Construction Automation Research at the Massachusetts Institute of Technology

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ABSTRACT

Approaches to automation range from very flexible machines designed to emulate humans to dedicated machines designed for a specific task. The latter approach is being used at M.I.T. in the development of computer controlled machinery to help automate construction processes. This paper presents current work on three types of construction robots: the Wallbots -- robots to build interior walls, the Blockbot -- a robot to build masonry block walls, and the Shear Studwelder -- a robot to weld shear studs to beams and decks. All these machines are currently being fabricated at M.I.T., with testing scheduled for the summer of 1987.

1. INTRODUCTION

Construction companies worldwide are experiencing a decline in business and profits. For example, the U.S. construction industry has suffered a 1.5% annual loss in productivity over the past 10 years [1]. Insurance costs are disproportionally high, a reflection on the strenuous and often hazardous nature of construction tasks [2]. To reduce cost and improve productivity and safety, many researchers have proposed the introduction of automation to the construction industry [2,3,4,5]. They have extensively analyzed processes for automation, but have not yet developed and demonstrated explicit machine design methodologies.

A method to efficiently and economically automate construction processes is currently being developed at M.I.T. [6]. Called ICADM (Integrated Construction Automation Design Methodology), the method calls for integrating the efforts of the materials supplier, the architect, the building contractor, and the machine designer. The design of machines to

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perform construction tasks is simplified and made more economical by considering task-specific computer numerical controlled (CNC) machines with construction workers as machine operators

With funding from the Army Research Office, the Department of Civil Engineering has established a Center for Systems Automation to further develop ICADM. Machines for automating construction tasks have been designed, and are being built and tested.

Automating construction processes requires measurement in an unstructured environment with a precision equal to that of many metal manufacturing processes. For example, tolerances in the design of an automobile engine are on the order of 0.05mm/5cm (l/1000). Electronic surveying equipment is used to measure large buildings during assembly to ensure straightness of 1 cm over a height of 100 m (l/1000). As a result, emphasis in machine design is placed on trying to achieve end-point feedback to minimize cost of components.

These ideas are illustrated through the design and fabrication of machines to automate construction of interior walls, construction of block walls, and welding of shear studs.

2. Machines to Build Interior Walls: Wallbots

The idea to apply ICADM to wallbuilding was developed while touring buildings of post and slab design. Discussions with contractors on site indicated that once the structural frame had been constructed, installing the interior framing was the next major step in the building process. After the walls were framed, the plumbing, electrical, and HVAC work could begin. Thus, in this case, completing the framing faster is as important as saving money.

At first glance, the automation of framing operations seems almost impossible, as shown in Figure 1. But observe the long hallways shown in Figure 2; they are prime candidates for automation. There are some obstacles, such as shear walls, extending into the plane of the wall, as shown in Figure 3. In other hallways, however, the shear walls are placed back from the wall as shown in Figure 4. The architect was consulted and saw no

1. Nuclear Waste
2. Wallbots
3. Block bot

problem with placing all the shear walls back from the main hallways. Further consultation revealed that in many new buildings, as well as those scheduled for rehabilitation, the room structure is very regular, allowing much of the framing work to be accomplished by machines capable of moving only in straight lines. The machines could install segments for walls dividing the rooms first, leaving gaps for the hallways. The hallways could then also be installed by machine.

Excluding land purchase, about 10% of the cost of a commercial office building is spent on interior wall construction. Of this amount, perhaps 20% could be automated. If 50% cost savings are realized through automation, then 1 % of the building cost can be saved. For a 100 million dollar office building, over one million dollars could be saved.

Following the ICADM design philosophy, a pair of machines to install interior walls, the Wallbots, were designed and are being built and tested. It was decided to require the machines to operate only in a straight line and to install only track and full height studs. Door headers will be installed manually. This division of labor made design of an economical machine possible.

A gap in current technology identified in the ICADM process is a guidance system suitable for sensing location of a machine with respect to the building frame. Therefore, the layout of the wall requires a worker to bridge this gap until new technologies are developed. Rather than indicating wall location with a chalked line as is now done, the worker will set up a laser beacon so that the beam coincides with the desired wall location. The laser is used for guidance by the first machine, the Trackbot. It can be removed once the Trackbot's task is complete, as the machine to install studs, the Studbot, guides off the installed track. Floor geometry (length and location of hallways, location and size of doors, location of obstacles such as elevator shafts) will be entered into a central database which will generate an optimal sequence of wall construction tasks. This information will then be provided to each machine's on-board microprocessor, and to the machine operator at the site.

2.1 MACHINE TO INSTALL TRACKS: TRACKBOT

The Trackbot, shown conceptually in Figure 5 and during the first stages of construction in Figure 6, positions and fastens the track on both the floor and the ceiling. Mounted on the machine base are two workstations which operate in parallel, an upper for the ceiling track and a lower for the floor track. The track sections are loaded in bundles as received from the manufacturer. Detectors for the laser guidance system are mounted at the end of the positioning arms, allowing precise positioning of the track. The vehicle path is corrected with respect to the positioning arms, producing a very efficient "course/fine" positioning system. With the track sections correctly aligned, the positioning arms raise/lower the piece to the ceiling/floor. Two pairs of pneumatic nail guns are used to fasten the track (one pair for the ceiling, one pair for the floor). A track section is firmly anchored into place with two nails on both the floor and the ceiling. The trackbot then moves forward, making two additional stops for nailing before placing the next section of track. Distance travelled is measured by an encoding wheel. The track is nailed according to the location of doorways and studs described in the previously stored floor plan.

2.2 MACHINE TO INSTALL STUDS: STUDBOT

The Studbot, shown conceptually in Figures 7 and 8 and during prototype construction in Figure 9, positions the studs and fastens them to the track. The vehicle path guidance system measures distance from the track flange to the vehicle. Distance travelled is measured with an encoding wheel or electronic distance measuring instrument (EDM). 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 previously stored floor plan database). A pair of material handling arms pick the top stud out of the bin. A positioning arm grasps the (still horizontal) stud, flips it so the web of the channel faces the track, rotates it near vertical, and moves it between the upper and lower tracks. The arm then rotates the stud to a vertical position, and twists it into place between the track flanges. The direction of twist is determined by the desired final orientation of the stud as detailed in the floor plan database. The positioning arm has a long beam which runs the length of the stud, and supports the spot welding mechanisms. It also provides the torsional support necessary to accomplish the twist.

2.3 WALLBOT ECONOMICS

A preliminary economic analysis of the Wallbots considers only the savings due to reduced construction cost on a per foot basis. Labor costs for manual installation are $1.80 per lineal foot (10' high wall, 4" studs, 24" o.c.) [7]. Assumptions used in estimating the cost of using the Wallbots 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.
- Each machine has a 5 year life with no salvage value.
- Each machine operates at a speed of 2 ft./min. (with maximum design speed of 5 ft./min.).
- Each machine operates only 16 hours per week.
- Each machine requires 40 man-hours per week (for operation and maintenance), at $20/hour.

Using these assumptions results in a maintenance cost of $0.20 per lineal foot of wall, and a labor cost of $0.83 per lineal foot of wall. The total cost using Wallbots is thus $1.03 per lineal foot of wall.

Use of the Wallbots thus results in a savings of $0.77 per lineal foot. The machines can install about 100,000 feet 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. This is a rate of return on investment on the order of 37% per year. Operating at two feet per minute, 16 hours per week, the wallbots 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.

3. ROBOT TO BUILD MASONRY BLOCK WALLS: THE BLOCKBOT

The construction of long, one and two-story concrete block walls is a prime candidate for automated assembly. It is a well-defined, repetitive task, which is time consuming, labor intensive, and potentially dangerous for workers. Although many other methods exist for building walls of moderate strength, the block-and-mortar wall is one of the most common. The National Concrete Masonry Association (NCMA) estimates that 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, the major cost is in labor; in this case nearly 60%. Automation could help to decrease construction time as well as a increase quality (improve straightness and plumbness).

The construction of concrete block walls by conventional techniques is slow, labor intensive, and highly repetitive. The rate of increase of the wall height per day is not a strong function of the mason's skill, but rather the setting time of the mortar between the courses. 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 of block resulting in a wall which may be uneven and out of plumb. Such a wall may also run the risk of falling over before it completely cures.

According to the NCMA, an experienced mason, with the help of a laborer, can set roughly 400 blocks per day. Preliminary estimates based on a $250,000 initial investment, a payback period of 2 years, and a $125,000 yearly maintenance cost indicate that this machine must place roughly 8 blocks-per-minute, four hours-per-day, four-days-per week to be feasible. Even with this intentionally conservative economic analysis, this 8 blocks-per-minute figure is thought to be quite reasonable. An arbitrarily selected goal of 10 blocks-per-minute is used in the initial machine design.

3.1 CONCEPTUAL DESIGN OF THE BLOCKBOT

It has been rumored that an inventor in Detroit, Michigan (USA) built a machine to lay block and mortar walls in the late 1960's. However no reference has been found.

It is currently envisioned that the complete wall assembly system will consist of 4 major components:

1) A six axis "head" that will actually place the blocks on the wall (approximate work volume 6' x 10' x 4').
2) A 20 to 30 foot hydraulic scissor lift used to coarse-position the placement head vertically and longitudinally.
3) A large-scale metrology system and sensors and other related computer control equipment.
4) A block feeding system/conveyor to continually supply the placement head.

Since the scale of this project is so large, current work focuses on the design of the actual block placement head. Two conceptual pictures of the placement head atop the scissor lift are shown in Figures 10 and 11.

The current 2 linear axis/4 rotary axis layout is the result of preliminary analysis of a field of 12 original configurations. It was felt that the current kinematic layout is the most compact, the easiest to build, the least expensive, and will be relatively easy to control. The sizing of the axes and overall layout were subject to the size of commonly available lifts, existing linear bearing and lead screw technology, and dynamic and static considerations.

3.2 MACHINE OPERATION

To facilitate automation, the blocks will be dry-stacked directly on top of one another without spacers. This will increase placement rate and at the same time will increase the "dry" wall's stability. Then the entire wall (or major section) will then be surface-bonded using a product called Surewall®. This material is a fiberglass-reinforced bonding cement which can be spray-applied to both wall faces. This fully certified technique will produce a wall with strength comparable to that of a conventional block-and-mortar wall.

4. ROBOT TO WELD SHEAR STUDS: SHEAR STUD WELDER

Since the advent of the stud welding gun, the use of shear connectors in composite steel/concrete construction has gained widespread popularity. Building and bridge deck construction incorporates large numbers of studs. Typically, two workers can place 2000 studs on a building deck in one day [8]. Bridge rates vary somewhat due to inconsistent site conditions. One worker will lay out studs and ferrules (welding shields/molds) where they are to be welded, and the other worker will follow with a stud gun and weld them in place. The first worker, in turn, breaks the ferrules away from the studs. Random testing is then done to insure good weld quality. With as many as 40,000 studs in a single building, the stud welding process is highly repetitive with very little variation.

A great number of automatic stud welding systems are currently in operation in factory environments, welding a vast array of studs. However, none of the systems deal with large, headed studs such as the ones used in buildings and bridges. This is due to the problems associated with feeding such studs into a welding chuck. Vibratory/pneumatic feed systems are generally too bulky to be used on a mobile stud welding machine. A successful shear stud welding machine will need a novel feed concept for both studs and ferrules. Additionally, this system must be adaptable to the varying conditions encountered at construciton sites.

There have been earlier attempts at speeding, if not automating, the shear stud welding process. Roughly 20 years ago, the Nelson Stud Welding Company marketed a device which held 4 stud guns and rolled along an I-beam[1, 2]. The operator manually indexed, loaded and welded the studs. While the machine made accurate, high quality welds, it was slower than a single operator.

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1 Conversation with Roger Scholle, Engineer, Nelson Stud Welding Division of TRW, Oct. 1986.

2 Conversation with Martin Molloy, Senior Sales Representative, Erico Fastening Systems, Nov. 1986.

I-beams and bridge decks are particularly suited to automated shear stud welding because machine guidance is simple. The welding machine merely uses the edge of the beam or deck as a guide. The Nelson product utilized this type of guidance even though the welder was moved along manually by the operator. However, in some instances there may be obstructions such as rebar and concrete forms in place before the stud welding operation commences. Depending on the region of the country, there may also be a thick layer of a rust inhibitive coating which must be ground away before welding can take place.

Building decks represent more difficulties in terms of guidance and obstacles for a stud welder and fewer difficulties in terms of site consistency. The studs must be welded through decking into stringers which generally abut vertical structural members. The stringers are visible to some extent through small holes in the decking. Stringer location can also be inferred by sighting directly down from the stringers supporting the floor above. In either case, this is easier for a human than for a simple machine to do. The corrugations in the decking may present some difficulties as the studs must be placed and welded in the valleys, while the machine itself will probably need to clear the peaks. Additionally, the vertical structural members in a building present periodic obstacles in what otherwise might be a simple, clear path for a stud welder.

Physical suitability for automation notwithstanding, it appears that stud welding on building decks may be the first choice for automation based on volume alone. Of all the studs used in buildings and in bridges, 70% to 80% are used in buildings[3,4]. The economic potential for automating the stud welding process in buildings appears to be much greater than that for bridges at this point. The remainder of this proposal assumes that an automated stud welding system will be developed primarily for buildings. This system could easily be adapted for use on bridge construction as well.

3 Conversation with Bob McGarrahan, Senior Engineer, Daniel Marr and Son Company, Nov. 1986.

4 Conversation with Bruce Weber, Vice President, East Penn Stud Welding, Oct. 1986.

For any new process to be successfully adopted, that process must be proven to be clearly superior to the old one in terms of productivity and quality. A new machine or system should have a short payback time on the initial investment along with a substantial rate of return. In order to asses the economic potential of an automated stud welding system, a comparison was made between similar manual and automatic stud welding scenarios. The assumptions used for both scenarios are listed below:

- Two workers can manually place 2000 studs per day (1000 studs per worker per day).
- Each worker costs $25 per hour including overhead and other related expenses.
- An automatic stud welding machine would have a retail cost of $12,000 not including power supply or controller. Large scale manufacturing costs may be as low as $500 per machine.
- One full-time worker is required to operate the automated system.
- When operating, the system welds one stud every five seconds.
- The machine is actually in operation for only 25% (two hours) of one eight hour shift per day. The remaining time is spent on reloading, repositioning, and maintenance. (Net output is 1440 studs per worker per day.)
- The system's expected operational life is five years.
- Maintenance costs are estimated at 30% of purchase price per year.

Material costs (which include power supply and controller), assumed to be the same for both systems, are neglected from the analysis. Calculations based on the above assumptions yield costs of $0.20 per stud in the manual case and $0.15 per stud in the automated case. The resulting saving of $0.05 per stud corresponds to a payback time of roughly six months and a net savings of $80,000 over the machine's five year life span. The annual return on the initial investment is better than 45%.

5. Conclusions

The goal of automating the construction of a major portion of a building will not be realized for many years. In the meantime, dedicated machines designed to automate specific processes can help to realize this ultimate goal by promoting industry confidence. In designing machines to automate construction processes, several factors should be considered:

1) The goal in automating construction tasks is to:

- Increase productivity
- Enhance quality
- Increase safety

2) The most effective way to automate construction tasks is to:

Combine a human's:	With a machines':
• Sensors	• Speed
• Intelligence	• Strength
• Adaptability	• Repeatability

3) The design approach for construction robots should be:

- 1 to 2 years concept to manufacture
- Task specific
- Rugged and reliable
- 1 to 2 year payback
- Minimum 5 year lifetime

4) These goals can be accomplished with ICADM, which seeks to coordinate actions of system's designers:

- Material Suppliers
- Architect
- Builder
- Machine Designer

Only when lines of communication are established between the many trades and professions that make up the construction process will the industry have any hope of seeing the introduction of automation technologies.

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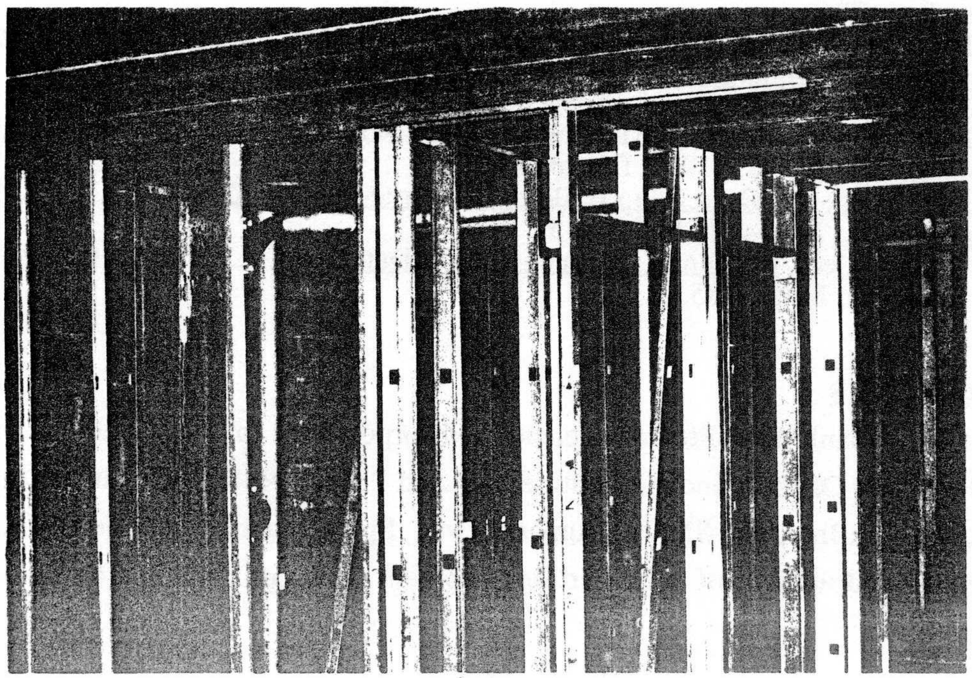

Figure 1 Complex interior wall framing

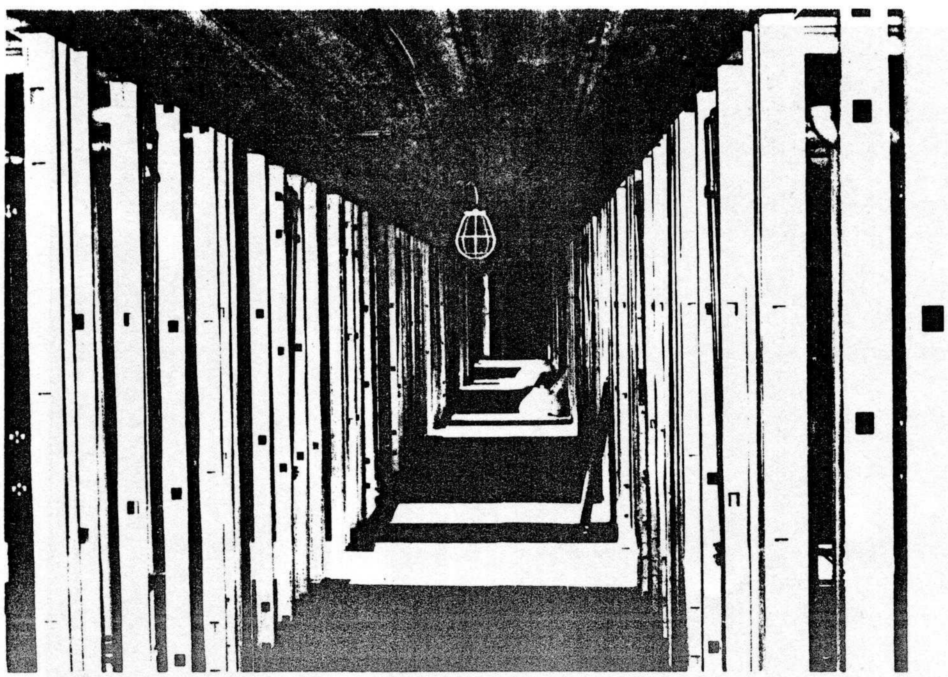

Figure 2 Automatable long hallway

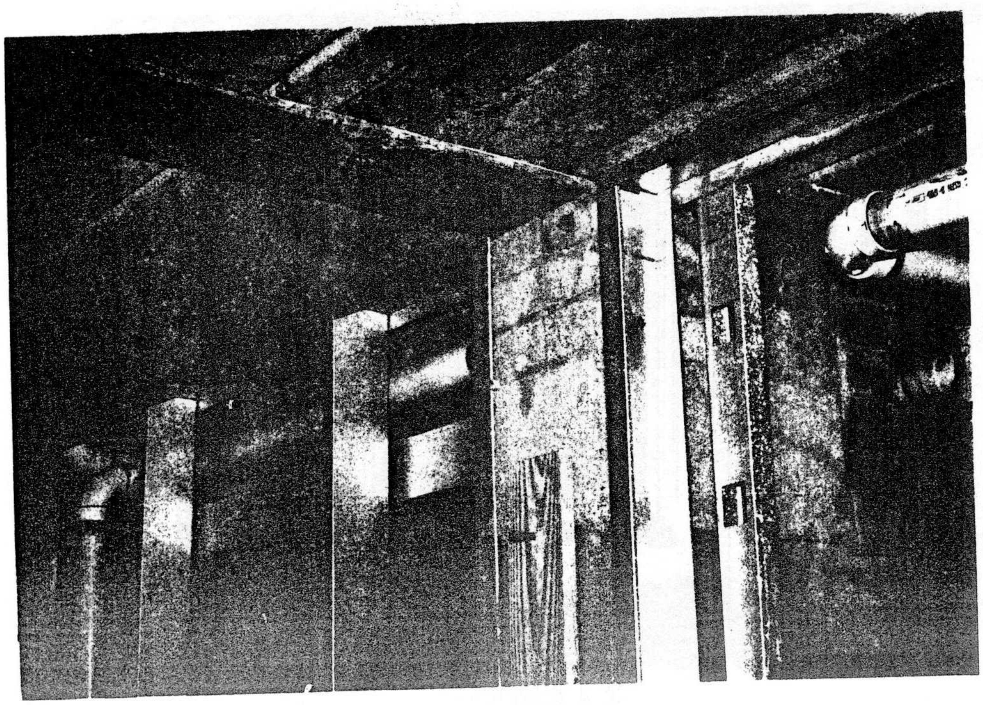

Figure 3 Shear wall disrupting continuity

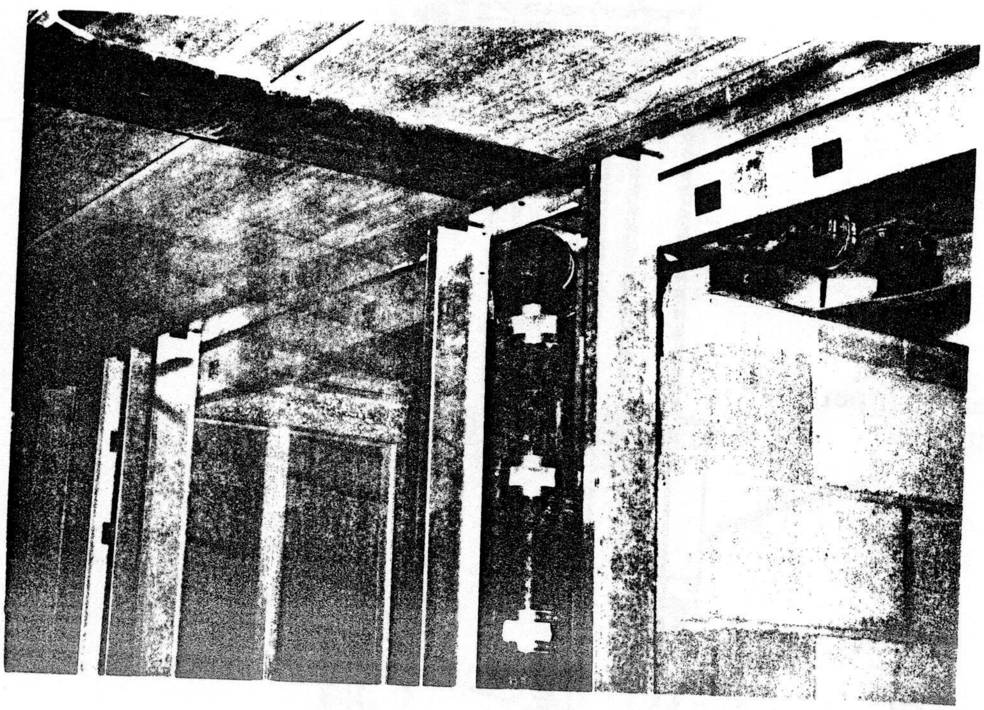

Figure 4 Shear wall set back from hallway

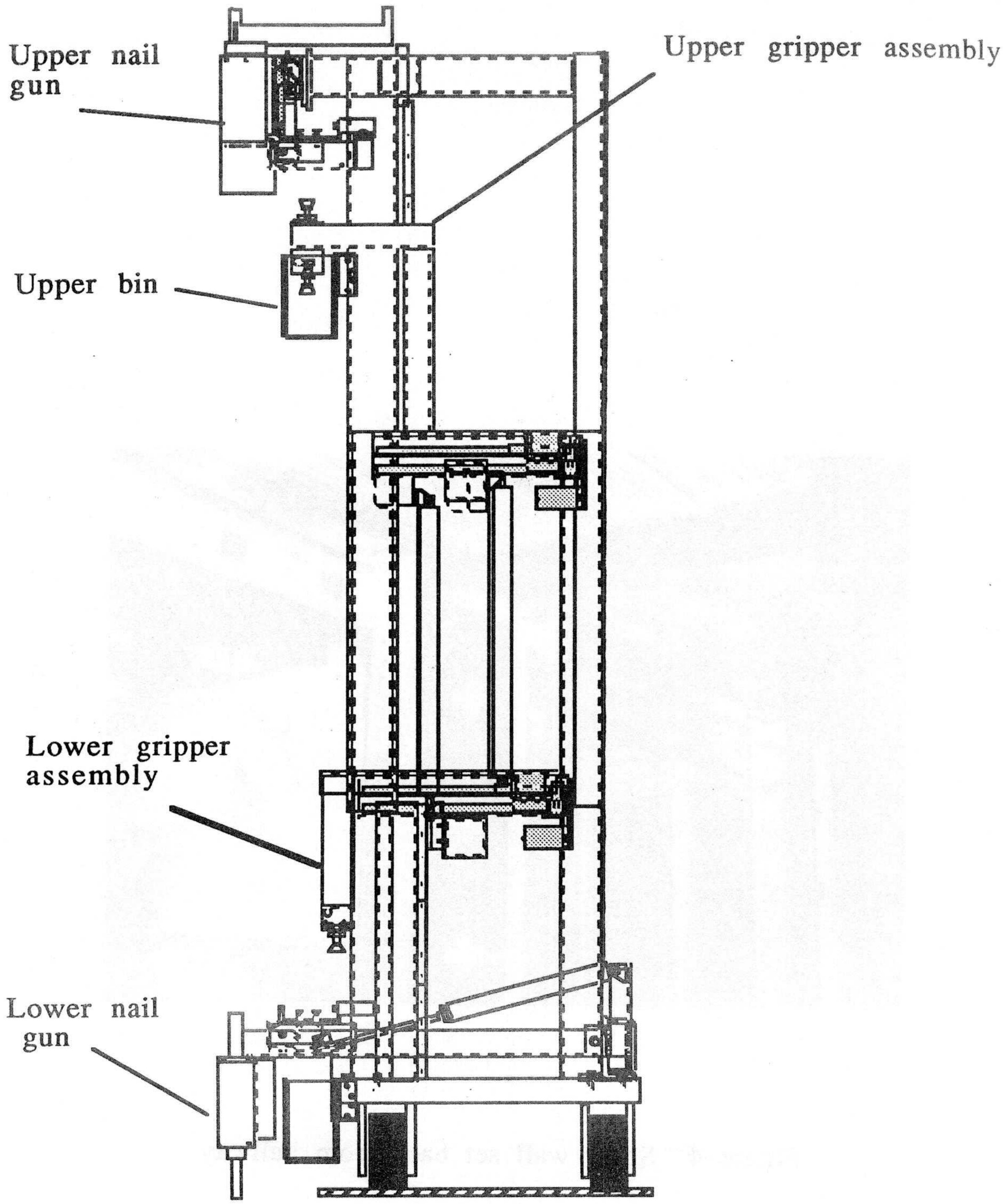

Figure 5 Schematic side view of Trackbot

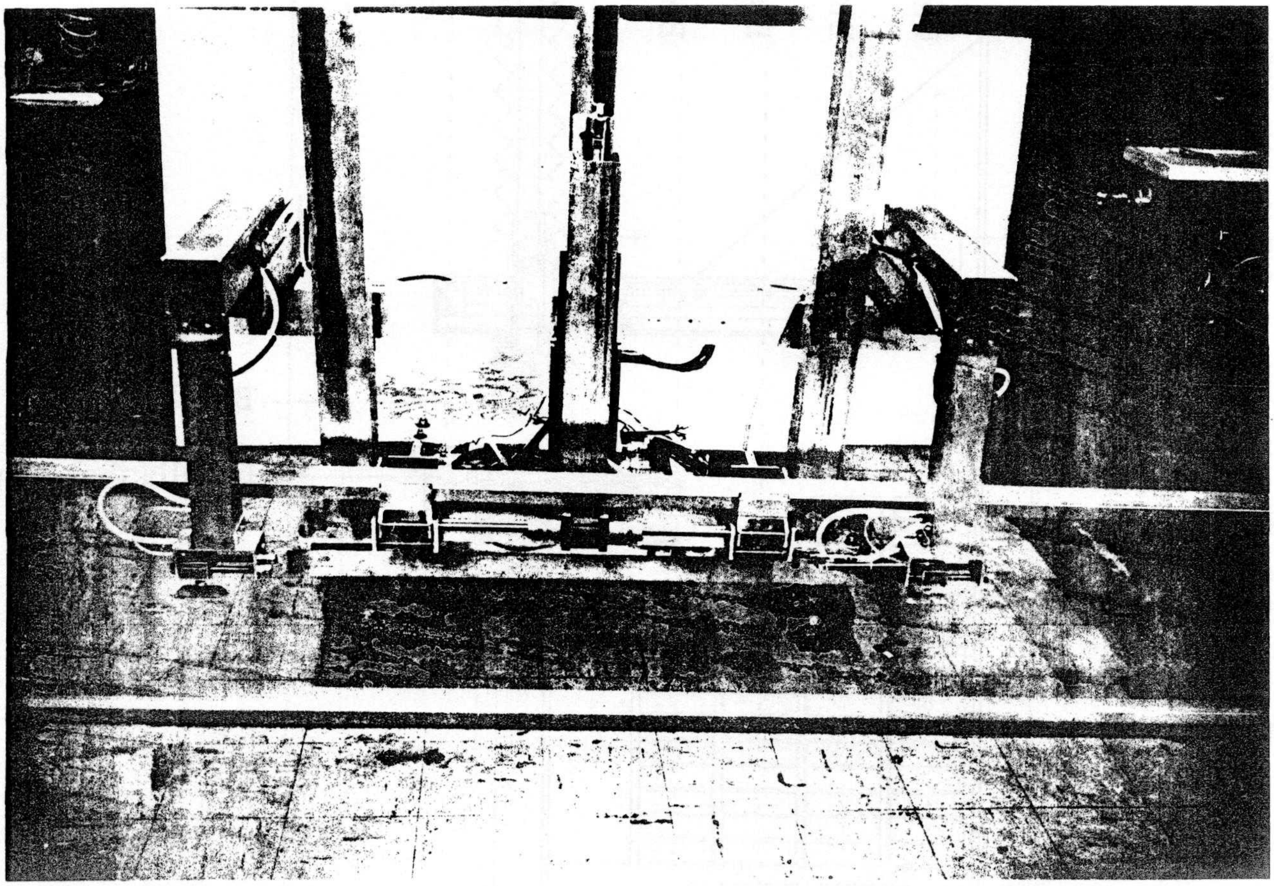

Figure 6 Trackbot during fabrication

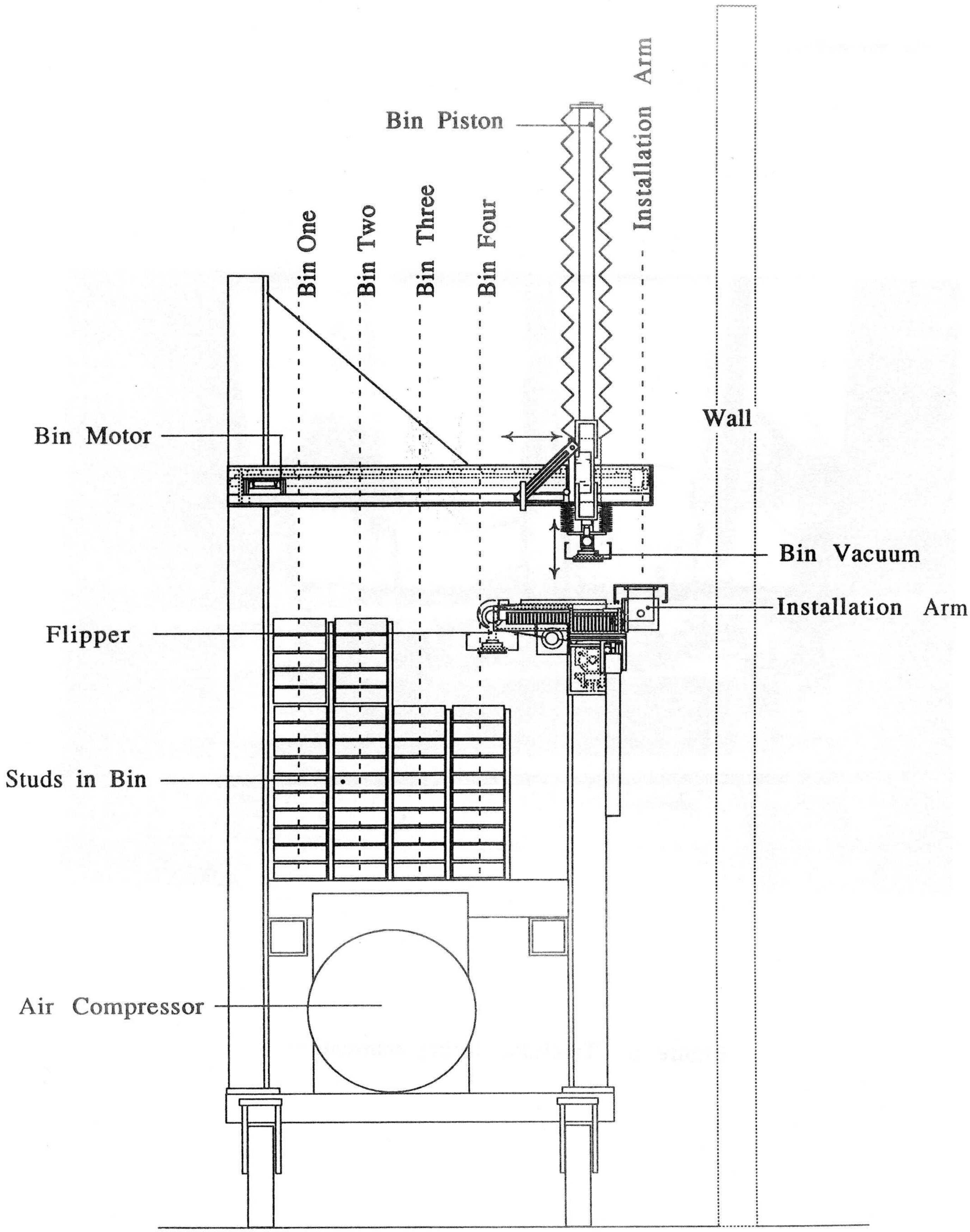

Figure 7 Side view of Studbot

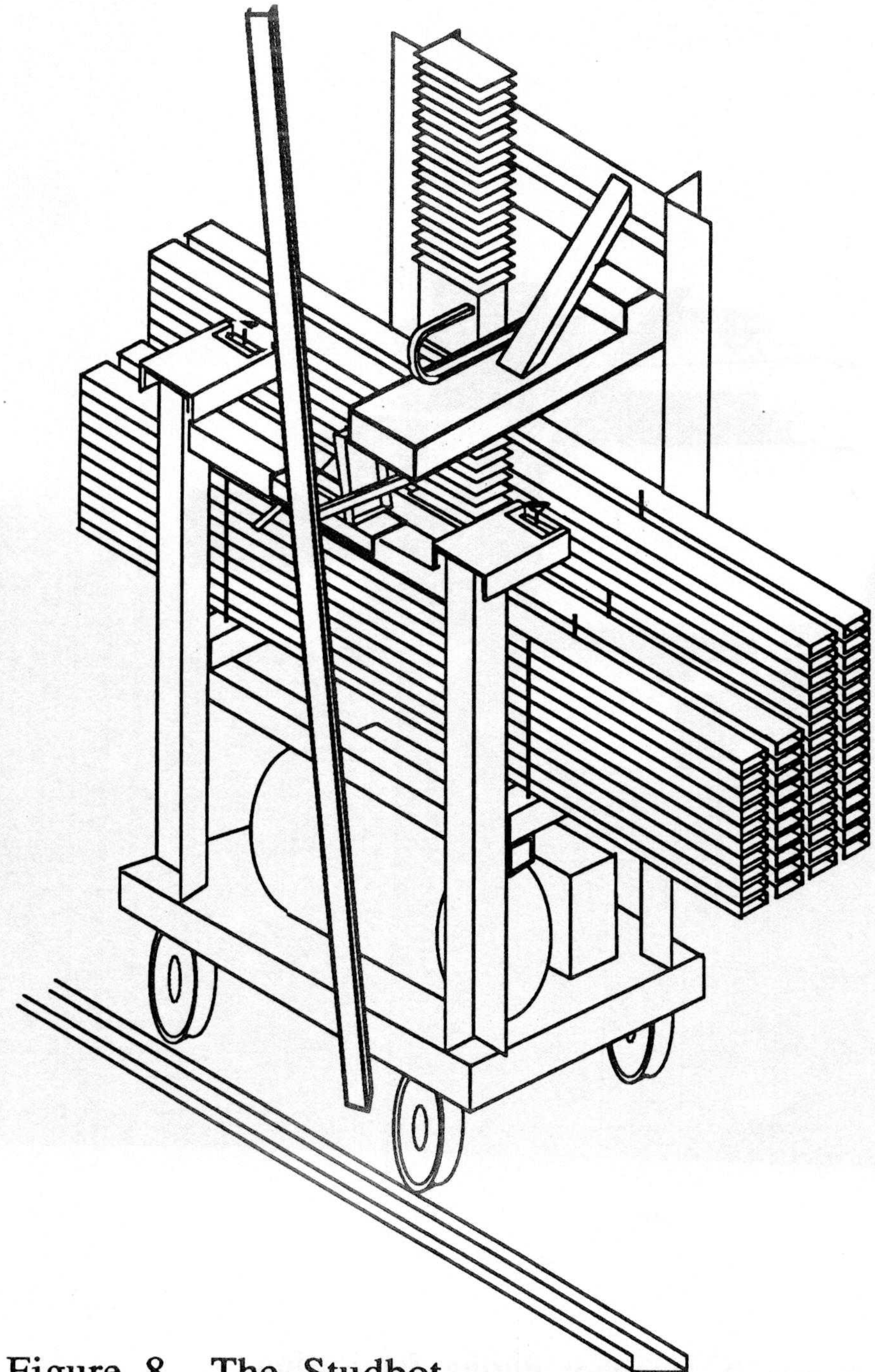

Figure 8 The Studbot

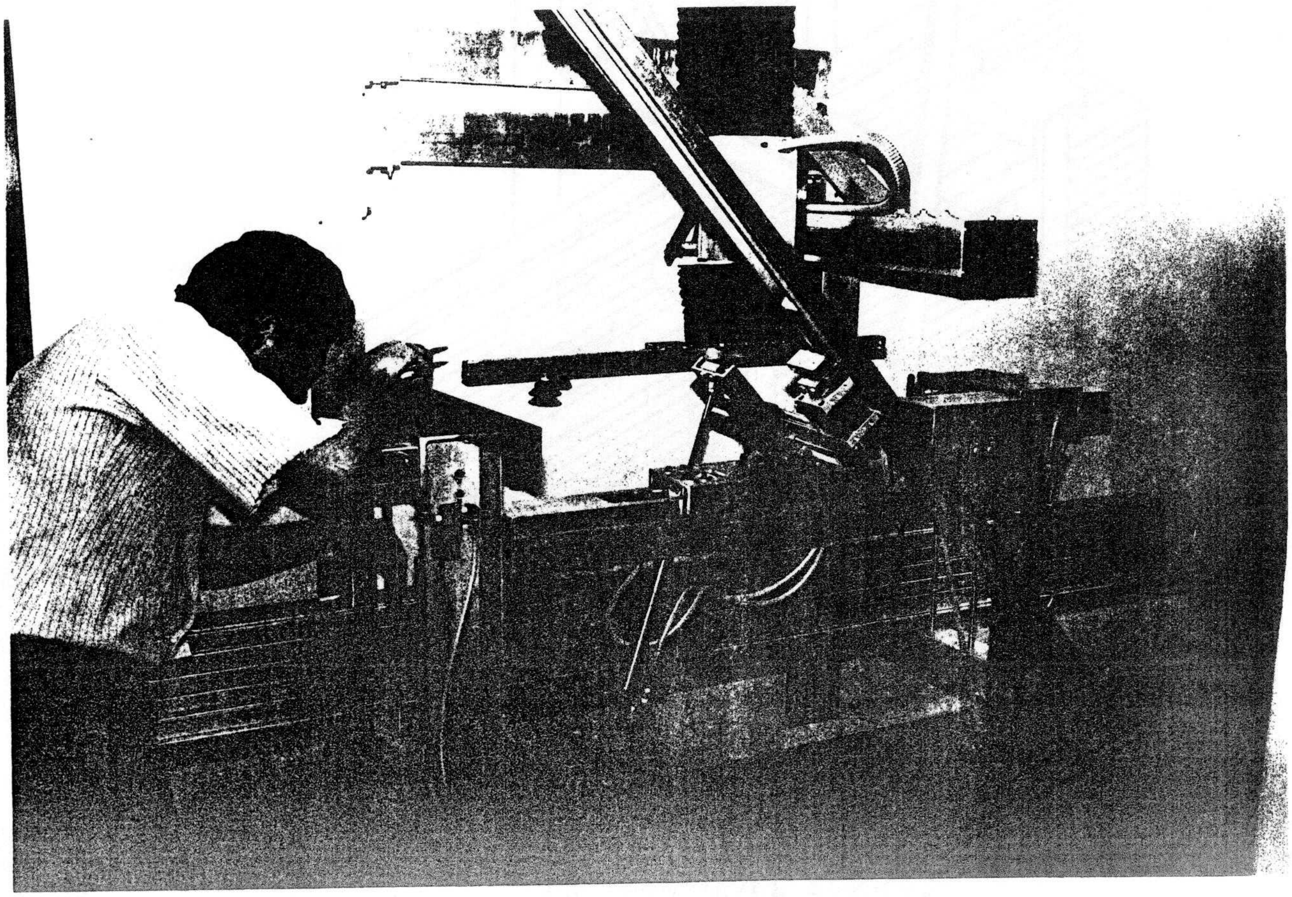

Figure 9 Studbot during fabrication

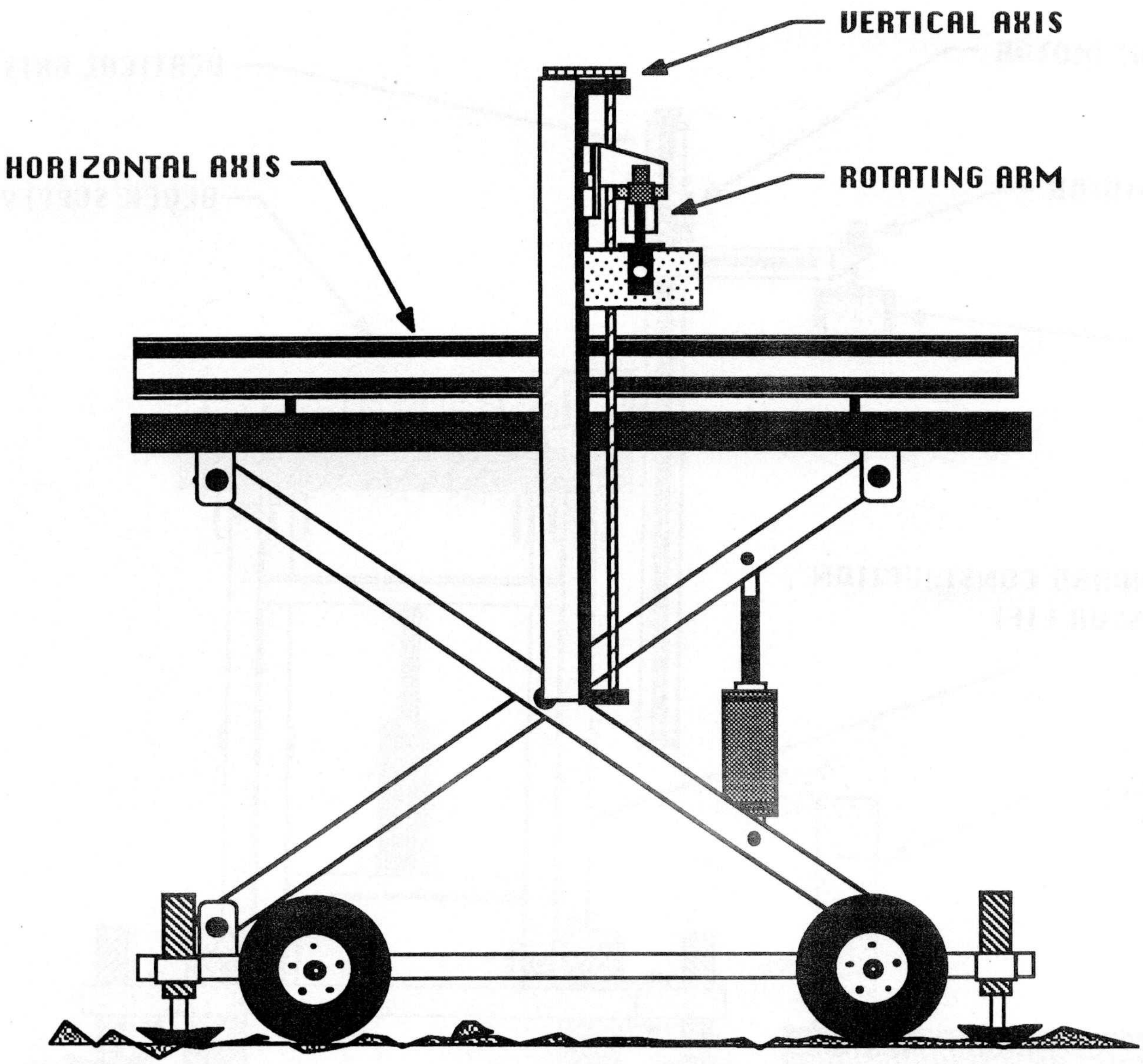

Figure 10 Blockbot side view

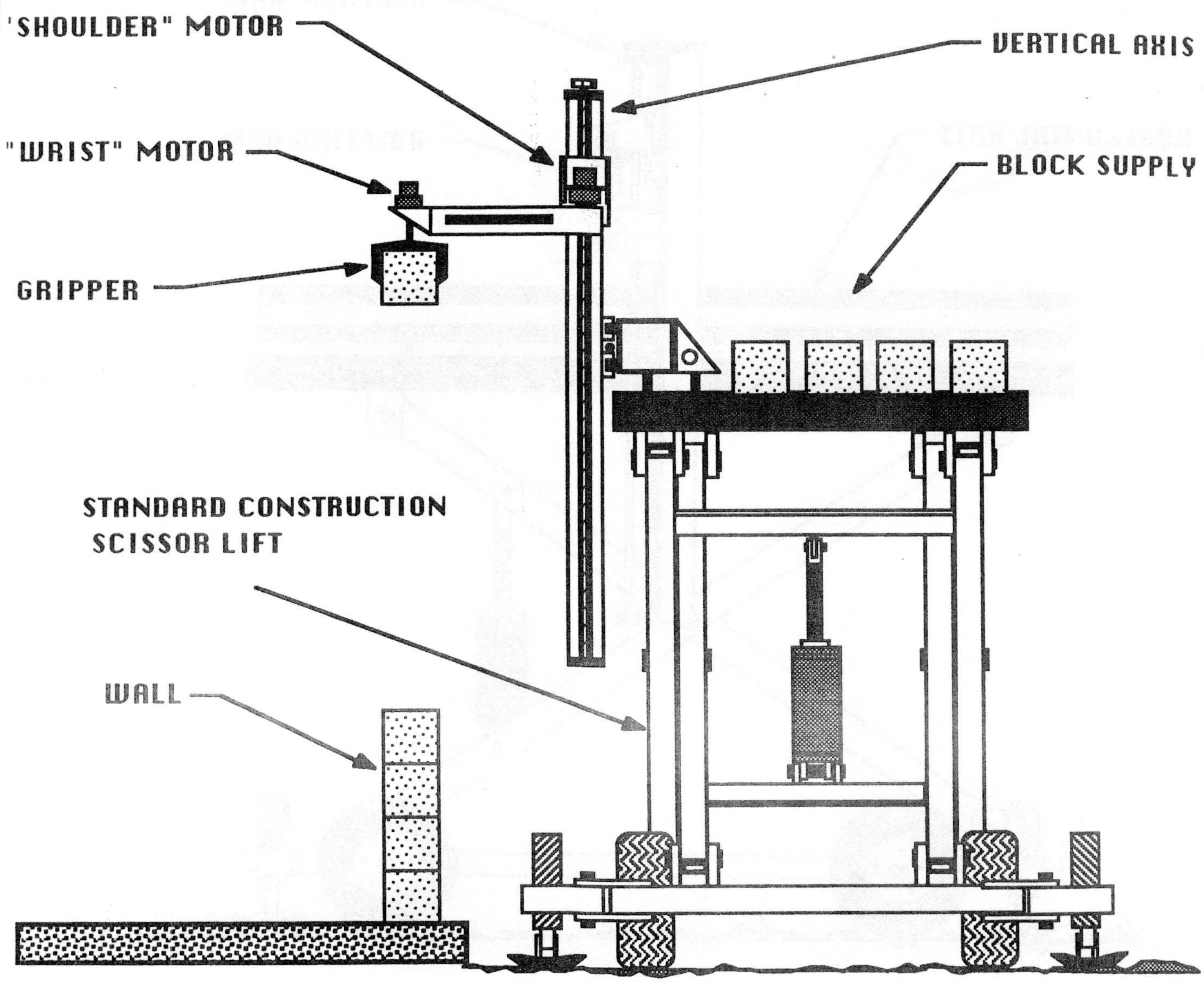

Figure 11 Blockbot End View