/95
4/21/95		

Layout Design Freeze		
5	0d	4/25/95
4/25/95		

Order Long-lead items		
6	2d	4/28/95
4/27/95		

Detail Modeling		
8	5d	5/5/95
5/1/95		

Solid Modeling Completed		
9	0d	5/5/95
5/5/95		

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Initial Project Schedule for Beta Redesign, PERT Chart

Motion Studies		
10	5d	5/12/95
5/8/95		

Assembly Studies		
11	5d	5/12/95
5/8/95		

Motion and Assembly Studies Completed		
12	0d	5/12/95
5/12/95		

Detail Drawings		
13	4d	5/16/95
5/13/95		

MIT Drawing Review		
14	2d	5/18/95
5/17/95		

Initial Project Schedule for Beta Redesign, PERT Chart

Print Final Drawings		
15	2d	5/22/95
5/19/95		

Vendor Review at MIT		
16	2d	5/24/95
5/23/95		

Teradyne Visit		
17	2d	5/24/95
5/23/95		

Beta Drawings Released		
18	0d	5/24/95
5/24/95		

Prototype Fabrication		
19	20d	6/20/95
5/25/95		

Order Short-lead Items		
7	2d	5/23/95
5/22/95		

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Initial Project Schedule for Beta Redesign, PERT Chart

Assemble Beta Prototype			
20		5d	6/27/95
6/21/95			

Beta Prototypes Assembled		
21	0d	6/27/95
6/27/95		

Ship Betas to Teradyne		
22	1d	6/28/95
6/28/95		

Completed		
23	0d	
6/28/95	6/28/95	

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Initial Project Schedule for Beta Redesign, PERT Chart

Name		
ID	Duration	
Start	Finish	

| Critical | Milestone | Subproject |

| Noncritical | Summary | Marked |

Project: Post-Interference Schedule
Date: 4/19/96