GRASP News
Volume 8, Number 1

MS-CIS-92-15
GRASP NEWS 302

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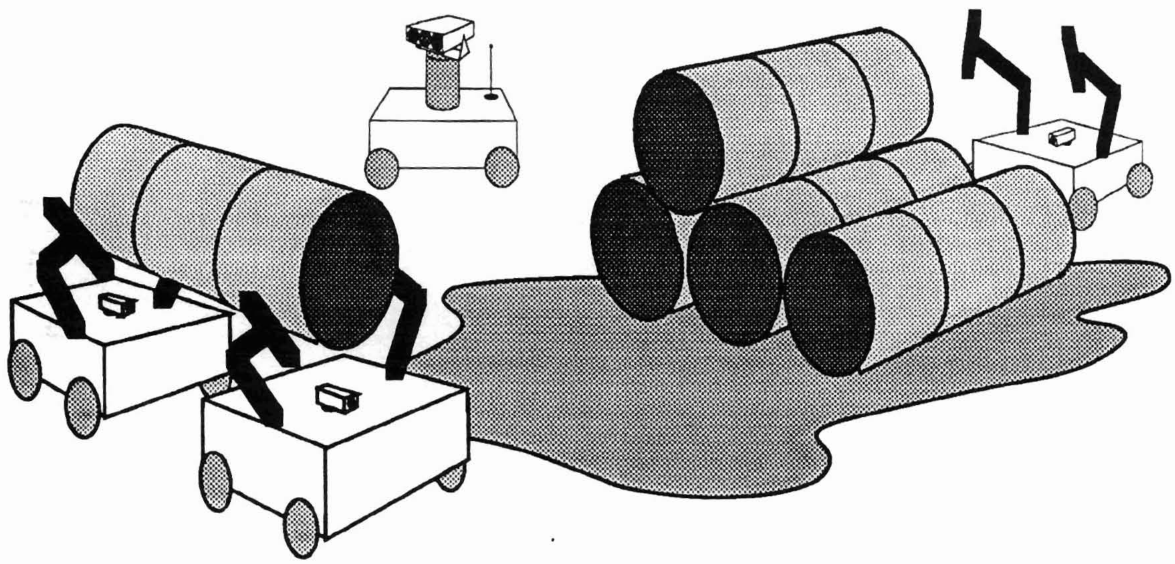
March 1992

GRASP News

Volume 8, Number 1 Spring 1992



UNIVERSITY OF PENNSYLVANIA

A Report of the General Robotics and Active Sensory Perception Laboratory

GRASP Laboratory

GRASP News

Volume 8, Number 1 Spring 1992

General Robotics and Active Sensory Perception (GRASP) Laboratory
University of Pennsylvania
Philadelphia, PA 19104-6228

GRASP News[1] is published by the Department of Computer and Information Science, University of Pennsylvania, Philadelphia, Pennsylvania 19104-6389. This edition of the *GRASP News* was edited by Thomas Lindsay.

Cover sketch of multiple agents cleaning up hazardous waste by Eric Paljug. Cover layout was designed by Tom Lindsay using Autocad, Postscript, and Macintosh software.

Grasp Laboratory research reported in this document was supported by DARPA Grant N0014-88-K-0630 (administered through ONR), AFOSR Grants 88-0244, AFOSR 88-0296; Army/DAAL 03-89-C-0031PRI; NSF Grants CISE/CDA 88-22719, IRI 89-06770, IRI89-17721, BCS-89-01352, MSS 9157156, CISE/CDA 90-2253; NATO CRG 911041; Du Pont Corporation, and the University of Pennsylvania Research Foundation.

GRASP News was typeset using Donald Knuth's TeX typesetting system and Leslie Lamport's LaTeX macro package running under SunOS Release 4.1. Printing was done on an Apple Laserwriter.

Additional copies of *GRASP News* can be ordered from the Department of Computer and Information Science as Technical Report MS-CIS-92-15, GRASP LAB 302.

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1 Forum

Editors' Foreword

GRASP News is published to chronicle the progress of our research efforts in the GRASP Laboratory. It is not meant to be an in-depth study of our work, for that is available in the publications and tech reports listed at the end of the newsletter. Rather, it is meant to give an overview of what we have accomplished, what we are currently researching, and the problems we are thinking about researching in the future. Some of the contributions here reflect years of research, while others represent the new directions of research in the lab.

For the first time, the feature article is based on a unified research project that we may all play a role in. At every turn in the lab in the past, we see other research projects and think about how that particular project could work well with our own. Now, we will be working to integrate our own research with others. At the local level, this means a multi-agent, multi-sensor project that will be built up from robust units designed for integration. At a more global level, our work can be integrated with other research groups, to share not only ideas and results, but also building blocks of research that can lead to synergy in the research community.

This issue of *GRASP News* covers the developments for the year 1991. It has been a dynamic year in the laboratory. Along with the changes in computers (the grasp computer no longer exists!), changes in grants, and changes in direction (all of which are noted elsewhere in the newsletter), there have been great changes in personnel, mainly as a result of that great scourge to university research, graduation. **Dr. Sanjay Agrawal** is doing multimedia research at Microsoft Corp. in Seattle. **Dr. José-Antonio Caraza** is an assistant professor at the University of Monterrey, Mexico. **Dr. Janez Funda** is currently working at IBM T.J. Watson Research Center, researching medical applications for robotics. **Dr. Alok Gupta** is a research scientist in the image analysis group at Siemens Corporate Research in Princeton. The projects he is working on include physically-based dynamic shape models for segmentation and representation, and multi-modality image fusion, specifically for medical image analysis. **Dr. Robert King** is a Technical Staff Member at the High Performance Computing and Communications directorate in IBM's T.J. Watson Research Center, working on software to support broadband networks. **Dr. Sang Wook Lee** is currently a postdoc here in the laboratory, and his current research is described in the newsletter. **Dr. Raymond McKendall** is a post-doc in the Decision Sciences department at the Wharton School, working with Dr. Stavros Zenios on modeling and simulation of mortgage-backed securities. **Dr. Pramath Sinha** is a Postdoctoral Research Fellow at the Robotics and Automation Laboratory (RAL) of the Department of Mechanical Engineering, University of Toronto, investigating transition phenomena in dexterous robot/environment interaction and their control through active/passive devices, and designing the sensory system for a facility for dexterous robot/environment interaction. **Dr. Tarek Sobh** has taken a position of Research Assistant Professor in the Computer Science Department of the University of Utah. **Dr. Victor Wolfe** is now an Assistant Professor at the University of Rhode Island. He is continuing research in real-time concurrency control by developing programming environments for POSIX 1003.4 and 1003.4a (IEEE standard real-time) operating systems and for object-oriented database systems.

Aleš Leonardis and **Jasna Maver** have returned to the Computer Vision Laboratory of the University of Ljubljana, Slovenia.

George Chou, who graduated with a B.S. last year, is currently at Media Laboratory, MIT, working with Prof. Ted Adelson on a mid-level image representation that will account for multiple motions within the scene.

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Director's Note

February 1992.

Perestrojka-Restructuring has hit the world, including the GRASP laboratory. Where are we going? Are we investigating the right research issues? There is always the good news and the bad news. I begin with the good news. Our vision on Active Perception is being more and more accepted by a wide scientific community. Our critical reexamination of two robot manipulation has payed off in unique new results in control of two cooperating robots while carrying an object. The work on telemanipulation with delays has shown how human agents can be incorporated in a nontrivial way into a family of cooperative agents. All this work has been acknowledged by funding agencies and we have now secured funding for the new exciting project of cooperative mobile, manipulatory, observer and human agents. While we have always loosely worked together, this new project is forcing us for a tighter cooperation. It is as if the robot agents are telling us: how do you want us to cooperate if you (people) cannot cooperate? Now I come to the bad news. Actually it is not bad news, but rather change in mode of our operation, hence restructuring/perestrojka. This new project is challenging all of us to think more globally (of the whole system), yet perform the best that we each are able to do locally, i.e. on each module. If the modules are not robust in the integrated system, the weakest link breaks the whole system. Finally, if I may conclude with a philosophical thought, I believe that what we are experiencing in this new cooperative project will be, or already is, symptomatic in our research paradigm. The problems in Robotics are not anymore in development of small modules, but in integrated, intelligent real time systems that clearly will be a result of cooperative efforts. Hence we all have to learn high professionalism at the individual level and great tolerance at the group level. Our results will be the testimony to the above.

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2 Feature Article

A Small-Team Architecture for Multiagent Robotic Systems

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Abstract

The GRASP laboratory has undertaken a research project to develop a multiagent robotic system for intelligent material handling. This article outlines the organization of the system. The goal of this research project is to investigate the architecture, coordination, and monitoring of *a multiagent robotic system* employed in the task of material handling, in an unstructured, indoor environment. In this research, manipulators, observers, vehicles, sensors, and human operator(s) are considered to be agents. Alternatively, an agent can be a general-purpose agent (for example, a six degree of freedom manipulator on a mobile platform with visual, force, touch and position sensors). Possible applications for such a system includes handling of waste and hazardous materials, decontamination of nuclear plants, and interfacing between special purpose material handling devices in warehouses. The fundamental research problems that are being studied are *organization*, or the decomposition of the task into subtasks and configuring the multiple agents with appropriate human interaction, *exploration*, or the process of exploring geometric, material and other properties about the environment and other agents, and *coordination*, or the dynamic control of multiple agents for manipulation and transportation of objects to a desired destination.

2.1 Introduction

This article presents an outline of a multiagent robotic system employed in the task of material handling, in an unstructured, indoor environment. In this research, manipulators, observers, vehicles, sensors, and human operator(s) are considered to be agents. Alternatively, an agent can be a general-purpose agent (for example, a six degree of freedom manipulator on a mobile platform with visual, force, touch and position sensors). Mobility is considered to be essential — if an agent is not mobile, it must be possible for it to "piggy-back" on another agent which is mobile. In addition there is a central station which is stocked with a variety of additional sensors, means of illumination, special effectors or tools, that the agents can employ depending on the environment, task and the outcome of the execution of the task.

A human operator always assumes the role of supervisor; it is the operator who gives tasks to the system to be carried out and it is the operator who then monitors task execution. If the system were completely autonomous the operator's interaction would relate only to the specification of tasks and the monitoring of their execution. However, as task execution always involves interaction with the real world, which is difficult, if not impossible, to limit, the operator must assume a more direct role in controlling the system during task execution when an unmodeled event occurs.

The operator is located remotely from the actual work site and interacts only by means of displays and input/output devices. The initial modeling of the task space is carried out autonomously under the operator's supervision. The operator's supervision of this modeling takes the form of correcting errors in task space identification and of suggesting possible interpretations of sensor data and of fruitful observing positions and strategies. In order to do this the operator must have the ability to see raw sensor data at any level in the system and be able to interact with the interpretation of that data at the appropriate levels in the system. The sensor data may come from general observers and from vehicles in which case the cost of obtaining that data must be weighed in terms of its utility.

During task execution the operator ideally assumes the role of supervisor with nothing to do if the task is executed correctly by the various autonomous agents. When an unexpected event occurs which might lead to incorrect action the operator takes a more active role by intervening at the appropriate level in the system. This might involve interaction at the highest level in redirecting the agents according to a different strategy or it might relate to assuming direct control of an individual agent to correct its situation. Once again the cost of low-level interaction with mobile agents must be weighed against the need of such interaction.

All forms of operator interaction with the system is by means of remotely gathered information displayed to the operator by the most appropriate means. At no time does the operator directly view the actual work site. Maintaining the ability of the operator to interact at any level in remote systems which are becoming increasingly autonomous is a direct challenge of our research.

Our primary goal is to develop a system which can carry out tasks with 100% reliability by invoking an operator's intelligence to solve problems which we have failed to fully automate. Our secondary goal is to automate tasks fully so that this operator intervention is unnecessary.

Some possible applications of such a material handling system and examples of the tasks and environments are outlined below:

- Interfacing between special purpose (but "inflexible") material handling devices (such as conveyor belts and part feeders) and sophisticated, but stationary, special purpose work cells (which could contain manufacturing machines or robots). Such a system would play the role of the human operator by off-loading components from the special purpose material handling equipment, loading workpieces on fixtures for machines/work cells, and fetching appropriate tools. In addition, the agents can perform tasks such as palletizing, retrieval from inventory, storage and clean-up operations.
- Handling of waste and hazardous materials in nuclear sites. This involves transportation of chemicals, waste material, old radioactive equipment and other toxic

substances. Such a system could also perform routine inspections with a variety of sensors (including visual, temperature, touch, radiation and chemical sensors) and monitor, for example, air quality or radiation levels. It could be used for buried waste retrieval, in which case it would be able to excavate, explore, identify and sort objects, in addition to being able to transport objects. Similarly, decontamination, which requires disassembly followed by removal of old equipment, would be facilitated with such a material handling system.

Central to the multiagent concept is *organization* or the decomposition of the task into subtasks and configuring the multiple agents optimally with appropriate human interaction. For example, this includes the determination of the number of agents required, their spatial and temporal distribution, the required effectors/sensors/tools and the organization of the task. With each task, there are two key aspects: *exploration* and *task execution*. These two phases are not independent and must be interwoven (and indeed, in some situations they can be carried out concurrently). The exploration allows the system to gather information about its environment including, for example, the type of material and the geometry of the object that must be handled. Of course, it is possible, that based on this information, a reorganization of the task may be required. In the second phase of task execution, the goal is the final destination of the transported object. It is assumed that a human operator outlines the general path from the initial to the final position, but local modifications of this path and redirecting during the transport is permitted if the need should arise.

We consider the example of lifting and transporting an object, say a long pipe (approximately 5 meters long, 15 cm OD, 20 kg mass) inside a warehouse. Assume that the approximate location of the pipe (for example, the location of the room where the pipe is stored) is known but the exact position is not available. The multiple agents are first *organized* into an *exploration* task in which they attempt to locate the desired object. In the process, they encounter several objects and using, for example, touch and vision, they are able to discriminate against "wrong" objects. An observer agent, periodically informs the human operator, who is a "super agent" in this scenario, of the status of the system. For example, this can be done *via* a graphical display. If necessary, the operator can intervene by interrupting the search and providing more information in order to speed up the search. If the display consists of visual images obtained by the observers(s), he/she can send agents directly to the object. Once the object is located, relevant properties, including the size, shape, position and orientation of the pipe are obtained. Agents with manipulatory and tactile capability extract necessary material and mechanical properties. The mass (weight) and inertia of the pipe are first inferred from size, shape and material information. With this information, the agents are *organized* for the *task execution* phase. Based on the payload characteristics and the capabilities of each agent, the system determines the number of agents, the stance (pose) for each agent, and allocates the load between the agents for the lifting task. This selection is based on a sufficing principle, although optimality and redundancy considerations are important. It is possible that the lifting task cannot be accomplished due to a poor estimate of the payload. Or, if the pipe is flexible, a failure may be reported due to a sag in the pipe. In either case, the system assigns additional agents and reconfigures them automatically. For example, if the pipe sags, additional agent(s) are commanded to support the pipe at appropriate points in order to remedy the problem. If the execution of the lifting task fails, the observer, which perceives that the system is not functioning as desired, could alert the operator. Alternatively, if the operator continuously monitors the system, although at a much lower bandwidth, he/she is able to intervene to assist the multiagent system, if necessary. The approximate path for the transportation is specified, possibly by the human operator. One or more observers position themselves appropriately so that their view is not occluded by obstacles. The proprioceptive sensing in each agent along with force/torque/tactile information allows dynamic, coordinated, control in the manipulation task. Obstacles in the path can be cleared by agents that are not involved in the transportation. If these obstacles are large, a modified path is sought by the system. In this approach, the multiagent system is intelligent in the sense that it is capable of learning by exploring and the agents can coordinate with each other. At the same time, the framework allows the robotic agents to interact with a human agent(s), who possesses superior intelligence. As time progresses, this interaction is reduced — the multiagent system becomes more sophisticated while the role of the human operator is reduced. This synergism increases the reliability, facilitates programming, and makes it possible to have a working system with less effort. What follows is an outline of the system organization.

2.2 Small-Team Architecture

Our design of a multiagent robotic system for intelligent material handling must address the following issues:

- How do we interconnect the agents in a communications network so that information sensed and processed by one agent can be delivered to one or more of the other agents in the form(s) and at the rate(s) needed for a given subtask?
- How do we design a priority scheme which determines what subtasks the agents will execute and in what order? The design of the priority scheme must address the inherent informational and physical couplings between agents as well as the constraints that these couplings impose.

Cooperation between agents can be delineated by two fundamental aspects: (i) information interaction; and (ii) physical interaction. Information interaction is defined as the act of transferring information between agents *without* recourse to either direct or indirect mechanical coupling. This transfer alters the agents' informational states, but it does not alter the physical state of non-agent objects in the workspace. The nominal pathways for information interaction are standard digital or hybrid links. In comparison, physical interaction is defined as the act of directly or indirectly manipulating non-agent objects and thereby temporarily or permanently altering their states. Physical interaction also provides the possibility of transferring information between agents. Here, the nominal pathways are the generally transitory mechanical linkages which are formed in the course of multiagent manipulation tasks.

The general problem of designing intelligent cooperative agents which can interact by exchanging information and by jointly altering the physical world is essentially unbounded. With the exception of very special circumstances, the goal of delineating a globally optimal system design is in practice unobtainable for fundamental mathematical and computational reasons. These ideas and the nature of these inherent difficulties have emerged in the course of studying *dynamic cooperative teams* [14, 15]. This theory is an outgrowth of *game theory* [13, 4] and was motivated initially by fundamental problems in mathematical economics, management science, and control theory [11, 12, 17, 19, 6, 3].

Our design of a multiagent robotic system for intelligent material handling is based on a *small-team architecture*. By a small team, we mean at most six agents who are organized in the following way. The design has four levels of supervision/competence. Level-1 denotes the manipulator-locomotor agents who can interact physically with the world. Level-2 denotes the mobile tactical observer agent who oversees the agents on level-1 and who has competence to give level-1 agents informational assistance at a medium level of granularity. Level 3 denotes the strategic observer agent who oversees the entire workspace and has competence to guide the level-2-1 agents on the global aspects of the task by providing broad advice with a concomitant reduction in detail. Level 4 denotes the human agent, who provides high level planning and resolves situations which are beyond the capability of all other agents (error recovery). This architecture is depicted in Figure 1, where there are a total of five agents[2].

In the small-team architecture, the human agent is connected to the strategic observer and all level-1 through level-3 agents are interconnected. We note that the links connecting different agents do not possess identical properties, e.g., channel properties such as bandwidth and symmetry are generally a function of the agent pair and reflect their joint role and thus their information interaction requirements. One of the design issues of this system is the priority scheme for determining who listens to whom when there is contention for an agent's attention.

The philosophy which governs this design embraces the following principles:

- Level-1 agents have final authority for subtask decision-making where the individual or collective safety of the manipulator-locomotor agents and payload is at stake[3].

[2]The limitation on each team to a maximum of three agents at level-1 is made to bound the scope of the hardware testbed in the initial stages of this research program. In principle, it is possible to expand the number of level-1 agents, particularly where the agents are homogeneous with regard to their attributes. However, the restriction on each team to one level-2 agent within the small-team architecture also imposes a limit on the number of level-1 agents. This limitation is a consequence of the need to maintain a given minimum required level of processing capability at level-2 per agent at level-1.

[3]The level-2 agent has final authority for its own movements where its own safety is at stake.

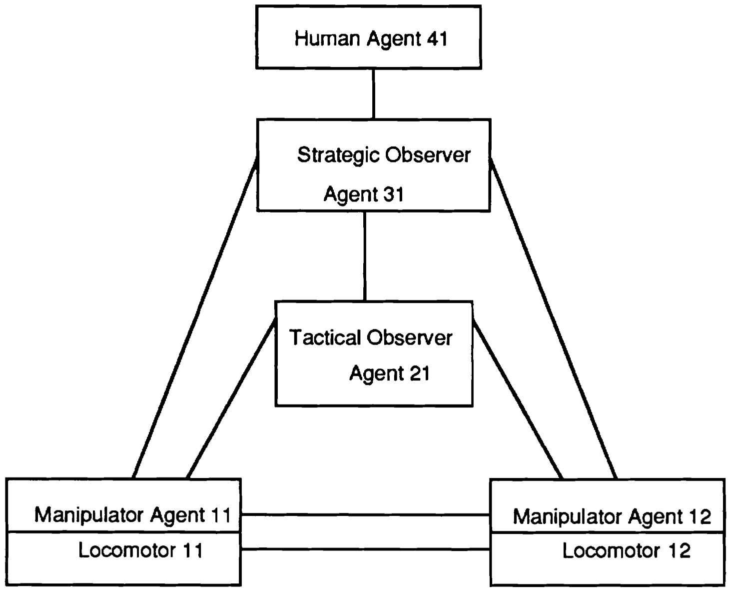

Figure 1: A Small-Team Architecture

- Level-1 agents have local sensing capabilities which provide high resolution capabilities. In contrast, the level-2 agent has a wider field-of-view which must allow for essentially concurrent monitoring of all agents at level-1. The relative increase in the field-of-view in going from level-1 to level-2 is paid for by reducing the sensory acuity at level-2. The role of the level-2 agent is to provide tactical information and advice to the level-1 agents in the course of carrying out the given subtask. The role of the level-3 agent is to provide strategic information and advice to the level-2 and level-1 agents. The advice tendered from level-3 is based on a combination of sensory information and *a priori* knowledge. The agent at level-3 has less sensory acuity than the agent at level-2. However, the agent at level-3 has the widest field-of-view. The word "advice" is important, since ultimate authority for fundamental actions does not reside at levels 2 and 3 but instead resides at level-1.

- The small-team approach allows for limited interaction between small teams. Such interaction would occur when the overall task or subtask requires more agent power than is available from a single team — but does *not* require any physical coupling between the two distinct agent groups at level-1. For example, consider the case where two nearby sections of pipe must be moved from a given storage location to a specified installation point. Suppose two level-1 agents can carry at most one section of pipe at a time. In principle, there are two approaches to solving this transportation problem — the sequential solution vs the coordinated parallel solution. The sequential approach simply dictates that a single small team moves the pipe sections sequentially. The parallel approach requires that two coordinated small teams move the pipe sections concurrently. In the parallel case, the interaction between the individual

> teams at level 1 and 2 is defined by the requirement that the teams members and payloads maintain a required minimum physical separation at all times. The minimum separation requirement imposes the need for inter-team coordination at spatial bottlenecks. This design permits direct communication between the level-2 observers as well as the observers at level-3. There is no direct inter-group communication at level-1. This design restriction limits the scope of the level-1 agent coordination and communications requirements.

An excellent compendium of research on architectural issues in multiagent robotics appears in [8]; specifically we cite [2, 7, 9, 16, 1, 10]. The fundamental work by Brooks and his colleagues, e.g., [2], on the subsumption architecture and its implementation and testing is very thought provoking. This work represents a major departure from traditional AI thinking. The subsumption architecture is organized as a series of incremental layers with each layer connecting sensor-based perception to action. The layers "communicate" by passing signals which serve to enhance or inhibit neighboring modules' behaviors. A collective behavior emerges from this built-in arbitrated reinforcement-inhibition schema. Internalized high-level models are basically eliminated in this architecture.

In comparison, our architecture lies between the rigidly organized and centralized modular form of traditional AI and the subsumption architecture. We believe that in order to effectively manipulate large objects in material handling tasks it is useful to employ distributed manipulator-locomotor and observer agents who can communicate at various level of abstraction and detail. Although it may be possible to achieve cooperative, coordinated manipulator-locomotor behavior with subsumption agents, it seems to us that the middle ground is a reasonable place to build these cooperative agents who must interact physically and informationally in the course of material handling and other similar tasks. One of the advantages of our architecture is its decomposability. In particular, one can study the interaction between levels 2 and 1 without recourse to level-3. The point here is that we can develop substantial experience working solely with levels 2 and 1 prior to implementing level-3.

We return to the pipe relocation paradigm to illustrate the roles of the agents in an application which is based on a single small team. Further details of these ideas and concepts appear in the sequel.

The strategic observer (agent 31) assigns the tactical observer (agent 21) and two manipulator-locomotor agents (11, & 12) to the task of: (i) locating a section of pipe within a specified area, and (ii) transporting the pipe to a required terminal destination. Initially, the task assignment will be performed by the human agent 41. The agents possess *a priori* information relating to themselves, their cohorts, and the task. This knowledge includes agent capabilities and limitations.

The Human Agent:

1. Agent 41 is remotely located at a site and can not directly see the work area.

2. Agent 41 has a graphical display. The graphical display shows a geometric world model which is obtained by processing images from level-1, level-2, and level-3 agents. Agent 41 may choose to display the world model viewed by a specific agent. If any ambiguity occurs in the world model due to segmentation, agent 41 may directly view the image and resolve the ambiguity.

3. Agent 41 can help specify tasks by moving object, or agents, around in the geometric model. In this way, agent 41 can organize the activity of many agents by sequentially attending to each agents, which in turn will follow along at a slower execution rate.

4. Agent 41 may be provided with kinesthetic feedback as well as positional input. Thus if an agent became "stuck" then the operator could be alerted by the agent itself or the observer agent and the operator station attached to the agent so that the operator could "feel" the constraints on the motion of the agent and could provide guidance, at a lower level, to extricate the agent.

The Strategic Observer:

1. Agent 31 knows the nominal layout of the entire work area.

2. Agent 31 knows the initial location of the pipe within a bounded search area, e.g., a given rectangular area.

3. Agent 31 has a map and grid system which specifies the search area by defining, for example, its North-East corner and its nominal dimensions.

4. Agent 31 does *not* necessarily possess a totally unobstructed view of the entire work area — there may be packing crates which obstruct agent 31's field-of-view.

5. Agent 31 does *not* possess the visual acuity to discern small objects on the floor in the transport zone, as well as detailed floor conditions, e.g., small wood chips or grease.

6. Agent 31 is not mobile, but it can change its field-of-view by by turning its head and craning its neck.

7. Agent 31 has a 50 m visual range limit.

8. Agent 31 provides agents 21, 11, and 12 with a suggested path through the work area for transporting the pipe. This path connects the search area, where the pipe is initially located, to the required terminal or destination zone.

The Tactical Observer:

1. Agent 21 has a 10 m visual range limit. Agent 21 is fully mobile, i.e., it is able to move throughout the free workspace.
2. Agent 21 can accomplish a visual mobile search or exploration of a local area where contact sensing and manipulation are not required. If contact sensing and exploratory manipulation are required, this subtask is carried out by level-1 agents.
3. Agent 21 provides refined advice to the level-1 agents for path segments 5-10 m in length.
4. Agent 21 coordinates and monitors the lifting task assigned to agents 11 and 12. This responsibility includes advising the level-1 agents when to expect to communicate through sensed forces at the commencement of the lifting subtask.
5. Agent 21 can visually monitor the current state of the manipulation and transportation subtasks assigned to the level-1 agents.

The Manipulator-Locomotor Agents:

1. Agents 11 and 12 have a 1-2 m visual range limit. This implies that they may not be in reliable visual contact during the course of the transportation task, if the pipe is more than 2 m in length.
2. Level-1 agents can communicate through force sensing as well as low-bandwidth high-priority signals, e.g., "a shout" to stop, or alter a lifting or maneuvering process.

Navigation and Reference Frames:

1. Agent navigation is based on a combination of absolute reference systems, e.g., geographic map coordinates, and relative displacement, e.g., turn counter-clockwise 15 degrees. Dead reckoning is employed where continuous absolute position determination is unavailable.
2. Each level-1 and level-2 agent is equipped with a compass to keep tracking directions.

Error Recovery: The error recovery in this system is accomplished by two ways

1. Seeking new information in combination with exploration;
2. Invoking the human agent.

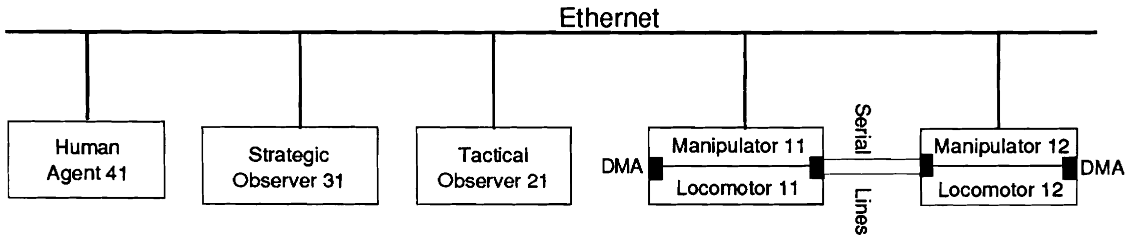

Figure 2: Multiagent Communications Architecture

If a situation out of nominal expectation occurs, e.g., a wheel of agent 11 is stuck, agent 21 moves there, tries to find reasons for being stuck, and provides agent 11 with recovery strategy. If it can not be resolved by level-1, level-2, or level-3 agents, the human agent is invoked to recover from the situation.

Priority Analysis The successful design of a distributed multiagent system for material handling depends critically on the priority schemes which determine: (i) what subtasks the agents execute and in what order; and (ii) who listens to whom when there is contention for an agent's attention. Task planning and decomposition represent one domain where priority assignments are needed. Interrupt handling is another domain where priority assignments are critical. For example, the tactical observer may need to warn agents 11 and 12 that the moving payload is too close to an obstruction in the workspace which is outside the visual range of both agents 11 and 12. In this instance, agent 21 must be able to gain the attention of both agent 11 and 12, possibly interrupting ongoing communications between agents 11 and 12.

Priority assignments for a small number of tasks or activities which are easily separable by their significance as measured by a single scale is not a difficult problem. However, the problem of having to assign priorities to a large number of dimensionally different tasks or activities based on multiple scales or measures can be a difficult problem. It is this latter case that defines the priority assessment problem in our distributed multiagent material handling system. We will apply a variant of the analytic hierarchy process developed by Saaty [18] to obtain: (i) an initial priority assignments for the system tasks and activities; (ii) a corresponding sensitivity analysis; and (iii) a method to update these priorities as dictated by changing system requirements. One of the advantages of this general method is its flexible application to systems which are not organized as linear structures. Further, these techniques can be applied in dynamically changing environments. Our variant of the analytic hierarchy process makes use of interval estimation techniques, e.g., [20, 5].

Communications In order for the multiple agents to operate cooperatively, each agent must have sufficient information about its environment, other agents, and itself. Each mobile agent is equipped with sensors to gather information about itself, e.g., positions and velocities. However, it is impractical and/or impossible for each agent to directly gather "first-hand" information about the global environment and the states of the other agents. Communication among the agents is a means to obtain the information needed to coordinate the operation of the multiple agents.

Based on our small-team architecture, we connect the agents within a single small team as depicted in Figure 1. The network architecture is an isolated Ethernet with some additional links: (i) agents 41, 31, 21, 11, & 12 are connected to an Ethernet; (ii) agent 11 and 12 are also connected by serial lines; and (iii) each manipulator agent communicates with its associated locomotor agent through shared memory. Although the Ethernet provides complete connectivity for all the agents, the purpose of the serial lines is to allow agents 11 and 12 to send brief messages to each other in a predictable amount of time in case, for example, a wheel of one locomotor agent is stuck or an agent perceives an obstacle. This network is depicted in Figure 2.

2.3 Conclusions

We presented an outline for a multiagent robotic system employed in the task of material handling in an unstructured, though indoor environment. There are a number of fundamental research issues that must be addressed. In particular, what information must be and should be communicated between agents so that they act in a cooperative fashion towards the given goal/task? How do agents make use of remote information transfer as well as information transfer *via* mechanical coupling? What are the representations that are needed for different agents and tasks? What is a theoretical basis that will guarantee the coherence between these representationss going from signals to geometric/material/kinematic/dynamic attributes, and then possibly to linguistic descriptions? What is the minimum intelligence and minimum knowledge that each agent must possess? This research project is aimed to develop a theory that answers such questions and to develop a testbed that validates the solutions.

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3 Current Research

3.1 Decision-Making

3.1.1 Statistical Approaches to Learning Theory

Kevin Atteson and Max Mintz

We investigate two statistical approaches to machine learning. In the first approach, Probably Approximately Correct (PAC) learning theory, the learner attempts to determine a binary classification from randomly chosen labeled exemplars. PAC learning theory gives exact circumstances under which learning can occur as well as upper and lower bounds on the number of exemplars needed by any algorithm to learn a given binary classification task. One strength of the theory is that it is independent of the distribution used to present the exemplars. However, a major weakness of the theory is that it does not give any insight into how to construct algorithms for learning. The results are developed by using strong versions of the Law of Large Numbers.

The second approach involves the estimation of probabilities in non-stationary environments. The problem of estimating probabilities is quite old and has a wide literature. However, most of this research investigates the case in which the probabilites do not change. This research focuses on the case in which the probabilities can change slowly in time, which can happen in many practical situations. We propose a model which is a form of ϵ-contamination model used in other branches of statistical decision theory. In order to develop statistical estimators, we use Bayesian and minimax estimation principles with information-theoretic loss functions, which can be justified in several ways.

3.1.2 Decision-Theoretic Approach to Robust Sensor Fusion

Gerda Kamberova and Max Mintz

We continue our decision-theoretic research on robust sensor fusion. The sensors measure some real parameter of interest θ, with known range $[-d, d]$. There is an uncertainty in the sensor measurements. The uncertainty is modeled as a random variable V with a CDF F, F does not depend on θ. We assume that the sensor outputs are observations from a random variable $Z = \theta + V$. We design a decision procedure for estimating θ from the observations. To select an optimal procedure we choose the minimax criterion with zero-one loss. The zero-one loss uniformly penalizes estimates which differ from the true parameter more than a given threshold e (these are unacceptable errors). The minimax criterion with zero-one loss is suitable for modeling problems in which it is desirable to minimize the maximum probability of getting unacceptable errors. Using this approach we obtain fixed size confidence intervals for θ with highest probability of coverage.

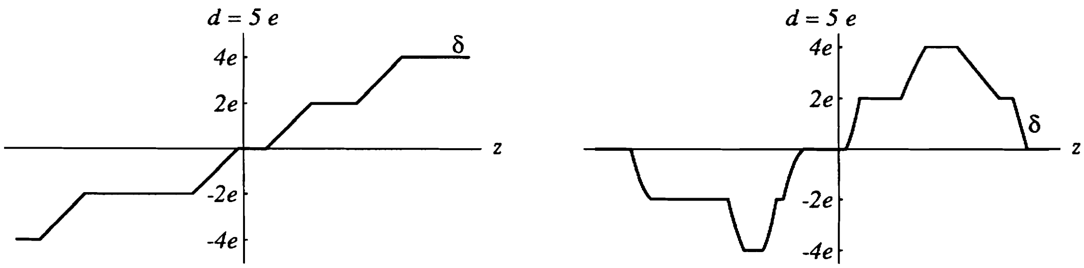

Figure 3: Examples of a monotone and a nonmonotone decision rule

We assume that the CDF F is absolutely continuous and belongs to a given uncertainty class $\mathcal{F}$. The class $\mathcal{F}$ represents the uncertainty in the noise model.

Nonmonotone decision procedures. In previous research we treated problems for which the noise distributions had monotone likelihood ratio (MLR). The optimal decision rules for this problems are monotone piecewise linear functions. When the noise distribution is non-MLR the decisions procedures, in general, are not as simple. (See Figure 3.) Our starting point for the study of problems with non-MLR noise distributions was the Cauchy CDF, $C(0,1)$. We showed that the optimal rules are nonmonotone when $d/e > 2$. We explored the structure of the equalizer rules. We obtained a lower bound on the risk of such rules, and computed an equalizer rule with nearly optimal risk performance. We generalized this approach to handle the case of any symmetric unimodal density.

Currently, we are exploring the structure of Bayes rules for $C(0,1)$. We believe that understanding of the structure of both the equalizer and Bayes rules is a necessary step towards the delineation of global minimax decision procedures. Further, we are studying the salient features of the CDF's which lead to nonmonotone minimax rules.

Robust estimation. There are many practical problems where the noise distribution $F(v)$ is precisely known in some interval $[-k\,,\,k\,]$, and the only available information about F outside that interval is an upper bound on the left of $-k$ and a lower bound on the right of k. Such problems motivated the study of the uncertainty class $\mathcal{F}_{k,F}$ represented on Figure 4. We solved the robust minimax problem for $\mathcal{F}_{k,F}$, in the MLR case, under the restriction $k > F^{-1}(2/3)$. Currently, we are studying the an ε-contamination uncertainty class. Future research includes empirical studies of sensor behavior to validate current models and develop alternative models if needed.

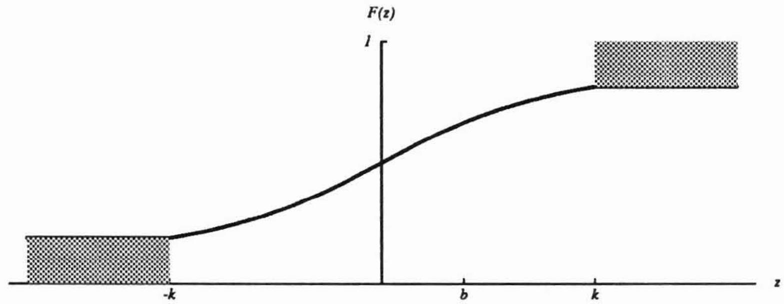

Figure 4: The uncertainty class $\mathcal{F}_{k,F}$, $b = F^{-1}[2/3]$

3.2 Multiagent Research

3.2.1 Force-Closure Grasping with Two Hands

José-Antonio N. Caraza and Xiaoping Yun

This work addresses grasping of large (but not necessarily heavy) objects by using two hands. The objective is to determine force-closure grasps of rigid objects of unknown shape. A grasp is force-closure if it can completely constrain the movement of the object.

In seeking force-closure conditions, the approach taken in this study is to establish useful sufficient conditions rather than necessary and sufficient conditions since the later requires the complete knowledge of the contact parameters. Based on the friction coefficient between hands and object, and on the grasp configuration (defined as the relative position and orientation of fingers and palms), a sufficient condition under which the two hands form a force-closure grasp has been established. The salient feature of this approach is that shape, orientation and location of the object, and contact point locations are not assumed in this condition. This makes it possible to use simple sensors and algorithms. A configuration of two hands in contact with the object satisfying this condition is called force-closure grasp configuration (FCGC). The two hands in a FCGC are capable of picking up and move the object by applying appropriate forces.

The two-dimensional case is initially studied. Later, the study is extended to the three-dimensional case. The hands considered are either flat-surface palms or grippers with two angular-motion fingers.

An algorithm has been developed to check the condition for FCGC in terms of the position and orientation of the hands. The algorithm was implemented on TRACS, an experimental multiagent robotic system developed at the GRASP Laboratory at the University of Pennsylvania.

The results obtained are readily applicable to grasping large but lightweight objects. The simplicity of the conditions and the practical assumptions make it feasible to implement these results in real time.

3.2.2 Coordinated Control of Multiple Manipulator Systems with Rolling Contacts

Eric Paljug and Xiaoping Yun

We investigate the task of manipulating large objects (relative to the size of the robot). In general, this task requires the use of more than one manipulator. Our approach is to use two robot arms, and to permit the robot to use any link surface for manipulation. Neither robot arm has a fixed grasp of the object. Its surface merely contacts the object surface. These contact points are capable of rolling, sliding and separation.

The analysis begins by developing the equations that govern the system. Rolling at the contact points is included in the system model. Contact separation is avoid by enforcing the unilateral constraints that each arm must push at the contact point. Sliding is avoided by constraining the applied force to fall within the contact friction cone. A control scheme is developed by employing nonlinear feedback obtained from applying differential geometrical techniques. A motion and force planner is also developed which specifies a rolling motion for each contact that avoids slipping by repositioning the contact points such that forces are applied along the surface normals. The rolling motion is calculated based on the object dynamics and the desired critical contact force.

Over the previous year, the development of TRACS (the Two Robotic Arm Coordination System) has been completed. A 6 DOF force sensor has been added to the system. The system serves as a testbed for the described project. We are in the process of implementing the results from the theoretical investigation with computer simulations and physical experiments. The intent is to understand the practical ramifications of the theoretical development.

3.2.3 Control of Mechanical Systems with Nonholonomic Constraints

Nilanjan Sarkar, Vijay Kumar, and Xiaoping Yun

The occurrence of nonholonomic mechanical systems is quite common in the field of robotics. We, in this research, are particularly interested in developing a general theoretical framework to control such systems and apply those results to the coordinated control of multiple manipulators with rolling constraints at the contact points and also to the dynamic control of mobile robots.

There are many tasks that require cooperative manipulation by two or more robot manipulators. For example, when an object that is much larger than the end effector must be manipulated, it is not possible to grasp the object rigidly with one effector. On the contrary, it is necessary to support the object with multiple effectors. Further, the effectors need not be grippers that are located at the end of the arms - they may be merely surfaces on the arms. The salient feature is that relative motion between a robot and an object is possible at each contact point. This relative motion at the point of contact introduces nonholonomic constraints into the system.

A wheeled mobile robot is another classic example of a nonholonomic mechanical system in robotics. Here, the nonholonomy arises out of the knife edge constraints of each wheel. Both trajectory tracking and path following are very important tasks for mobile robots. In trajectory tracking problem, a time history of the output variables is prescribed. How closely to reach a point and when to reach the point are equally important in this case. In a path following problem, however, a geometric path is prespecified and it is required to follow the path closely.

The problem of controlling mechanical systems having both holonomic and nonholonomic constraints has been the subject of intense research interest in recent years. It has already been shown that a system subject to nonholonomic constraints is always controllable, but cannot be stabilized to a single equilibrium point by smooth feedback. In this research, we develop a unified approach to the control of mechanical systems subject to both holonomic and nonholonomic constraints. We first present a state space realization of the constrained system and show that it is not input-state linearizable if at least one of the constraints is nonholonomic. We then prove that input-output linearization is possible with appropriate output equations. Further if the system is position controlled it has a zero dynamics which is Lagrange stable but not asymptotically stable.

We successfully demonstrate through computer simulation that we can control both the tasks using our unified control approach. We will implement our control schemes on a test bed of two robotic manipulators(TRACS) which has been developed in the laboratory and on a Labmate mobile platform respectively.

The ultimate goal of this research is to develop a general theoretical framework to control any mechanical dynamic systems subject to both holonomic and nonholonomic constraints. It will have immense application in coordinated control of multiple manipulators, mobile robots, mobile robots and manipulators and in many other areas of robotics in particular and mechanical systems in general and will eventually lead to the development of truly autonomous systems.

3.2.4 Coordination of Locomotion and Manipulation

Yoshio Yamamoto and Xiaoping Yun

The objective of this project is to study coordination of locomotion and manipulation of a mobile manipulator. The mobile manipulator considered in this project consists of a mobile platform (TRC Labmate) and a manipulator (PUMA 250 robot arm). The manipulator is installed on the top of the mobile platform. Coordination between locomotion and manipulation of a mobile manipulator is important for a number of reasons. First, combining a mobile platform and a multi-link manipulator creates redundancy. A particular point in the workspace may be reached by moving the manipulator, by moving the mobile platform, or by a combined motion of the both. Second, the dynamic response of a manipulator is, in general, faster than that of a mobile platform. Third, the motion of a typical wheeled mobile platform is constrained by nonholonomic constraints while a manipulator itself is generally unconstrained. Fourth, the mobile platform and manipulator dynamically interact with each other.

The specific problem under investigation is to control a mobile manipulator to perform the task of pushing against and following a moving surface in the environment. The solution to this problem will be essential for a mobile manipulator to interact with the environment and other mobile manipulators. In particular, the results for this study will be directly applied to coordination of multiple mobile manipulators which interact with each other in the course of task performance (*e.g.,* collectively transport a large object).

To have a mobile manipulator follow a moving surface, we consider three major topics: (1) modeling the motion of the environment, (2) control of locomotion, and (3) control of manipulation. To better understand the issues in control of manipulation in this case, we consider the following two simpler problems. The first one is to have the mobile platform fixed (equivalent to having a fixed base manipulator) and the external surface move within the workspace of the manipulator. The second one is to have the surface fixed and the mobile platform move. In both cases, the goal of manipulator control is to compensate the motion of the moving surface or the mobile platform in order to keep the manipulator in contact with the surface with a desired amount of pushing force. As for control of locomotion, we recognize that the mobile platform has a slower dynamic response than the manipulator and has nonholonomic constraints in its motion. Taking these factors into consideration, we define a preferred operating region for the manipulator in its workspace. As long as it remains in the preferred operating region, the manipulator compensates for the motion of the moving surface. The goal of the mobile platform is to bring the manipulator into its preferred operating region. As for modeling the motion of the environment, there are two issues to be investigated: what should be known about the motion of the moving surface *a priori* (such as upper bounds on its velocity), and what should be known about the motion of the moving surface in real time in order for the mobile manipulator to successfully follow it.

3.3 Robotics Research

3.3.1 Robotic Exploration of Material and Kinematic Properties of Objects

Mario Fernando Montenegro Campos

In order to physically interact with the unstructured external world a robotic systems should be able to extract material and kinematic properties of objects around them. The focus of this research is on the recovery of material properties including thermal, hardness and mass properties and of kinematic properties such as mobility and geometric parameters of objects and their parts. We invoke the active perception paradigm and use exploratory procedures (EPs) which are based on stereotypical motor procedures executed by humans when exploring objects. We develop methodologies for the design of such procedures and sensors which support their use in the robotic domain and demonstrate their effectiveness.

Our model is composed of a control module and two exploratory sub-modules: the visual and the haptic sub-modules. Prior to haptic exploration, vision is activated in order to obtain the initial conditions for the haptic exploration. The visual information consists of 2 1/2 D range data obtained by a mobile real-time laser range scanner. Global models of the object are recovered by fitting super-ellipsoids to the object's image. The output of the visual module includes the object's location in space and its geometric features such as moments, major and minor axis, and volume.

The haptic module performs its exploration using non-destructive techniques. Thermal properties of the unknown object are evaluated by the temperature EP. A new approach for the design and modeling of thermal sensors for robotics is presented. A model of this sensor is developed and its validity is experimentally verified with different materials using an EP. Mass density is returned by the weight evaluation procedure. An estimate of the homogeneity of the object's composition is obtained by comparing the center of gravity computed by the visual module, with the center of mass computed from force torque measurements. Hardness is evaluated by means of stress-strain tests, modulo the force-torque characteristics of the manipulator. Compression and tension tests are performed to determine this property. The object's elasticity and plasticity are estimated from those tests.

The kinematic characteristics of the object are explored by the mobility EP. We describe a novel methodology, based on results from screw theory, to identify the degrees of freedom and the geometric and mobility characteristics of the object and its components with respect to its environment. The identification happens in real-time, as the robot grasps and moves the unknown object, sensing and recording forces/torques and displacements.

We also present the design and implementation of the robotic haptic architecture testbed where all of the above concepts are smoothly integrated into a working system. The architecture controls and coordinates of two 6 degrees of freedom manipulators, a parallel jaw gripper equipped with force/torque sensors on each finger and a mobile laser range scanner.

3.3.2 Modeling and Control of Backlash in Involute Spur Gear Transmissions

Chris Gerdes and Vijay Kumar

In the design of geared transmissions, backlash performs many valuable functions such as the provision of space for lubrication, the accommodation of machining errors and the reduction of jamming. From the standpoint of a control system, however, backlash represents an undesirable mechanical nonlinearity that may result in limit cycling when linear control methods are employed. Very often, the solution to this problem is to eliminate the backlash entirely by pre-loading the gears, thereby increasing friction. From the standpoint of robotics, this solution is clearly suboptimal, since the added friction may lead to instabilities under force or position control algorithms. The objective of this project is to examine the dynamics of gears in order to develop design parameters and control schemes capable of minimizing the problems associated with backlash.

Currently, we are employing a rotational model of spur gear dynamics based upon the work of D.C.H. Yang at UCLA. This model incorporates such features as the variation of stiffness with the number of contact pairs and damping based upon a coefficient of restitution dependent upon initial contact velocity. We have implemented this model in a software simulation and are using this simulation to demonstrate the inherent instabilities that arise with linear control schemes. Other work with this simulation includes determining how such design parameters as gear ratio, pitch, and gear material affect the dynamics of gears with backlash and what control schemes will serve to increase the stability of such a system.

All results obtained through numerical simulation will be verified on an experimental test bed currently under construction. This apparatus allows for continuous variation of the distance between gear shafts, thus enabling the backlash to be altered as desired. Because of the large scale used in the design of the experimental system, linear backlashes on the order of 1/8" may be achieved without loss of gear contact. Thus, the theoretical results can be demonstrated experimentally in a manner that allows for easy measurement and hence greater precision.

3.3.3 Design, Implementation, and Evaluation of a Real-Time Kernel for Distributed Robotics

Robert King and Insup Lee

Modern robotics applications are becoming more complex due to greater numbers of sensors and actuators. The control of such systems may require multiple processors to meet the computational demands and to support the physical distribution of the sensors and actuators. A distributed real-time system is needed to perform the required communication and processing while meeting application-specified timing constraints. Our research is the design and evaluation of a real-time kernel, called *Timix V2*, for distributed robotics applications.

TimixV2 provides threads with dynamic timing constraints, execution environments as basic units for resource allocation and memory management context, and events to signal message arrival, device interrupts, alarms, and exceptions. The salient features of *TimixV2* are support for uniform scheduling and timely communication. *TimixV2* uses the notion of consistent scheduling to uniformly schedule both application and kernel threads to guarantee that the application's real-time constraints are met. All device interrupt handlers, except the periodic clock interrupt, are converted to threads that are scheduled like any other thread. *TimixV2*'s port-based message passing primitives support real-time communication by allowing individual message priorities to be used to order messages on a queue and by propagating scheduling information from a message to the associated thread on message arrival.

The kernel has been implemented on a distributed test-bed and evaluated with respect to distributed real-time robotics applications.

3.3.4 Teleprogramming: Towards Delay-Invariant Remote Manipulation

Janez Funda and Richard P. Paul

This research addresses the problem of teleoperation in the presence of communication delays. Delays occur with earth-based teleoperation in space and with surface-based teleoperation undersea using untethered submersibles and acoustic communication links. The delay in obtaining position and force feedback from the remote slave arms makes direct teleoperation infeasible.

We are developing a control methodology, called teleprogramming, which draws on the experience in the development of supervisory control techniques and robotics over the last three decades and introduces a number of new ideas in operator-model interaction as well as the nature and content of the information being sent to the slave robot. A teleprogramming system allows the operator to kinesthetically, as well as visually, interact with a graphical simulation of the remote environment and to interactively, on-line teleprogram the remote manipulator through a sequence of elementary robot instructions. A key feature and contribution of this work is the fact that these instructions are generated automatically, in real time, based on the operator's interaction with the simulated environment. The slave robot executes these commands delayed in time and, should an error occur, allows the operator to specify the necessary corrective actions and continue with the task.

3.3.5 Teleprogramming: Remote Site Research Issues

Thomas Lindsay and Richard Paul

Research is progressing in the development of a remote site workcell for teleoperation with significant communication delays (on the order of one to 20 seconds). In these situations, direct teleoperation becomes difficult to impossible due to the delays in visual and force feedback. *Teleprogramming* has been developed in order to overcome this problem.

An integral part of teleprogramming is a semi-autonomous remote site system. The remote system is composed of a robot manipulator, sensors, controlling computer, and tools. The constraints on the remote site system and the amount of autonomy needed are partially defined by the teleprogramming system. Development of the remote site system for teleprogramming evokes some pertinent research issues. The following issues are under investigation: low level manipulator control using an instrumented compliant wrist for sensory feedback, semi-autonomous command execution implementing real-world parameters, and manipulator tool usage and control.

Low level manipulator control is based on a hybrid control scheme using wrist-based sensory feedback. Implementation of this control is under constant improvements, and problems related to controlling the manipulator in an arbitrary frame are being investigated.

Higher level command execution is dependent upon semi-autonomous motions of the remote site manipulator. Implementation of tolerance checks and guarded moves are being researched, including the detection of motion termination conditions in a partially known environment.

Many powered tools introduce redundant degrees of freedom into the manipulator/tool system. In these cases, the tool is actively controlled in its natural degrees of freedom, and the corresponding degrees of freedom in the manipulator become passive. Feedback for the manipulator/tool system is supplied by the wrist-based sensor. Examples of sensing and control for tools are being implemented.

3.3.6 A Robotic System for Learning Visually-Driven Grasp Planning

Marcos Salganicoff and Ruzena Bajcsy

We are using findings in machine learning, developmental psychology, and neurophysiology to guide a robotic learning system's level of representation both for actions and for percepts. Visually-driven grasping is chosen as the experimental task since it has general applicability and it has been extensively researched from several perspectives. An implementation of a robotic system with a dexterous three-fingered hand, compliant instrumented wrist, arm and vision is used to test these ideas. Several sensorimotor primitives (vision segmentation and manipulatory reflexes) are implemented in this system and may be thought of as the "innate" perceptual and motor abilities of the system.

Applying empirical learning techniques to real situations brings up such important issues as observation sparsity in high-dimensional spaces, arbitrary underlying functional forms of the reinforcement distribution and robustness to noise in exemplars. The well-established technique of non-parametric projection pursuit regression (PPR) (Friedman,1985) is used to accomplish reinforcement learning by searching for projections of high-dimensional data sets which capture task invariants.

We also pursue the following problem: how can we use human expertise and insight into grasping to train a system to select both appropriate hand preshapes and approaches for a wide variety of objects, and then have it verify and refine its skills through trial and error? Towards that end, we are developing a hybrid system which learns to recognize different basic-level interaction categories as well as generate the binding functions corresponding to each of those categories. The binding functions map sensed quantities into motoric values.

Finally, at a practical level, the use of any learning process generally implies failures along the way. Therefore, the mechanics of the untrained robotic system must be able to tolerate mistakes in task execution and emerge undamaged. We address this by the use of an instrumented, compliant robot wrist developed by Lindsay et.al. (Lindsay,1991) which effectively controls impact forces.

3.3.7 Moving Toward a Practical Implementation of the Teleprogramming Concept

Craig Sayers and Richard Paul

The feasibility of the teleprogramming concept and its ability to permit teleoperation in a delayed environment have previously been demonstrated by Janez Funda, Tom Lindsay and Richard Paul.

Recent work has been directed toward a move from the previous experimental system to a more practical implementation. On the hardware side this has been achieved by replacing custom designed equipment with more general-purpose "off-the-shelf" components. This process has improved the reliability of the system as well as facilitating future upgrades. On the software side the move to a more object-orientated style of programming using C++ is expected to further improve the reliability and maintainability of the system.

In previous work it was assumed that at least an approximate model of the remote site geometry was known a priori. A current research topic involves consideration of the more practical case where a world model is built, with operator interaction, using sensor data received from the remote site. Future research will examine how the constant stream of sensor data received during a teleprogramming session might be used to continuously update the world model. The issue of how the operator might be made aware of and allowed to interact with this information will also be considered.

3.3.8 Robotic Exploration of Surfaces and its Application to Legged Locomotion

Pramath Raj Sinha and Ruzena K. Bajcsy

Material properties like penetrability, compliance, and surface roughness are important in the characterization of the environment. While concentrating on issues of geometry and shape, researchers in perceptual robotics, until recently, have not quite addressed the issue of the extraction of material properties from the environment. The goal of this research is to design and implement a robotic system that will actively explore a surface to extract its material characteristics. Further, the relevance of material properties in the legged locomotion of robots is also recognized and our research objectives are extended towards building a robotic system for exploration such that it actively perceives material properties during the process of legged locomotion. The chosen approach to the design and implementation of such a robotic system is to first select an appropriate environment model and then to design exploratory procedures salient to each attribute of interest. These exploratory procedures are then implemented through an experimental setup and the results show that material properties can be reliably measured. The design, implementation, and results of a framework for surface exploration to recover material properties are presented.

Further, the exploratory procedures for exploration are integrated into an active perceptual scheme for legged locomotion. The perceptual scheme is designed around creating the ability for the robot to sense variations in terrain properties while it is walking, so that it may be able to avoid sinking, slipping, and falling due to unexpected changes in the terrain properties, and make suitable changes in its foot forces to continue locomotion. Finite element simulations of the foot–terrain interaction are used to justify some of the strategies used in this active perceptual scheme. The active perceptual scheme is implemented by simulating a leg–ankle–foot system with a PUMA arm–compliant wrist–foot system and an accelerometer mounted on the foot to detect slip.

3.3.9 Towards Delay Invariant Remote Manipulation

Matthew Stein and Richard Paul

Research has been conducted at the GRASP Laboratory of the University of Pennsylvania in the area of teleoperation in the presence of feedback delays. GRASP lab researchers have implemented intervening graphics models to accommodate time delays and uncertainty in teleoperation. The proposed research will expand the current capability to allow the specification of limited motion sequences. The establishment of the framework for specification and the man-machine interface requirements will be investigated.

A challenge to the advancement of the state of the art in teleoperation is the inability of many researchers to share results. A new thrust of the telerobotics project is the establishment of a cooperative effort with the Man Machine Systems group at the Jet Propulsion

Laboratory of NASA. A goal of this project will be the implementation of results obtained in the GRASP lab in the Advanced Teleoperation and Man-Machine Systems Laboratory at JPL. To demonstrate compatibility, a milestone of this project will be the teleoperation of portions of the Solar Maximum Satellite Repair - Orbital Replacement Unit (ORU) changeout experiment at JPL using a master manipulator located in the GRASP Lab.

3.3.10 Design and Control of a 3DOF in-Parallel Actuated Manipulator

Thomas Sugar and Vijay Kumar

The mechanics, design, and simple control, of a three degree-of-freedom in-parallel, pneumatically actuated manipulator have been completed. The manipulator consists of two platforms connected by three serial chains. The kinematic design is such that the three relative degrees of freedom between the two plates allow the manipulator to accommodate uncertainties and sustain impacts while contacting and interacting with unknown environments. The manipulator is naturally compliant in translation along the approach direction as well as in rotations about the axes perpendicular to the approach direction. This manipulator can then be used as an active compliant end effector which can absorb energy from unforeseen impacts.

Because of the compliance intrinsic to pneumatics which allows for a pneumatic actuator to withstand large impacts, work has continued in this area. Pneumatic actuators do have some drawbacks though, such as low position and force control bandwidths. Work has been completed with a one degree of freedom test bed that has been designed for greater performance. This high performance test bed utilizes graphite glass actuators, small transmission lengths, and an Atchely flow control valve. With the original actuator system on the 3DOF manipulator, position and force control bandwidths were never greater than 12 Hertz. With the new test bed, position control bandwidths are as high as 28 Hertz, and force control bandwidths are as high as 17 Hertz. Position control is greatly improved because of the low friction actuators and low friction linear bearings. Force control performance is greatly improved also by using an inner pressure feedback loop. The force control bandwidth improves greatly as the inner feedback is increased.

Current work with the 3DOF in-Parallel Manipulator is directed towards implementing some of the ideas from the one degree of freedom test bed such as shorter transmission lengths and an inner pressure feedback loop. Also, the Jacobian of the system will be defined and hybrid force control will be implemented. The three degrees of freedom of the manipulator are exactly those that are required for hybrid force control. These degrees of freedom are translation along the approach direction and rotation about the axes perpendicular to the approach direction. With the implementation of hybrid force control, this manipulator can then be used as an active compliant end effector in an unknown environment.

3.3.11 Analysis and Simulation of Mechanical Systems with Multiple Frictional Contacts

Yin Tien Wang and Vijay R. Kumar

There are several applications in robotics and manufacturing in which nominally rigid objects are subject to multiple frictional contacts with other objects. In most previous work, rigid body models have been used to analyze such systems. There are two fundamental problems with such an approach. Firstly, the use of frictional laws, such as Coulomb's law, introduce inconsistencies and ambiguities when used in conjunction with the principles of rigid body dynamics. Secondly, hypotheses traditionally used to model frictional impacts can lead to solutions which violate principles of energy conservation. The research in the dissertation is an attempt to develop a systematic method for the simulation and control of such a system.

A new approach to the simulation of mechanical systems with multiple, frictional constraints is proposed which is free of inconsistencies. This approach involves the integration of rigid body models with contact stress models and nonlocal frictional laws in order to resolve inconsistencies. Analytical results of rigid body impact laws are derived which have led to an improved understanding of contact mechanics and the rigid body interaction with unilateral constraints. Formulation involving elasticity, viscoelasticity and plasticity theory are derived in order to model the compliance deformation and energy dissipation of the system.

The simulation is interfaced with a three-dimensional graphical display on a high resolution workstation. A planar experimental test-bed is constructed to study cases with inconsistencies and to experimentally validate the results of the simulator. The integration of the simulation with CAD databases is investigated. A CAD tool is made to allows concurrent consideration of the design of the mechanical component as well as the control of manufacturing process.

3.3.12 Supporting Real-Time Concurrency

Victor Wolfe, Susan Davidson and Insup Lee

Victor Wolfe, Susan Davidson and Insup Lee have completed a study of techniques to support concurrent real-time programming. Their results include:

- Development of a paradigm and set of constraints for concurrent real-time programming.
- Implementation of the *RTC* language constructs and a run-time system to express and enforce real-time concurrency constraints.
- Development of a deadlock prevention technique for concurrent real-time systems.

- Implementation of a graphics simulation of two Puma arms picking up a moving object under timing constraints.

This research developed an approach to concurrent real-time programming where the programmer explicitly expresses *real-time concurrency* constraints using the *RTC* language constructs. They also implemented a run-time system that enforces the constraints using the *TimixV2* real-time operating system developed in the GRASP lab by Robert King. They used this software system to program solutions to a general problem called *timed atomic commitment* and to program a graphics robotics simulation. In the robotics simulation, accurate graphic models of Puma 560 robot arms were controlled by a distributed *C + RTC* program executing on three MicroVax II computers running the *TimixV2* real-time kernel, a MicroVax II computer running Ultrix, and a 16 MIPS Personal Iris 4D-25 computer with a hardware turbo graphics option, all connected via an ethernet. The Iris executed software based on a 3-D modeling package provided by the Computer Graphics Laboratory at the University of Pennsylvania. The package was extended by Janez Funda of the GRASP Laboratory to simulate the control of Puma 560 robot manipulators in a kinematic environment. Wolfe extended Funda's model to include a model of two Puma 560 manipulators and an object that moves as if it were on an assembly line. He also changed the interface to the graphics simulator to accept commands from a *TimixV2* MicroVax II over the ethernet.

3.4 Vision Research

3.4.1 Representation and Interpretation of Objects *via* Functionality

Luca Bogoni and Ruzena Bajcsy

Interacting with any environment requires knowledge or means of acquiring information and processing it. Specifically when performing a task we need to obtain information about the physical and geometrical characteristics of the objects. Some of the data is then interpreted and functional and/or relational labels are attached. This process allows us to classify objects and, in the context of a task, to assign them a suitable interpretation. Thus, we are going to recognize whether within a group of objects any one possesses the appropriate functionality to perform a task. Functionality is seen as key factor for object interpretation in the context of a goal to be performed. Currently we are investigating the fundamental factors involved in the formulation and specifications of this process.

In the analysis of interaction/manipulation tasks we identify

- *Physical* and *Geometrical* properties: quantizable measures whose attributes are defined in terms of units – geometrical dimensions, weight, constituent material, etc...
- *Functional* properties: relations between physical and geometrical properties which are necessary for a given action to be successfully carried out.

Thus, we can characterize functionality as inherent (intrinsic), intended and imposed (extrinsic);

- *Inherent* functionality defines the functional specifications which arise from the physical properties of the object. Namely if the object has a rather pronounced concavity it is possible that it can contain, liquids or solids pending upon the material it is made out of. That specification arises independently of any actuator interaction.
- *Intended* functionality defines the specifications which were defined as a part of the object at the time of construction. Unlike the previous one, such functional specifications are not directly deduced or inferred from the physical structure of the object – a hammer or screwdriver for instance.
- *Imposed* functionality defines the ability of using an object to absolve a function for which is neither intended nor inherent in it. The use of a bowl for hammering would be such an instance.

These distinctions allow us to focus on the recovery of functional attributions in the object for its recognition and classification.

So far, when attempting to recover functionality in an object, researchers have focussed on vision as the principal means to attribute functionality. From geometrical properties they have reasoned and inferred functional relations. While we do believe that it is important to reason about the geometrical components, we consider such processes as only an hypothesis forming stage in the actual recognition process.

In our approach, we focus in connecting this aspect with the interactive component, in accordance to the philosophy of the active vision approach. This allows us to

- incorporate in the recognition process physical properties of the objects and tools obtained from real data which have up to now only been assumed.
- address the issue of proving the hypotheses by "doing" (verification).
- provide a methodology for recovering properties of objects by observing the result of the interactions taking place in a system – object, tool, manipulator.
- address the issue of purposive recognition.

This approach allows us to take advantage of many exploratory procedures to acquire real data to substantiate our hypothesis. Furthermore, it sets the stage for dealing with real world problems and unstructured environments in which one must account for fusion of different sensory perceptions, uncertainty, and expectation of interactions.

3.4.2 Visual Maps and Beyond

Ulf Cahn von Seelen and R. Bajcsy

There is a growing feeling in the Computer Vision community that the goal of a vision system need not necessarily be a full reconstruction of the perceived scene but that it depends on the purpose of the system which aspects of the scene have to be extracted. By looking at the evolution of biological vision systems and the tasks they were designed to solve, one can hope to get an indication for the relative difficulty of various visual tasks. Additionally, evolution poses strong constraints on the way in which these visual tasks can be solved.

Given the prevalence of retinotopic visual maps in the early stages of the visual system of animals and man, I examine which tasks can be solved on the level of visual maps alone or even below, and how the information from several visual maps can be combined to effect texture discrimination, shape analysis, and Gestalt perception.

3.4.3 A Visual Observer Agent for Guiding Manipulation Process

Michael Chan and Ruzena Bajcsy

One of the functions of an observer agent is to *monitor* or *observe* a sufficient execution of a given task or a subtask of it. The task of relocating a pipe, for example, will involve grasping , lifting and transportation subtasks. The observer has the responsibility of monitoring the current state of the manipulation or transportation subtasks assigned to the manipulator(s) and reporting errors if necessary. Two manipulators holding an object cooperatively or a mobile vehicle following another at fixed distance are examples of such subtasks.

To deliver real time performance in a dynamical environment as such, division of the observer's task into parallel modules is considered. Current work involves development of these observer modules, each of which is responsible for monitoring a different aspect of a given task. Implementation is undergoing on both the *Connection machine CM-2* and ordinary sequential machines.

In addition, error recovery must be an integral part of any multiagent distributed system. Although the error recovery problem is essentially unbounded, it is nevertheless necessary to build in a mechanism which seeks out new information when the nominal expectations lead to an error. Incorporation of human advice or decision in error recovery would be considered also, so that execution of task can be continued from intermediate state. The other question is which agent(s) should be informed in case of error and what form of information should be conveyed, i.e. *who* should receive *what*?

3.4.4 The Recovery of 3D Scene Structure from Motion and Intensity Segmentation Information

George T. Chou, Ales Leonardis and Ruzena Bajcsy

Structure recovery from motion is a task central to many vision systems. Previously, we have formulated an integrated approach for the recovery of 3D scene structure using motion and intensity segmentation information. The computational rationale behind combining these unrelated visual information is based on the following observation: In textured regions, where image segmentation process tend to fail, changes in image intensity provide an abundance of motion and depth information. On the other hand, in textureless regions where a lack of intensity variation induces the infamous aperture problem, destabilizing the motion and depth sensing system, the intensity segmentation process tends to perform rather well.

Our goal is to exploit the inherent complementarity of these two processes in order to construct a dense depth map. The motion/ depth information is obtained through a bank of spatio-temporal Gabor filters. For the task of intensity segmentation, the paradigm of [Leonardis, Gupta & Bajcsy 1990] is applied. These two pieces of information are integrated by searching for three-dimensional surface models that are consistent with all the depth points in the corresponding intensity region. Results from real and synthetic image sequences have demonstrated some success.

Current work involves embedding the system in a coarse-to-fine multi-resolution control for improving the overall speed, and extending the paradigm using robust estimation theory. These new extensions will enhance the performance and the understanding of our structure recovery system.

3.4.5 Vision for Navigation Using Two Road Cues

Gareth Funka-Lea and Ruzena Bajcsy

An autonomous vehicle must be able to find and maintain visual contact with a negotiable path before it. In outdoor environments this generally means locating a road in front of the vehicle. We presented a strategy for road tracking that uses two road cues in order to maintain better visual contact with a road than could be achieved with either cue alone. Until recently, most autonomous vehicles relied on a single cue to find the road in front of them. Using multiple measurements from the image we can produce a more robust system. Also, using two cues to find the road, we have been able to study the ability of the system to recover when contradictory evidence exists concerning the location of the road in front of the vehicle.

The two cues to the road's location we use are the road's surface shading and its boundaries. The road's surface properties as captured in an image are modeled by bi-variate polynomial surface patches of up to second order. This is the first time that shading information has been used in vision for autonomous navigation. The road's boundaries, and other line-like features of a road, are modeled by line segments fit to image edges. With these two cues, we have a complementary description of an image - the surface patches describe the continuous portions of the image and the line segments describe the discontinuous portions of the image. The two cues also provide different information about the three dimensional environment in which the road and vehicle exist. The surface patches provide information about the material characteristics of the road and the illumination properties of the scene. The line segments representing the sides of a constant width road provide information about the relationship between the road and the vehicle in space in accordance with the laws of perspective viewing.

The surface patches and line segments that model the road in one image are used along with knowledge of the vehicle's motion to predict the appearance of the road in a subsequent image. At each image frame the models are updated to take into account new aspects of the road's appearance. The modeling starts with the system segmenting under guidance from a human operator an image of the scene in front of the vehicle.

We are currently working to extend our system to make use of multiple visual cues obtained in parallel for autonomous navigation. By taking greater advantage of the information inherent in images we plan to address the problem of recognizing shadows, surface markings, and cracks on a road. We also plan to incorporate robust egomotion estimation and a more sophisticated control structure into our existing framework. Finally, we hope to address the issues of obstacle avoidance, obstacle tracking and landmark recognition within our framework for vision for autonomous navigation.

3.4.6 Surface and Volumetric Segmentation of Complex 3-D Objects using Parametric Shape Models

Alok Gupta and Ruzena Bajcsy

The problem of part definition, description, and decomposition is central to the shape recognition systems. We present an integrated framework for segmenting dense range data of complex 3-D scenes into their constituent parts in terms of surface (bi-quadrics) and volumetric (superquadrics) primitives, without *a priori* domain knowledge or stored models.

Surface segmentation is performed by a novel local-to-global iterative regression approach of searching for the best piecewise description of the data in terms of bi-quadric models. Region adjacency information, surface discontinuities, and global shape properties are extracted and used to guide the volumetric segmentation. Superquadric models are recovered by a global-to-local residual-driven procedure, which recursively segments the scene to derive the part-structure. A set of acceptance criteria provide the objective evaluation of intermediate descriptions, and decide whether to terminate the procedure, or selectively refine the segmentation, or generate negative volume description. Superquadric and bi-quadric models are recovered in parallel to incorporate the best of the coarse-to-fine and fine-to-coarse segmentation strategies. The control module generates hypotheses about superquadric models at clusters of underestimated data and performs controlled extrapolation of part-models by shrinking the global model.

We present results on real range images of scenes of varying complexity, including objects with occluding parts, and scenes where surface segmentation is not sufficient to guide the volumetric segmentation. We conclude by discussing the applications of our approach in data reduction, 3-D object recognition, geometric modeling, automatic model generation, object manipulation, qualitative vision, and active vision.

3.4.7 Real-Time Visual Feedback Control Loops In Robots

Stamps Howard and Vijay Kumar

This work involves exploring the use of a visual feedback control loop to improve the capabilities and robustness of a robotic manipulator. With the advent of very fast multiple parallel processors, there is a rapidly growing ability of vision systems to produce results in real time which hold the potential to be used to control the motion of robots. Visual feedback will be able to significantly improve the abilities of a robot by allowing it to react to unexpected events or obstacles. The objective of this research is to determine the optimal method for incorporating a control loop within the control system of the robot, as well as determining the parameters necessary and sufficient for this operation.

Initial efforts are aimed at incorporating a visual feedback control loop into the mobile base of the two mobile robots. The visual system will be used to calibrate the position and orientation of the base. Once completed, the techniques used for the base will be expanded and incorporated in the robots themselves.

3.4.8 Computer Vision Representation, Classification, and Recovery from Range Images – A Study with the Common Cup

Stephen Intille and Ruzena Bajcsy

Most machine perception researchers have approached object recognition and classification problems by using pattern matching algorithms and inflexible, complex object representations. Ultimately, however, truly versatile vision systems will need to employ resilient, relatively intelligent recognition models. Few robust object recognition systems have been developed which can recognize an entire "class" of objects such as a cup, even when only one object is in the current scene.

In this study, I hope to show that early predictions of object structure directly from 2-1/2 dimensional range data can be used to improve the object recovery process. By combining low level segmentation processes with high level object descriptions, I will attempt to develop algorithms which classify a given object into one of several categories. This classification will be used to generate additional information which might be useful for future recovery algorithms. Essentially, I will investigate the feasibility of combining low and high level vision recovery processes in order to improve recognition performance. In order to restrain what is already a difficult problem, I will limit my study to the recognition of the objects we commonly describe as "cups," and I will use synthesized 2-1/2 dimensional data which might be obtainable from a sophisticated laser range scanning system. While I have chosen the specific object domain of common cups, the concepts I hope to develop will be applicable to the general problem of computer vision object recognition and recovery.

3.4.9 CAD-Compatible Data Description from Range Data

Visa Koivunen and Ruzena Bajcsy

In general CAD systems are used to design new shapes and vision systems are used to analyze existing objects. Objects in manufacturing industry are usually designed with a CAD-system, and computer vision is used in manufacturing automation, and for automatic visual inspection of manufactured objects or object parts. There are no direct links between CAD-systems and vision systems. CAD database could be used as a model database for a vision system, and a vision system should be able to communicate with other automation subsystems using standardized, mathematical description data formats.

Geometric modeling applications could use geometric models created automatically by a 3-D computer vision system. Such systems could be used for off-line model building (reverse engineering), and dynamic modeling in robot path planning, for example. In the model building step the type of representation must be chosen. The representation should be able to describe the geometry and the topology of the objects and the object parts. In addition to simple geometric primitives, it should be able to describe sculptured free-form surfaces. The data description format should enable data exchange between cooperating automation subsystems.

The research topics will include the extraction of 3-D surface points of the object from multiple views, data description, model building and importing the obtained model to a CAD-system. The work is partially based on the research on image segmentation and volumetric data description at the GRASP laboratory.

3.4.10 Polarization Based Material Classification

Jana Košecká and Sang Lee

Some previous work has been done in the Grasp Lab in understanding the reflection properties of opaque metallic or dielectric surfaces using color and multiple views. The reflection properties of multiple layers of transparent surfaces are currently under investigation. So far, the integration of multiple cues (color and multiple views) has been used. Recently some preliminary work has been done using polarization as another cue.

The majority of objects can be classified into two categories, according to their electric properties: metal objects that conduct electricity well and dielectric objects with poor conductivity. A simple technique for identifying material properties of objects in an image was implemented that uses multiple images taken through a polarizing lens. The obtained images are used to classify the material surface at all points of a specular highlight. The technique is based on the observation that the polarization property of the specularly reflected light is strongly dependent on the conductivity of the material. When initially unpolarized light is specularly reflected off a smooth surface at an oblique angle, the transmitted radiance through a polarizer oriented perpendicular to the specular plane of incidence is higher than the transmitted radiance through a polarizer oriented parallel to the specular plane of incidence. This observation reflects the relation between the perpendicular and parallel Fresnel reflection coefficients $F_{\perp}$ and $F_{||}$, which are functions of the angle of incidence and the refractive index of the material. The ratio $F_{\perp}/F_{||}$ is substantially higher for dielectric materials than for metals. The ratio $F_{\perp}/F_{||}$ estimated from the transmitted radiances of reflected light using differently oriented polarizing filters allows a robust classification of materials at points of specular highlights. The observations from the experiments with multiple layers of transparent surfaces, using specularly reflected light from polarization, can provide us with some additional information. The suitability of using polarization cues for extended light sources and rough materials has yet to be evaluated.

3.4.11 A Retina-Like Space Variant CCD Sensor

G. Kreider

The retina is a smart sensor, but in the sense of intelligent design and not on-chip computing power. It uses a unique layout and elementary charge computing elements to implement in hardware a polar-exponential transform on visual data. The final chip includes a large section of photosites arranged in a circular pattern. Further, the pixels grow in size as radial distance increases. The retina also has a fovea (a high resolution area at the chip's center) and the computational circuitry. The sensor works and will serve as the key component of a real-time imaging system.

3.4.12 Understanding of Surface Reflections in Computer Vision by Color and Multiple Views

Sang Wook Lee and Ruzena Bajcsy

Recently there has been a growing interest in the visual measurement of surface reflectance properties in both basic and applied computer vision research. Most vision algorithms are based on the assumption that visually observable surfaces consist only of

Lambertian reflection. Specularity is one of the major hindrances to vision tasks such as image segmentation, object recognition and shape or structure determination. Without any means of correctly identifying reflectance types, the presence of specular highlights will cause image segmentation algorithms to misidentify specular highlights as separate regions or different objects with high albedo. Algorithms such as shape from shading and structure from stereo or motion can also produce false surface orientation or depth from the non-Lambertian nature of specularity. Therefore it is desirable to have algorithms for estimating reflectance properties as a very early stage or an integral part of many visual processes. In many industrial applications, there is also a great demand for visual inspection of surface reflectance which is directly related to the quality of surface finish and paint.

We have been performing research on specularity detection using color, and we have previously proposed a color image segmentation algorithm. The algorithm uses only color information for the separation of diffuse as well as sharp specularities and inter-reflections from Lambertian reflections through image segmentation. A computational model based on the dichromatic model is presented for interpretation of various surface reflections in a spectral space with three orthogonal basis functions. The established model is used for arranging color data for segmentation and separation of specularity. The limitation of the algorithm has been that applicable objects and illumination for the algorithm are restricted to uniformly colored dielectrics under singly colored scene illumination.

Recently we extended our research by presenting some more models for the detection and separation of specularities from Lambertian reflections using color and multiple images with different viewing directions. From the models, two new algorithms have been proposed and they are called *spectral differencing* and *view sampling*, respectively. Both algorithms use multiple views in different viewing directions, and are based on the *Lambertian consistency* that image irradiance from Lambertian reflection does not vary depending on viewing directions, while image irradiance from specular reflection or from the mixture of Lambertian and specular reflections can change. The *spectral differencing* is a detection algorithm that detects specularities by color difference between two images without relying on any geometric feature correspondence. The object and illumination domain for detection is extended to nonuniformly colored dielectrics and metals under multiply colored scene illumination. With densely sampled views in wide angle and with known viewing directions, the *view sampling* algorithm reconstructs object structure as well as separates specularities from Lambertian reflections. The *view sampling algorithm* does not require color information, and is applicable to dielectrics and metals. It has been shown that experimental results conform to the models and algorithms well.

The key contribution of the newly developed models and algorithms is to suggest the use of multiple views in understanding reflection properties. Although multiple views have been one of the major cues in computer vision in obtaining object shape or structure, it has not been used for obtaining reflection properties. Future directions of research include detection of transparent objects, and of specularity from transparent objects, and detection of shadows.

3.4.13 Finding Parametric Curves in an Image

Aleš Leonardis

We advocate the view that the purpose of machine vision is not to reconstruct the scene in its entirety, but rather to search for specific features that enter, via data aggregation, a symbolic description of the scene that is necessary to achieve the specific task. Unfortunately, the high degree of variability and unpredictability that is inherent in a visual signal makes it impossible to design precise methods for detecting low-level features. Thus, almost any output of early processing has to be treated only as a hypothesis for further processing.

We have investigated a method for extracting simple geometric structures from edge images in terms of parametric models, namely straight lines, parabolas, and ellipses [Leonardis 1991 (A Search...); Leonardis and Bajcsy 1992]. These models satisfy the criteria for the selection of geometric representations (invariance, stability, accessibility, 3-D interpretation, perceptual significance). Our main objective has been to develop a novel control strategy, by combining several existing techniques, that achieves a reliable and efficient recovery of geometric parametric models and can serve as a powerful early vision tool for signal-to-symbol transformation. The method consists of two intertwined procedures, namely *model-recovery* and *model-selection*. The first procedure systematically recovers the models in an edge image, creating a redundant set of possible descriptions, while the model-selection procedure searches among them to produce the simplest description in terms of the criterion function. The method is efficient for two reasons: firstly, it is designed as a search which utilizes intermediate results as a guidance toward the final result, and secondly, it combines model recovery and model selection in a computationally efficient procedure. The scheme is inherently parallel and can easily be implemented on a massively parallel machine.

The method for extracting parametric geometric structures is a tool that has already proven useful to other tasks in computer vision [Leonardis, Gupta and Bajcsy, 1990]. We would like to extend the paradigm by using different types of models or models of the same type on different scales. Moreover, the same principle can be extended to operate on a hierarchy of different models which would lead to the recovery of more and more abstract structures.

3.4.14 Occlusions and the Next View Planning

Jasna Maver and Ruzena Bajcsy

Existing sensing equipment acquires in one measurement only a portion of the information present in a 3-D working domain. To resolve the ambiguities that are caused by occlusions in images, we need to take sensor measurements from several different views. An intelligent sensor system should be able to automatically determine where and how to position itself in order to obtain yet unknown 3-D information of the scene. The task addressed in our work deals with the strategy of acquiring 3-D information, i.e., computing the viewing directions from which 3-D data of an unknown scene can be acquired.

We have limited ourselves to range images obtained by a light stripe range finder which can measure the distance only of those portions of a 3-D scene which are simultaneously illuminated by the light and visible to the camera. Two types of occlusions can be encountered in a range image. An occlusion arises either when the part of the illuminated surface in the scene is occluded to the camera or when the direct laser light does not reach a part of the surface because it is reflected from another part of the scene.

The problem of 3-D data acquisition is divided into two subproblems due to two types of occlusions. After taking the range image of a scene, the regions of no data due to the first kind of occlusion are extracted. The missing data are acquired by rotating the sensor system in the scanning plane, which is defined by the first scan. After a complete image of the surface illuminated from the first scanning plane has been built, the regions of missing data which are due to the second kind of occlusions are located. Then the directions of the next scanning planes for further 3-D data acquisition are computed.

In the work we propose a strategy of acquiring 3-D data. In order to compute the next move we model only the scene at the borders of the occlusions and assume a very simple shape of the occluded scene.

3.4.15 Active Observer : A Discrete Event Dynamic System Model for Controlling an Observer Under Uncertainty

Tarek M. Sobh and Ruzena Bajcsy

In this work we establish a framework for the general problem of observation, which may be applied to different kinds of visual tasks. We construct "intelligent" high-level control mechanisms for active visual recognition of different processes within a hybrid dynamic system. We address the problem of observing a manipulation process in order to illustrate the ideas and motive behind our framework. Active and autonomous tracking mechanisms are developed for the observer agent which is completely decoupled from the manipulation agent.

A discrete event dynamic system is used as a high-level structuring technique to model the manipulation system. The formulation utilizes the knowledge about the system and the different actions in order to solve the observer problem in an efficient, stable and practical manner. The model uses different tracking mechanisms so that the observer can "see" the workspace of the manipulating robot. An automaton is developed for the hand/object interaction over time and a stabilizing observer is constructed. Low-level modules are developed for recognizing the visual "events" that causes state transitions within the dynamic manipulation system in real time. A coarse quantization of the manipulation actions is used in order to attain an active, adaptive and goal-directed sensing mechanism. The formulation provides high-level symbolic interpretations of the scene under observation. The discrete event framework is augmented with mechanisms for recovering the continuous parametric evolution of the scene under observation and for asserting the state of the manipulation agent.

This work examines closely the possibilities for errors, mistakes and uncertainties in the manipulation system, observer construction process and event identification mechanisms. We identify and suggest techniques for modeling these uncertainties. Ambiguities are allowed to develop and are resolved after finite time. Error recovery mechanisms are also devised. The computed uncertainties are utilized for navigating the observer automaton state space, asserting state transitions and developing a suitable tracking strategy for the observer agent.

The approach used can be considered as a framework for a variety of visual tasks, as it lends itself to be a practical and feasible solution that uses existing information in a robust and modular fashion. Theoretical aspects and experimental results of the work support adopting this framework as a new basis for performing several task-oriented recognition, inspection and observation of visual phenomena.

4 Hardware Developments

Fil Fuma and John Bradley

The overall configuration of the Grasp laboratory computers has changed dramatically over the past year. At the end of the spring 1992 semester, the layout shown in figure 5 will be complete.

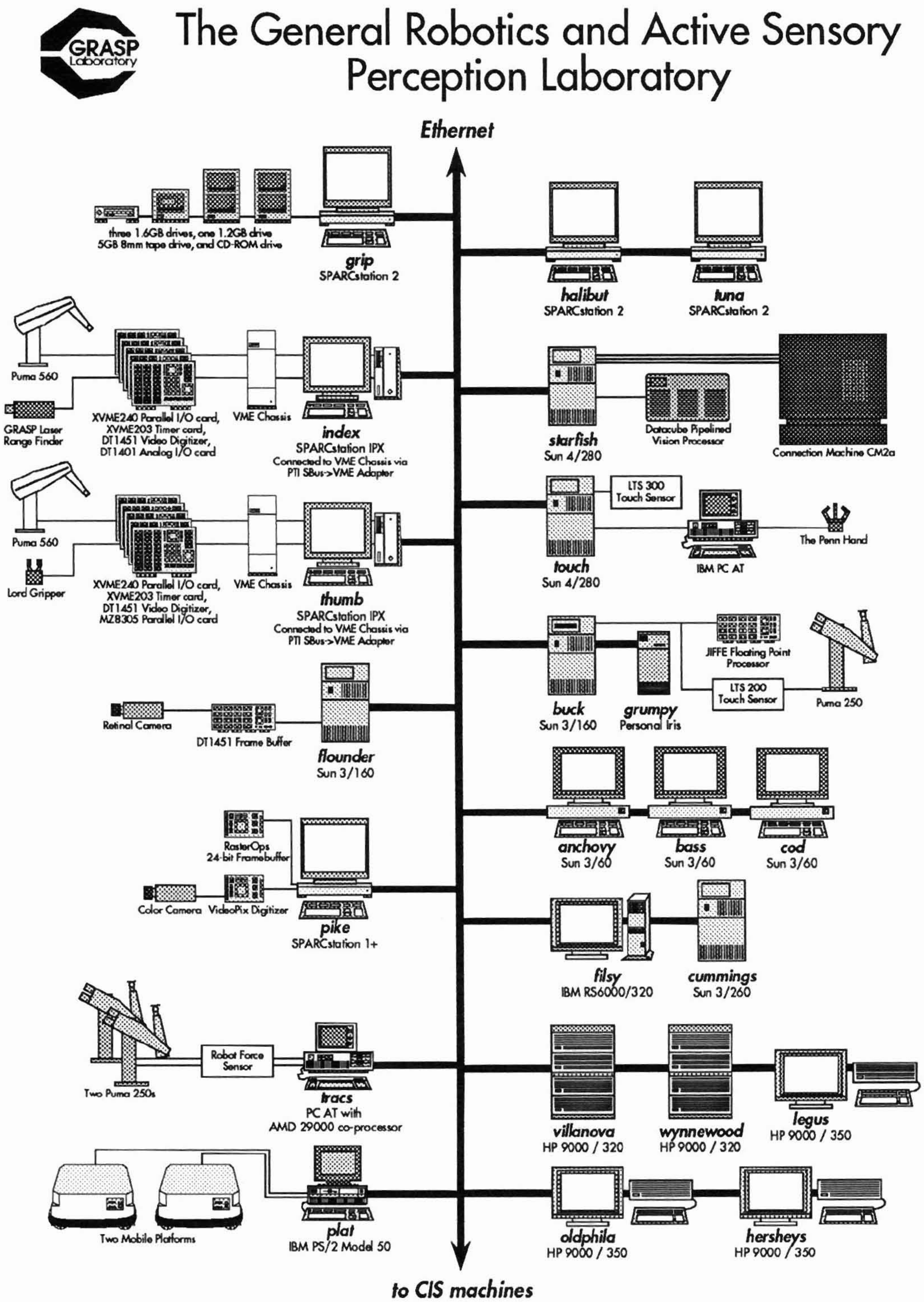

Figure 5: Grasp Laboratory Systems Layout

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CIS	Computer and Information Science
CSE	Computer Science and Engineering
ECE	Electrical and Computer Engineering
EE	Electrical Engineering
MEAM	Mechanical Engineering and Applied Mechanics
SSE	Systems Science and Engineering

6 Journal and Conference Publications

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