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Research in Progress

Introducing Carnegie-Mellon University's Robotics Institute

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Carnegie-Mellon University has established a Robotics Institute to bring its expertise in Engineering, Science, and Industrial Administration to bear upon the problem of national industrial productivity The Institute has been established to undertake advanced research and development in seeing, thinking robots and intelligent systems, and to facilitate transfer of this technology to industry The Institute is engaged in broad programs of research in robotics, artificial intelligence, manufacturing technology, micro-electronics technology, and computer science. The Institute offers the promise of dramatic advances that will not only improve the productivity of all types of employees but also lead to improvements in the "quality of life" for all

A demonstrated need for research and development in the field of robotics, intelligent systems, and programmable automation exists today in the United States As long ago as the 1960's experts predicted that the most explosive growth area during the next decade would be in computer-based automation of the manufacturing process. All steps of manufacturing -- design, prototyping, production engineering, part forming, assembly inspection, material transfer and storage -- were expected to become directly controlled by computers. Furthermore, computer control would bring a new flexibility to automation; the machines that perform manufacturing operations would be programmable, allowing one machine to perform a variety of manufacturing steps. This capability, combined with the complete computer-based scheduling and allocation of resources, would result in a major increase in manufacturing productivity, especially in the important area of batch production and job shop operations.

A variety of forces, including economic pressures, human productivity limitations, advances in basic technologies, increased complexity of design, and broadening foreign competition, provide the impetus for the development of computer-based manufacturing, yet few of the past decade's expectations have been fulfilled Even in the production sequence the use of industrial robotic manipulator arms is so expensive in the U S. that most robotic tasks either serve only as human enhancement or for human protection. In contrast, many major Japanese companies are now pursuing specialized robotic devices for their present or future needs, and are actively developing completely automated self-contained factories to be sold to developing countries.

The major problem in the development of robotic and intelligent systems is the paucity of research Secondly, little of existing research is applied to industrial problems. Consequently, the research programs of the Institute have as an objective the development of "integrated intelligent systems" in the following areas

- □ Programmable manufacturing leading to a "factory of the future";
- □ Remote sensing, inspection and maintenance under hazardous conditions such as those existing in nuclear systems, off-shore exploration, space, and mining,
- □ Space exploration, exploitation, and industrialization;
- □ Medical applications such as prosthetics and microsurgery.

Institute Organization

The Institute is a separate entity within Carnegie-Mellon University. Raj Reddy is the director Organizationally, it is structured as a matrix of projects and laboratories The projects provide the application environment for the Institute, while laboratories provide the research base Five projects have been tentatively chosen to begin over the next five years. They are

1. The factory of the Future
2. Undersea exploration
3. Mining
4. Space construction and exploration
5. Micro-surgery and prosthetics.

The Institute's goal is to have one primary industrial sponsor for each project, with additional sponsors at an affiliate level. A project sponsor provides both an aplication environment and research funding; the sponsor and the Institute jointly define what applications pose research problems whose solution will be of benefit both to the sponsor and industry in general. The affiliates program, currently being formulated, has the purpose of effecting rapid transfer of ideas and technology to industry. An affiliate will have access to all non-proprietary research and will be aided, by the Institute, in its transferal. Additionally, an affiliate can participate in periodic research review meetings held at the institute The cost of becoming an affiliate is tied to the company's size.

The Institute has a growing full-time staff of research scientists, with additional faculty cross-appointed from university departments.*

Jerry Agin (R)· Sensors, Robot Coordination

Eugene Bartel (R,E)· Automated Coal Mining

David Bourne (R)· Manipulators, Vision

Jim Crowley (R)· Vision.

Mark Fox (R,G)· Artificial Intelligence, Management Systems.

Alex Holzer (M,R) Mechanical and Manuafacturing Engineering

Takeo Kanade (R,C) Computer Vision.

John Kender (C,R). Computer Vision

Hans Moravec (R)· Computer Aided Design, Mobile Robots

Tom Morton (G,R) Operations Management

Marc Raibert (R,C)· Mobile robots.

Raj Reddy (R,C) Computer Vision and Speech, AI.

Arthur Sanderson (E,R)· Pattern Recognition, Sensor-based Robotic Control Systems

Frank Wimberly (R). Computer Vision and Inspection, Adaptive Process Control.

Paul Wright (M,R)· Mechanical and Manufacturing Engineering

Additionally, graduate and undergraduate students from many departments in the university are supported by the Robotics Institute It is projected that with each new funded project about 10 faculty members will be added.

The Robotics Institute has acquired many pieces of research equipment and numerous others are presently on order The Institute has the following

- □ DEC 2060 System
- □ Unix System with 5 LSI controllers
- □ Vax 11/780-Grinnell Color Display
- □ 1 Cincinnati-Milacron T^3 Arm
- □ 1 Autoplace Arm
- □ 1 Fanuc Arm
- □ 2 PUMA Unimation Arms
- □ 1 Seiko Arm
- □ CNC Bridgeport Milling Machine
- □ NC Brown and Sharp Machining Center
- □ 3 MIC Vision Systems
- □ Voice Input Stations
- □ Aerotech Computer Controlled X-Y and Rotary Tables
- □ 2 RCA Vidicon Cameras
- □ 2 GE Automation Cameras

The major departments affiliated with the Robotics Institute include Electrical Engineering, Mechanical Engineering, and Computer Science The Electrical Engineering department has extensive facilities including

- □ Several DEC PDP 11/40 Systems

*Following each name is a list of their university appointments R-Robotics, C-Computer Science, E-Electrical Engineering, M-Mechanical Engineering, G-Graduate School of Industrial Administration (Business School) The ordering of the letters determines their primary department

- □ Extensive Solid State Laboratories
- □ Laser Optical Data Processor Laboratories
- □ Extensive Machine Shop

The Mechanical Engineering Department has the following:

- □ Manufacturing Sciences Laboratory
- □ 1 DEC PDP 11/40 Mini-Computer
- □ 1 Trallfa Robotic Arm
- □ 1 Intel MDS Microprocessor Development System
- □ Large Laboratory Rolling Mill
- □ Complete Machine Shop

The Computer Science Department has the following·

- □ 1 DECsystem-10 KL10
- □ 2 DECsystem-10 KA10s
- □ 6 VAX-11/780 Unix Systems
- □ 1 DEC PDP-11/40 Unix System
- □ 19 Xerox ALTO processors and displays
- □ 3 Perq Computer Systems.
- □ 1 Xerox DOVER printer
- □ 1 Omnitech 2000 photo-type setter.
- □ CM*: a 50 processor system.

Institute Laboratories

As described earlier, the Institute is a matrix organization where laboratories serve to perform basic research. Currently, there are six laboratories. The following describes briefly their research goals.

Intelligent Systems Laboratory

The purpose of the Intelligent Systems Laboratory is to investigate artificial intelligence techniques and apply them to non-perceptual tasks in the projects. Primarily, research is done in the areas of knowledge representation and acquisition, planning and problem-solving, model analysis, and user-interfaces. In the factory of the future project, the lab is constructing an intelligent management system which will sense, model, manage, and optimize the running of the factory at both the plant and managerial level.

Vision Laboratory

The Vision Laboratory is concerned with the development and application of techniques for use of non-contact visual information for robotics Visual non-contact sensing and recognition (including infrared, x-ray and other electromagnetic radiation) is one of the most essential capabilities for versatile, intelligent, sensor-based robots in the future.

While use of visual sensing and perceptual ability increases the performance of present-day virtually-blind robots, it raises the importance of new manipulators with better dynamics (light-weight and high-speed) which can truely take advantage of including visual sensory capability in the control and decision loop. Thus, the vision laboratory not only endeavors development of new visual-sensing devices and algorithms for robotics vision, but also it aims to build total robot systems with increased performance and versatility based on vision.

The projects undertaken currently and in the near future in this laboratory include·

- □ Visual inspection in industrial manufacturing processes: printed circuit board, surface inspection, etc.
- □ Locating and identifying parts in a bin.
- □ Development of a fast and accurate 3-dimensional shape measurement device.
- □ Development of a new proximity distance-and-orientation sensor.
- □ 3-Dimensional shape processing techniques.
- □ Manipulator dynamics theory for using visual sensory feedback.
- □ Development of a light-weight, high-speed manipulator

Sensor Laboratory

The sensor lab is concerned with doing research in non-visual sensing, which includes tactile, chemical and electrical sensors. A primary aspect of this research is to increase sensor flexibility by applying artificial intelligence and pattern recognition techniques. Current research areas include adaptive sensing systems, tactile sensors, and fault-diagnostic sensors.

Mobile Robots Laboratory

Research in the mobile robot laboratory is concerned with the development of techniques and hardware for autonomous and semi-autonomous robot rovers Such rovers are needed for both natural environments (on the planets and under the sea, for example) and artificial ones (on the factory floor). Much of the effort will be in the areas of computer vision and three dimensional modelling and integration of data from multiple sensors. Visual and navigation techniques will be tested on physical robots Initially these will be relatively small, so that experiments can be conducted in modest indoor spaces.

Flexible Assembly Laboratory

The Flexible Assembly laboratory provides a facility for experimentation with robotic approaches to assembly of batch-produced parts. In general, when parts are manufactured in quantities of 10,000 to 1,000,000 or more, it is advantageous to install "fixed automation" equipment to perform part or all of the assembly. But when batches are smaller the cost of developing and setting up this equipment outweighs the savings to be gained by its actual use. "Flexible automation" is an approach to bridge this gap, bringing the lower limit of automation to batches of 100 parts or so.

Small-batch assembly is presently done manually by poorly-paid workers. Automation of the most tedious aspects of assembly would raise productivity and free these workers for more challenging assignments. Product quality would rise. Automation could increase product uniformity, but it could also provide for diversity. Coupling the assembly system to appropriate data-processing facilities would make possible parts-on-demand: custom assemblies of units with selected styles and options. If intelligently and sensitively applied, robotic assembly can have a positive influence on the quality of life for both workers and consumers.

Flexible Machining Laboratory

The flexible machining laboratory is concerned with problems in materials processing and manufacturing. Areas under investigation include:

- ☐ Flexible machining system
- ☐ Materials for metal cutting
- ☐ Analyses of metal forming operations
- ☐ Surface inspection studies
- ☐ Programmable powder metallurgy techniques

Factory of the Future Project

The "factory of the future" is the first project to acquire a primary sponsor. The Westinghouse Corporation is providing both funding for research and factories for testing ideas. Three application areas were chosen jointly by CMU and Westinghouse. They are turbine-component production, printed circuit-board production, and lamp production. In evaluating applications, problems that were important to Westinghouse and posed interesting research issues were selected. We list the set of problems chosen, followed by a more indepth description of a few of them.

- ☐ Component Verification: endcoding of circuits for automatic verification (Agin).
- ☐ Device Control Standardization: manipulator-independent reconfigurable control (Bourne).
- ☐ 3-D Measurement with light striping (Crowley and Agin).
- ☐ Organization Modelling: AI knowledge representation models of factories(Fox).
- ☐ Organization Management: AI planning and constraint analysis techniques applied to factory planning and scheduling (Fox, Morton, Miller, Rachamadugu).
- ☐ Organization Analysis: AI simulation of organizations (Ramana Reddy and Fox).
- ☐ User-Interfaces: Graceful interface with planning-based request amplification (Fox).
- ☐ Vibration Adaptive Machining: Dynamic parameter control of NC machines for reducing vibration and increasing machining efficiency (Holzer).
- ☐ Scanning laser ranging device for medium reange (20cm to 1m). 10,000 pts/sec (Kanade).
- ☐ Manipulator Design: High performance manipulator with sensory feedback (Asada and Kanade).
- ☐ Circuit-Independent Techniques for PCB inspection: Nicks, cuts, etc. (Kender).
- ☐ 3-D Modelling for simulation and dynamic graphic display (Moravec).
- ☐ Precision assembly in electronic systems (Sanderson).
- ☐ Force Adaptive Machining. Force detection and correction in machining (Wright).

Intelligent Management System

During the last 20 years a dramatic change has taken place in industry and organizations. Products and services are ever increasing in complexity and the technology to produce them is changing rapidly. Organizations, whether factories, ships, hospitals, etc. are becoming more complex and difficult to run. Managers are unable to manage due to the shear complexity of the task. Long-range planning is often ignored due to the ever increasing day to day problems. It is no longer the case that simple information systems providing information access capabilities are sufficient, information systems must take over more of the day-to-day management. They must be more *intelligent.*

The goal of the Intelligent Systems Laboratory of the Robotics Institute is to discover theories of knowledge acquisition, representation, and utilization that enable the construction of an *intelligent management system* (IMS). An IMS must:

- ☐ *Sense*: Automatically acquire state data. Sense the location of objects, state of machines and status of activities both on the plant floor and in supervisory departments.

- *Represent*: Represent state, physical, functional, and historical information of objects and machines; tasks, goals, interests, etc. of people
- *Model*: Model the complete organization at many levels of abstraction. For example, machines, people, materials, orders, departments, etc will be modelled in detail from both an attribute and a process view, including their interactions.
- *Manage*
  - Analyze and manipulate the model to answer short and long term state and planning questions The system is *passive* in that it responds to user initiated queries
  - Construct an *active* intelligent information system. Active systems continually monitor the organization and inform responsible personnel when important events occur. For example, when a machine breakdown occurs, not only is the foreman informed, but also maintenance, and the salesman who must inform the client that the order will be delayed
- *Optimize* Analyze how the structure and the processing of the organization should be changed to further optimize some criteria such as cost, throughput, quality, etc

Such a system, if it is to succeed in a business environment, must have the following characteristics:

Accessability: Most computer interfaces are difficult to learn and use. And when they change, users must be re-educated Our goal in the IMS is to enable personnel to meaningfully communicate with the system. The interface will gracefully interact with the user and provide guidance and help in deciding what the user needs. It must be able to amplify a request into a series of system function executions.

Adaptability: Most systems are hand-tailored to their environment. Organizational changes require extensive re-programming. The goal of our research is to construct a theory of system design which will allow the users to modify the model, analysis and processing functions, etc in the system without the aid of programmers. The end user introduces changes via dialogue

Accountability: A major problem with computer acceptance is that users are unable to question how the system's output was created Our goal is to construct an explanation system which will allow the IMS to explain the actions executed by the system at various levels of detail to the user

Reliability: Centralization of processing and/or data reduces reliability. We are constructing a distributed system with distributed control. The system will not fail if one of its parts fails No resource is critical

Reactability The system, via its sensors and data monitoring is able to detect changes in the organization. Detrimental changes are corrected if possible Interested personnel are informed of the change and only receive the information required to carry out their task.

The above description describes our vision of what an IMS should look like. While pieces of this system can be constructed, the final integrated system may take 5-10 years (or more) depending on scientific and manpower constraints. Currently, research is progressing along two paths: knowledge representation and system organization which form the foundation of the IMS; and function capabilities such as a short-term scheduler and simulation system. The following describes some of the projects

Organization Modelling

Mark Fox, Ari Vepsalainen

The management and analysis of an organization require a richness and variety of information not commonly found in the databases of management information systems For example, a simulation system requires knowledge of existing processes including process times, resource requirements, and its structural (routing) relation to other processes. It must also know when routings for products are static, or are determined by a decision process such as a scheduler. In the latter case, it must know when and where to integrate the scheduler into the simulation. If the IMS is to generate the sequence of events to produce a new product, it must have knowledge of processes (e g., machines) which includes the type of processing it can do, its operating constraints, the resources it consumes, and its operating tolerances. If data is to be changed in an interactive, possibly natural language mode, the IMS must have knowledge of generic processes such as machines, tasks, and departments if it is to understand the interaction It must also know what information is important and how it relates to other information in order to detect missing information and inconsistencies. Hence, the organizational model must be able to represent object and process descriptions (structural and behavioral), and functional, communication and authority interactions and dependencies. It must represent individual machines, tools, materials, and people, and also more abstract concepts of departments, tasks, and goals.

Current organizational models are found typically in databases fragmented across one or more computer systems How information in the database is interpreted is defined by the program and not by agreed upon conventions of field and relation names (though work in relation schemata is proceeding). By taking an AI knowledge representation approach to organization modelling, the variety of information described above can be represented. The model is accessable by all subsystems while the semantics of the model is jointly understood. Secondly, an AI approach to organization modelling enables the application of AI research such as question-answering and inference systems.

During the summer of 1980, a simplified model of a bare printed-circuit board production plant was constructed. The model was created using a concept (schemata, frame, unit, .) style knowledge representation (Fox, 1980). A concept is composed of three aspects, each of which contains slots The VIEW aspect specifies similarity links to another concept (Fox, 1979) Typical slots in the VIEW aspect are IS-A and PART-OF. The META aspect has slots defining meta information for the concept. Typical slots are CREATOR and HISTORY. The CORPUS aspect defines attribute and structural descriptions of the concept. Each slot has a meta-description, defining information such as RESTRICTION, and DEFAULT values. Each value in a slot has a META-VALUE defining who put it there, when, why, etc. In the model, concepts of the plant, such as machines and work-areas, are related using the PART-OF relation The semantics of PART-OF allows the inheritance of locational information only (containment). For example, only the CORPUS slots for CITY, COUNTRY, and STREET are inherited The IS-A relation is used to construct type hierarchies of concepts. For example, NUMERICAL-CONTROLLED-DRILL --> DRILL --> MACHINE --> PHYSICAL-OBJECT. Information in the model is restricted to that necessary to support the simulation of the factory and a color graphics display of the factory at multi-levels of abstraction (PART-OF hierarchy)

Research is continuing in extending the model to describe more of the factory, including behavioral description of departments and workers. Also, the inheritance research in (Fox, 1979; 1980) is being applied to the inheritance and automatic specialization of procedural descriptions down a similarity link (e.g., IS-A).

Organization Management

Mark Fox, Tom Morton, Steve Miller, Ram Rachamadugu

Poor scheduling leads to under-utilization of resources (e.g., machines and people), and high in-process inventory Orders may be unduly delayed or lost. A scheduling system that can cope with the complexity of the organization in a satisfactory way would increase the efficiency of the organization and reduce production costs. But optimal scheduling in multiple-machine and multiple-routing factories is NP. Consequently, current approaches to scheduling are either manual, or computerized but highly inflexible; they do not allow the inclusion of arbitrary external (user-defined) constraints, nor are they optimal.

Three approaches to factory scheduling are being investigated. In the first approach, we are constructing a production-system model of what human schedulers actually do, with optimizations in the appropriate places. The second approach is to extend operations-management scheduling theory to include multiple machines and routings. The third approach is to reformulate scheduling as a resource assignment problem with constraints. Similar to a relaxation process (Zucker, 1976), multiple machines, materials, tools, workers, etc are assigned to an order. Constraints such as operation ordering and timing are then applied and propagated thoughout the the orders to reduce the set of possible assignments. The novelty of the approach lies in the dynamic, heuristic characterization and assignment of resources at different levels of abstraction in order to reduce complexity

Organization Analysis

Ramana Reddy

Questions of organizational change require the construction and evaluation of complex simulations which can take weeks or months to construct. If the intelligent management system already has a model of the organization, why not circumvent the construction process and let the simulation system interpret the model?

A simulation system has been constructed that interprets directly the factory model, negating the need for constructing separate simulation systems. Research is now focussing on three problems:

1. A production-system based model-acquisition module which includes model verification

2. The capability of simulating the model at different levels of abstraction. Departments are composed of sub-departments, machines are composed of smaller machines, tasks are broken down into sub-tasks. A simulation can be run at one of many levels of abstraction in this process hierarchy.

3. The embedding of the simulation code directly in the model Concepts would inherit their simulation-process description code via a similarity link. The organization model's processes (departments, machines, people etc.) are members of a type hierarchy in which the root process defines how to execute these concepts in a simulation. Each object

inherits this definition which is modified to reflect the concept's specialization, e.g., resources consumed and produced and how this is done both abstractly by some probability distribution and exactly by subprocess definition. A concept is executed directly using the abstract definition if it is at the proper abstraction level, else its sub-process concepts are executed. The event list is updated automatically.

User-Interface

We are designing a user-interface process (UIP) which will allow a manager to communicate to and dynamically alter the IMS Each employee will have access to a personal computer which can communicate to all other machines in the factory. Each employee will have a personalized UIP with some form of natural language and speech input (Hayes & Reddy, 1979). The UIP will act as both an amplifier and reducer of user capabilities. A UIP planning system will amplify a request by planning a series of module executions that can accomplish a request. Each module in the IMS will have a profile describing its uses, requirements, constraints, etc* that will allow the UIP to choose and sequence their executions. The UIP will also restrict access to information and function by comparing the capabilities necessary to satisfy the request to the user's capabilities defined in their profile The UIP will provide natural language output for the conveyance and explanation of results.

Robot Rover

Hans Moravec

This research extends Moravec's thesis (Moravec, 1980), in which a card-table sized, PDP-10 guided robot picked its way through a cluttered area, avoiding obstacles to get to a desired destination. It built a 3D model of its surroundings from what it saw with its onboard TV camera, and executed optimum obstacle-avoiding paths on the basis of its model. It was reliable but slow, moving in meter lurches every fifteen minutes.

A smaller, more capable rover will be built It will have a significant speed-up over the old system. A Grinnel TV digitizer and an array processor connected to a VAX can each save about a third of the time. The remainder can be reduced by optimizing code, taking advantage of the large address space of the VAX, and possibly using CM*. Step three is to improve performance and reliability by trying new methods.

Later work will involve difficult environments including uneven ground and cliffs. Some problems are recognizing extended featureless obstacles, recognizing landmarks from different points of view and classifying objects.

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*Similar to Consul's process sctipts (Lingard, 1981)

A Three-D Modelling Machine

Hans Moravec

This is a multiprocessor for simulating complicated things in three space and making very realistic graphics. Special strengths are the complexity attainable and the realism of the synthesized images. The key idea is a *space-oriented* data representation. Imagine surrounding a modelled volume with a large cube. A procedure decides if the contents of the cube are simple, by some definition. If so, the cube is represented by a description of its contents; otherwise, it is subdivided into eight smaller cubes, each described by a recursive call to the procedure. The process builds a tree and continues until all "leaf" subcubes are either simple or below a certain quantum in size. Image generation would be done with an efficient ray throwing procedure which tells where a given ray hits. It would permit modelling the effects of multiple scattering of light from surface to surface.

A version currently runs on a PDP-10, with further research to continue on a VAX and possibly the 50-processor CM*. Eventually a design for a specialized multiprocessor would be generated. A 1000-micro-processor system should be able to do real-time TV. A new technique using a wave (rather than ray) model of light, which promises to increase the realism as well as the speed of image generation, is being investigated; its fundamental calculations permit efficient use of existing array processors.

Bush Robots

Hans Moravec

Imagine a tree-like robot where each branch divides into two, half the size, twenty (!) times. Each sub-branch has an azimuth/elevation joint at its base and an axial rotary joint at the top After twenty branchings we have a million microscopic cilia. Each branchlet has force sensing The robot needs a lot of compute power and has enormous capabilities. Its touch sense has the data rate of human vision. The effector data rate is also an unprecedented gigabaud. It can reach into a machine to feel and then rearrange multitudes of parts for an instant repair without special tools With localized control, communication and power, segments of the tree could detach to become smaller, mobile, robots These could climb walls and ceilings by using their cilia to grasp microscopic cracks Though the components of the bush are "mechanical", the complex whole behaves very "organically"

A twenty level robot is for the future, a three or four level model is possible now. More exciting is devising problem solvers for higher level bushes, based on a "divide and conquer" strategy where heuristics split a task into subproblem pairs for the next level sub-bushes, including constraints to prevent tangling. The 3D machine will be able to simulate the bush in action. Imagine realistic movies of it repairing itself or playing ball.

Development of a Light-Weight High-Speed Manipulator with Direct Drive Joints

Haruhiko Asada and Takeo Kanade

Present-day manipulators are still far inferior to human arms and unsatisfactory for many applications in terms of speed, accuracy, power and versatility. One of the reasons for their poor performance is the use of transmission mechanisms with high gear ratios which are necessary to increase the driving torque, since conventional servo motors are capable of generating relatively small torque. However, transmission mechanisms tend to give the following problems:

- □ extra overhead in weight,
- □ increase of inertia,
- □ friction and backlash, and
- □ ripple in transmitted torque.

Recently high performance motors using new rare-earth magnetic materials (e g , rare-earth-Cobalt) have been developed and are becoming available for industrial use. Because of the higher density of magnetic flux, these motors provide much improved capabilities in terms of lighter weight, more compact bodies and higher output torque These features are well suited for driving the manipulator joints without the use of a transmission mechanism

Based on these ideas, we are developing a new robot manipulator with direct-drive joints using rare-earth DC-torque motors. Because of the advantages mentioned above, we can expect to construct manipulators with better performance in terms of:

- □ simpler structure (reliable, easier to model)
- □ heavy duty relative to the arm weight,
- □ fast dynamical response,
- □ low friction and no backlash, and
- □ light weight and high speed

We have finished the design of a seven-degree-of-freedom anthropomorphic manipulator, and are in the process of constructing it.

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