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Design Methodology for Automated Construction Machines

Final Report for the period

1/1/87-1/1/88

by:

Alexander H. Slocum
George Macomber Career Development
Assistant Professor of Civil Engineering

and

Laura A. Demsetz, David H. Levy, Bruce Schena
Graduate Research Assistants

December 11, 1987

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Department of Civil Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts

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ABSTRACT

Poor productivity in the construction industry has led researchers to consider the automation of various construction tasks. Automated installation of partition wall framework and cement block walls is addressed here. The wall building task and constraints imposed on machine design are discussed along with the design of a pair of machines which automate framework installation. Preliminary analysis and testing indicate that these machines provide a cost effective method of constructing partition walls. The cement block wall building process also lends itself to automation, and the design of a machine to accomplish this task is also discussed. The principal common denominator among the majority of construction automation projects studied was found to be "how to optimize automated surveying systems to minimize mechanical complexity".

KEY WORDS: Automation, Construction, Design, Machines, Surveying, Robots

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1. INTRODUCTION

This final report describes results of research performed to develop a design methodology for automating construction processes. Two robots, the Wallbots and Blockbot, were designed and laboratory prototypes built to help guide the development of the methodology. Based on their development, an assessment is made on common denominator mechanical, electrical, and sensor systems. One of the most critical technologies identified with respect to successful implementation is automating surveying techniques for real time control of construction machinery.

1.1 BACKGROUND

The U.S. construction industry represents roughly 8% of GNP [1]. Yet it has notoriously low productivity (40% lower in 1982 than the average for private industries [2], and decreasing 1.5% annually over the last 10 years [3]). Workers must contend with harsh and often dangerous conditions. As much as half of their work week may be spent idle or performing ineffective labor [4].

This combination of low productivity and difficult working conditions in a large industry has motivated researchers to investigate automation of construction tasks. In Japan, where the major construction firms each have R & D budgets in excess of $10 million [3], prototype machines have been developed for shotcreting, fireproofing, concrete finishing, rebar placement, positioning of structural members, and tunneling [3,5]. U.S. construction firms typically allocate little or no funding for R & D; progress to date in construction automation has primarily been through research projects carried out at educational institutions. At Carnegie Mellon University, machines have been developed to aid in the inspection and cleanup of the Three Mile Island nuclear power plant [6] and to excavate buried pipes [7]. In addition, four general purpose robots for building construction tasks [1] and the automation of sandblasting and concrete formwork cleaning have been considered [8].

A methodology for the efficient automation of construction processes has been proposed by researchers at M.I.T. [9]. It addresses the decomposition of construction processes into specific tasks and the evaluation of current technology to determine whether a particular task should be automated or assigned to construction workers. Cooperation between architects, machine designers, building contractors, and materials suppliers is emphasized, along with the reduction in automated sensing requirements possible through use of information available from previously completed tasks whenever possible and reliance on humans when necessary.

The work described in this report was performed as part of a demonstration of the applicability of this design methodology to a typical building construction process. Characteristics deemed important in selecting the process included the following: complexity (the process should be complex enough to divide into tasks, yet reasonable to address in one to two years with limited student manpower), repeatability (the process should require fairly regular placement of materials), independence (automation should be possible without disrupting the traditional building process), and size (the construction and testing of prototype machines should be feasible on a limited budget in restricted laboratory space).

2. Automating Installation of Interior Framework

The installation of non-load bearing partition walls using standard steel stud framing in buildings of post and slab design satisfies the above stated requirements for automation susceptibility. Installation of walls is a fairly repeatable process; observe the regularity in the long hallway shown in Figure 2.1. Preliminary discussions with contractors on site indicated that the individual tasks involved could be automated without much disruption to the building process. And, compared with most construction materials, the members used in partition walls are fairly lightweight -- a 10 foot (3.0 m) section of track or stud weighs under 5 lbs. (22 N), a 1/2" x 4' x 8' (1.3 cm x 1.2 m x 2.4 m) sheet of gypsum wallboard weighs 55 lbs (245 N).

2.1 Wall Installation

The process of installing partition walls can be divided into the following five tasks:

Layout--Working from a drawing, the hallway location is marked, and a line chalked on the floor where the wall is to be placed.

Track installation--Ten foot sections of U-shaped steel track are placed end to end along both the floor and ceiling. Each section is fastened to the floor or ceiling 2" (5 cm) from each end and intermediately at a spacing not exceeding 24" (61 cm) on center using concrete stub nails, shielded screws, or power driven fasteners [10]. Installation of the ceiling track is done by workers on ladders. The track sections must be accurately

Figure 2.1   Typical Hallway

aligned, both along the floor and ceiling and between them, or the finished wall will be wavy or angled.

Stud installation--Steel U-shaped studs positioned vertically in the track complete the support system for the wall. Precut holes provide passage for wires. The studs are spaced either 16" (41 cm) or 24" (61 cm) on center, depending on ceiling height and layers of drywall used [10]. The studs are fastened to the track flange using self-tapping screws or by crimping. Studs are fastened either (1) on one side at the ceiling and the other side at the floor, (2) on one side at the ceiling and the same side at the floor, or (3) on both sides at the ceiling and both sides at the floor. The third method is required for studs adjacent to door frames and partition intersections [10]. Accurate positioning of the studs is necessary to provide attachment locations for the drywall. The on-center spacing of the studs should be accurate to 1/8" (3 mm); the vertical alignment to 1/8" (3 mm) over the length of the stud (8' to 12', 2.4 m to 3.7 m) [11]. Again, ladder work is required for attachments to the ceiling track.

Drywall installation--The gypsum board which forms the wall surface is placed against the frame formed by the track and stud and fastened using steel screws. Each panel of gypsum board is generally 4' (1.2 m) wide and the full height of the hallway. The panels are positioned so that each edge is placed over a stud, and are fastened to each stud that they cover. Screws along each stud are spaced on either 12" (30 cm) or 16" (41 cm) centers [12]. The gypsum board is heavy, bulky, and fragile. Ladder work is again required.

Finishing--After the drywall is fastened, the seams between the panels are filled with taping or all-purpose compound, joint tape is pressed in place, and the excess compound is wiped away. A second coat of compound is applied and sanded if necessary to provide a smooth even plane [12].

Figure 2.1.1 shows a cut-away section of wall. Wall construction using track, stud, and drywall results in a smooth, sturdy wall. Power and data transmission lines may be installed through the studs before the drywall is put in place.

An alternative method of construction uses prefabricated panels. While a detailed comparison of this method with steel stud construction may be desirable in the long run, this project's

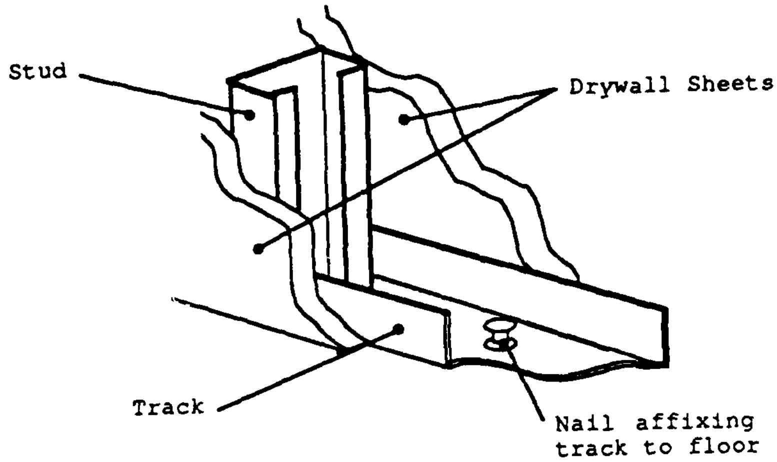

Figure 2.1.1 Cut-away view of wall.

requirement of minimal disruption of the construction process dictates the use of the current method of construction.

A machine designed to perform any of the wall-building tasks discussed above must satisfy constraints on size, weight, and durability dictated by the environment for which it is intended. Specifically, it must be able to operate on walls from 8' to 10' (2.4 m to 3.0 m) high (only a small percentage of sites have hallways 12' (3.7 m) high), yet fit through a standard doorway (36" wide x 80" high, 0.9 m x 2.0 m). In order to be transported between floors, it must fit into a standard construction elevator. For several of the building types in which wall-building machines might be used (hospitals, libraries, schools), concentrated floor loads specified by the Uniform Building Code are as low as 1000 lbs (4.4 kN)[13]; machine weight (including materials) should therefore be under 1000 lbs (4.4 kN). In addition, any machine intended for application on a construction site must be designed to withstand both a dusty environment and unintentional loading that may occur during transportation and set-up. Finally, any degree of automation proposed must hold reasonable promise of competing economically with both union and non-union labor.

2.2 DETERMINING THE BEST DEGREE OF AUTOMATION

There are several degrees to which the wall-building process could be automated. General considerations are presented below, followed by a discussion of issues relevant to each task. A survey of drywall contractors provided some of the information used here [11].

2.2.1 GENERAL CONSIDERATIONS

In many buildings, room structure is very regular. A large percentage of walls could therefore be installed by machines capable of only straight line motion. This greatly simplifies machine design.

Obstacles along the path of the wall complicate automated installation. While several of the contractors surveyed noted that installation of HVAC ducts and/or plumbing may occur before layout and framing installation, others held the opposite to be true. The sensing required to detect these obstacles, and the flexibility necessary to work around them, would increase machine cost and complexity. The machines were therefore designed for use when framing can be installed prior to HVAC ducts and plumbing.

Even when mechanical support systems do not obstruct the path of the wall, it is unreasonable to assume there will always be a clear space in which machines can work. A construction site is a complex, cluttered environment; there will surely be unforseeable obstacles to any machine. Machines will require either elaborate sensing systems or a human operator to prevent their being tripped up by misplaced tools or debris. The presence of a machine operator provides additional advantages. An operator can restock materials as needed and can monitor both machine performance and site conditions, making minor repairs and adjustments as necessary. Each of the machines discussed below were designed under the assumption that an operator would be available.

2.2.2 LAYOUT

Layout requires moving to a particular location within the building as indicated on a drawing and then marking the wall position. In the future, it is possible that buildings may be constructed incorporating bar-coded elements or metallic grids embedded in the floor to facilitate automated location sensing; perhaps then it would be feasible for a machine to move itself to a particular location within a building and lay out a wall. At present, though, the layout task must be left to a human. Locations should, however, be marked in a manner easily detectable by machine.

The method we have chosen uses a laser beam rotating about an axis perpendicular to the wall to produce a vertical plane of light coinciding with desired wall location. This laser unit is available as a standard surveying tool. A photodetector array produces a current proportional to the location at which the laser beam strikes it. Mounted in an appropriate location on a machine, it can be used to detect the intended wall location.

2.2.3 TRACK INSTALLATION

Track is currently supplied to the site in bundles of ten 10 ft. (3.0 m) long, U-shaped sections with every other section inverted. Two different degrees of automation were considered for track installation. In the first, the channel-shaped track is both formed (from a continuous roll of flat metal) and installed by the machine. In the second, the machine installs (precut) 10 ft. (3.0 m) sections of track.

Requiring the track installation machine to form the track offers two advantages. First, a minimum space is required for material storage, both on the machine and on route to the site. In addition, the accuracy with which the machine must be positioned along the wall's length is reduced, as it is no longer necessary to butt a piece of track up against the previously installed section There are two main drawbacks to this approach. Equipment currently available for roll forming in a fabrication facility is heavy and expensive (roughly 1000 lbs (4.4 kN) and $10,000 per roll former). While smaller, lighter roll formers could be designed, addressing this problem was not reasonable given the time constraints placed on the project.

Installing precut sections of track is desirable in that currently supplied materials are used and heavy roll forming apparatus is not required on the machine. The disadvantages of this method are the need for better control of the machine's position (to ensure that there is not a large gap between adjacent track sections) and the larger storage space required for materials.

Since the roll forming equipment is prohibitively heavy, it was decided to pursue the second approach and design a machine capable of installing precut sections of track.

2.2.4 Stud Installation

Studs are currently supplied to the site in the same manner as tracks, bundles of ten studs with alternate studs inverted. Again, two levels of automation were considered-- manual *installation* followed by automated fastening, and automated installation and fastening.

Dividing the stud installation task between man and machine was considered because the task split cleanly into types of motions: those easily performed by machine and those more readily performed manually. A human can easily pick up a stud and snap it into place between the flanges of the track. However, ladder work is required to attach the stud at the ceiling. A machine can easily be designed to reach the ceiling, but design of a mechanism to insert the studs seemed difficult. Since studs will remain in place temporarily without being fastened, it would be possible to have a worker insert studs between the track flanges and design a machine to align and fasten them. This would eliminate ladder work while simplifying machine design.

Although this second approach might be viable, the complete automation of the process would not significantly increase design or materials costs. It was therefore decided to investigate the design of a machine to both install and fasten studs.

2.2.5 Drywall Installation and Finishing

Automated drywall installation presents a major material handling problem. Sheets of drywall are shipped to the site in a stack with good sides facing alternate directions for protection. The sheets are large (relative to the space available for a machine) and fragile. Material for 50 ft. (15 m) of wall weighs at least 700 lbs. (3.1 kN),depending on sheet size, making design of a machine that can cover even this distance without restocking difficult. In what seemed to be the most feasible configuration for a drywall installation machine, sheets of drywall are stored upright at a near vertical angle with their 'good sides' facing the same direction. The motions required for the operator to stock this machine are similar to those required by a worker to manually install the drywall. Since the machine would have to be restocked every 50 ft. (15 m), the amount of manual material handling involved would not be significantly different from what is currently required.

It seemed doubtful that a machine would be economical to operate under these conditions, and we have decided not to consider the automated installation of drywall at this time. Since a preliminary study of the feasibility automated joint taping was inconclusive, we chose to focus our initial efforts on automating the installation of the track and stud framework.

2.3 Machines to Install Partition Wall Framework: The Wallbots

The following sections contain descriptions of the two machines we have designed for the installation of partition wall framework, the Trackbot and the Studbot. Each machine carries an air compressor on board; electric power is provided through a cable from a source on site (survey results indicated distance from power on site averaged 125 ft. (38 m) [11]). As noted above, layout must still be done manually. Photodetector arrays mounted on the Trackbot allow it to use the rotating laser for guidance. The laser can be removed following track installation, as the Studbot relies upon the installed track for guidance. Floor plans entered into each machine's database prior to the start of a job indicate door and stud locations. Eventually, an algorithm for the generation of an optimal installation sequence could be incorporated.

2.3.1 Machine Base

Although each of the machines is designed to perform a distinctly different function, both the Trackbot and Studbot must be capable of powered motion and steering. Since the machines are approximately the same size and weight and have similar positioning requirements, a simple chassis which can be used in both machines was designed. The chassis is 4 ft. long, 2-1/2 ft. wide and 10 in. high (1.2 m x 76 cm x 25 cm). The frame is supported on four solid rubber wheels; the front wheels are steerable. Distance travelled is measured by an encoder attached to the rear wheel. Power is provided by a DC gearmotor through a chain drive. A removable handle can be used to tow the machine around the site.

2.3.2 THE TRACKBOT

The Trackbot, shown in Figures 2.3.1 and 2.3.2, positions and fastens the track on both floor and ceiling. The machine consists of two independent track positioning systems, an upper for the ceiling track and a lower for the floor track. Track sections are loaded in bundles as received from the manufacturer. The track storage bins hold material for 100 ft. (30 m) of wall. The center of the bin is located 23 in. (58 cm) in front of the vehicle center (see Figure 2.3.3) so vehicle motion along the hallway is required in one direction only.

Each positioning system consists of two 2 degree-of-freedom arms (one at the front of the vehicle, one at the rear) and an orientation mechanism. The arms move horizontally (toward the wall) and vertically. Each supports a vacuum gripper and a pneumatic nail gun. The photodetector arrays are mounted just above the vacuum gripper to provide end-point feedback. The orientation mechanism consists of a piston actuated gripper to locate each track section precisely with respect to the vehicle, and an actuator to flip every other section piece of track 180^{o} (so that the flanges point away from the surface on which it is to be installed).

To install a track section, the arms first pick the top piece out of the bin and move it to the orientation mechanism. Here, the track is repositioned and, if necessary, flipped. The positioning arms again pick up the track section, raise/lower it close to the floor/ceiling, and position it horizontally based on feedback from the photodiode detectors. The nail guns then fire, firmly anchoring the track section into place. The Trackbot moves forward, making two additional stops for nailing before placing the next section of track. Since the Studbot relies on the track flange for positioning, doorways must be cut out manually after the studs have been installed. However, nails that fall within doorways are omitted wherever possible.

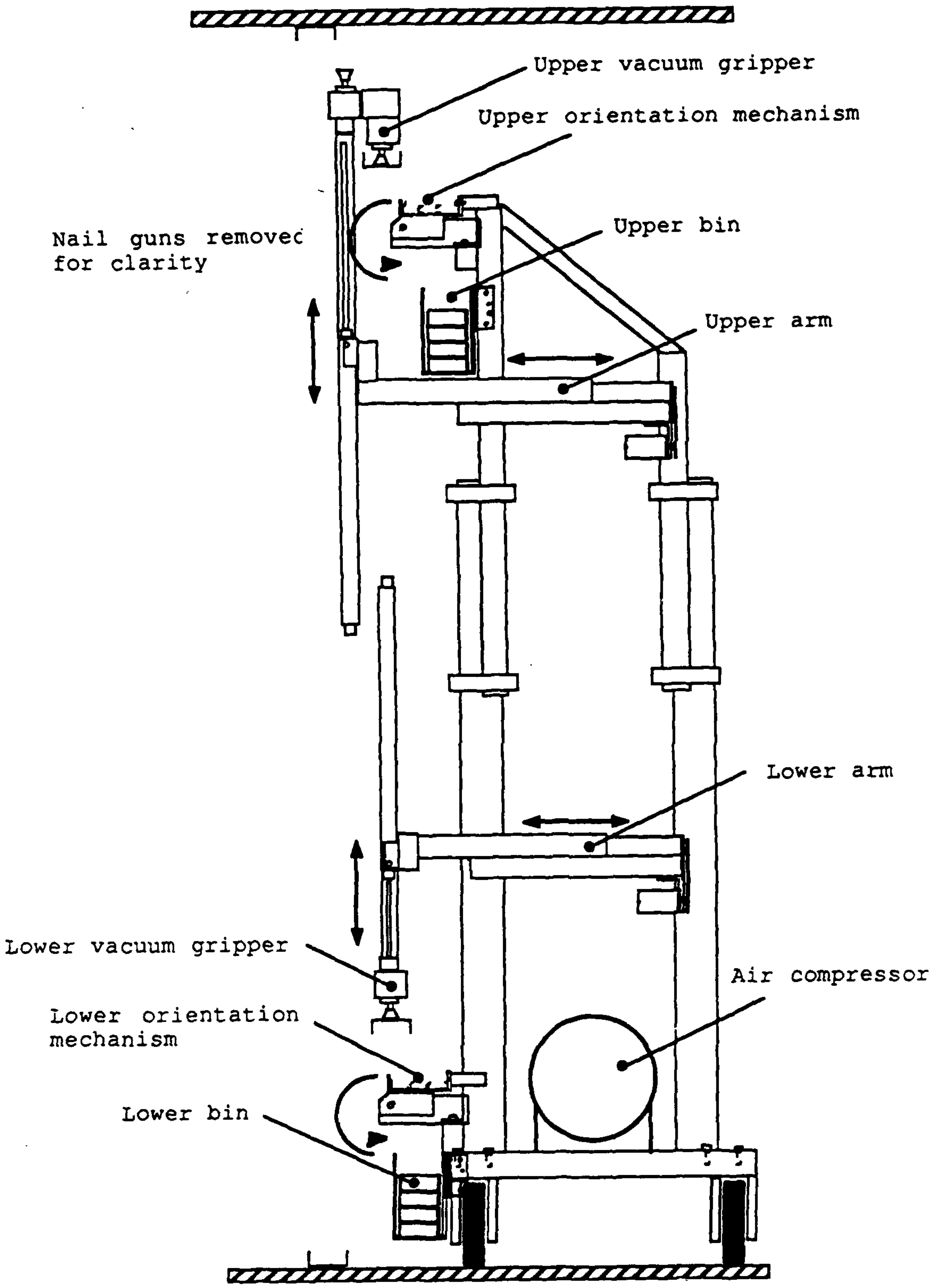

Figure 2.3.1 Trackbot schematic rear view

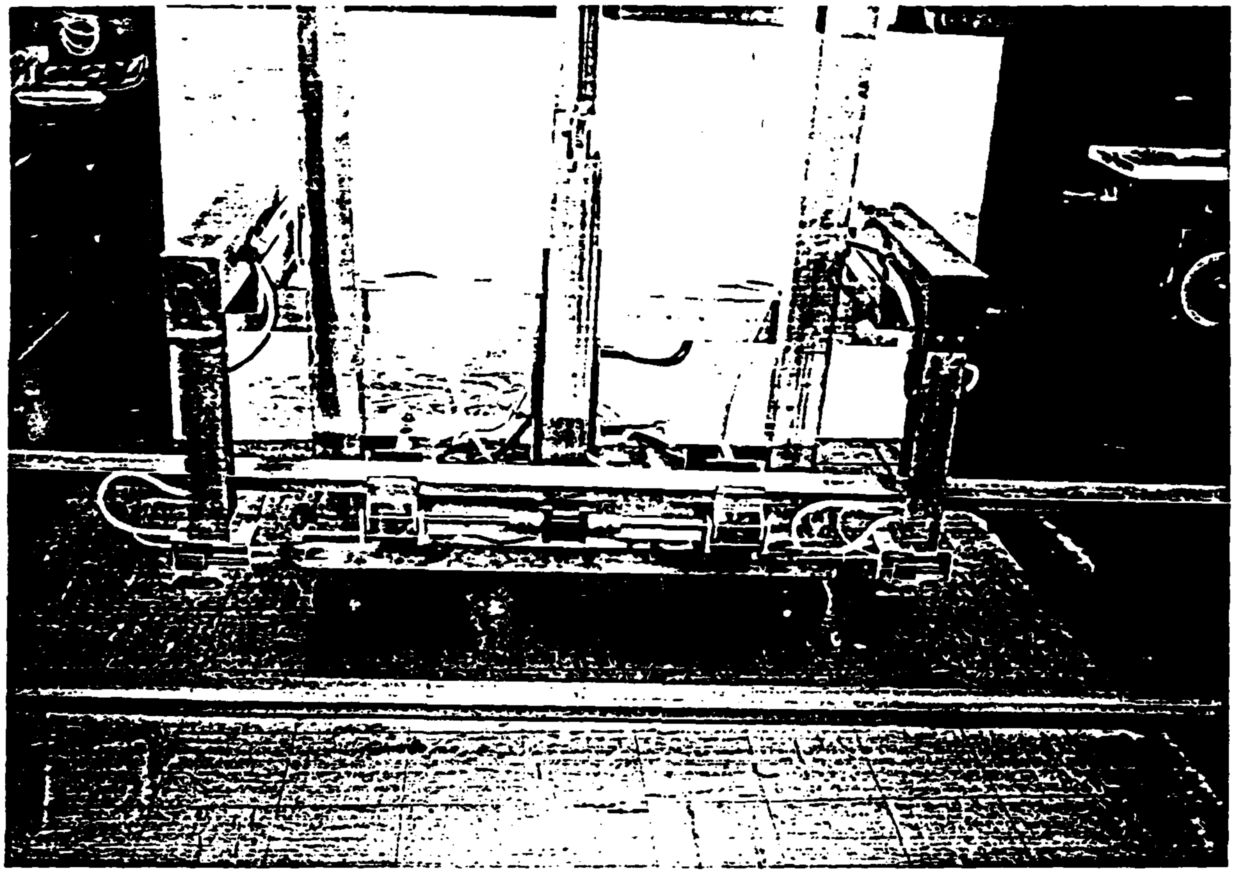

Figure 2.3.2 Trackbot under Construction

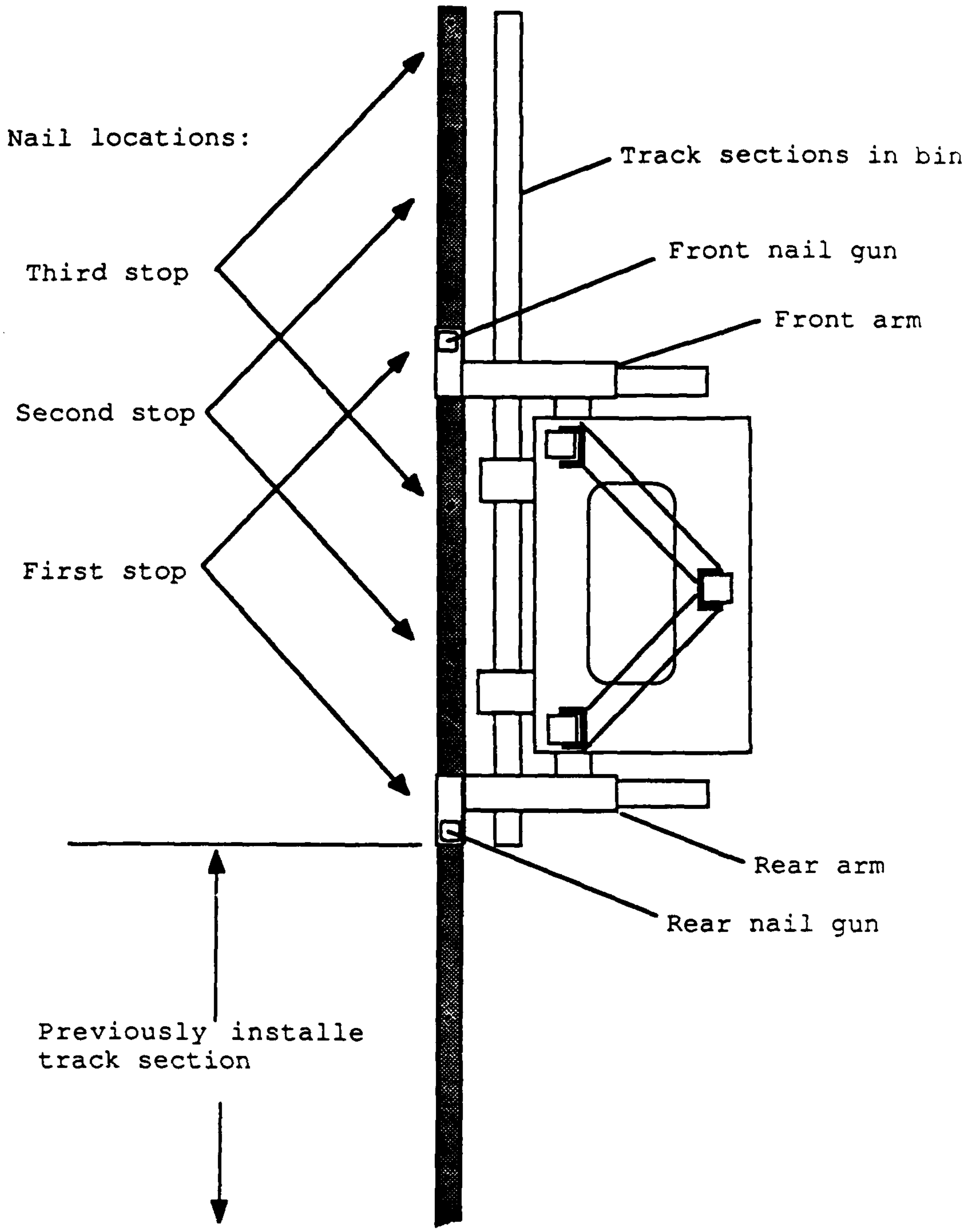

Figure 2.3.3. Trackbot Schematic top view

Horizontal motion of the arms is accomplished using a stepping motor and ball screw, permitting precise location of the track based on the output of the photodiode sensors. The photodiode output is also used to update vehicle steering. Since all vertical stops that must be made by the positioning arms are fixed with respect to the vehicle, vertical motion is accomplished using a pneumatic cylinder with reed switches indicating stop points. The cylinder also acts as a shock absorber, reducing the magnitude of the nail gun reaction force transmitted to the horizontal motion assembly.

2.3.3 THE STUDBOT

The Studbot, shown in Figures 2.3.4 and 2.3.5, can position and fasten up to 100 studs without reloading. The vehicle path guidance system measures distance from the track flange to the vehicle. The studs are stored horizontally, again loaded in bundles as received from the manufacturer. The vehicle moves forward along the track until it reaches a position where a stud is to be installed, as indicated by the floor plan database. A pair of material handling arms pick the top stud out of the bin and establish its orientation. If the stud is upside-down, it is delivered to a second arm which flips it over before delivering it to the installation arm.

Because of this material manipulation and the asymmetry inherent in a stack of studs, a large amount of misalignment may be expected prior to delivering the stud to the installation arm. Therefore, this arm must be capable of accepting and realigning misaligned studs. This problem was solved using a cam gripper (see Figure 2.3.6) which operates internal to the stud flanges. Two such mechanisms are mounted on the installation arm. The material handling arms settle the stud onto the installation arm, partially realigning it. Then, as the cams rotate out to grip the stud, they center the stud on the installation arm.

The installation arm flips the (still horizontal) stud so the web of the channel faces the track, rotates it near vertical, moves it between the upper and lower tracks, and rotates the stud to a vertical position. The piston which operates perpendicular to the track then becomes passive, and hence compliant as the stud is twisted left or right into its final position between the track flanges.

The installation arm has a long beam which runs the length of the stud and provides the support necessary to twist the torsionally flexible studs into the track flanges. The direction of this twist is

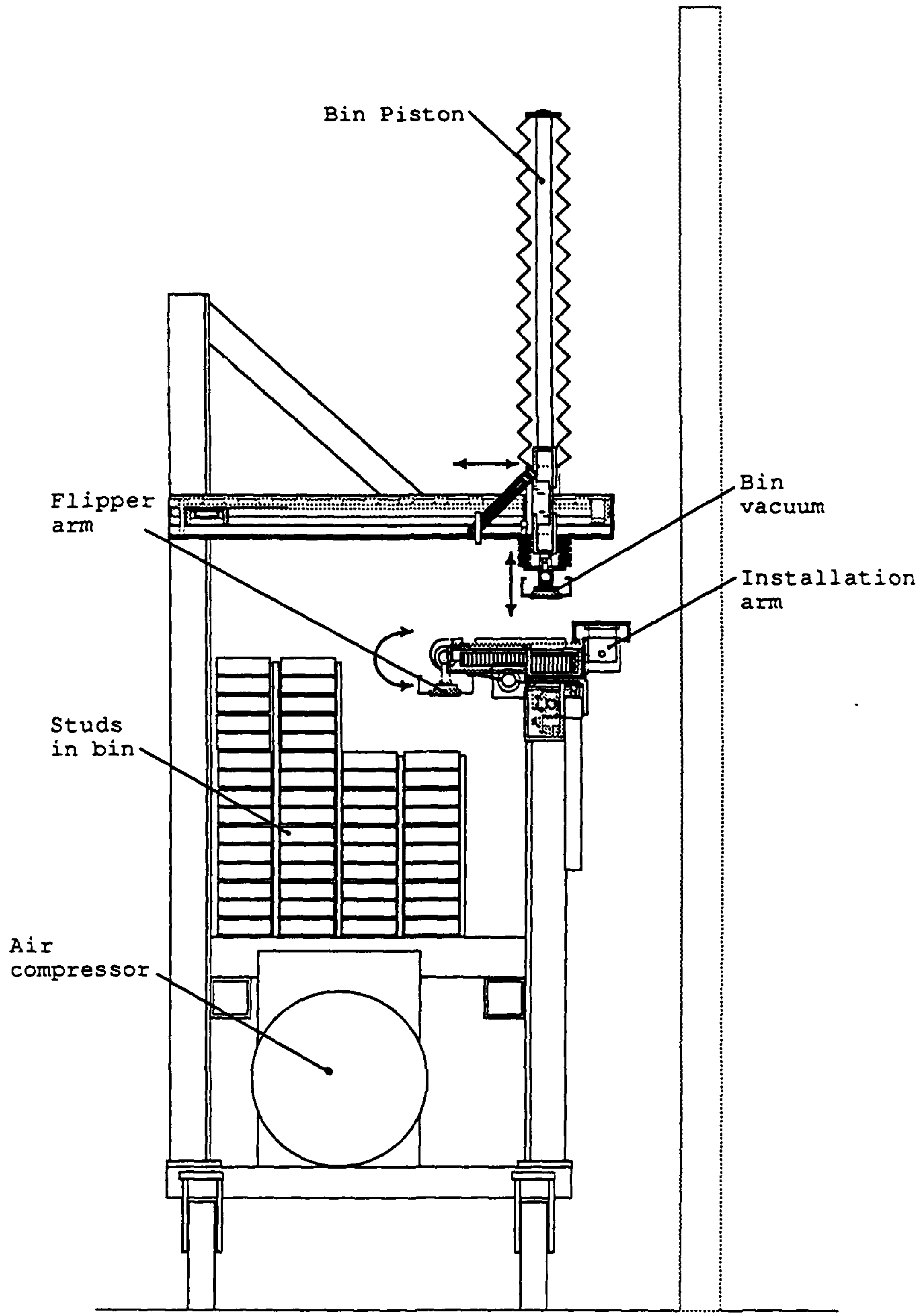

Figure 2.3.4. Studbot schematic rear view.

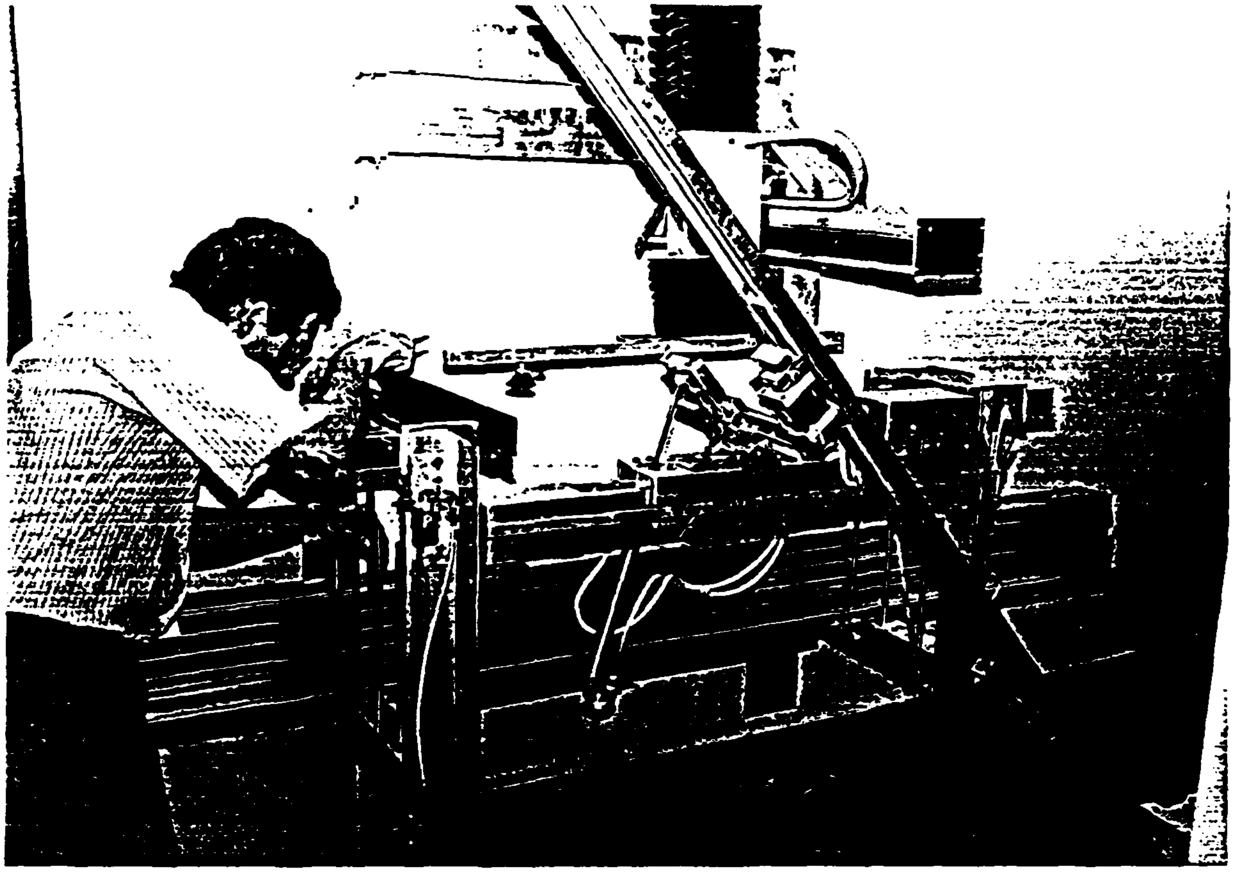

Figure 2.3.5 Studbot during preliminary tests

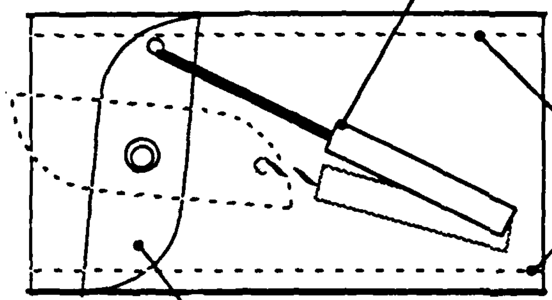

Figure 2.3.6. Studbot cam gripper.

determined by the desired final orientation of the stud as detailed in the floor plan database. Another purpose of this arm's long beam is to support the two crimping tools, one at the ceiling, the other at the floor. Once the stud is in place, the crimping tools fasten both flanges of the stud to the track (fastening configuration 3 described above). Screwing studs into place is a much more common method of attachment, but reliable automated screw feeders are prohibitivly priced (approximately $10,000). Commercially available manual crimpers were not easily automated, so a new mechanism was designed.

2.3.4 Trackbot and Studbot Control

For prototype development, each machine is controlled by a personal computer equipped with digital and analog I/O cards. Once a suitable control strategy is developed, a machine specific EPROM will be programmed and incorporated into a hardened controller which will include analog and digital I/O and a communications interface. The communications interface will be used by the machine operator on site to enter floor plans for the current job.

2.4 Evaluation

While a final evaluation cannot be made at this time, the following preliminary economic analysis indicates the machines' potential value.

This analysis considers only the savings due to reduced construction costs on a per foot basis; additional benefits due to improve quality and reduced construction time are not included. Labor costs for manual installation of the track and stud framework are $1.80 per linear foot (30 cm) for 10' (3 m) high wall with 4" (10 cm) studs placed 24" (61 cm) on center [14]. Assumptions used in estimating the cost using the Trackbot and Studbot are:

- The total cost to build the two machines is $40,000; the two machines sell for $80,000.
- The combined maintenance cost (parts only) for the machines is $20,000 per year (considered conservative).
- Each machine operates at a speed of 2 ft./min. (61 cm/min.); design speed is 10 ft./min. (3 m/min.).
- Each machine operates only 16 hours per week; the remainder of the week is spent in transport and set up
- Each machine requires 40 man-hours per week (for operation and maintenance), at $20/hour.

These assumptions result in a maintenance cost of $0.20 per linear foot (30 cm), and a labor cost of $0.83 per linear foot (30 cm). The total cost using the machines is thus $1.03 per linear foot (30 cm) of wall. Operating at two feet per minute (61 cm/min.), 16 hours per week, the machines and crew of two operators are capable of installing approximately 4 times the length of hallway installed by a two man crew working a 40 hour week.

Use of the Trackbot and Studbot thus results in a savings of $0.77 per linear foot. If used 16 hours per week, the machines can install about 100,000 feet (30 km) of wall per year, resulting in a payback time of approximately 15 months, with savings of $77,000 per year over the remainder of the machines' lives. Even with the conservative assumptions used, the resulting rate of return on investment is on the order of 37% per year.

The Trackbot and Studbot are nearly complete, with testing and debugging scheduled for Summer 1988.

3. BLOCKBOT: A MACHINE FOR AUTOMATED CONSTRUCTION OF CEMENT BLOCK WALLS[1]

This section discusses development of a robot which is capable of dry-stacking precision concrete blocks. The majority of this chapter involves detailed discussions on how to design a large machine down to the component level.

Although many other methods exist for building walls of moderate strength, the block and mortar wall is the most common. According to the National Concrete Masonry Association (NCMA), over 2.5 billion square feet of wall are built each year at a total cost of 8.4 billion dollars. As with virtually all assembly tasks, a significant percentage of this cost is in direct labor; in this case nearly 60%.[2]

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1 This section is a condensation of a Master of Science Thesis done by Bruce Schena, "Design Methodology for Large Work Volume Robotic Manipulators: Theory and Application" Master of Science thesis, Department of Mech. Eng. MIT, June 1987. Bruce was one of Prof. Slocum's graduate students.

2 Kevin Callahan, Vice-President of Technical Services, National Concrete Masonry Association, Herndon, Virginia, October 1986.

The construction of concrete block walls is slow, strenuous, repetitive, and a potentially dangerous task for human workers. These characteristics make it an excellent candidate for automation. In order to be economically feasible, however, this or any assembly operation must increase productivity or improve the quality of the final product. In this case, it is doubtful that any increase in the quality of the finished wall could offset initial capital investment of an automated system. Therefore, for such an application to be cost-effective, significant increases in productivity are required.

Large and moderately sized companies could potentially save a significant percentage of labor costs by utilizing automated assembly techniques to aid in the construction of block walls. These savings could also result in decreased construction time and improved quality. It is felt that the most practical application of this technology is in building long, relatively low, continuous sections of wall. Warehouse, factory building, and sound abatement walls along urban highways are good examples of this type of construction.

3.1 Wall Building Methods

It would be very difficult to achieve the productivity levels necessary to offset the investment in automated block laying machinery using conventional block-and-mortar construction techniques. This is due to the fact that the rate of increase of wall height per day is not generally a function of just the mason's skill level, but rather also of the setting time of the mortar between the courses (rows) of block. If the maximum number of courses-per-day is exceeded, the additional weight can cause compression and subsequent extrusion of the mortar between the lower courses. This may result in a wall which is uneven, out-of-plumb, or unstable to the point of collapse.

Therefore, in order to economically automate block wall construction, it is necessary to develop new technologies which eliminate the physical limit on current construction techniques. Fortunately, two such technologies already exist. The first is a fiberglass-reinforced bonding cement called Surewall® which can be applied to both sides of a block wall in a manner similar to plaster or stucco, as shown in Figure 3.1.1. This fully certified technique, called "surface-bonding", results in a wall with structural properties as good, or better than, a conventionally built wall. The main advantages of this technique are 1) the blocks can be dry-stacked without the use of mortar and 2) the bonding cement can be applied

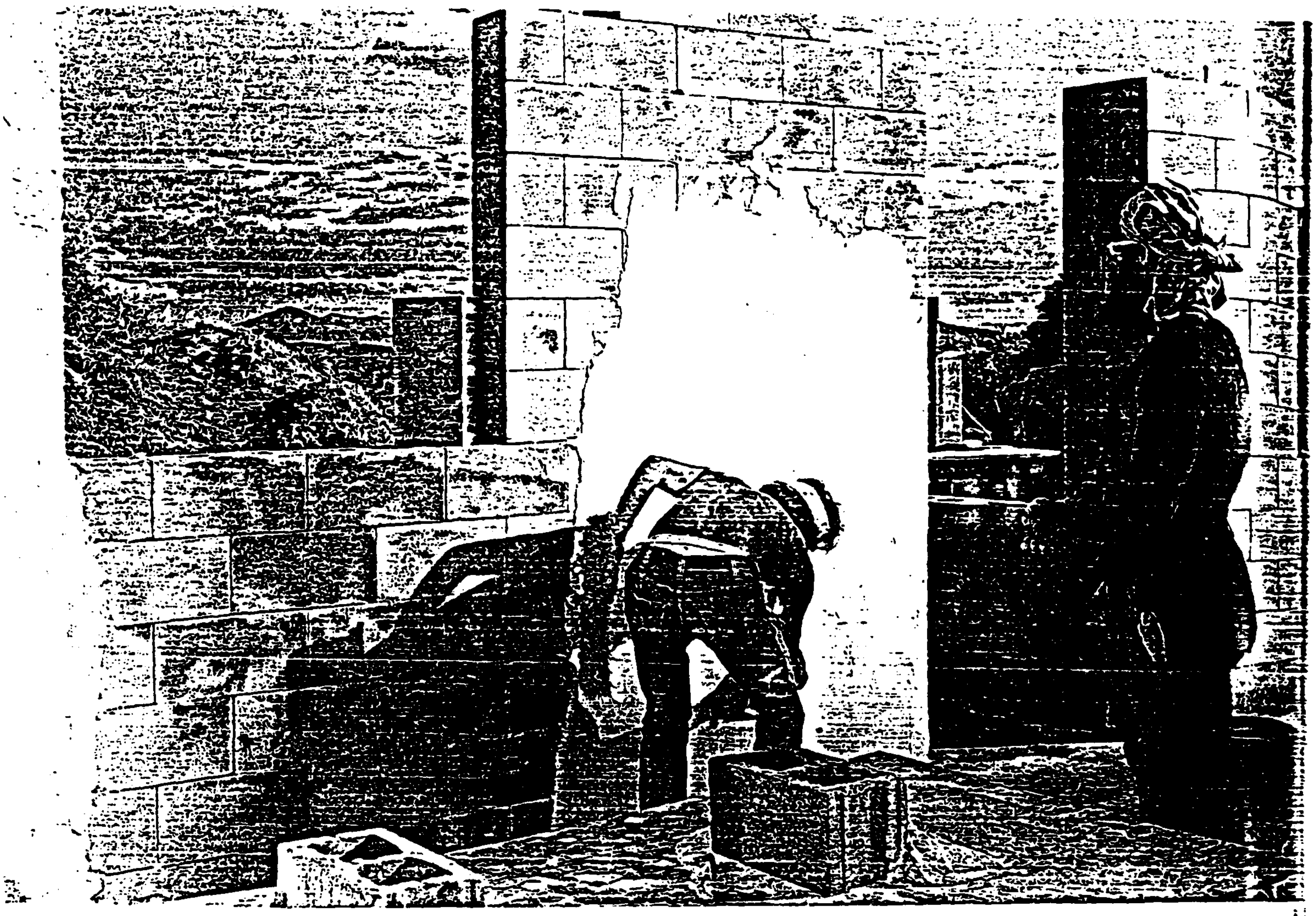


Figure 3.1.1 Application of Surewall™ surface bonding compound
(From Fine Homebuilding Construction Techniques, Taunton Press, July 1984, p88)

to the wall face using a spray gun. Because this technique eliminates the use of mortar, the maximum rows-per-day limit is also eliminated. In addition, because the surface bonding cement can be spray-applied, it is conceivable that the complete construction process could be automated.

Because this technique has obvious merit in terms of automation, it stands to reason that this could also boost productivity in manual wall construction as well. There are two technical reasons that this technique is not used more widely. One of these problems is not relevant when automated machinery is used for construction and the second can be solved by using a new type of precision block manufactured in Sweden.

The first problem is that surface-bonded block construction is currently only certified for use in single and two story construction. This eliminates it from use in large building applications. Although this is a problem for conventional construction, it is not for automated construction. This is due to the fact that current mechanical technology has practicality limits in the one to two story height range already. This is mainly due to structural rigidity problems associated with a tall machine. Even if the Surewall technique could be used for 3 or 4 story construction, robotic placement of the block at this height would probably be technically impractical. Thus, the two techniques (surface bonding and automated placement machinery) are ideally compatible from this point of view.

The second problem associated with dry-stacking block for surface bonding is traditionally available blocks are manufactured accurate to only ± 1.5 mm (±1/16"). This is mostly due the wear of the block molds during manufacturing[3] . The blocks at the beginning of the run are undersized while the ones at the end of the run about 300,000 blocks total. are oversized.

This discrepancy between block sizes does not present much of a problem when using mortar between the courses because the blocks can be individually leveled, but can cause problems for dry-stacking. There are two ways around this problem. The first is using

[3] Interview with Doug Buss, Plant Manager of Tarmac Florida, Tarmac manufacturing facility, N.W. 79th Avenue, Miami, Florida, January 1987.

some type of shim between the blocks and the second is using special blocks currently manufactured in Sweden, that are made for dry-stacking. These Swedish blocks, called Leca™ blocks, are precisely ground to exact dimensions following molding. This produces uniform blocks which can be dry-stacked without the problems associated with built up tolerances.

For the purpose of this case study, it was assumed that both surface-bonding and precision blocks would be used in the construction of the robotically assembled wall. Further, it was assumed that the wall would be built in a "staircase" configuration and does not contain any doors, windows, or thermal expansion joints. Although this may seem overly simplistic, the addition of such discontinuities would only affect the design of the placement algorithm and not the mechanical design of the machine. Construction of a long continuous wall (sound abatement walls along urban freeways are a perfect example) would proceed in the manner depicted by Figure 3.1.2. The exact dimensions of the "staircase" will be determined by the mechanical constraints of the manipulator.

3.1.1 ECONOMIC ASSESSMENT

With the following fixed-value assumptions about the operating scenario, the required cycle time per block as a function of the number of operators, payback period, maintenance percentage per year, and the initial cost of the robot was determined[4].

1) Manual block placement rate of 200 blocks/day
2) Total labor cost of $45 per hour, 40 hours/week
3) Machine operating 4 hours/day, 4 days/week
4) One block moved per cycle

The lowest cycle time was found to be 10.8 seconds. This corresponds to a 6 block-per-minute (BPM) placement rate and the following operating conditions:

1) 1 year payback period
2) $200,000 initial purchase price of robot
3) 50% maintenance cost per year (i.e. $100 K/year)
4) 3 human robot operators

[4]See Section 2.2, "Analyzing Market Potential"

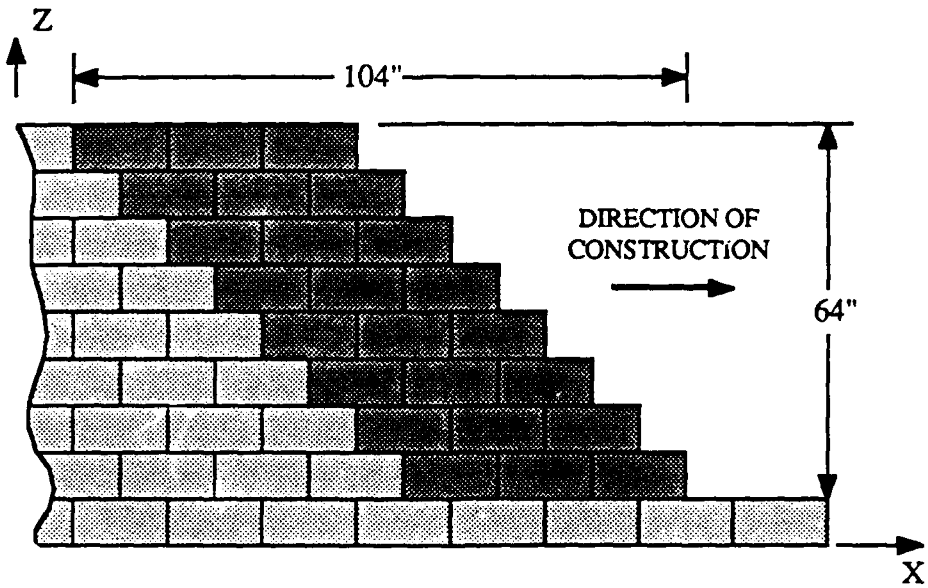


Figure 3.1.2 Staircase wall construction method

Thus the economics of the application indicate that the robot, under worst-case conditions, must place 6 BPM, 4 hours per day, 4 days per week. This was thought to be a technically feasible number. In fact, allowing for a margin of error, the target speed for the robot designed in this case study was 8 blocks per minute.

3.2 DESIGN CONSTRAINTS AND CONSIDERATIONS

In order to maintain high efficiency, the machine must have a large enough work volume so that it can keep itself busy between major changes in the global coordinates. The question of course is "How large is large enough?" Currently available, stock machine tool components such as ball screws[5] and linear bearings quickly exclude any machines larger than about 2 m (6') per axis. Machines larger than this may require very expensive custom components. A common rule of thumb in manipulator design is for every Kg of payload, approximately 10 Kg of machinery is required. In this case the payload is a concrete block (reasonably large by conventional robot standards) which weighs 150 N (35 lb). Using the rule of thumb, the manipulator will weigh approximately 1500N (350 lb). Add to this the weight of any auxiliary equipment such as block conveyors and the total system weight easily approaches 3800 N (850 lb). This is in addition to a lift needed to move the system to the proper height and position along the wall.

In order to move this much weight around a construction site a relatively large mobile base is required. Fortunately, mobile, electro-hydraulic scissor lifts are very common on construction sites. A typical lift has a top platform 3 m long, a payload of 4500 N, and a reach height of 8 m. Thus, placing a precision, high-speed robot on top of one of these lifts seems to be a very attractive solution to the large scale positioning requirement.

3.2.1 SUPPLYING BLOCKS TO THE MACHINE

Two systems for supplying block to the machine are possible: The first is an extendable conveyor system with a fixed loading station. In this configuration, workers (either human or robotic) would unload blocks from pallets and put them on a conveyor which would deliver them to the placement robot. The loading station would be in a fixed location for a given section of wall. The second method is to load a pallet of blocks onto the robot vehicle or an accompanying trailer. This pallet could then be unloaded by the

[5] Precision rack and pinion drives can be easily pieced together to achieve almost any length of travel.

robot itself, or an assistant (human or robotic) as the machine moves along the wall.

3.2.2 Dimensional Metrology System

In order for the robot to place blocks in the correct position on the wall, it must know exactly where it is in relation to a known global reference frame. This would be achieved through a large scale laser metrology system. This system could be based on currently available rotating laser beacons, large linear diode arrays. Electronic Distance Measuring Instruments (EDMI), and precise electronic theodolites (angle measuring devices). By implementing a self-checking frame and utilizing redundant measurements, dimensional closure of the system can be checked. This will enable precise measurement of the position and orientation of the robot in the global reference frame.

It takes all these different types of measuring systems, as opposed to a single sensing unit, because no single system currently exists. Thus by using several types of systems, measurement closure can be assured.

3.2.3 Manipulator Design Constraints

The number of degrees of freedom (DOF) required for the robot are directly related to the task that it is trying to accomplish. In this case, a full six degrees of freedom are required to place a block on a wall. Three of these DOF's are used to translate the load to a position in space while the other 3 are used to orient it rotationally. For this application the 3 DOF's used for translation must be large, while the 3 used for orientation are small since that are only used to compensate for the pitch, roll, and yaw errors associated with the lift.

The geometry of a typical scissor lift itself imposes a serious constraint on the manipulator design. Because the top platform of a fully collapsed lift is 1.3 m off of the ground, any manipulator placed on top of the platform must be able to reach down the side in order to place the lowest course of block onto the slab or footing.

In order to achieve any reasonable accuracy of block placement, some sort of end point measurement system is required. Typically, it would be located on the platform that raises the block laying head into position. Thus the block laying head should have an accuracy, even when loaded by its own weight, on the order of twice that of a typical block (1/16") or 0.03".

Besides the static deflections of the structure, there are three other concerns. The first is the lowest natural frequency of the structure which should be 3-5 times higher than the operation it performs. This avoids inducing large oscillations in the structure during placement of the block. The second concern is the stress levels in the structural elements. As in any good design, the dynamic and static stress levels should be well within the elastic region of the material to insure accurate positioning capabilities and long life.

The final concern is that of thermal effects. Such affects can contribute to overall structural deflections, large internal stresses, and binding of motion components. In particular, where a machine may be subjected to environmental extremes, it is important to consider not only expansion of single components, but also the differential expansion of mating components. Large thermal mismatch leads to serious performance problems in sensitive elements. Thus kinematic design principles should be adhered to whenever possible.

Another very important aspect of manipulator design is consideration of how it will be manufactured and assembled. Neglecting to think through the assembly process completely can lead to serious problems at a later point in time, usually when they cost a lot of money to fix. Ease of assembly must also be considered with respect to maintenance issues. It is all too common for a repair technician to be infuriated by a piece of equipment that was designed assuming it would never break down or wear out. Thus, assembly issues are continuously addressed in this case study.

3.2.4 STATE OF THE ART TECHNOLOGY ASSESSMENT

The complete system to automate the construction of concrete block walls consists of four major subsystems:

1) The hydraulic scissor lift used for coarse positioning in the global reference frame.
2) The block supply system such as a conveyor belt or supply trailer
3) The large scale dimensional metrology system and control electronics
4) The large work volume block laying robot

The first item can be purchased directly from a supplier and easily retrofitted with a more accurate control system. The second item, the conveyor system, is well within the scope of currently available conveyor technology and thus will not be addressed here. The large scale laser metrology system can be similar to ones developed for machine tool applications. It is the detailed mechanical design of the large work volume robot that will be discussed in the remainder of this case study.

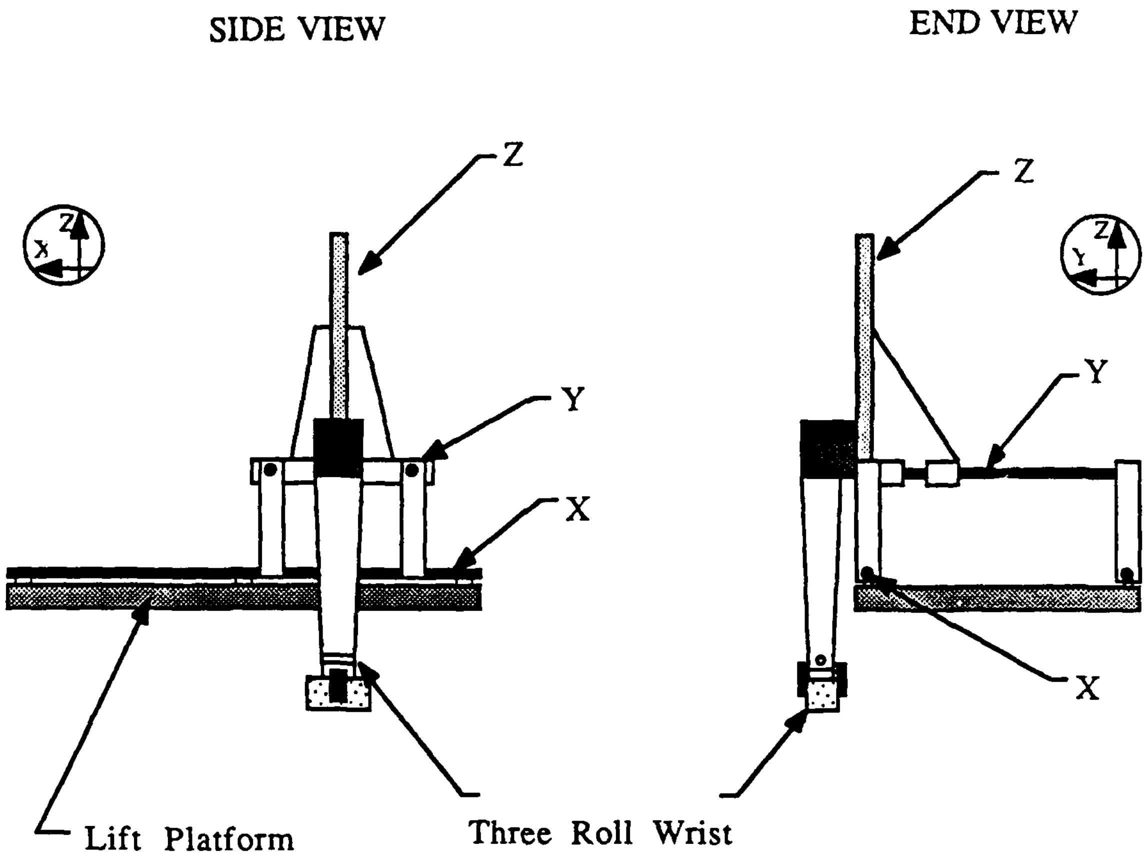
Although there are hundreds of manipulators on the market, there are few that are suited for the application of building block walls. Traditional factory robots are typically designed to operate in a horizontal plane, performing operations such as loading machine tools or palletizing parts. There are very few which are designed to perform the majority of their work in a vertical plane.

Typical revolute-axis robots which may be large enough to handle a payload of 200 N (one concrete block and gripper) can weigh 4500 N or more and only have a reach of 1-1.5 m. For these reasons, they are also unsuitable for use on a construction site. The most practical solution to this problem is thus to design a task specific robot which is specifically designed to build block walls.

3.3 CONCEPTUAL DESIGNS

A six degree-of-freedom manipulator is required for this task. However, three of the degrees of freedom only require small rotational motions: θ_x, θ_y, and θ_z. These motions have the following minimum values because of positioning ability of the hydraulic scissor lift: $\theta_x = \pm 2$ degrees, $\theta_y = \pm 5$ degrees, $\theta_z = \pm 5$ degrees. The θ_x and θ_y values are from the design specifications of a typical construction lift. If the top platform of the lift pitches more than 2 degrees or rolls more than 5 degrees, an alarm sounds on the lift indicating unsafe operation. The θ_z range was determined through actual tests on the steerability of a construction lift; it was found that the lift could be positioned within ± 5 degrees relative to a desired direction of motion. However, a larger range on θ_z would be desirable for picking a block off the delivery system.

Two broad categories of manipulators for this purpose can be defined and are shown in Figures 3.3.1 - 3.3.11. The first is the "conventional" manipulator which uses the first three DOFs (counting outwards from the base) to position the load and the final three in some form of a "wrist" used to orient the load. The second category



Advantages:

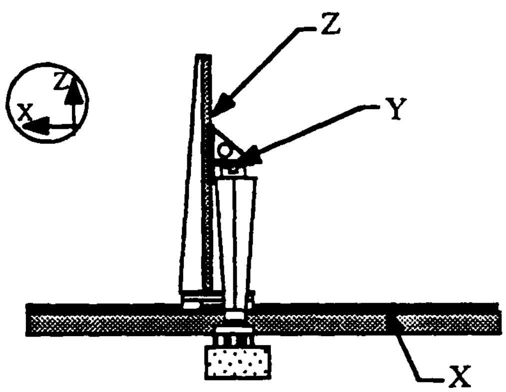
Easy to control (cartesian)
Low power consumption
Good load capacity
Relatively rigid (wide bearing spacing)
Easy to service

Disadvantages:

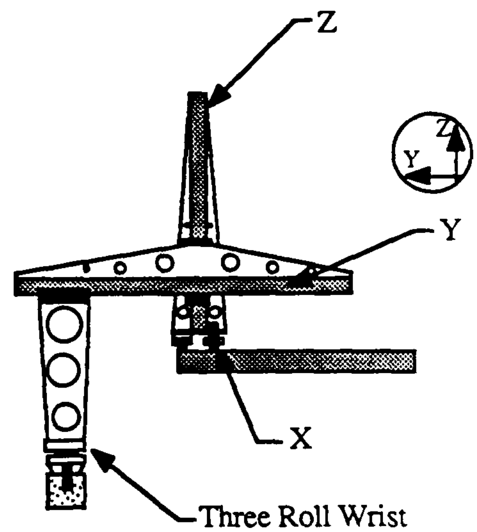
Complicated and heavy wrist
Restricts conveyor placement
Difficult to seal
Long arm may vibrate
Vulnerable to abuse
Hard to keep ways parallel
Moderately difficult to wire

Figure 3.3.1 Design #1, 3 Axis cartesian with 3 DOF wrist

SIDE VIEW



END VIEW



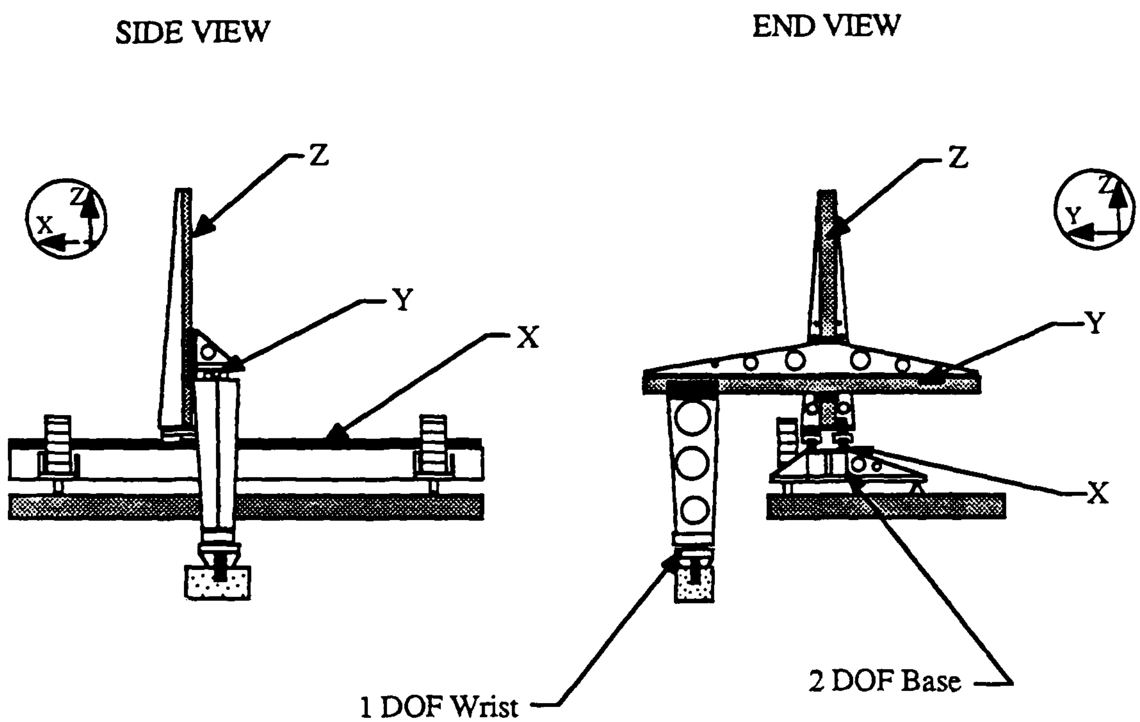
Advantages:

- Easy to control (cartesian)
- Easy to build
- Low power consumption
- Offers flexible conveyor placement
- Relatively compact
- East to service

Disadvantages:

- Cantilevered arms may vibrate
- Complicated and heavy wrist
- Difficult to seal
- Moderately difficult to wire

Figure 3.3.2 Design #2, 3 Axis Cartesian with 3 DOF wrist



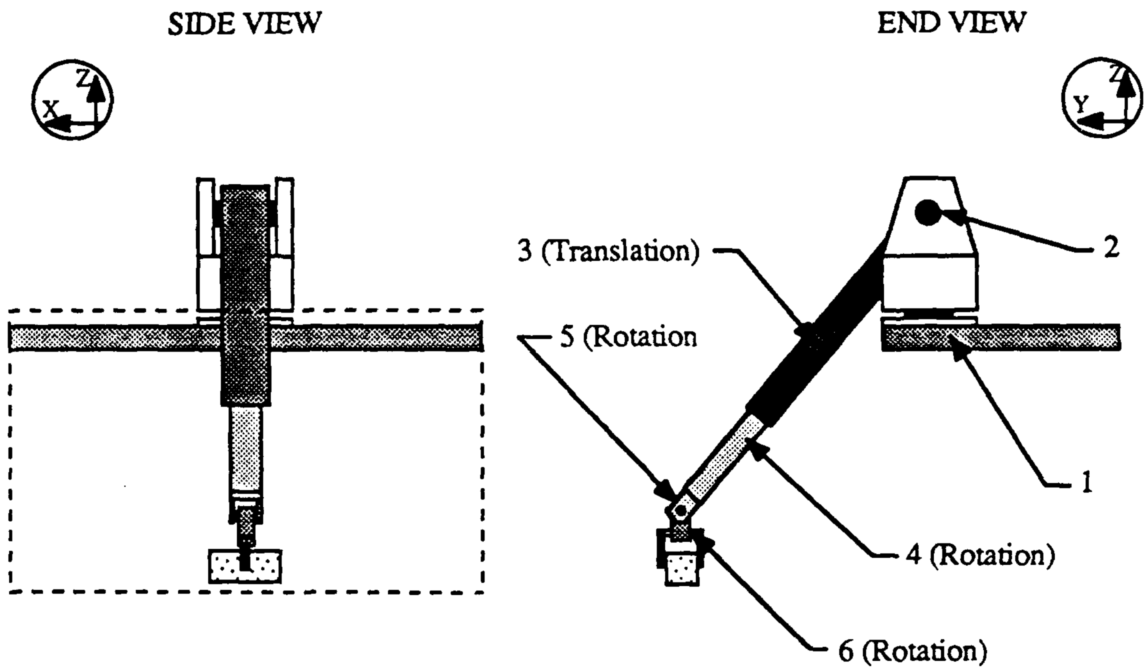
Advantages:

Easy to control
Low power consumption
Low tip mass
Relatively servicable
Offers flexible conveyor placement
Simple wrist

Disadvantages:

Cantileverd arm may vibrate
Not compact
Difficult to seal
Moderately difficult to wire
Complex base

Figure 3.3.3 Design #3, 3 Axis Cartesian with 1 DOF Wrist and 2 DOF Base



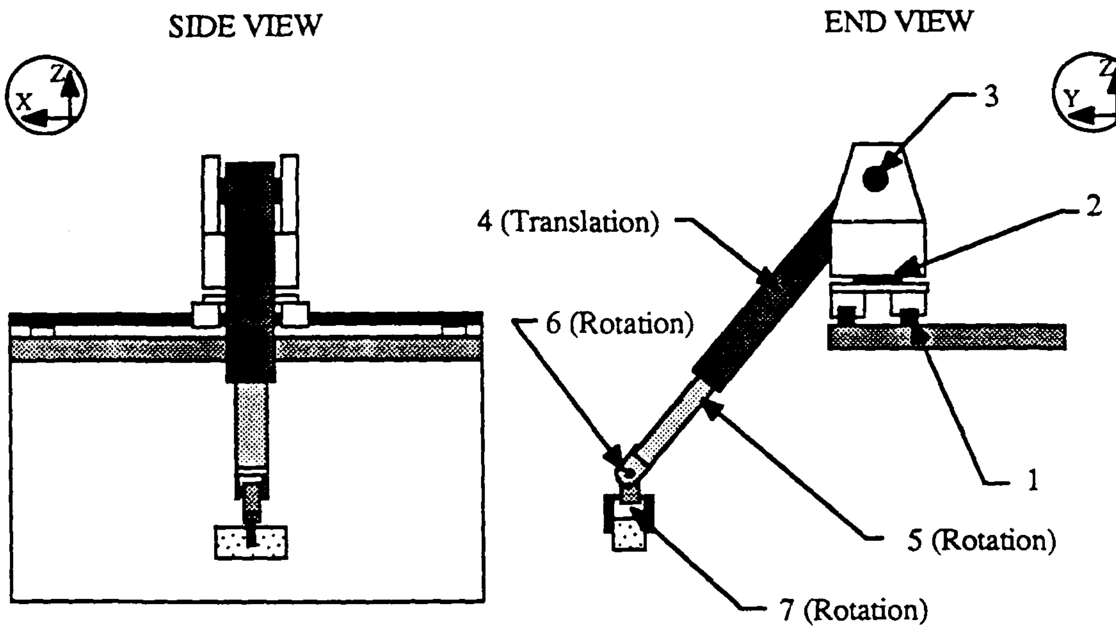
Advantages:

Easy to seal
Offers flexible conveyor placement
Relatively compact

Disadvantages:

Wiring difficult
Low stiffnes
Complex kinematics
Difficult to build telescoping arm
Difficult to control
Large rotational inertia
High power consumption
Heavy wrist
Low load capability

Figure 3.3.4 Design #4, 6 DOF Hybrid with Telescoping Arm



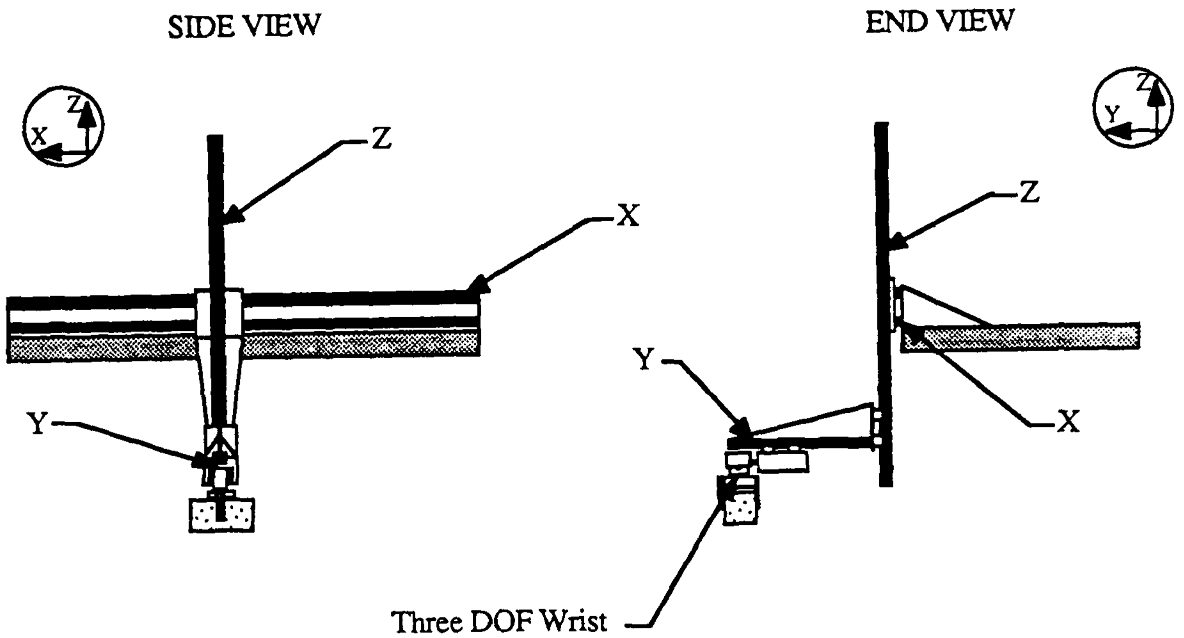
Advantages:

Easy to seal
Offers flexible conveyor placement
Relatively compact
Improved stiffness over #4

Disadvantages:

Difficult to build
Difficult to control
Complex kinematics
Arm stiffness may still be a problem
Difficult to build telescoping arm
Heavy wrist
Large rotational inertia
Low load capability
High power consumption
Wiring not simple

Figure 3.3.5 Design #5, 7 DOF Hybrid with Telescoping Arm and Travelling Base



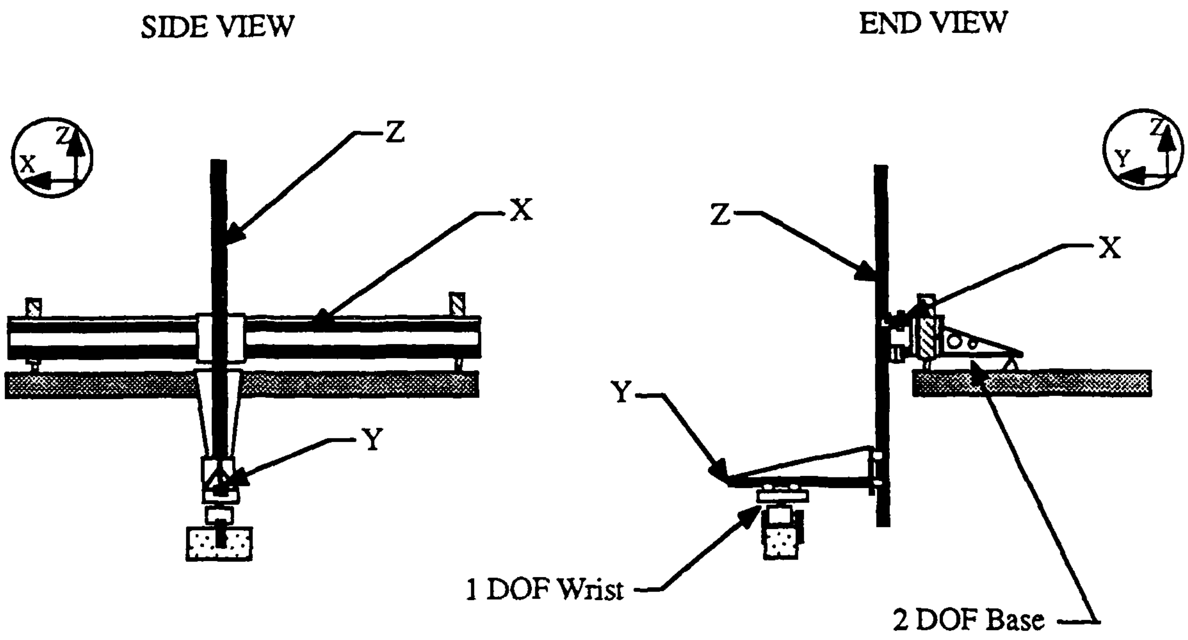
Advantages:

Easy to control
Easy to build
Low power consumption
Easy to service

Disadvantages:

Complicated and heavy wrist
Poor conveyor interface
Large cantilever loads and moments
Only moderate stiffness
Wiring complicated
Difficult to seal

Figure 3.3.6 Design #6, 3 Axis Cartesian with 3 DOF Wrist



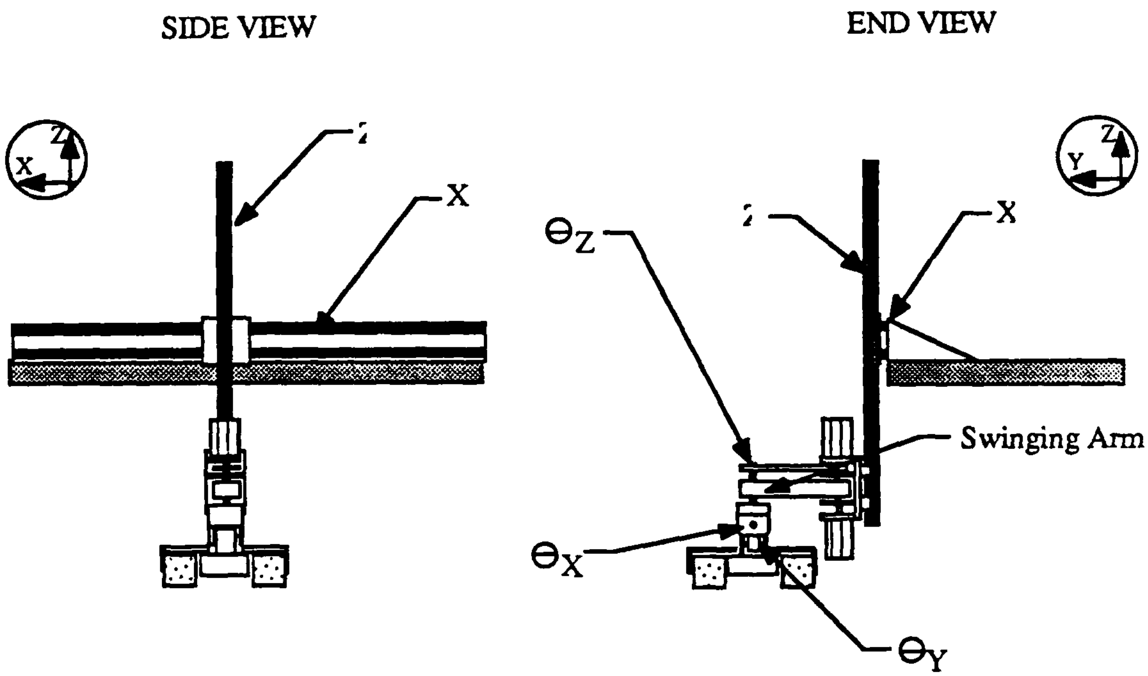
Advantages:

Easy to control
Tip mass reduced
Easy to build
Low power consumption
Easy to service

Disadvantages:

Not very compact
Poor conveyor interface
Large cantilever loads and moments
Only moderate stiffness
Wiring complicated
Sealing difficult
Complex base

Figure 3.3.7 Design #7, 3 Axis Cartesian with 1 DOF Wrist and 2DOF Base



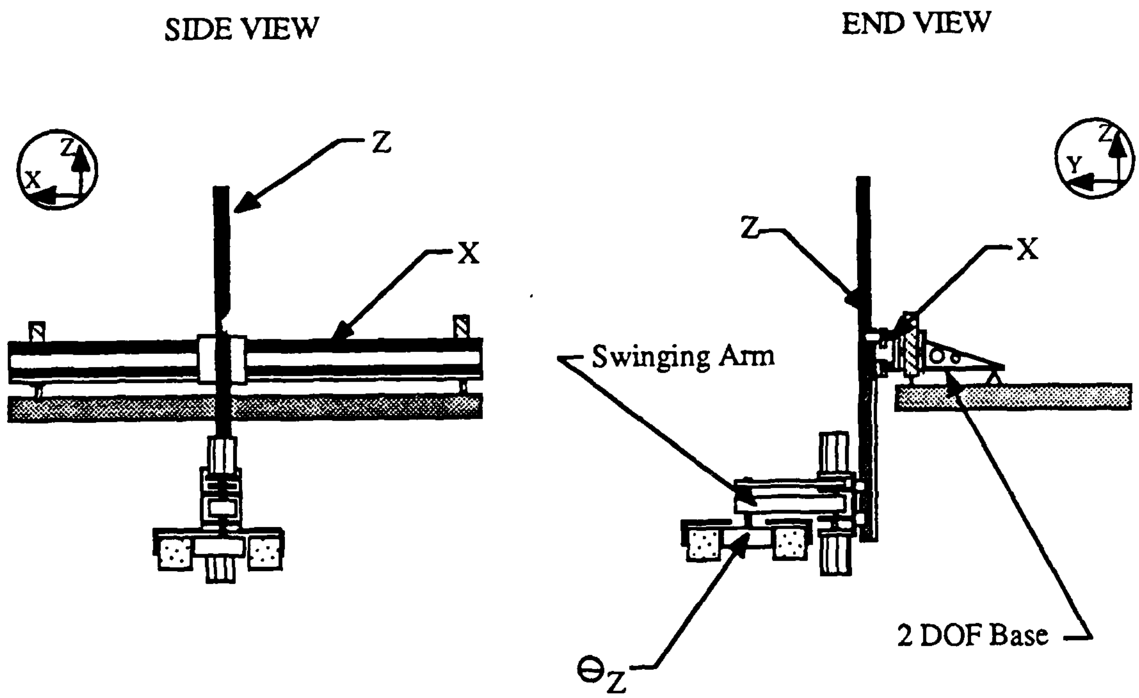
Advantages:

East to control
Good Conveyor interface
Easy to build
Medium load capability
Serviceability good

Disadvantages:

Complicated and heavy wrist
High loads on X and Z axes
High rotational inertia
Stiffness may be a problem
Sealing moderately difficult
Wiring moderately difficult

Figure 3.3.8 Design #8, 6 DOF Hybrid with 3 DOF Wrist



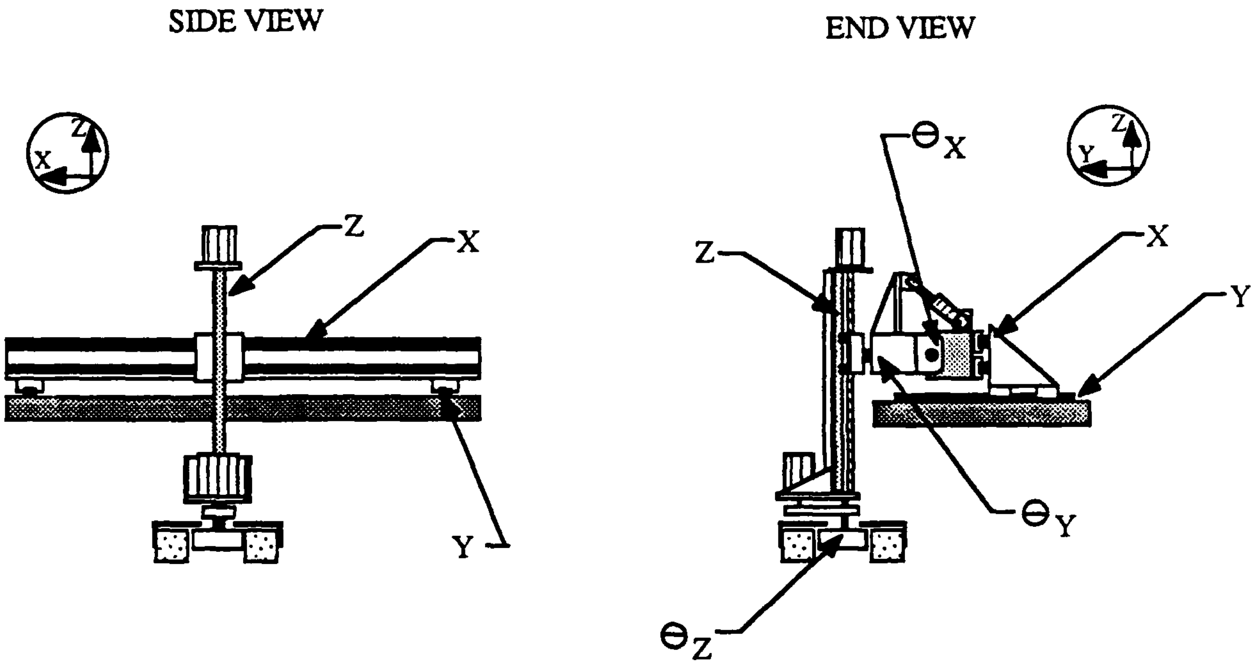
Advantages:

Easy to control
Easy to build
Wrist simpler than #8
Good conveyor interface
Servicability good
Medium load capability

Disadvantages:

Large loads on X and Z axes
High rotational inertia
Moderate stiffness
Difficult to seal
Moderately difficult to wire

Figure 3.3.9 Design #9, 6 DOF Hybrid with 1 DOF Wrist and 2 DOF Base



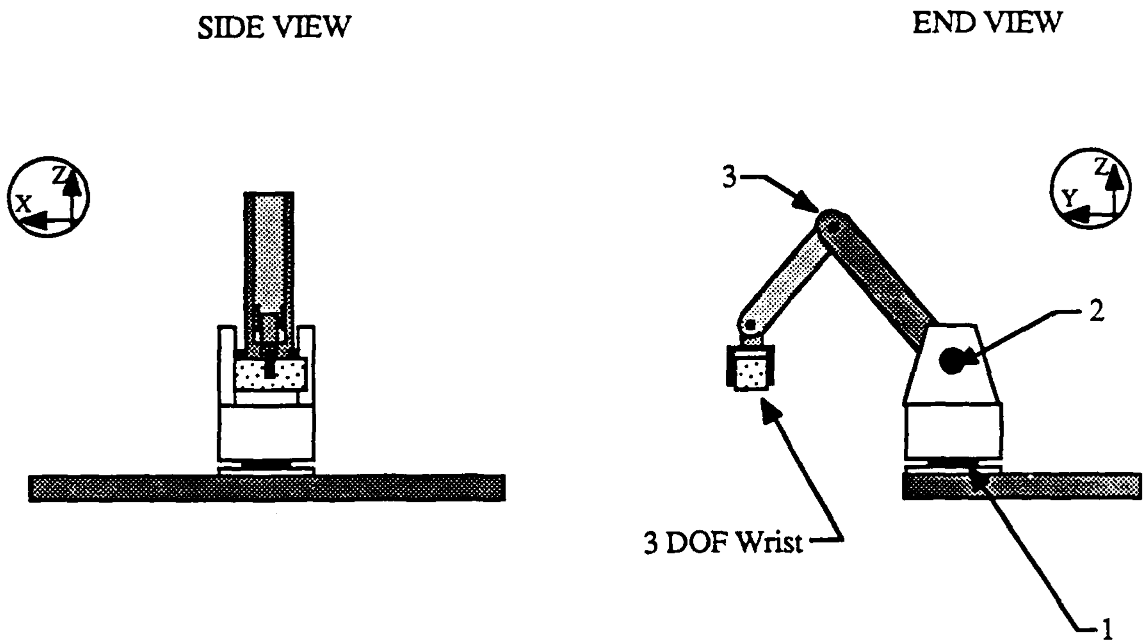
Advantages:

Good conveyor interface

Disadvantages:

Difficult to control
Large loads on X and Y axes
Requires precise alingment of Y-axis slides
Large θ_X actuator
Large inertia on Z axis motor
Difficult to wire and service
Complex design

Figure 3.3.10 Design #10, 6 DOF Hybrid with 1 DOF Wrist, 2 DOF Base and Live Z-Axis



Advantages:

Easy to seal
Offers flexible conveyor placement
Relatively compact

Disadvantages:

Low arm stiffness
Complex kinematics
Difficult to control
Large rotational inertia
High power consumption
Heavy wrist
Low load capability

Figure 3.3.11 Design #11, 6 DOF Anthropomorphic Arm includes the "unconventional" designs. These are manipulators which have the first two axes compensate for errors in θ_x and θ_y (i.e. "level the robot"), followed by three DOFs which translate the load, and finally a θ_z axis which performs the final orientation of the load about a vertical axis.

Based on a rough analysis of the DOF requirements and work volume, a number of conceptual designs were generated. Briefly, these are:[6]

- Design #1: 3 axis Cartesian with a 3 DOF wrist (gantry-type).
- Design #2: 3 axis Cartesian with a 3 DOF wrist (compact-type).
- Design #3: 3 axis Cartesian with a 1 DOF wrist and a 2 DOF base.
- Design #4: 6 DOF hybrid with telescoping arm.
- Design #5: 7 DOF hybrid with telescoping arm and travelling base.
- Design #6: 3 axis Cartesian with 3 DOF wrist (cantilevered).
- Design #7: 3 axis Cartesian with 1 DOF wrist and 2 DOF base (cantilevered).
- Design #8: 6 DOF hybrid with 3 DOF wrist.
- Design #9: 6 DOF hybrid with 1 DOF wrist and 2 DOF base.
- Design #10: 6 DOF hybrid with 1 DOF wrist, 2 DOF base, and live Z-axis.
- Design #11: 6 DOF anthropomorphic.

Each design presented in the figures is annotated with a subjective assessment of its advantages and disadvantages. Some of the heuristic rules that were used in evaluating the designs were:

1) Linear axes are more difficult to seal than rotary axes.
2) Cartesian manipulators are easier to control than revolute ones.
3) The more complicated the wrist, the harder it is to wire.
4) The shorter the cantilever length(s) the stiffer the structure.
5) The shorter the cantilever length(s) the higher the load capability.

---

[6] Figure #s 15.3.# correspond to design #. Note that the sizes of the elements are only guestimates at this point.

6) Gravity back-drivable joints require more power to actuate and need failsafe brakes.
7) Revolute robots are more difficult to service than Cartesian ones.

Designs #1 and #10 both have parallel linear bearings mounted on the top platform of the scissor lift. Twisting and bending of the lift could cause accuracy and binding problems in these bearings. For this reason, these two designs were eliminated.

Since this machine must be relatively compact and robust in order to be moved around and used on a construction site, the fixed cantilever arm on designs #2, #3, #6, and #7 is highly impractical. Any contact between this arm and a fixed object (such as a completed block wall) could cause significant damage to the wall, machine, or a human operator. For this reason (and others) these four designs were eliminated.

Design #4 was also eliminated on the grounds of structural limitations. In this case, these limitations were due to the required length of the telescoping arm. An arm this long (2 m) is likely to have a very low natural frequency as well as mechanical accuracy problems. In addition, extremely large actuators would be required to move the arm up and down and to rotate the trunk of the manipulator. The pure anthropomorphic configuration, design #11, was also eliminated for the same reasons.

Design #5, although it reduces the problems associated with the long telescoping arm, is impractical from both an economic and control standpoint. The 7th degree of freedom adds undue expense and complication to the actuation and control of such a robot. It was felt that a more economical solution could be found.

Only 2 designs remain at this point, #8 and #9. These two are in fact very similar; the only major difference being how the 3 rotational axes are implemented. While #9 would have problems with a distorting top lift platform, design #8 would have to carry around a very heavy, bulky wrist in order to move the turret. Neither of these solutions is particularly attractive. A reasonable way around these problems is a hybrid combination of the two: Remove the turret, replace it with a single block gripper, and eliminate the powered θ_x and θ_y motions. If these motions are replaced by a passive universal joint-type mechanism between the gripper and the powered θ_Z axis, then the block will automatically orient itself with gravity if it is held at its center of mass. Since this is what the two servo axes would be doing anyway, it seems like a reasonable solution.

Replacing two servo axes with passive joints has obvious advantages. It also has some potential disadvantages. Three foreseeable problems include:

1) Error due to variation in block center of gravity.
2) Error due to bearing friction.
3) Swinging of the block during block transfer from conveyor to wall.

It is felt that all of these problems can be reduced or eliminated by using a specially designed joint and precision blocks.

If precision blocks are used (as previously assumed) the variation in the location of the center of gravity should be negligibly small. Since the mix used to produce these blocks is extremely homogeneous, large variations in material density from one side of the block to the other are not anticipated. Block to block variations in total weight are unimportant.

Assuming the following about bearing friction:

- 0.001 coefficient of friction for quality roller bearings
- 12.5 mm diameter universal joint shaft
- 150 N block
- 50 N gripper
- 200 mm distance from block CG to joint axis

the total lateral positioning error for the block, due to bearing friction, is approximately 0.025 mm. This is acceptable for this application.

Swinging of the block during the pick and place operation can be prevented with the use of a locking universal joint sketched in Figure 3.3.12. The universal joint is mounted in the center of a hollow-rod, double-acting pneumatic cylinder. When the cylinder is actuated in one direction, three fingers lock the joint in a position

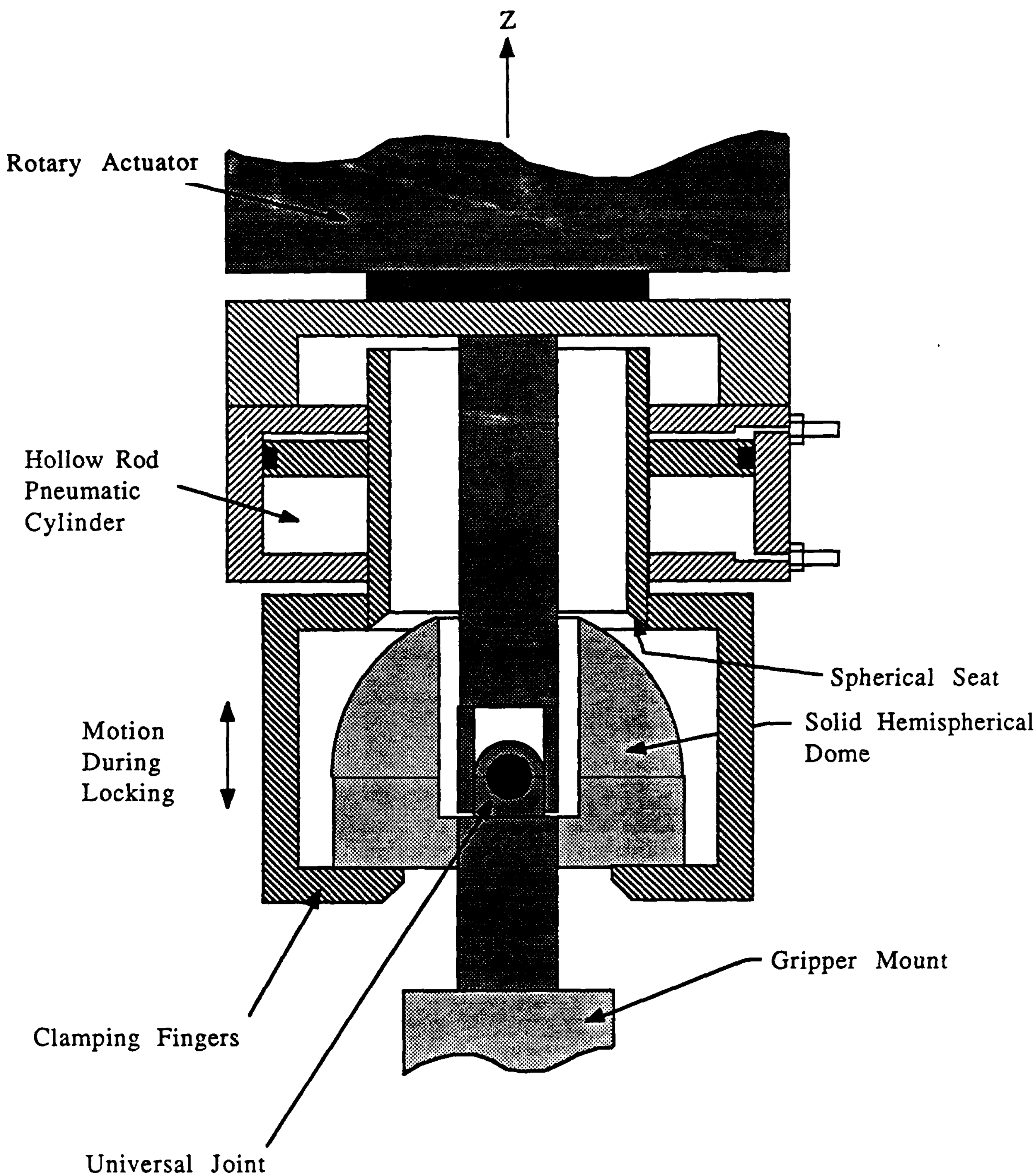


Figure 3.3.12 Lockable Universal Joint

perpendicular to the Theta arm. In this position, a block can be picked up from the conveyor and servoed to position along the wall without swinging. When it is near its final position on the wall, the cylinder is released, allowing the block to swing free and align itself with gravity. If desired, the cylinder could be then actuated in the downward direction which would clamp the hemispherical dome in its current position. Final servoing and block placement could then occur. Following the release of the block, the joint would be rigidized again and the process repeated.

It is felt that this design would have the following benefits over a 3 axis powered wrist:

- Reduce manipulator tip weight and inertia
- Eliminates 2 expensive servo-actuators and coupling hardware
- Eliminates 2 servo systems and electronic hardware
- Reduces system power consumption

This somewhat unconventional configuration thus seems to be the best design.

Figures 3.3.13 and 3.3.14 schematically show the final configuration for the robot axes. In general, the manipulator has 6 DOF; four of which are powered. Gross horizontal and vertical motions are provided by the X and Z linear axes. Motions in and out from the wall are provided by the swinging "Theta arm". The fourth and last powered DOF is the θ_Z motion at the wrist of the manipulator. The two unpowered degrees of freedom are generated by a hanging universal joint connected to the θ_Z motor. This overall configuration has the following attractive features:

- Easy to build
- Easy to control
- Easy conveyor interface
- Reasonable to wire
- Reasonable to service
- Compact to transport
- Uses gravity to orient blocks

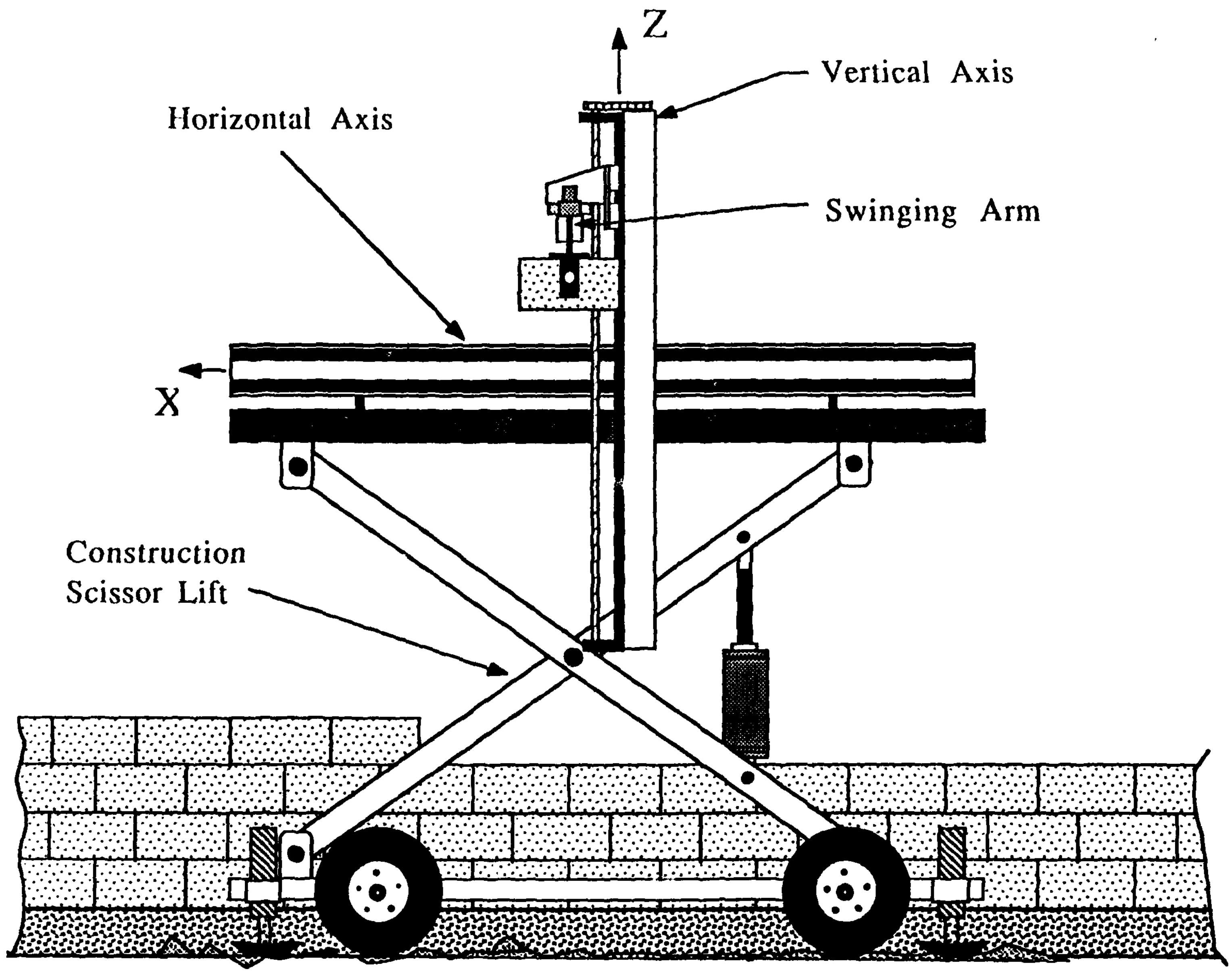


Figure 3.3.13 Schematic side-view of Blockbot

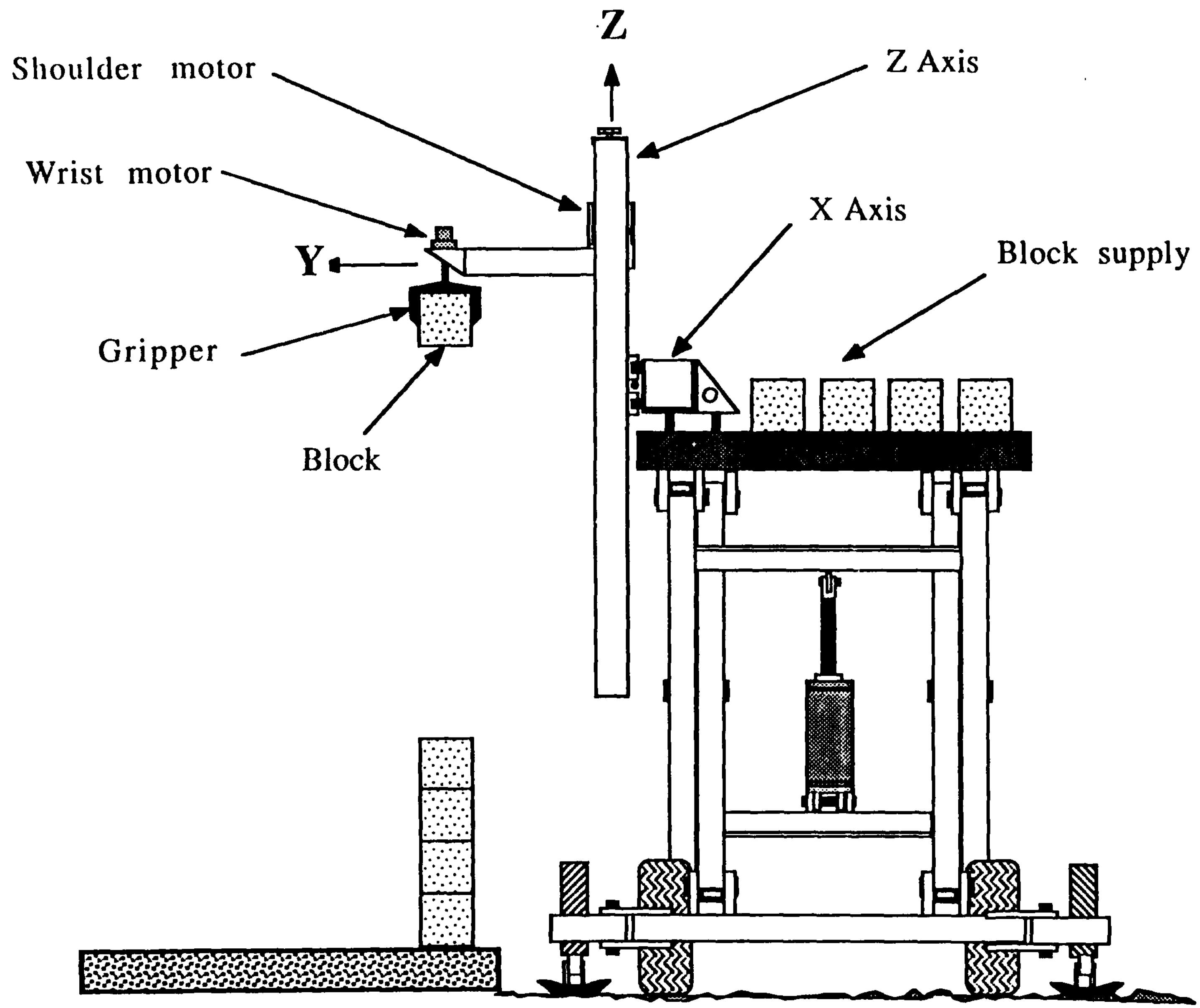


Figure 3.3.14 Schematic end-view of Blockbot

3.4 SIZING COMPONENTS FOR THE THREE PRINCIPAL AXES

Before machine components could be sized, the acceleration profiles were calculated for the various axes to achieve the target speed of 8 blocks per minute.

X-axis:	2 meters in 3 seconds
Z-axis:	0.3 meters in 1 second
Shoulder:	180 degrees in 1.0 seconds (negotiable)
Wrist:	90 degrees in 0.6 seconds (negotiable)

Under static operating conditions, the joints of a robotic manipulator can be assumed to be servoed to the desired positions by the control system.[7] This assumption allows the joints to be regarded as rigid and any deflection at the end-point due to deflection of the structural elements alone.

The most severe loading condition for the robot occurs when the Z-axis is accelerated upwards (+Z) while the Theta arm is at full extension and carrying a concrete block. With an estimated tip mass of 36 kg (including the arm structure and load), an applied acceleration of 1.4 m/s^2 (derived from the cycle times of section 5.3), plus the acceleration due to gravity, the worst-case tip load is about 400 Newtons. With a reasonable safety factor of 1.5, the design load, applied at the tip of the structure, is 600 N (150 lb). This is the value used to calculate the Z-direction deflection of the entire structure. The deflections of the structure in the Y and X directions are not critical since both can be easily servoed with respect to a vertical plane of laser used to indicate straightness of the wall.[8]

The detailed engineering analysis done during the course of the design of the prototype is too extensive to present in this paper, but is available in the form of a Master of Science Thesis[9]. For reference, Figures 3.4.1 through 3.4.5 show the mechanical detail of the principal assemblies.

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[7] This of course is assuming that the position control loop has an integrator and a reasonably high gain.

[8] Hint for designing the dimensional metrology system.

[9] Bruce M. Schena, "Design Methodology for Large Work Volume Robotic Manipulators: Theory and Application" Master of Science thesis, Department of Mech. Eng. MIT, June 1987.

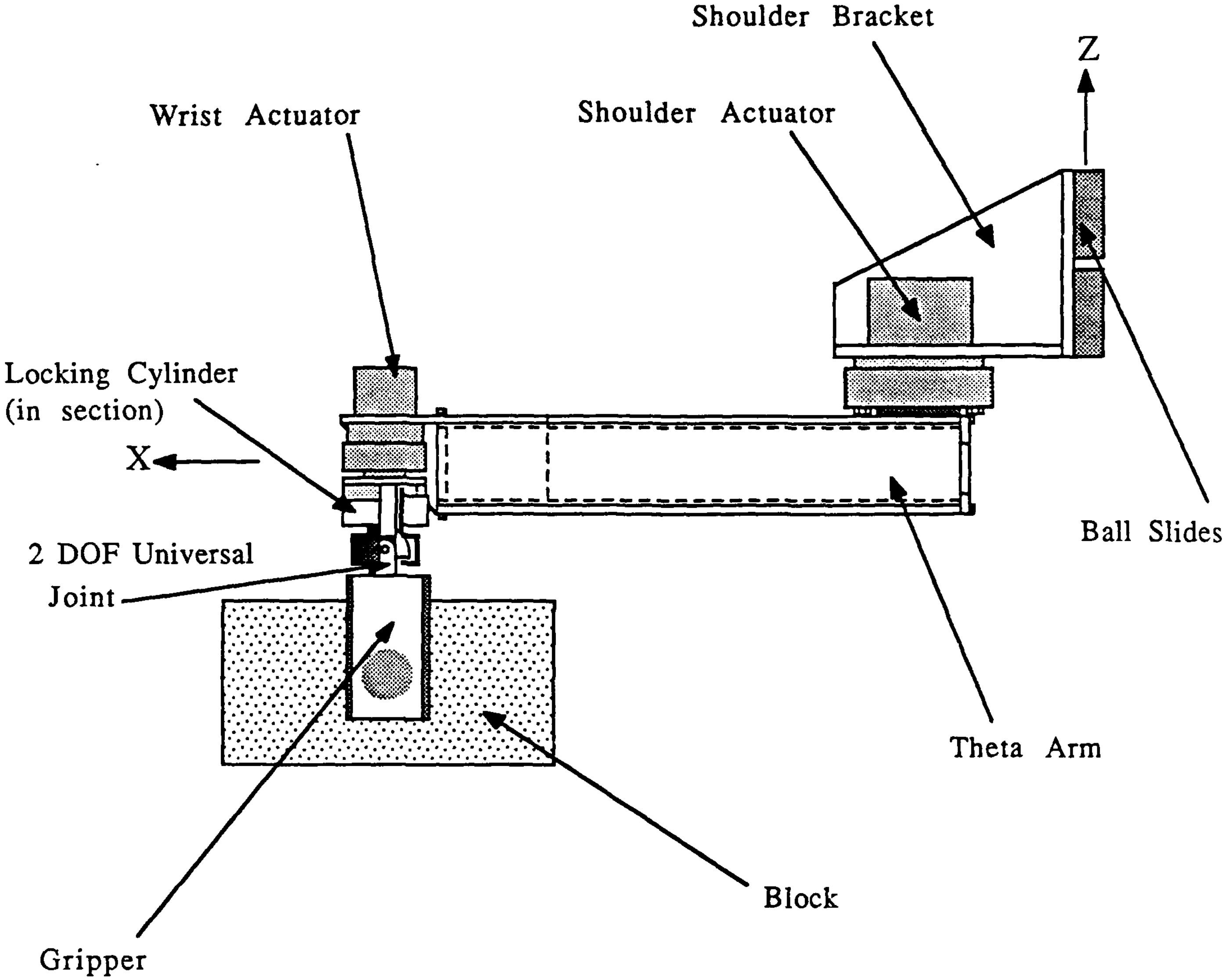

Figure 3.4.1: Theta Arm Configuration

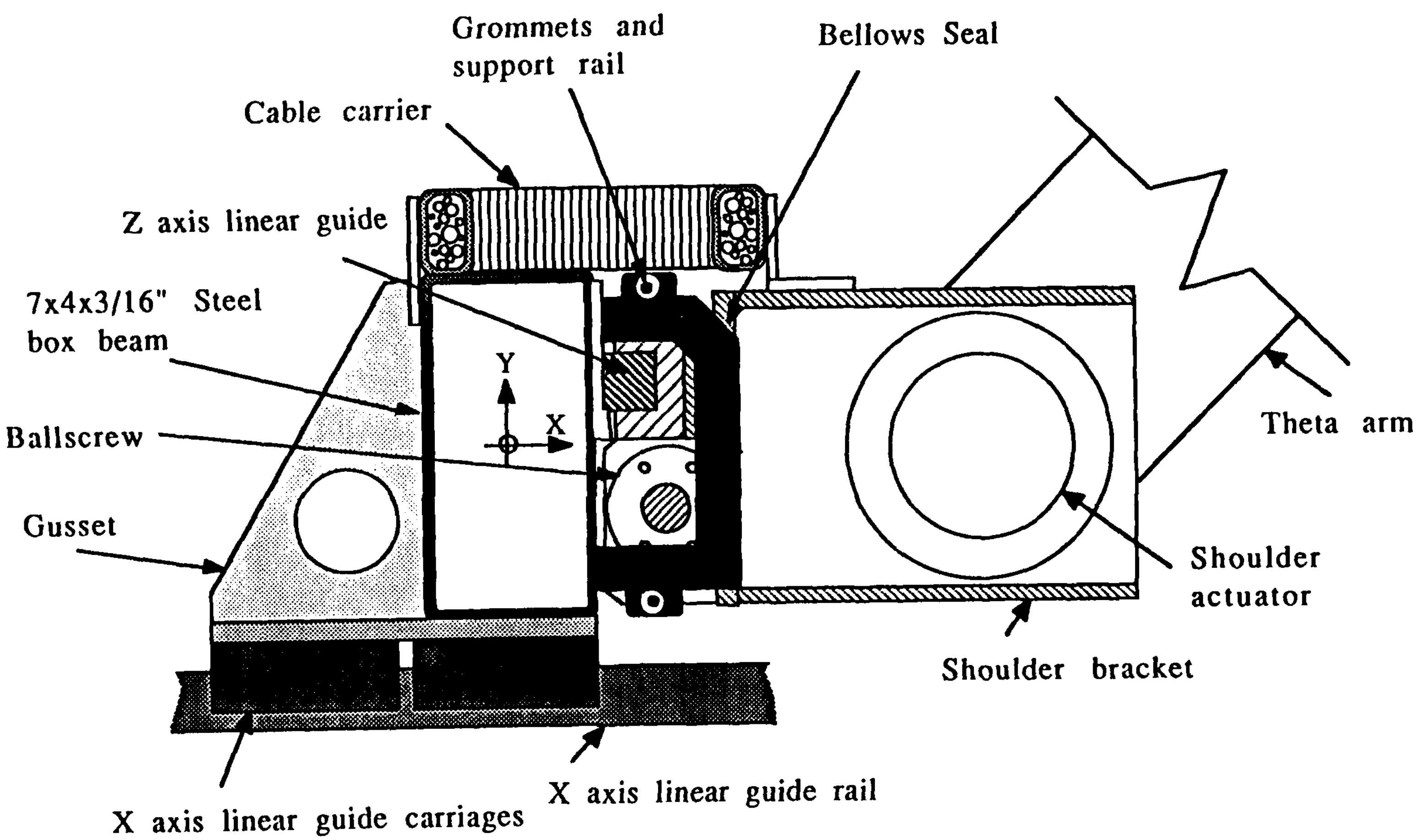

Figure 3.4.2: Detail of X-Y Axis interface

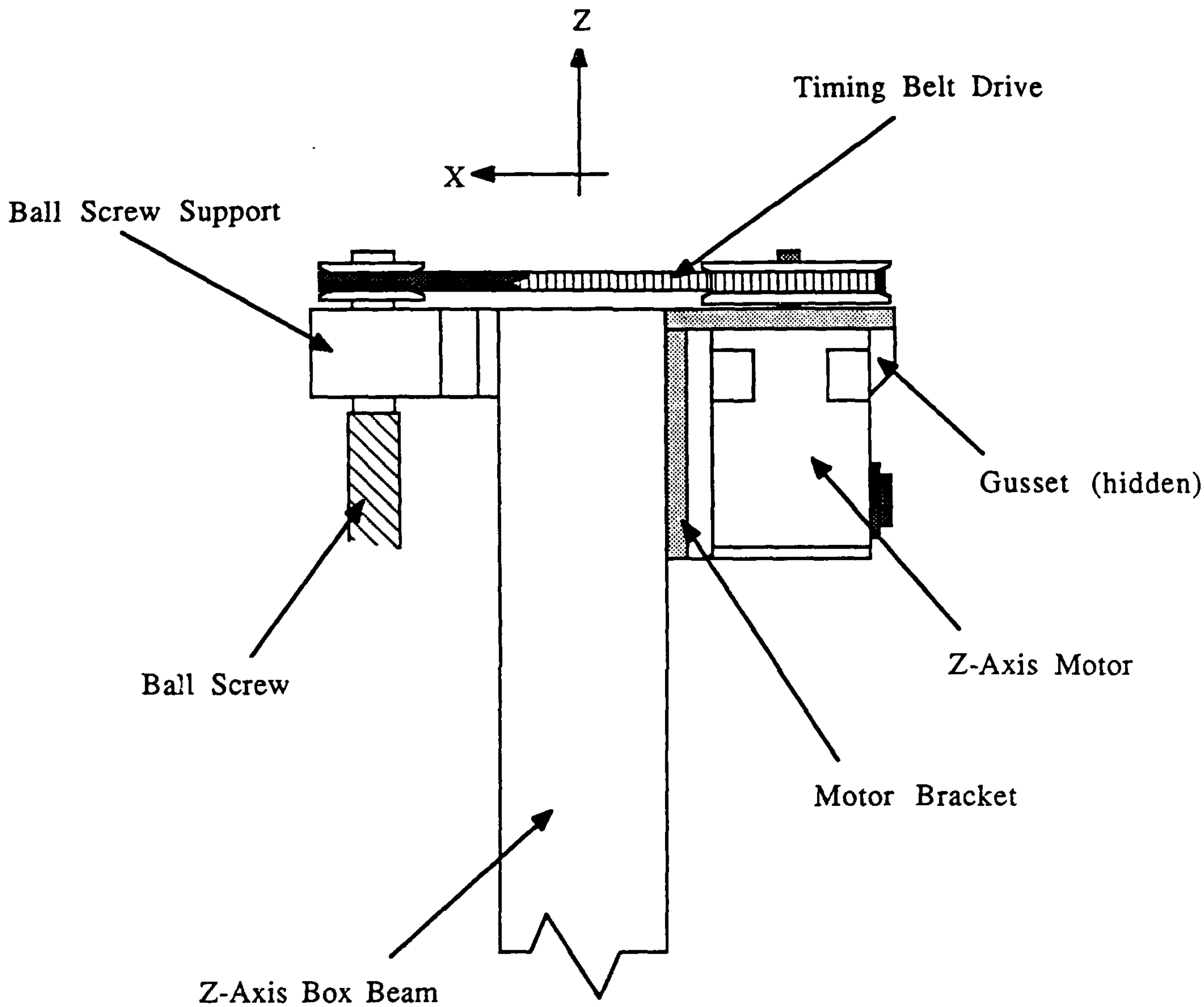

Figure 3.4.3: Z-Axis Servomotor Mount

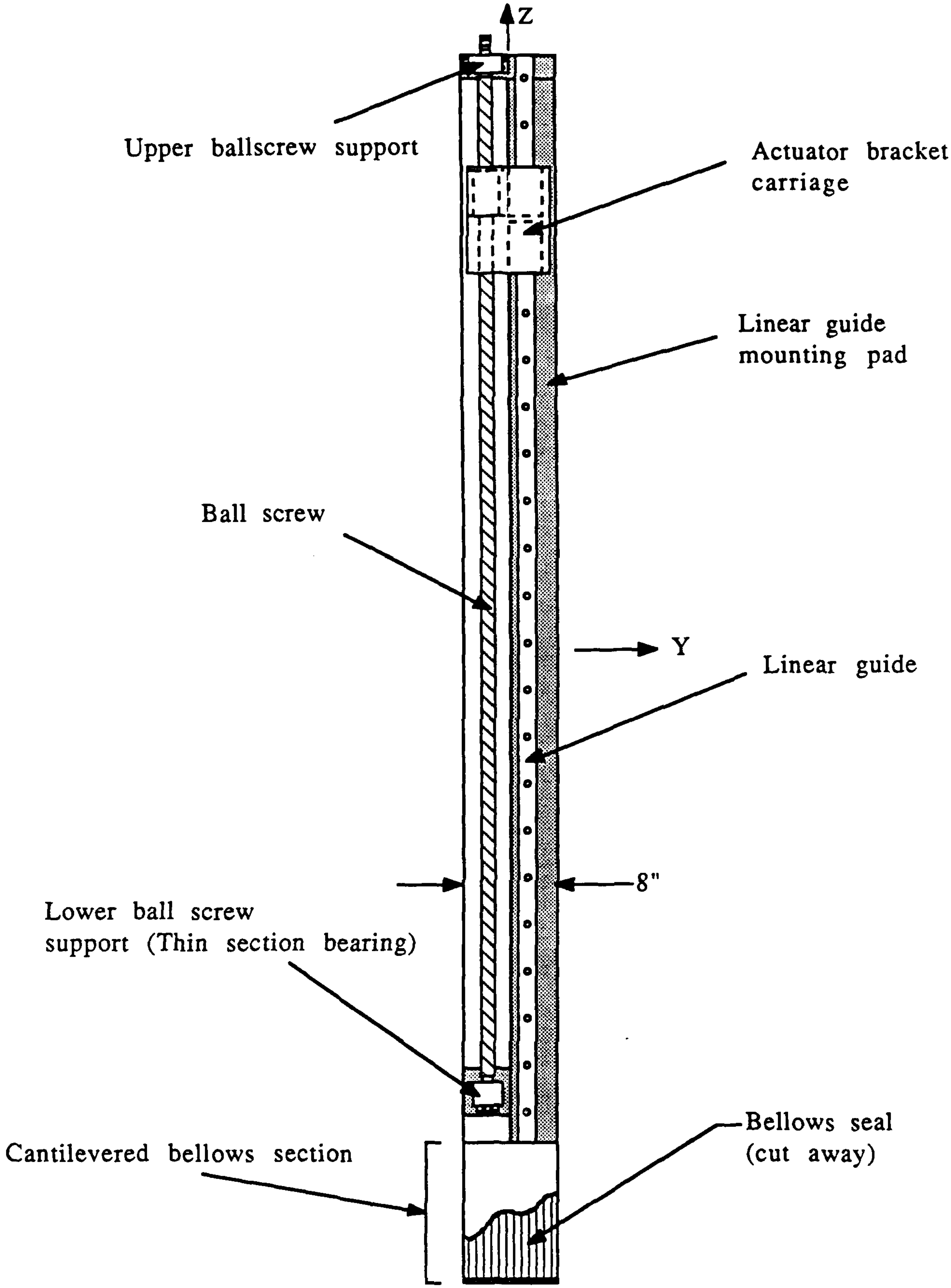

Figure 3.4.4 Front view of Z-axis assembly

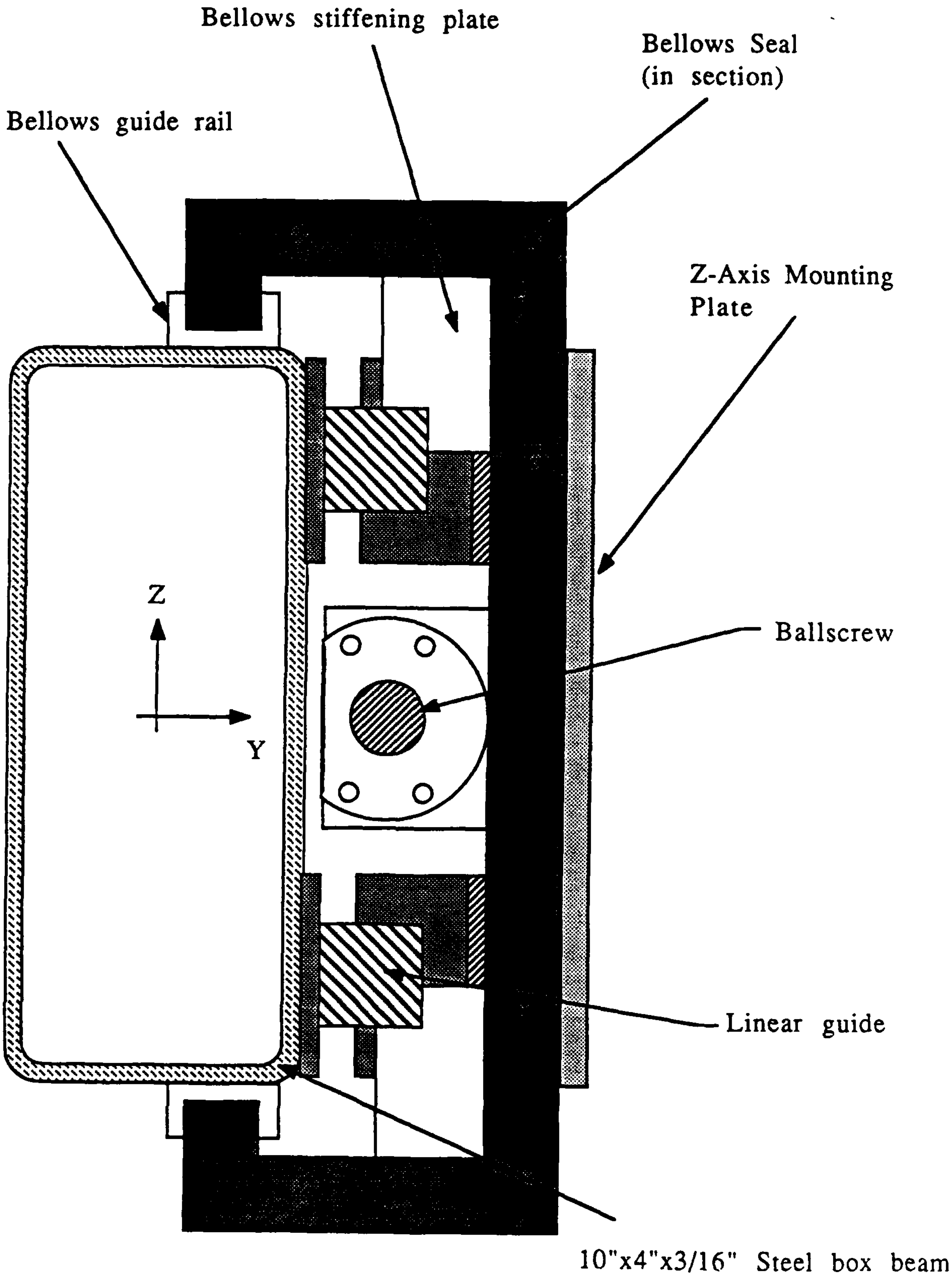

Figure 3.4.5 X-axis cross-section

3.5 Fabrication of a Prototype Manipulator

In order to demonstrate the concept of stacking concrete blocks with an automated system, a prototype manipulator was built. Photographs of the finished arm and control stand are shown in Figures 3.5.1 and 3.5.2 respectively.

Due to financial, time, and laboratory space constraints, only the shoulder and wrist axes were built to specification. A simple pneumatically-actuated Z-axis was also built so that blocks could be picked up. Specifically, the prototype had the following features:

- Full-size/full-capacity pneumatic gripper
- Full-size theta arm, exactly as designed
- (1) DJDE-02, 96:1 actuator with resolver
- (1) DJDE-04, 196:1 actuator with resolver
- Full-size DJDE-04 mounting bracket
- Pneumatically-powered Z-axis (20" stroke)
- 5" x 5" x3/8" steel box tube test stand
- (2) Moog 152 Series PWM controllers
- (1) Moog 150 Series Power Supply
- (1) Moog 3 winding power transformer
- (1) IBM PC-AT for real-time control
- (1) 96 channel digital I/O BaseBoard
- (1) 6 channel A/D and 2 channel D/A Data Translation Board

Intentionally left out of the prototype were:

- Full-size X-axis
- Full-size Z-axis
- Locking wrist universal joint
- Scissor lift platform

All arm components were machined by the author using in-house facilities. All parts were machined from the materials as specified in this thesis. Following completion of the hardware, a real-time control system was implemented.

3.6 Summary and Concluding Remarks

The final configuration for a robot which is capable of performing concrete block wall building task was selected from a field of 11 conceptual designs. This final design consisted of 2 linear axes, 2 rotary axes, and 2 unpowered rotary wrist axes. The exact

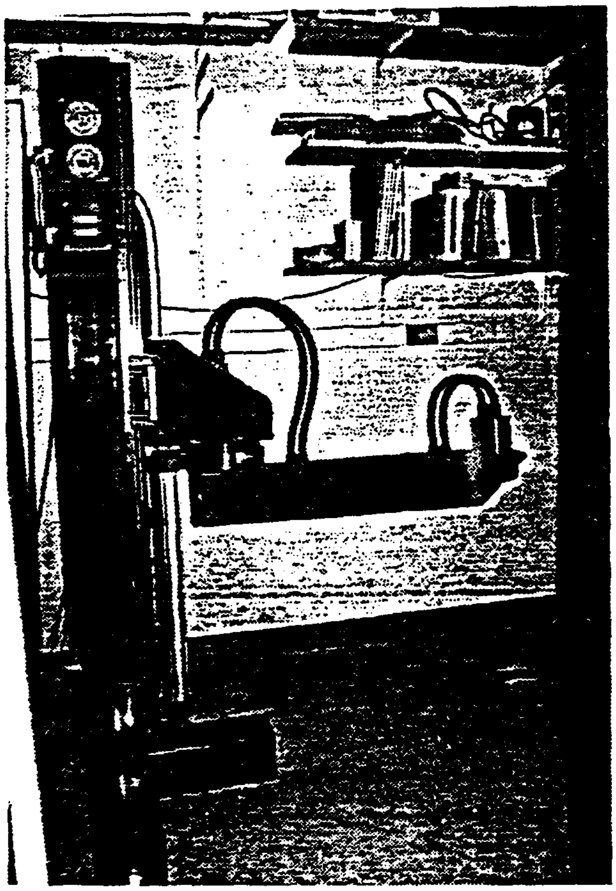

Figure 3.5.1 Completed Prototype Arm

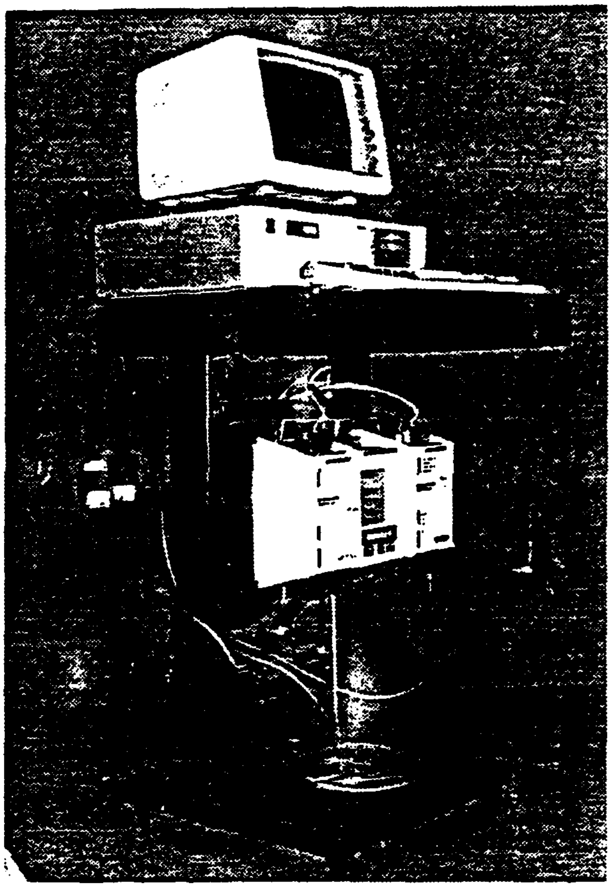

Figure 3.5.2 Control Stand

range of motion of each axis was determined by available ball screw, linear guide, and scissor lift technology. The structural elements were sized through static deflection and stress analysis using Castigliano's energy methods while the lowest natural mode of the structure was calculated using a lumped-parameter model. This natural mode was found to be dominated by the torsional stiffness of the shoulder actuator.

The linear guides and ball screws for the linear axes were initially sized using standard heuristic rules and manufacturer's data. The sizing of these components was then independently checked by the manufacturer's applications engineer. It was found that although the target design speed could only be achieved using custom ball screws, it would be much more economical to build a prototype using stock screws.

Dolan-Jenner Corp.'s precision rotary actuators were chosen for the two rotary axes of this robot. These drives were sized using the procedure recommended by the manufacturer. The two linear axis motors were sized by calculating the load power requirements and comparing this to the output power of a variety of motors. Two brushless DC Moog motors were selected to drive these axes.

Based on the experience of building two of the axes of this robot, a preliminary cost estimate of an entire robotic block placement system was made. This included the following direct equipment costs:

Motors (4 axes)	$10,000
Control hardware (4 axes)	10,000
Control computer	5,000
Structural components	10,000
Linear guides	3,000
Ball screws	5,000
Misc. mechanical	10,000
Misc. electrical	10,000
Laser metrology system components	20,000
Construction scissor lift	25,000
Block supply system (trailer type)	15,000
Bonding cement spraying equipment	15,000
Total materials cost for quantities of one item:	**$138,000**

The target (retail) price was $200,000. Whether the device could be manufactured in quantity for less than $100,000 would require a more detailed economic analysis by marketing and manufacturing experts that is beyond the scope of this work.

4. CONCLUSIONS

Designing the Wallbot and Blockbot construction robots has facilitated the identification of the following common parameters:

Mechanical systems

There is a need for lightweight kinematically designed linear servoactuator-bearing assemblies that can be assembled with other components in module form. Most sub-assembly components (e.g. bearings, ballscrews, and motors) exist as individual stock items, but there should be modular interface units that allow the easier assembly of these components into a design. This will facilitate economical design and fabrication of dedicated modular construction robots that would be easy to repair under harsh field conditions.

Electrical systems

Electrical system components are already available in the modular "plug-in" mode that is desired for mechanical components. Technology in this area is thus entirely adequate.

Sensor systems

Conventional surveying systems are far too slow, inaccurate, or require too much human input to make them useful as sensor feedback elements for real time control of construction robots. To date, the only surveying tool that is useful for construction automation is the rotating laser beacon and light mast that is often used to control blade height during precision grading operations. Other sensors such as tilt meters, theodolites and EDMs are either too slow, too inaccurate, or require too much human effort to be effective. The attainment of a fully active Global Positioning System will help layout location of system boundries, but will not be fast enough to achieve the 0.001 second update times required to facilitate real time control of robots. Thus research is needed in the area of fast, automated, accurate sensors for angle and distance measurement with part per million accuracies.

Overall Conclusions

The principal conclusions to this work are thus:

1) Construction robots can be designed to effectively increase productivity and quality of specific construction tasks.

2) General purpose construction robots (e.g. robots which emulate a human worker) are neither technologically or economically feasible, and will not be for the forseeable future.

3) Because only dedicated machines are technologically or economically feasible, the technology for designing dedicated construction robots is well known by experienced designers of machine tools and robots.

4) The principal research endeavors needed to advance the state-of-the-art of construction robots are:

a) Identification of which processes to automate. This requires a thorough detailed analysis of the construction process on a case by case basis for all types of construction processes. Only then can the go-ahead for the design of a specific robot be given.

b) Development of advanced angle and distance measuring sensors with order of magnitude greater accuracy and speed than are presantly available. Because sensors are so expensive, the number required needs to be minimized in reduce cost, but more importantly, to reduce the chances of damage on-site. Maximizing the autonomy of any given construction robot requires an increase in sensor accuracy so the robot can perform for a longer period before a sensor is needed to pick up where another sensor's accuracy is left off. Research in this area could overlap with the Strategic Defense Initiative program.

<u>5. PUBLICATIONS AND TECHNICAL REPORTS</u>

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3) Schena, Bruce, "Design Methodology for Large Work Volume Robotic Manipulators: Theory and Application", S.M.M.E, Sept. 1987.

4) Levy, David, "Studbot: A Construction Robot for the Automated Assembly of Steel-Stud Partition Walls", S.M.M.E, Sept. 1987.

5) Slocum, A.H., Demsetz, L. and Levy, D., "Automated Construction of Partitioned Wall Framework",

6. Participating Scientific Personnel

Prof. Alexander H. Slocum, George Macomber Career Development Assistant Professor of Civil Engineering

Ms. Laura Demsetz, Research Assistant, Department of Civil Engineering

Mr. David Levy, Research Assistant, Department of Civil Engineering

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