Trip Report: Japanese Progress in Robotics for Construction

James S. Albus
Chief, Robot Systems Division, Center for Manufacturing Engineering, National Bureau of Standards, Building 220, Room B-124, Gaithersburg, MD 20899, USA.

Location visited

Tokyo, Japan; May 27–June 1, 1985.

This trip was part of a study mission sponsored by the Technology Transfer Institute, and co-sponsored by the Construction Robotics Laboratory at Carnegie Mellon University. The study mission visited six of the largest construction firms in Japan, a University, and a Robotics Research Association.

Perhaps the most important finding is that all the major Japanese construction companies have large research budgets and impressive in-house research staff. Of the companies we visited, all had research laboratories staffed with more than 200 people, and budgets in excess of $10 Million. These companies aggressively compete with each other in many areas of advanced technology, including construction robotics, and are actively transferring results from the research laboratory to the construction site.

Although there is as yet no significant direct government funding of construction industry research in Japan, many of the government contracting procedures for large construction projects seem to be designed to encourage research into innovative techniques. Also it seems that building codes and regulations set by the government can be changed rather easily to accommodate newly developed building techniques. Thus, any Japanese company which implements a new technique to improve productivity or quality can reasonably expect to reap a large profit.

It is also important to note that the Japanese practice of saving and investing between two and four times as much as Americans has created a growth economy in which construction is 20% of the GNP. Construction is about 8% of GNP in America. Thus, the Japanese construction industry is very healthy, aggressive, and searching for new technologies to exploit both at home and abroad.

The Japanese emphasis on new construction technology contrasts sharply with the situation in American where construction firms typically spend *absolutely nothing* on research. Furthermore, American construction companies rarely use any machine that is not a well established product, and are reluctant to introduce new techniques onto the construction site unless forced by competitors. Also building regulations and union grievances work to discourage attempts to change construction procedures.

My distinct impression was that the Japanese construction industry will provide significant competition to American firms within the next decade. The large Japanese companies have about 10% of their operations overseas. While they may not choose to directly compete for construction contracts in the American domestic market, they will surely be formidable competitors for American firms with overseas operations. It also seems possible that within the next decade Japanese construction machinery may begin to dominate world markets much the same as Japanese automobiles and machine tools do today.

Keywords: Construction robotics, Research, Software

Dr. James S. Albus is presently Chief of the Robot Systems Division, Center for Manufacturing Engineering, National Bureau of Standards. He is responsible for robotics and automated manufacturing systems interface standards research at NBS, and designed the control system architecture for the Automated Manufacturing Research Facility. He has received several awards for his work in control theory including the Department of Commerce Silver Medal, the Industrial Research IR-100 award, and the Joseph F. Engelberger Award which was presented at the International Robot Symposium in October 1984 by the King of Sweden.
Before coming to the Bureau of Standards, he worked 15 years for NASA Goddard Space Flight Center where he designed electro-optical systems for more than 15 NASA spacecraft. Seven of these are on permanent display in the Smithsonian Air and Space Museum. For a short time, he served as program manager of the NASA Artificial Intelligence Program.
Dr. Albus is the author of numerous scientific papers, journal articles, and official government studies. He has also written for popular publications such as Scientific American, Omni, Byte, and The Futurist. He is often quoted on the subject of robotics by national media such as Time, Fortune, Wall Street Journal, and the N.Y. Times, and has appeared in a number of radio and TV interviews.
He has written two books, "Brains, Behavior, and Robotics" (Byte/McGraw-Hill 1981) and "Peoples' Capitalism: The Economics of the Robot Revolution" (New World Books 1976).

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1. Specific Sites Visited

1.1 Taisei Corporation

Taisei has net annual sales of $4.5 Billion, 64% of which is building construction, and 30% is civil engineering. Construction projects include hotels, office buildings, schools, hospitals, nuclear power plants, and factories. Civil engineering projects include oil refineries, high speed railway tunnels, dams, and water treatment plants. About 10% of annual sales were from overseas projects, primarily in Southeast Asia, the Middle East, Africa, and South America. Only 4% of Taisei business is housing, but they have some very interesting new techniques of using concrete foam and wood in ways designed to satisfy the taste of the Japanese consumer.

The Taisei Corporation commitment to high technology is exemplified by their Technical Research Institute with a yearly budget of $25 Million, a staff of 130 researchers, and 90 persons dedicated to development and transfer of advanced technology into use on the construction site. Taisei conducts research in building materials, construction techniques, structures, earthquake engineering, and off-shore construction. They built the world's first undersea sewage disposal plant, have made pioneering developments in abrasive waterjet methods for cutting steel, rock, and concrete, and are conducting research and development of new tunneling techniques based on the New Austrian Tunneling Method. They have developed a microcomputer control system for shield tunnel boring machines, an underwater T.V. system for inspection, robots for spraying concrete, and inspecting wall tile. They are also developing computer software for concrete laying robots such as shown in Fig. 1 to control the position of the hose, the amount of concrete applied, and to prevent collisions between the hose carrying mechanism and the existing building structure.

1.2 Takenaka

Takenaka is a $3.1 Billion per year company. It constructs government and office buildings, educational, medical, and health care facilities, hotels shopping centers, high rise housing, transportation, industrial, and communication facilities About 10% of its sales are overseas, primarily in

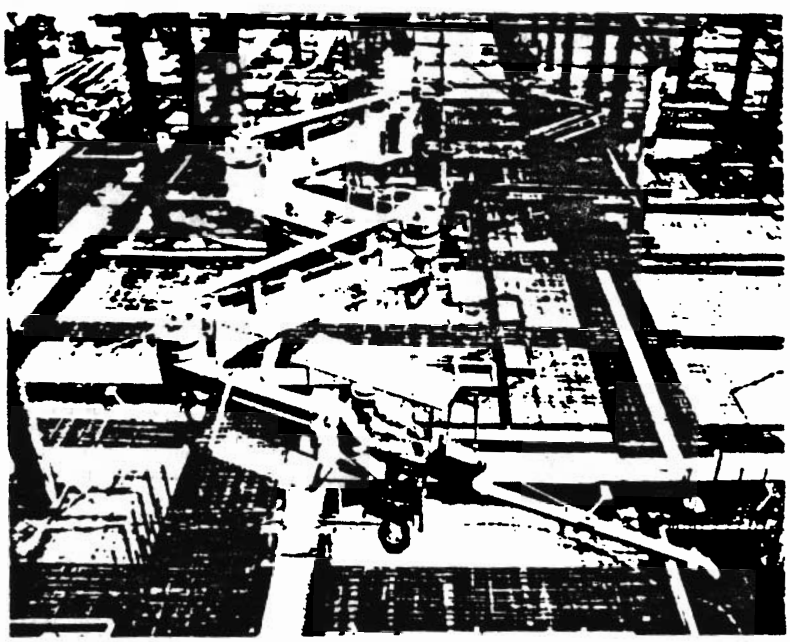

Fig. 1. Horizontal concrete distributor.

Southeast Asia, Europe, and the Americas. It has offices in Los Angeles and New York. The company, which has been in business since 1610, attaches foremost importance to construction technology. This is evidenced by the fact that over 60% of the staff are engineers, and the company supports a Technical Research Laboratory employing 256 people. Its staff have published many papers in conferences and the company has received many citations and awards for its technological achievements including the Demming prize for the top company in the construction industry.

Takenaka has developed an impressive concrete placement and finishing system. This system uses robots to arrange the steel reinforcing bars, and robots to distribute, compact, level, and finish the concrete. A computer simulation system calculates the proper path and flow rates for the concrete distribution robot. The concrete leveling robot shown in Fig. 2 is a small walking bulldozer which uses a laser leveling instrument to control the height of the blade and an automatic navigation system to control the path. The surface finishing robot also has a tracked mobility system with automatic navigation, and uses eight rotary trowels which rotate completely around the vehicle so as to smooth the surface of the concrete both in front and in back of the tracked vehicle as it moves. The latest version of this robot finishes concrete at the rate of 300 square meters per hour, the equivalent of three human workers. The pressure of the trowels is automatically adjusted to the hardness of the concrete, and finished surface.

The most impressive achievement that Takenaka showed us was a robot tower crane for lifting and positioning steel reinforcing bars for concrete buildings, such as nuclear power plants. This robot has a tower fixed to a rotating base, a horizontal boom, and a vertical telescoping arm with a 10 meter working radius, and a 15 meter vertical travel. They are working on a larger version. The existing device has six degrees of freedom, can grip and position loads up to 150 kg., and can be operated manually or in an automatic teach-playback mode. The robot crane is used to pick up steel reinforcing bars from an automatic feeder. It then lifts and positions the bars to be tied in the proper location by a human worker. By this means a framework of steel reinforcing bars can be constructed very quickly. The use of this crane has cut the manpower required for reinforcing bar placement from a crew of seven to three. The crane can be taken down, moved, and setup again in about one hour. Takenaka has a film of this robot in operation which can be obtained on request.

Takenaka not only builds industrial buildings,

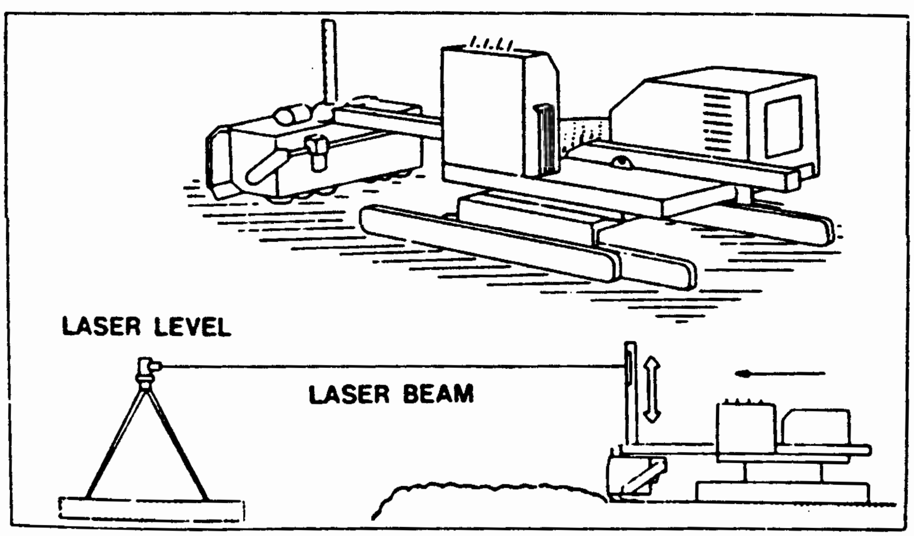

Fig. 2. Takenaka concrete leveling robot. The robot is propelled by a walking mechanism. The spreader blade is controlled in height by a laser level.

but also manufactures automated storage and retrieval systems, and can install flexible manufacturing systems on a turn-key basis.

1.3 Hazama Gumi, Ltd.

Hazama Gumi is a $1.8 Billion company, most of which is civil engineering such as dams, tunnels, railways, highways, subways, airports, waterways, and shipyards. 5% of their business is overseas. Our tour visited their research lab where we were given a presentation on the Hazama Tunnel Shield Driving Automatic Control System (SDACS) shown in Fig. 3. The SDACS controls the direction of the shield (which supports the cutting head and prevents earth and water at the working face from falling into the finished tunnel). The shield is driven by hydraulic jacks which push against the tunnel liner. The position of the shield is measured by a laser and compared against the desired path of the tunnel which is stored in a computer memory. The error signal is used to control the hydraulic jacks so as to servo the tunnel boring machine to the desired path. There are thirty jacks spaced evenly around the periphery of the shield. The computer selects which combination of these to pressurize so as to drive the shield for the next sampling period. This system keeps the center line of the tunnel within 150 milimeters of the design specification.

We were then taken to a site of a 10 meter tunnel being bored under the streets of Tokyo. We were taken to the tunnel face and showed the laser measuring equipment, the shield driving jacks, and the soil extraction equipment which consists of a machine to turn the soil into a slurry, a concrete pump, and pipes to the surface. A diagram is shown in Fig. 4. Data from the laser instruments is carried to a control room on the surface where there are three desk top computers (NEC PC 9801s) shown in Fig. 5. One is used to display data from 45 sensors. The second is used to compute the error signals (pitch and yaw corrections) and calculate control signals for the hydraulic jacks.

DIAGRAM OF SDACS FLOW

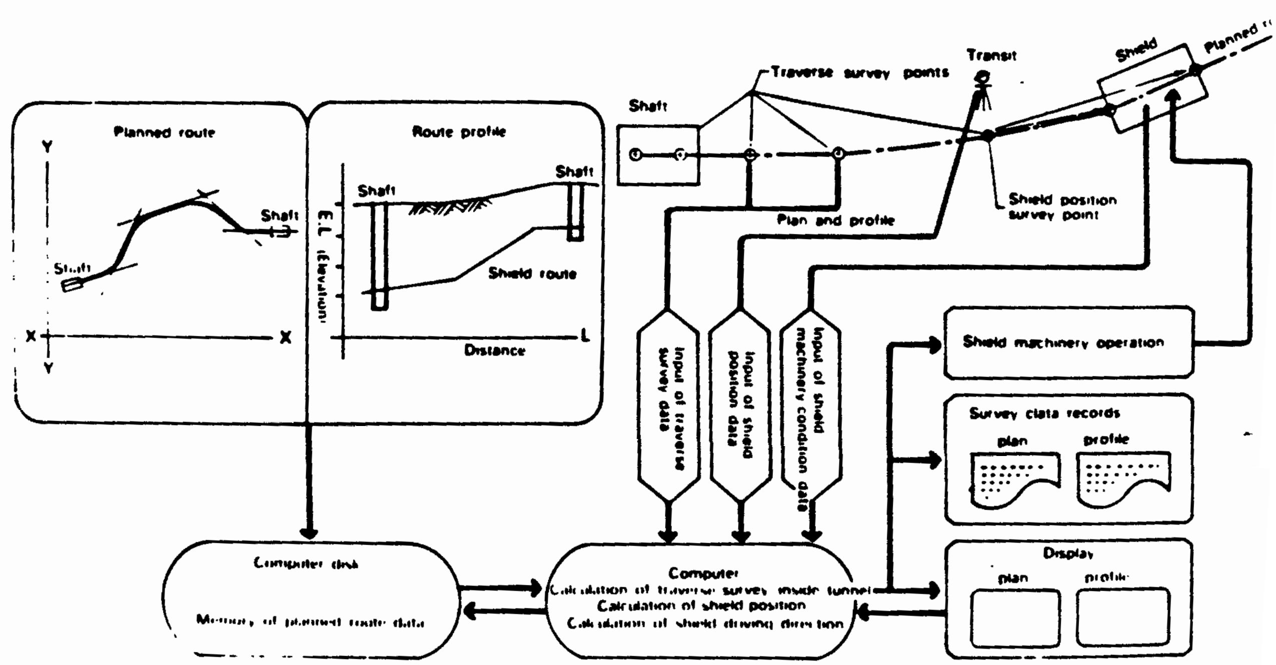

Fig. 3. Hazama shield driving automatic control system.

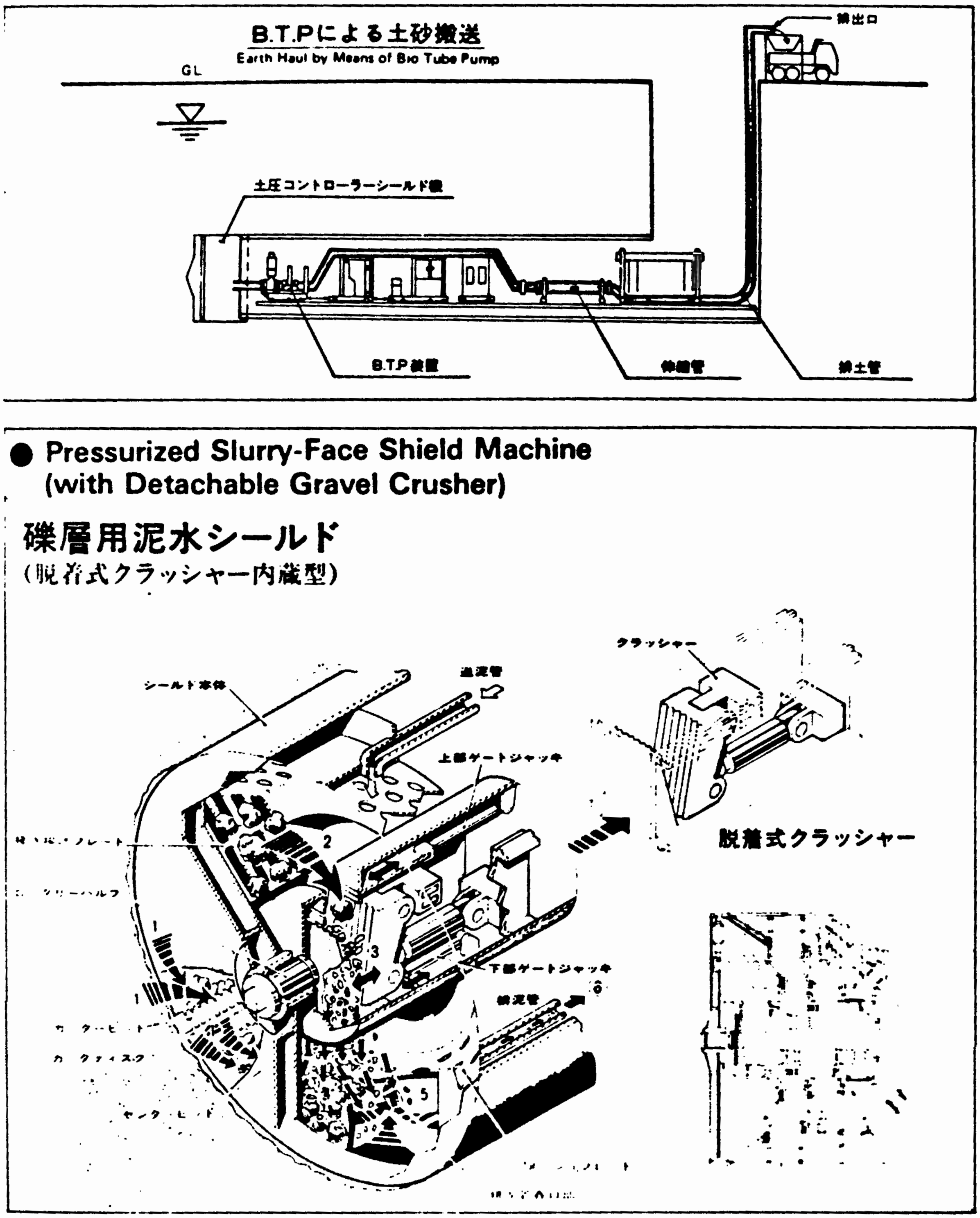

Fig. 4. (*top*) Soil extraction system which pumps slurry to surface. (*bottom*) Diagram of shield face showing gravel crusher (3).

All the data and control parameters were displayed in real-time on color graphics monitors as shown in Fig. 5. Future plans are to use the third computer to control the application of concrete to the tunnel walls.

The Hazama engineers were very interested in acoustic, and other sensors, for measuring density, hardness, and other soil properties directly in front of the shield. This information would allow them to automatically control the rate of material extraction and the shield velocity so as to maximize tunneling speed and efficiency.

Perhaps the most impressive thing about the Hazama project was the people working on it. The research engineers and computer programmers were Hazama employees who were implementing advanced technology on a working project. They had authority to interrupt the project schedule to make technical adjustments. The moral was very high. They were obviously proud of what they were doing and anxious to show it off. They indicated that other Japanese companies were working on similar projects, and that there was considerable competition among companies to be first to implement the latest technology.

1.4 Shimizu Construction, Ltd.

Shimizu is a $4.3 Billion company. It builds a wide variety of office buildings, airports, bridges, tunnels, underground storage facilities, shopping centers, dams, nuclear power plants, ocean platforms for oil development, and port facilities. Its overseas business (12% of the total) is in Asia, Africa, Europe, and the Americas.

Shimizu supports a Research Institute with 213 people (including 10 with doctorate degrees) and an annual budget of $10 Million. It has extensive computer-aided design and structural analysis facilities built around an IBM-3081K computer system. Research activities include earth-quake resistant walls, clean room technology, processing and disposal of nuclear waste, and automatic installation of ocean platforms.

Our tour visited the Research Institute and saw the robot Shimizu has developed for spraying fireproofing on structural steel in high rise buildings. The robot follows a guide-wire and has a model of the steel framework stored in a computer. Touch sensors are used to locate the precise position of each beam, and the robot control system applies the fireproofing material to a uniform thickness. The robot is a Norwegian Tralfa paint spraying robot mounted on a mobile platform built by Shimizu. Several papers describing this robot have been published [1].

Shimizu also has developed robots for industrial cleaning, concrete cutting, painting with rollers, and a robot crane mechanism for lifting and positioning steel beams.

1.5 Kumagai Gumi Company, Ltd.

Kumagai Gumi is a $3.3 Billion company with 22% of its sales overseas. The company build office buildings, factories, housing, dams, railways, highways, water systems, subways, and bridges. The company was the first to introduc the New Austrian Tunneling Method to Japan. I also developed the first tunnel boring machin with a shield with a cross section for double trac railway tunnel.

Kumagai Gumi has an Institute of Construc tion Technology with a large scale structural tes ing facility, one of the largest wind tunnels in th industry, a laboratory for studying liquid natur gas storage, and a facility for developing ne shields and techniques for tunnel boring. They ar also actively researching a number of novel meth ods for driving piling, and for building walls b applying hardeners to the soil.

We were shown a movie of a robot they a developing for automatically assemblying the se ments of tunnel lining. A photo is shown in Fig. Their goal is to produce a completely automate shield tunneling system for deep underground tu neling. If this tunnel lining robot were used install spiral lining segments, instead of the cu rent cylindrical segments, it would be possible build a continuous tunneling machine which cou install the liner as it went along. The comput control of the jacks (as demonstrated by Hazam could keep the shield moving straight even wh several of the jacks were retracted for liner se ment insertion. Theoretically this could increa tunneling speed by a factor of three, since t digging operation must now be stopped in ord to install liner segments, and the time spent i stalling liner segments is twice that spent digging

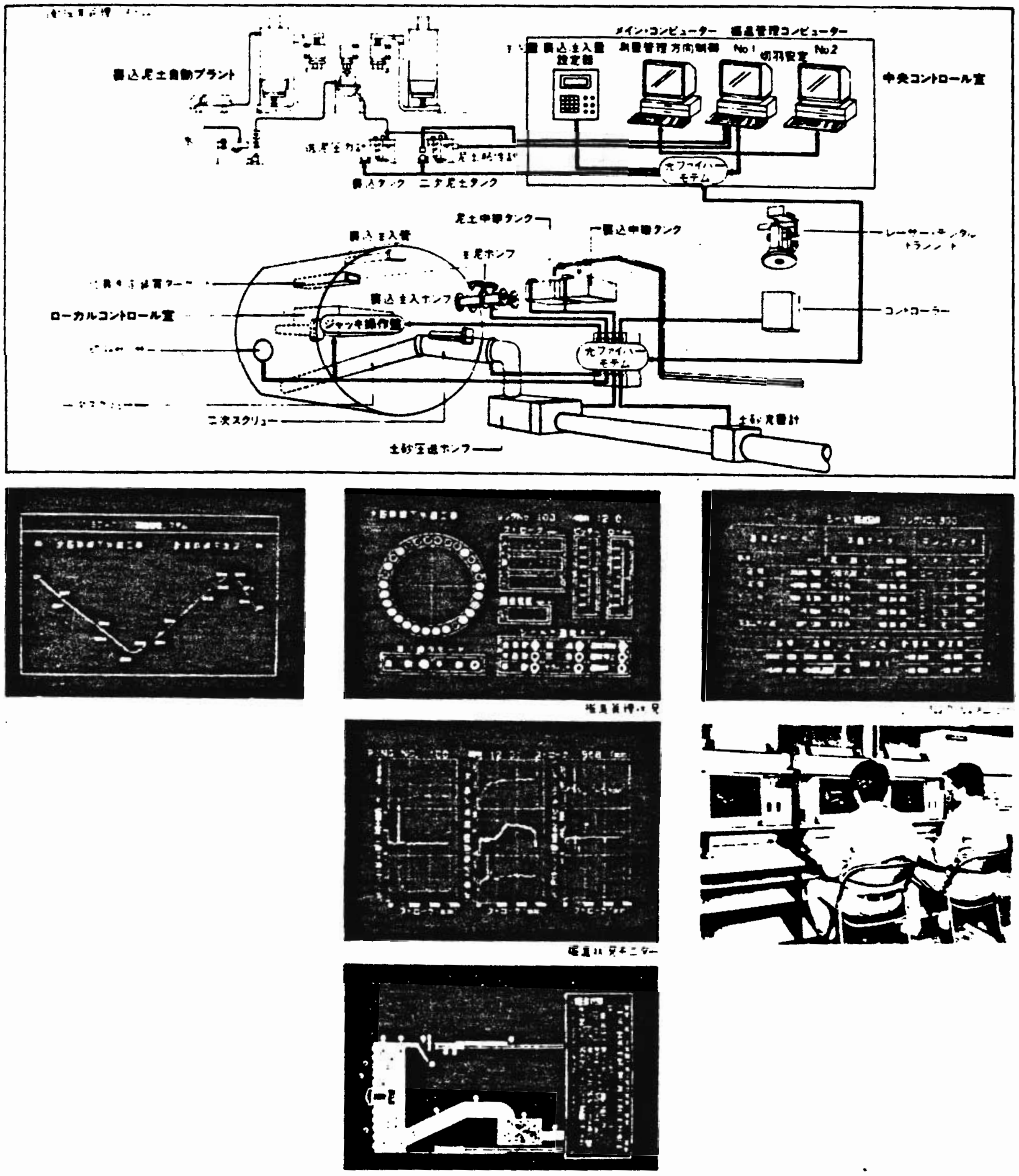

Fig. 5. (*top*) Hazama shield driving system diagram. (*bottom*) Photo of computers and display screens showing control data and jack actuation pattern.

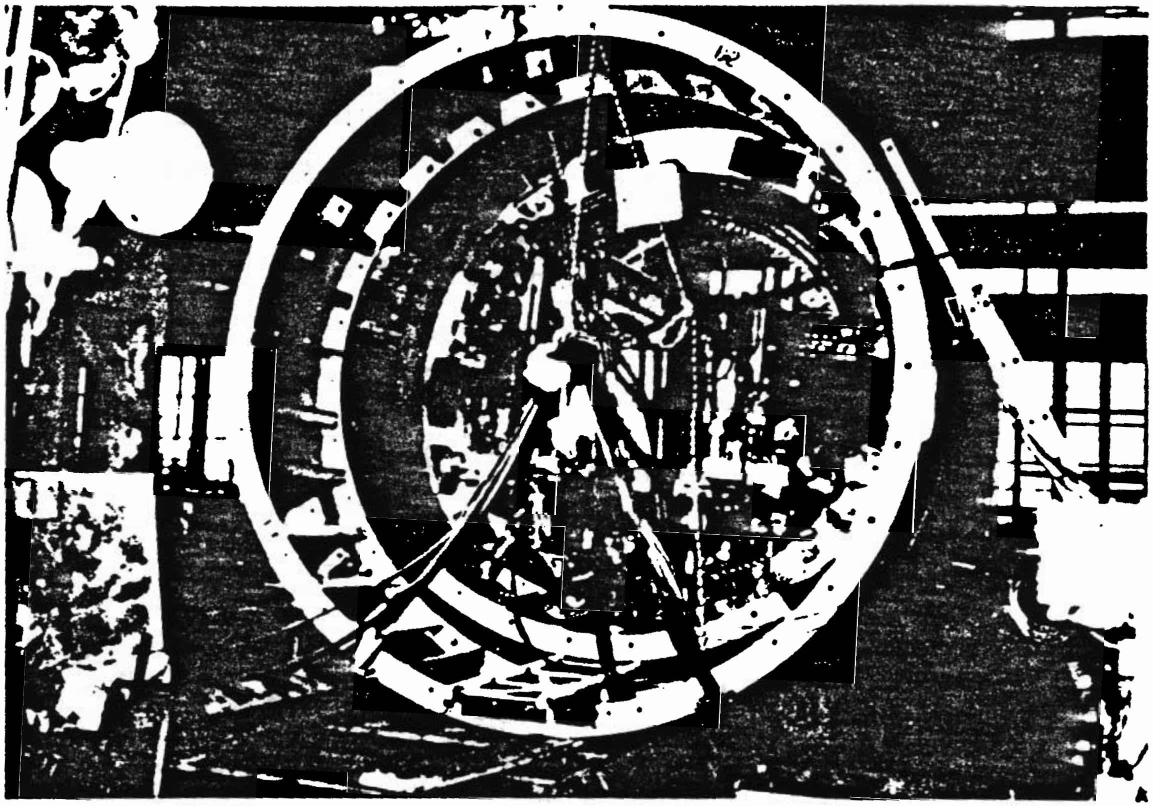

Fig. 6. Kumagai Gumi automatic tunnel liner assembly experiment.

1.6 Toshiba Nuclear Group

Of the 40 nuclear plants in operation or under construction in Japan, 25% are boiling water reactors built by Toshiba. The company makes a number of robotic devices, including an Automatic Control Rod Drive Handling machine, an Automatic Refueling machine for removing and replacing control rod drives and fuel rods, and a variety of Inservice Inspection devices which move on guide tracks for ultrasonic inspection of welds. Toshiba has also developed several mobile robot devices with wheels and tracks that can maneuver from room to room and even climb stairs. These are used for inspecting the interior of nuclear plants where the radiation level is too high for humans. One particularly interesting device, which we viewed on film, was a snake-like arm mounted on a cart. This arm could reach through a hole, and twist itself through a labyrinth of pipes to inspect areas that are difficult to reach. The ar carries a TV camera on the end, and is controll by an operator watching the TV image. The op ator controls the motion of the camera by simp pointing it in the direction he wishes it to go. computer keeps track of the shape of the path t camera traces out, and causes the arm to assu that shape, so that the arm can snake its w through a convoluted space without hitting stacles.

1.7 Waseda University

The robotics research activities at Waseda U versity are directed by a faculty of 19 profess headed by Professor Yukio Hasegawa, wh perhaps the best known robotics researche Japan. The famous music playing robot at 1985 Tsukuba Science Fair which reads mu scores and plays the organ with both hands feet was designed and built by the faculty and students of Waseda. We viewed a number of student projects, including a robot hand actuated by "memory metal" wire which shrinks when it is heated by passing an electric current through it, and lengthens as it cools.

Of primary interest to our study group was the WASCOR (WASeda COnstruction Robot) Research Project. This project consisted of a three year study (now complete) by Waseda University and 11 companies, including all of those listed above. One year was spent on each of three topics:

1. Robot construction of prefabricated homes.
2. Robot assembly of steel reinforcing bars for concrete.
3. Robot assembly of concrete molds.

The three year study was completed at the end of July 1985, and the top managers of the 11 companies will now meet to discuss future directions of research for construction robotics. Results of some of the early studies have been published in recent Proceedings of the International Symposium for Industrial Robots.

1.8 Advanced Robot Technology Research Association

We were given a briefing by Mr. Kenichi Kido, the Senior Director of the Advanced Robot Technology Research Association. This Association consists of 18 large companies, including Hitachi, Fanuc, Fujitsu, Fuji Electric, Matsushita, Mitsui, Mitsubishi, NEC, Toshiba, Komatsu, Kawasaki, and Kobe Steel, plus the Japan Industrial Robot Association, and Japan Power Plant Inspection Institute. The Association is organized by the Agency of Industrial Science and Technology, a division of MITI. It is part of the National Research and Development program "Advanced Robot Technology". The plan is to spend about $80 Million over eight years to improve the technological capabilities of the member companies in robotics. About $12 Million has already been spent.

There are four major application areas that are targeted:

1. Nuclear Power Plant Applications.
2. Undersea Operations.
3. Fire Fighting and Rescue Operations (particularly for oil and gas fires in ports and refineries).
4. Fundamental Technologies: locomotion, manipulation, sensors, actuators, control, teleoperation, telepresence, and system support.

Work on nuclear power plant applications is funded by a special tax on electricity, and the fire fighting and rescue work is funded by a tax on oil. As is typical of Japanese projects of this kind, 90% of the funding is for hardware, and only 10% for software.

2. Summary and Conclusions

The scope of the research being done by Japanese construction companies is far beyond anything American construction firms even contemplate. One of our study mission members, a Vice President of one of the largest construction firms in America, reacted to the Taisei Research Institute by saying he "could not believe all these [research] employees just running wild," and said that "if he were head of Taisei he would fire every one of the R&D staff and save the company $25 Million per year."

This attitude toward research is apparently not unusual among executives of American construction companies. Comments made at a Construction Robotics Workshop at Carnegie-Mellon, June 17–20, 1984 [2] by executives of a number of large American construction firms indicated that American construction firms do NOT do any research in-house. They depend on construction machinery suppliers to develop and market innovations. On the other hand, construction machinery suppliers are reluctant to develop new products until there is a large and proven market. This produces a "Catch-22" situation where innovation comes very slowly and mostly from outside the industry.

The exact opposite seems to be the case in Japan. Taisei representatives told us that Japanese construction firms are working hard to differentiate themselves by introducing advanced technology, particularly robotics. The research is done in-house in large, well financed laboratories, by company engineers. It is introduced into the construction site as soon as possible, and refinements are made on-site. Japanese construction firms are vertically integrated, so that the construction firms are also the designers, architects, builders, and construction machinery manufacturers. This produces an environment wherein construction research is vigorously pursued, and new technology finds its way very rapidly into use on the job.

Although there are no direct government subsidies for construction research per se in Japan, there are efforts by the Ministry of Construction to get electronics, robotics, and high technology into construction machines manufactured in Japan. At present, these efforts consist only of studies such as that reported above at Waseda University. Manufacturers of construction machinery are eager to get MITI support for construction robots, but there is not yet a major integrated effort.

Yet even without direct government support, it *is clear* that Japanese construction firms will present a formidable technical and economic challenge to their competitors in the future. The American construction company Vice President, despite his derogatory comments about the Taisei Research Institute, was surprised and clearly shaken by the sum total of what he saw. He was deeply apprehensive about the future of the American construction industry.

The Japanese are taking risks and making extraordinary progress. Their progress is mostly in hardware rather than in software, as is true in manufacturing. This may give hope to us in the United States, but is no cause for complacency, especially in light of the relative lack of progress in *all* areas of construction research in this country. Productivity has actually declined in the American construction industry by 1.5% annually for an entire decade. If present trends continue, the Japanese will soon achieve a dominant position in construction technology.

It is clear that robotics will play an increasingly important role in construction in Japan within the coming decade. However, the fact that the Japanese are not concentrating on software presents a clear opportunity for the United States. A Construction Robotics Workshop sponsored by the Robot Systems Division and the Center for Building Technology of NBS in February 1985 [3] identified Computer-Aided Design database standards, interfaces standards, computerized inventory control, and computer-assisted measurement technology for developing as built databases as the most important technologies for improving productivity in construction. The development of construction robots, while considered important, was placed after the other issues in order of priority. Thus, *even though* the Japanese have a large and growing lead in construction robotics, it might be possible to negate that lead if the American Advantage in computer software were vigorously applied to the issues of database and interface standards, inventory control, and measurement technology.

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