where $x_i(0)$, $i = 2, 3, 4, 5$, are the initial conditions on USE, C & C, FREEDOM, and SPEED respectively. Evaluating (11) and (12) for the assumed initial conditions yields

$$c_{\text{USE}} - 0.2a_{\text{USE/COST}} \leqslant -7 \tag{13}$$

and

$$c_{\text{COST}} \geqslant -0.7. \tag{14}$$

Note that (11) and (12) explicitly demonstrate the sensitivity of the model policy to assumed initial conditions and cross impacts, as well as suggest a range of parameter values through which the policy may be implemented. Note also, that (14) represents a considerably less drastic change than the $c_{\text{cost}} = +9$ of the HOPE policy. Equation (13) confirms that the $c_{\text{USE}} = +1$ and $a_{\text{USE/COST}} = +9$ values of the HOPE policy are insufficient to guarantee auto use decreases monotonically. Indeed, simulation confirms that, under the HOPE policy, auto use gradually increases for many time periods before beginning a declining trend. If the monotonicity condition of Policy 3 is removed, (13) becomes

$$c_{\text{USE}} - a_{\text{USE/COST}} \leqslant -7,$$

a less restrictive condition than that given in the HOPE policy.

V. Summary and Conclusion

In the preceding sections a constructive procedure for analyzing KSIM models has been developed and demonstrated. The procedure is based upon recognition of the direct mathematical relationship between the composite value of cross-impact terms and the trend of corresponding state variables. Although shortcuts were adopted in Section IV, the complete procedure can be summarized as follows.

1) Specify the desired trend for each of the subset of variables of policy interest.
2) Apply (7) and (8) to determine a (set of) conditions on cross-impact and input parameters sufficient to guarantee the desired trends.
3) Simulate the model to determine the resulting trends of the remaining state variables.
4) Using the trend information generated by simulation, apply (9) and (10) to determine the (set of) necessary and sufficient conditions on model parameters to guarantee the desired trends.
5) On a variable-by-variable basis, test the effects of relaxing monotonicity conditions.

The simple operations required to implement steps 2) and 4) of the procedure may be hand-calculated, or easily can be incorporated into existing KSIM computer codes.

Through the example model considered in Sections IV and V, the constructive approach developed in this paper has been proven demonstrably superior to the trial-and-error mode of analysis which typifies the current KSIM methodology. The procedure can greatly reduce the time, cost, and effort associated with a KSIM modeling project by reducing the number of simulation runs required for model analysis and policy testing. In addition the procedure quickly and easily generates insight into the behavior and parameter sensitivity of a KSIM model which can be obtained otherwise only by exhaustive sensitivity analysis.

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An Overview of the Basic Research Needed to Advance the State of Knowledge in Robotics

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***Abstract*—A summary of a workshop on robotics is presented.**

On April 15–17, 1980, a workshop was held to identify the advanced scientific knowledge which is needed to provide a firm foundation for robotics. The workshop probed contributions from computer science, artificial intelligence, pattern recognition, control theory, kinematics, dynamics, geometry, operations research, and other disciplines within the context of the special needs of robotics. The focus was on fundamental knowledge, not applications dependent knowledge or constraints imposed by industry.

A robotic system may be described as one capable of receiving communication, understanding its environment by the use of models, formulating plans, executing plans, and monitoring its operation. Fundamental gaps in knowledge exist about such systems. The workshop was needed to identify what areas are currently being investigated, what areas are not being pursued, what areas should be drawn upon, what should be done, and who is available to conduct the research. For this workshop advanced robotic systems were explored in terms of six constituent functions: intelligence and decisionmaking, control, manipulation, locomotion, sensors, and communication.

This overview summarizes the entire workshop and presents the research topics upon which participants argued for more work. The topics are presented with different degrees of specificity, perhaps representing the maturity of different forms of knowledge. There is no intent to judge the value of the different

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kinds of knowledge which would emanate from the proposed research investigations. Some reasons for the proposed topics are provided, but no uniform justification has been applied. No claim is made that the research topics in this paper exhaust all good research opportunities. The topics are arranged, for the most part, according to the six robotic functions which were used to organize the workshop.

Intelligence and Decisionmaking

A key ingredient in advanced robotics is knowledge representation. Work is needed not just to find any representation, to find the right representation to answer questions and to compute efficiently. It may be that a representation which is very general may lead to computational problems. The trade-off between algorithm complexity and representation complexity needs to be understood. Multiple representations are needed as is the ability to go approximately, and sometimes exactly, between one and another (e.g., between surface and volume representations for objects). The role of hierarchical representations remains to be explored. The intersection problem and the hidden surface problem, when representing objects with generalized cylinders or with higher-order splines, remains to be worked out.

It would be helpful if representations existed to enable qualitative reasoning about physics and space, particularly about interacting objects and the nature of objects in space. For example, the exact trajectory of a falling object often is not needed, just the fact that it is falling down and that it will rest in some stable state on the floor. Coupling qualitative reasoning with problem solvers is also desirable. Research is also needed on learning by analogy, particularly with regard to physical assemblies, so that the complete details of robot assemblers need not be specified for every new task.

Research is needed on the knowledge of how to build a complete design facility with multimodal interaction, namely, inputs which are not only drawings, but also, for example, text. The man, the group, or the system who is going to use robots will need a machine intelligence aid and this need also merits investigation.

Problem solving or planning is the construction of a sequence of actions to transform one world model into another. The integration of existing capabilities into a single plan generation and execution system is in itself a formidable research goal. Further capabilities which require research include the use of multiple effectors and better means of dealing with time, since actions don't happen instantaneously. Another issue is to plan for acquiring information from sensors which could not be known during planning. Another possibility is to use a planner for planning, namely, to determine what to do next at each stage while the plan is being developed. Plans can be at various levels, for example, the force feedback level. Plans should be made reuseable by employing parameters to deal with objects other than those present in the original problem, by making them applicable to a wide variety of initial conditions, by indexing them so they can be selected efficiently from a large plan data base, and by establishing criteria to determine when a plan in a data base is worth saving. Semiautomatic planners which accept human advice also merit investigation. More work is needed on new techniques which can diagnose errors efficiently during execution and which can repair plans effectively. Plans are needed which work in the presence of other robots having independent planners to which there may be little or no communication. Ways are needed to use large amounts of domain-specific knowledge to guide planning and responses to recognized situations so that robots can exhibit intelligent behavior in certain narrow domains.

Control

Research is needed on the optimal simultaneous management of a large number of command signals and control variables for controlling manipulators which have flexible members and which have large changes in the moments of inertia of their joints during typical motions. Flexible members occur when manipulators are designed for light weight, lower power consumption, and more maneuverability. Important changing inertias may possibly be inferred in part from the system's dynamic response to commands. Vibration modes and bending may possibly be controlled by using strain gages on the members, joint force sensors, and end point sensing. Graceful mode switching may prove better than changing control gains on a continuous basis, which can lead to a highly nonlinear system.

There is a need for research on the quantitative modeling of a robot system and the tasks it is to perform in measurable, calculable, and controllable terms. This type of modeling relies on physical laws, empirical rules, and mathematical techniques. There is a need for sensitivity studies on the impact of model completeness on robot control. Studies on model simplification for classes of tasks are needed. Modeling is also needed for cooperating robot systems, such as two arms performing a single task. Robot task modeling should include ways to integrate geometrical and dynamic components.

Research is needed on the integration of real-time vision with manipulation in terms of a control system. Advances can be made in processing sensory data. Modern estimation techniques should be applied to acquire robot system data that is not measurable by sensors directly, but is useful and desirable for robot control. Algorithms should be developed for structuring multidimensional robot sensor data to facilitate their use in the control system. Since robots can actively search for information by controlled behavior, it would be beneficial to study control strategies that coordinate sensing with robot motions.

Advances in the theory of two forms of control structures, namely hierarchical controls and control logic systems, could aid robotics. Hierarchical control systems can be improved by making unique and optimal the causal ordering of references available within subsequent control levels. A theoretical framework is needed for the analysis and synthesis of control systems with pattern reference feedback logic which is sensitive to events and not just the time continuum.

There is a need to study the proper and efficient utilization of man's capabilities in combined analog and symbolic man-machine interface environments. Another issue is the constraints and requirements this form of interaction creates for control system design.

"Intelligent controls" is the discipline of coupling system theoretic approaches with advanced methodologies, such as speech recognition, image analysis, data base analysis, decisionmaking, learning, and theorem proving. This type of control has been studied for prosthetic arms. A generalization of these concepts is needed for autonomous robots.

More work is needed on dynamic control for manipulators which are equipped with multidimensional force feedback to improve performance on various tasks such as insertion. More analysis is needed on the role of compliance in manipulation control systems. Devices are needed which can give variable compliance, compliance in arbitrary directions, or both. Methods are needed to indicate the optimal degree of compliance for a given job.

More detailed studies should be done on human performance during assembly work to understand how humans use touch, feel, and multifingered hands to bring together closely fitting parts. Although anthropomorphic solutions may not be optimal in an engineering system, the existence proof of humans performing certain tasks implies at least one possible solution which could be considered for engineering systems if it were understood.

Typically manipulators have six axes to completely position and orient objects. However, research is needed on redundant axis manipulators to aid in working around obstacles. Research is needed on designing fault-tolerant robotic systems which have the capability of graceful degradation, that is, systems which continue to operate in a degraded mode. This may be particularly important for robots that fail, for example, while inside a car which is on a moving assembly line.

There is a need for basic research on actuators since there is nothing that compares with natural muscle in terms of force, weight, inertia, and energy utilization.

Manipulation

Kinematic design involves choosing the structural parameters which relate adjacent joints. Kinematic performance could be evaluated by time-based measures, such as velocities and accelerations, but such work is not known. Some work has been done on geometric measures of kinematic performance using working volume and solid angles. However these measures require a position-by-position evaluation. What is needed is an understanding of the functional dependence between performance measures and the structural kinematic parameters. Another useful set of performance measures could be based on forces and torques. Performance evaluation might also entail aspects of reliability and floor space usage.

Another topic is the kinematic geometry of systems having two or more manipulators to determine the number of freedoms and how they should be distributed. Better methods are needed to understand the mutual interdependence between the kinematics of an end effector and the kinematics of a manipulator. Also important is the interdependence between the kinematics of the manipulator and the kinematics of the work environment which includes everything which moves or resists motion. Kinematic strategies for assembly deserve attention. The trade-off between the generality offered by skewed rotary joints and the easier control of simpler kinematic manipulators is an issue.

Manipulator kinematics should be studied from the point of view of minimizing the collision avoidance problem. Another research issue is the representation of objects which should be used for collision detection programs. Planning paths for collision avoidance is another problem.

There is a need for research on high-speed manipulation, particularly for industrial applications. Some of the difficulties in controlling high-speed manipulators are that the inertias can change with the arm configuration and with the payload, such as on the space shuttle. Structural flexibility complicates dynamic control, especially if it interacts with the discrete-time effects of a digital controller. Furthermore, there are nonlinear velocity squared terms. New manipulator materials, which are rigid and lightweight, such as composites, merit investigation. Using flexibility to attain high-speed motion, such as with a fly fisherman's rod, is another possible approach, but such manipulators would require control algorithms which are far more advanced than any in use today. Substantial research would be needed on modeling flexible manipulator systems. A promising approach is the combination of a structural analysis program, such as Nastran, and a component mode perturbation coordinate dynamic formulation. Another topic meriting investigation to improve the dynamics of manipulation involves learning how to exploit kinetic energy. It would be helpful to recover this energy to aid acceleration into the next phase of a trajectory. Another promising area for research is the selection of manipulator trajectories which minimize task time. Learning can be beneficial in this respect, especially in industrial environments where repetitive operations are common. Sensory control developments should be integrated with arm design and hand design to simplify the dynamics problem. Radically new designs for manipulators should not be ignored.

Procedures have recently been developed for efficiently obtaining and solving the governing dynamic equations for robotic systems with flexible links and joints. These procedures include the use of Euler parameters, Lagrange's form of d'Alembert's principle, quasicoordinates, relative coordinates, finite element techniques, and body connection arrays. The work needs to be extended in several directions, such as closed chains, vibrations due to impact forces, and sizeable deflections in comparison to the general dimensions of the system. Furthermore, nonlinear material effects and solid-fluid interactions effects at the joints need to be modeled with greater precision. Recent advances in finite element techniques, modal analysis, and Fourier analysis techniques can potentially be used to obtain advances in the automated analyses of robotic systems.

Work should continue on the formulation of equations of motion for multibody systems which can be coded for rapid solutions. Existing dynamic control schemes should be evaluated to determine which are best from a computational point of view. Simple dynamic models for the control of manipulators are needed, as opposed to the complicated models which exist today.

Research is needed to find theoretical guidance for kinematic configurations for manipulators that optimize dexterous capabilities. The requirement of dexterity for general purpose robots leads to the remote positioning of electrical actuators. Advances over tendon cables are needed because cables have troubles with durability, maintenance, and scaling properties. Hence a research area is the development of improved power transmission devices. Rules for actuator selection would be helpful since several parameters are important, such as power efficiency, inertia, size, and shape. Research on micromanipulators is needed.

Task definitions are important in evaluating a kinematic design and control strategy. Precise definitions of the constraints and performance requirements of the task are needed. Safety requirements for manipulation should be defined. Another research topic is manipulation tasks involving moving frames.

Locomotion

Mobility systems can be classified according to their kinematics, their means for propulsion, and the environment in which they must function. A mobility system for robotics is typically the way to move a sensor or a manipulator to reach a larger space. Mobility systems amplify compliance and vibration problems for manipulation. Research is needed to minimize these effects, perhaps by the use of better control and sensors including direct end of arm sensing. Research is needed on new mechanical mechanisms for mobility in complicated environments with space limitations, such as occur in nuclear power plants and perhaps underwater and in space. Under what conditions are wheels, legs, loops, tracks, balloons, or screws the best choice?

For those cases where full automatic operation is not yet feasible, more research on teleoperators is needed, particularly when the complications of mobility require more than one operator. New levels in supervisory control might help here. Research is also needed on the optimal partitioning of the task between the operator and the machine.

Research is needed on the locomotion of robots and teleoperators over terrain which is so uneven that an active suspension system is necessary. The problems of climbing over large three-dimensional objects or of moving up ladders or similar structures with grasping feet are essentially untouched. Such work is essential to the development of multilimbed robots in space and for some types of emergency and rescue operations on earth. Essentially nothing is known about optimal foothold selection. Automatic planning for navigation with these vehicles is also needed. Naturally solutions to this problem would be aided by good methods of finding out what the terrain is. Another issue is the method of modeling obstacles for locomotion.

Linear programming algorithms can find the joint torques which minimize energy consumption for locomotion. However, these algorithms require excessive computation. Thus research is needed on improved algorithms or on a special purpose computer. Improvements in actuator efficiency and weight are important issues for the locomotion of vehicles which carry their own power sources. The weight of energy storage mechanisms is also important in this case.

Further work is needed on optimal motion synthesis for locomotion. One criterion which is currently used is maximization of the minimum value of static stability over one cycle of locomotion. In the future dynamic stability studies should be possible. Further work is also needed on the optimal configuration of joints. There appears to be no published work on specialized programming languages for the control of locomotion. Another research question is the proper testing of a mobile robot which has to work in unexplored territory.

Sensors

There is a need to improve the performance of existing visual sensors. TV cameras should have higher resolution and improved pixel quality in terms of fewer defects, wider dynamic range of intensity, antiblooming, and a higher and more uniform sensitivity. Lenses should have lower distortion and better focusing in the infrared. Faster methods are needed to pan, tilt, focus, and zoom. Controlled illumination work offers the advantages of a high signal to noise ratio and three-dimensional data collection.

More work is needed on range sensors. For example, more work is still needed on the correspondence problem in stereo vision. Triangulation techniques using a projector and a TV camera suffer from missing data due to shadowing. The laser scanner and photomultiplier scheme to measure time of light flight is too slow, especially if the target is dark. Attempts to scan with acoustic range finders run into the problem of echo signals, which remains to be addressed.

Current arrays of touch and force sensors suffer from coarse resolution, from low speed due to mass and friction, and from an excessive number of wires. There is a need to develop a high resolution, compliant, two-dimensional transducer array and to integrate it with local microprocessors. As with developments in other sensors, new devices must be bounded in cost.

More applied research in the use of acoustic and temperature sensors with robots offers promise. With regard to hot temperature sensors, there is a need to improve accuracy. In general, sensors should be made available with very high overload capabilities.

There is a need for the formalization of interpretation, the mapping between observations and object models, which includes predictions and descriptions. Predictions are maps from models to observations. Descriptions are maps from observations to models.

Contact sensors can be used to direct contact, monitor and guide operations, and confirm data from noncontact sensors. Some of the questions which contact sensors might be used to answer include: "Is a vector of contact constraints satisfied?" "What object has been grasped?" and "Is grasp stable enough for carrying or assembling?" Research is needed to more effectively use contact sensing data. Currently algorithms come from someone who is quite familiar with the robot and the objects to be manipulated. One research topic in this respect is the search for a good set of language primitives for obtaining and acting upon contact information. Another topic is the search for techniques to deal with the multitude of circumstances which could occur during execution. More knowledge is also needed for the choice of compliance matrices for robots. It may be possible to relax the precision to which positions are specified during robot programming if the robot is given the power to learn positions by contact sensing and search. This approach is particularly appropriate for repetitive tasks.

The correct interpretation of contact data deserves attention, because there are friction effects when forces are being measured while parts are in sliding contact. Problems with noisy data may be addressed with the use of Kalman filters and statistical pattern recognition techniques.

A perennial research problem is the selection of the proper sensor to provide the data to which the proper processing algorithm can be applied to supply the information required for a task. It would be helpful if the processing algorithm could detect an invalid model. It would be helpful if better methods to encapsulate and use contact sense experience were available. For this a better understanding of how humans use contact sensing might prove helpful. Another challenge is to determine the conditions under which two sensors can be substituted for each other and when a mechanism can be used to replace the need for a sensor. There is also a need to understand the trade-off between the use of sensors and imposing more structure in the robot's environment. Contact sensors are commonly used to provide a specific piece of information. There is a need to go beyond specific instances of the use of contact sensors to a categorization which identifies classes of algorithms in contact sensing. More testing of contact sensing algorithms is needed to grade them. The role of models in creating new processing algorithms needs clarification.

Robot vision might be considered as a process with four stages which might interact. Restoration is the process of producing an accurate image despite degradations in the sensed image. Segmentation is the process of decomposing an image into regions corresponding to objects or parts of objects. The segmented parts can then be described, such as by size, shape, and color. Model matching can then be done to make decisions about objects. More work is needed on all these topics to improve performance and make vision systems more general in terms of object variety and the environment in which they can function.

Several specific problems in vision were addressed. For example, good statistical models for describing classes or region sizes and shapes are not available. More work is needed on the analysis of image sequences. Since the extraction of three-dimensional information is important, investigations using tomographic reconstruction techniques merit consideration. More work on models for images and scenes is needed to design optimal techniques. Methods to disambiguate the factors influencing image brightness, such as illumination, reflectivity, and surface shape would be helpful. There is evidence that by examining the fine structure of edges, distinctions can be made among edges, due to reflections, occlusion, and shadowing. More work could be done on this.

Improved visual processing capabilities are needed to recognize objects and determine their position and orientation even if the objects are overlapping and the background is cluttered. There is a need for work on processing three-dimensional data such as can be obtained with the use of a projector and an imaging device. Inspection tasks present difficult problems to be overcome.

The speed of visual processing must be improved, for example, by investigating the use of special purpose hardware and clever algorithms. The size and cost of processing can be attacked by continued work on metal–oxide–semiconductor (MOS) and charge-coupled device (CCD) electronic chips.

Industrial applications do not require complex vision as much as other applications, such as firefighting, household servants, and terminal guidance. More work is needed to handle three-dimensional objects, specifically edge extraction, texture, and shape description. Research on complex vision should become more feasible in the near future due to the rapid developments in computing power. Vision research will not just be a user of the new forms of computing power, but the computers will be structured according to the needs of vision.

Communication

Robots are general machines, that is, they can perform a wide variety of tasks. Unfortunately, getting robots to perform the specific task which a human has in mind is not easy. Currently this form of communication is aided by using the manipulator to specify positions and by writing programs which can be entered via a keyboard. Several research investigations can help overcome some of the current problems with robot communication.

For certain tasks, the number of statements which are included specifically for handling contingencies and error conditions is becoming excessive. This problem will only become worse as we strive to develop robots that are more autonomous in handling the unexpected. Research is needed on methods which automatically check for errors in robot activities and initiate corrective action when necessary.

Currently a great deal of effort is needed to supply and adjust the parameters which are utilized in specifying trajectories. This issue is complicated by the manufacturing tolerances of the manipulated parts. New methods for expediting the specification of trajectory parameters, including forces, would be helpful.

The current difficulty of debugging and altering robot programs will only become more difficult in the future when high-level languages are used that incorporate geometrical modeling systems and enormous data bases. How can a robot operator make a small programming change when the robot is driven by an enormous, complex program which was automatically generated? Furthermore, particular motions may only take place after significant computation and after data from sensors has been processed. Work on debugging sophisticated robot programs is needed to make such systems a reality. Aids must be developed to assist in identifying and correcting erroneous data. Along with the development of robot systems which know better how to manipulate objects, must come systems that allow humans to understand what the robot is doing.

Unified engineering data bases which describe the physical and volumetric properties of objects will prove useful for robot programming. By the simulation of robot motions, off-line programs can be written and verified which have collision free paths. However, research is needed to simulate contact phenomenon. Also advances are needed in the model-based generation of programs that use local sensory information to fit objects together and to compensate for variability from assembly to assembly. Such variability results from tolerances in part dimensions, from the lack of motion repeatability of robots, and from a lack of repeatability in the position of parts in fixtures. Tolerances of dimensions raise several research questions: "How do you analyze them?" "How do you design with them?" "How do you represent them in models?" and "How can they be used when writing a robot program?"

Current geometric modeling systems do not have all the capabilities desired in terms of shape description. In the future more work will be done on general curved surfaces. Representations will be sought with optimum efficiency in terms of computation time and storage requirements. Work is also needed on representing flexible objects, such as the hydraulic hoses and electrical cables on robots. A need exists to provide the automated conversion from present data bases to the volumetric and topological forms needed for simulation of the manufacturing process. Another need is to obtain models by presenting sample parts to the system.

In order to model cutting and forming, there is a need to automate the finite-element solution process and to drastically reduce the computational load. The problem of automatically generating no connection numerical control (NC) tool paths from geometric models also needs more work.

There is a need for the symbolic analysis of constraints on objects. Such an analysis might aid in answering questions like: "Can I pick up the object?" "Which way can it be moved out?" and "How does motion of this part affect the mechanism it is in?" The laws of physics will probably have to be combined with geometrical models to answer some questions. Another issue is whether all interesting properties of objects can be derived.

All research need not be focused on higher-level languages. Much remains to be learned about the fundamentals of manipulator languages, the assembly language level of robots. Work on a language with the following properties was advocated: The ability to conveniently create and manipulate coordinate frames is essential. For each of the six degrees of freedom of the control object, either position, velocity, or force should be conveniently specified. The remaining variables should be available to the manipulator program. The specification of each control variable may be in functional form with other variables as arguments. It should be possible to describe portions of a trajectory in terms of acceleration or velocity constraints. Various data types are needed. Terminating conditions for each step must be readily expressed. All sensor data, such as force and vision, should be timed in terms of a common clock and coordinated. The language should be similar to Pascal in structure and form. Interaction with external sensors and parallel motion primitives are two more desired features. Synchronization with machines is also helpful. Real-time performance with realistic computers is the ultimate test.

With multiple arms, multiple sensors including vision, a cluttered environment, and perhaps even mobility, the task of writing a program to effectively orchestrate manipulation is extremely difficult. Sometimes the cooperation between subsystems of a robot must be close, as for example, when two arms are moving a mutually grasped workpiece. Sometimes subsystems must work synchronously and at other times they work asynchronously. Fine cooperative assembly motions by multifingered hands are also a problem. Smart hands will prove helpful. Operating systems for robots need a real-time means to cope with dynamic collision avoidance, particularly when manipulators use redundant kinematic solutions which are selected on the basis of how an object was grasped. When an unanticipated error occurs, it is desirable for the system to be able to sense data which can be used to decide that a conflict exists with the robot's model of normal behavior. Then the proper kind of corrective action must be taken. This problem may be stated as the "Something is wrong! Who's fault is it?" problem. Research is needed to provide the knowledge which will permit robots to have these abilities.

Robots are sometimes required to perform a generic task, such as assembling motors, but various part sizes lead to thousands of slightly different models. It is desirable not to have to write a specific program for each model. However, research is needed in how to write a general program which can generate specific programs in real time. One problem in writing general programs is that the argument list for general commands can get excessively long and experience indicates that programs can often be more easily written with some primitive commands. Another issue is to get robots other than the one which was used for teaching to function on the taught task, perhaps even using a robot with a different kinematic configuration. Another challenge is to substitute robots which are less mechanically precise.

The coordination of complex robots will most likely benefit from a better understanding of modular hierarchical structures. It would be helpful to have mathematical guidance on: "How to define levels?" "What kind of information attenuation is appropriate for interlevel communication?" and "What kind of lateral communication is right?" The properties of adaptation and learning should be exploited. Research on distributed processing and architectures for massively parallel electronic computation nets should also help in making possible advanced robots.

Cooperating intelligent systems sometimes must function in an environment which limits communication, such as in space and undersea. These systems would benefit from more research on what the nature of their communication and cooperation should be. It would probably help if the receiver had some expectation of what the other intelligent system will say.

There is a need to measure the efficiency of programming languages. With simple languages, robots can propagate more readily.

Miscellaneous

From an industrial point of view, the most important research areas are those which will enable robots to perform new tasks or to improve performance in existing jobs. Several areas were suggested for priority: handling parts which are on belt conveyors or hook conveyors, visually tracking parts, unloading pallets, the bin picking problem, feeding parts, handling imprecisely positioned parts with robots that are not very accurate and thus not very expensive, visually guided arc welding, inspection, faster arms, languages for sensor-based robots, modeling a workstation to aid the programming of a new task, and reliability.

A central problem with industrial robotic intelligence is that a robot may have a large number of alternative actions, but the user does not want to be burdened with specifying them. This problem can be addressed by work on interfacing robots to existing information systems, on designing products for automation, on the off-line simulation of robots with sensory feedback, and on restart procedures.

Several other issues were raised. Research on identifying research activities can help in promoting efficiency in research and in the selection of research activities. Some form of inexpensive and standardized research facility might help in enabling more research groups to form and interact. Communication within the robotics research community could benefit from work on definitions and a more limited set of sources in which publications appear. The field of robotics can benefit from the knowledge gained recently in other fields, such as operating systems and automatic programming. Educational programs in robotics are currently quite limited.

Organization of Robotics Research

One problem with the workshop was an organization which caused occasional overlap. For example, object modeling was discussed both under "Intelligence and Decisionmaking" and "Communications." Another example is that dynamics was discussed under "Control" and "Manipulation." As with most endeavors, it is usually possible to organize an effort in a more efficient manner the second time. If another workshop is held on the basic research needed to advance the state of knowledge in robotics, the organizational structure listed below is recommended as an improvement.

1) Representation, Modeling
   a) Objects
   b) Laws of Nature
   c) Processes
2) Sensors
   a) Hardware
   b) Interpretation
   c) Interaction
3) Manipulation
   a) Hardware
   b) Kinematics
   c) Dynamics
   d) Skills
4) Locomotion
   a) Hardware
   b) Kinematics
   c) dynamics
   d) Skills
5) Intelligent Superstructure
   a) Hardware
   b) Organization
   c) Languages
   d) Problem solving
   e) Learning
6) Integration and Applications

Summary

From this compendium of research problems in robotics, several conclusions can be reached. A large number of reasonably well-defined research problems exist. A substantial knowledge base already exists with which to solve these problems. Research is needed both on many individual facets of the robotics problem and on integrated systems.

The knowledge needed for advanced robotic systems cannot just be purchased. It must be gained sequentially to some degree. Only by experiments on new integrated robotic systems can the ability to function in new environments or on new tasks be investigated properly. The time and financial resources which are needed to conduct these investigations should not be underestimated. Presumably our national needs for industrial productivity, energy, health, defense, and the use of space should help to justify the provision of these resources. Naturally, basic research in robotics will not provide all the answers, but it can have an impact and it should be given a chance to yield the knowledge which a research community believes is attainable.

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