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**GRASP News: Volume 7, Number 1**

Faculty & Graduate Students
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GRASP News: Volume 7, Number 1

Abstract
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Comments

This technical report is available at ScholarlyCommons: https://repository.upenn.edu/cis_reports/760
"Active Multiple Agents"

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

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1 Forum

Editors’ Foreword

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Director's Note

Every new edition of the GRASP news is an opportunity to look back on our accomplishments and perhaps, failures, as well as to look forward to our future aspirations. The GRASP Lab has come long way. By now we have established ourselves as a serious laboratory that carries out research in active perception, manipulation, and exploration of unknown environments. Our research not only has strong theoretical foundation but every theory is also painfully tested in carefully thought out physical experiments. We have had many visitors from US institutions as well as from abroad, which is very gratifying though sometimes quite time consuming. We are represented in all major international conferences, either in computer vision or robotics. Our graduates are in distinguished places, both in academic institutions and industrial laboratories all over the world. We are very pleased to acknowledge that we are slowly but surely building a strong GRASP Lab network. During last year, we have made several accomplishments that we can be proud of. Just to mention some:

1. Understanding material properties from reflectance measurements, in particular separating the highlights and interreflections from the color of the material; along these lines we are on the verge of understanding transparency.

2. Given three dimensional range data, we have a general method of segmenting this data into zero, first, or second order surfaces, whichever fits the data the best. This procedure does not make any a priori assumptions about the arrangement of objects and/or scenes.

3. Again, given range data, we have a new segmentation process which decomposes an arbitrary scene into parts, where each part is represented by a superquadric model.

4. We have resolved the problem of where to look next, depending on the complexity of the scene, and the information that we obtain from the first view.

5. We have the capabilities to identify material properties, such as compliance, penetrability, conductivity, weight, slippage/friction, using contact sensing: position, velocity, acceleration, force, conductivity, and their combinations. These properties are extracted via specific procedures, called Exploratory Procedures (EPs).

6. More complex EPs are the ones that test for manipulability of the parts, such as hinges, wheels, and so on. They have also been developed.

7. We have solved the coordinated control problem with unilateral constraints that arises in lifting and manipulating objects with two arms.

8. We have completed the development of the three fingered hand with a palm, and its control, that has distributed tactile sensors both on the inside and outside of the fingers. This hand allows us to grasp objects in a clutter that otherwise cannot be grasped.
9. We have completed the development of a force reflective six degree freedom device connected to a graphics world which allows us to generate robot task programs for carrying out the task.

10. None of the above could have been developed without the theoretical underpinnings that come from studies of sensor/manipulator, world, and task modeling. By using interval representation for sensor/manipulator and the task, we have succeeded in formulating the problem of task directed sensory fusion in a coherent and consistent manner. This formulation allows us to control and make decisions about how much sensory information one must have and when to stop, given a task with a given accuracy of a desired performance. This is all related to robust estimation and decision making under uncertainty.

As it must be obvious from the above, most of our accomplishments are in the understanding and development of components and modules rather than systems. Looking ahead, we are now in the position to ask bigger questions, investigating tasks that require more sophisticated systems to verify them. The overall direction is to study MULTI-AGENT SYSTEMS that includes the human operator. Although our ultimate goal is to have autonomous systems, we realize that this is impossible to achieve in general. Hence, we wish to study systems that include the human operator for a common task. For that we need to understand where machine-agents and where human-agents are the most applicable, for a given task. We also need to understand the interface and the means of communication between different agents. The tasks that we shall consider are in the area of material handling and mechanical maintenance. Applications are numerous in decontaminating and refueling contaminated airplanes, repackaging ammunition, defusing unexploded trophies, destroying chemical weapons, cleaning up nuclear waste, underwater and outerspace exploration, and so on.

Some of the underlying research issues are:

1. Testing the functionality of an object; i.e. what does it mean to have a supporting surface, a container, a cutting tool, a scooping tool, a pricking tool, etc.? In other words, here we are interested in coming up with a representation of functionality, which we claim is not only the form. Functionality implies form but not the other way around!

2. How do we know where to step, so that we do not fall and can continue to walk? This is related to functionality of the surface as support, but with respect to an object that has particular weight, shape, and desired mobility.

3. What are the EPs (i.e. how much do we need to know about the environment), their sequence-control structure, in order to be able to lift arbitrary shape/weight objects and transport them or perform other manipulation?
4. What must be given in representation of geometry, material properties, kinematic and dynamic properties, manipulatory actions, and some learning rules in order for a system to be able to learn a given manipulatory or mobility task?

5. Finally, there is a big question of how to model the world. How to model the terrestrial world as opposed to the underwater or the zero gravity world? Furthermore, the terrestrial world can be subdivided into outdoor scenes versus indoor scenes, and so on. This is typically called context. Recognizing the context has great ramifications in reduction of search for not plausible or less likely interpretations.

So when we look into the future, we see many challenges and exciting problems that we believe are in our reach to solve.

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2 Feature Article

Research at the GRASP Laboratory
Helen Anderson

The General Robotics and Active Sensory Perception (GRASP) Laboratory of the University of Pennsylvania does research in several areas of robotics and machine vision including coordinated control of multiple robot manipulators, strategies for robotic sensing, multi-sensor integration, distributed real-time operating systems, telerobotics with communication delays, image understanding, and range image analysis. Major equipment includes three PUMA 250's, two PUMA 560's, two custom sensorized robotic hands, two grippers, a foveal/peripheral pair of robot-mounted Sony CCD cameras, a robot-mounted structured light laser rangefinder, and other range measurement devices and cameras. Computational equipment includes Sun 4's, SparcStations, Sun 3 workstations, MicroVaxes, HP workstations, a Personal Iris, IBM workstations, a Datacube, a pyramid processor, and a Connection Machine CM2a with a dedicated Sun 4/280 front end.

The GRASP Laboratory has approximately thirty graduate students, seven faculty members, five staff members and five undergraduate employees. The students and faculty are from four departments (Computer and Information Science, Systems Science and Engineering, Mechanical Engineering and Applied Mechanics, and Electrical Engineering). The multidisciplinary approach of the GRASP Laboratory reflects the mission of the University of Pennsylvania's School of Engineering and Applied Science, where students participate in the creation of knowledge at the leading edge of their particular fields of interest, and integrate knowledge to create new devices and systems. Funding for the GRASP Laboratory comes from governmental and industrial sources.

- Coordinated Control of Multiple Manipulators

Dynamic coordination of multiple manipulators is investigated to enhance the capability of manipulators for grasping and manipulating large, heavy, and irregularly shaped objects. Using differential geometric control theory, a coordinated control algorithm, which explicitly controls both the interaction force and motion trajectory, has been developed. The algorithm utilizes dynamic nonlinear feedback to exactly linearize and decouple the nonlinear system of multiple manipulators. The control of contact conditions (rolling and sliding) in multi-arm manipulation and multi-handed grasping is also been studied. To demonstrate the approach, the Two Robotic Arm Coordination System (TRACS) has been developed, using two PUMA 250 robots and an IBM PC/AT based controller. Using two instrumented open-palm end effectors developed in the lab, the TRACS is capable of grasping and dynamically transporting large objects such as cardboard boxes, not graspable by individual manipulators.
• Active Sensory Perception

Visually guided perception makes use of robot-mounted CCD cameras, range imaging systems, and tactile sensors. Mobile cameras seek to position themselves in the best viewing location for maximum information extraction. This technique, employing a passive sensor in an active fashion, purposefully changes the sensor's state parameters according to sensing strategies. The active sensing paradigm includes taking multiple measurements and integrating them, and including feedback not only on sensory data but on complex processed sensory data. An example of this work is the construction of a complete spatial map of a 3-D scene using a robot-mounted structured light (laser) rangefinder. A single range image is taken, then a strategy is developed to select the appropriate next view. A PUMA 560 moves the scanner, a new range image is taken, and the new data is integrated with data from the first view. The process continues until a complete spatial map is obtained.

• Identification of 3-D Shapes

To identify 3-dimensional shapes, we use information from contour and surfaces in addition to boundary based representations. Separate Volumetric, Contour and Surface modules have been developed and tested. The Segmentor Control Module has been designed and an initial version of it has been implemented. It performs volumetric segmentation given a surface segmentation, at the same time it monitors the orientation axis of the shape. This shows that it is possible to grow rather than just to recover superquadric models of objects, which is important for improving segmentation over time given additional information. The Segmentor Control Module provides feedback to the individual primitive description modules, and evaluates the intermediate descriptions and formulate hypotheses about parts. The parallel application of these processes will give us a general method of 3-D shape representation and identification from non-contact sensing.

• Color Image Segmentation

To improve color image segmentation techniques, we identify and remove interreflections and highlights in color images. An orthonormal color metric space, based on physical models of our camera and filters, is used to better represent and process image colors. A white reference object is used to determine the spectral characteristics of scene illumination. Spectral distribution (color) of an object surface is not changed by shading and shadow under the white illumination, but it is changed by highlights and inter-reflections between the objects. Image segmentation is done by hue and saturation values. Highlights add whiteness to the object color and can be detected by observing the change in saturation, when objects are uniformly colored. Changes in saturation and hue values are used to detect inter-reflections.

• Perception via Manipulation

The ultimate goal of robotics in the GRASP Laboratory is to build robotic systems that function in completely unstructured environments. Irrespective of the actual control algorithms used, a complete model of the system is absolutely essential. Such a model of a
robot system must account for the dynamics of the robot manipulator, the end effector, the sensor devices, the environment or external object, and the controller itself. For a given robot, it is reasonable to assume that models of the manipulator, the end effector, the sensors and the controller are available. It is the model of the environment or object that is, in most cases, not known since real world environments are unstructured. A solution to this apparent paradox is to incorporate in the robot system the “learning ability” to acquire knowledge about the properties of the environment. An important means by which people learn about the environment is by manipulation. People touch an object to feel its temperature, manipulate an object to learn the relationship among its different parts, and turn an object to see its back side. Our goal is to provide the robot with the ability to learn about its environment through manipulation. Particular areas of research include geometric and mechanical properties of objects, such as identifying movable and removable parts of an object.

- **Teleoperation with Feedback Delay**

Delay occurs with earth-based teleoperation in space and with surface-based teleoperation with untethered submersibles when acoustic communication links are involved. The delay in obtaining position and force feedback from remote slave arms makes teleoperation extremely difficult. We use a combination of graphics and manipulator programming to solve the problem by interfacing a teleoperator master arm to a graphics based simulator of the remote environment coupled with a robot manipulator at the remote, delayed site. The operator’s actions are monitored to provide both kinesthetic and visual feedback and to generate symbolic motion commands to the remote slave. The slave robot then executes these symbolic commands delayed in time. While much of a task proceeds error free, when an error does occur the slave system transmits data back to the master and the master environment is be “reset” to the error state.

- **Multisensor Integration Theory and Application**

The combination of sensor data can be modeled as a statistical problem and then analyzed using statistical decision theory. Robust sensor fusion can be used in an environment with sensor noise and inexact statistical descriptions. The GRASP Laboratory has developed techniques which allow us to accommodate uncertainty in real sensor noise distributions, to gain significant improvements in estimation of location (range) data. In addition to work on range data, which is one dimensional, work is being extended to the multi-dimensional case. For each uncertainty class of real noise distributions, we need to obtain a minimax rule based on a zero-one loss function. These rules minimize the maximum probability that the absolute error of estimation is greater than an error tolerance. At the GRASP Laboratory, these developing theories of multisensor integration are applied to real sensor data.

- **Real-time Distributed Systems**

The multi-sensor multi-robot systems in the GRASP Laboratory execute in real-time on a number of different processors linked by a local area network. To facilitate the development
of such systems, we have been investigating the programming, operating systems and formal
specification issues of distributed real-time systems. For real-time systems to be correct,
they must not only be functionally correct but also satisfy timing constraints. Our approach
is to treat “time” explicitly within programs so that their temporal behavior can be specified
and reasoned about. We have been developing programming concepts: temporal scope for
expressing timing constraints, timed communication for communication with predictable
delay, timed atomic commitment for timely coordination of subsystems. As a testbed, we
have been developing a real-time kernel called Timix. The salient feature of Timix is the
integrated scheduling of processes and messages based on timing constraints. A distributed
two-robot system is being implemented using this kernel. To provide a formal framework
for specification and analysis of the temporal properties of real-time systems, we have been
developing a resource-based computation model of time dependent processes and a process
algebra based on the model, called Communicating Shared Resources.

For further information about research activities at the GRASP Laboratory, contact Ms.
Trisha Yannuzzi (215-898-0371, trisha@cis.upenn.edu). Laboratory reports and publications
are available upon request.
3 Current Research

3.1 Vision Research

3.1.1 Analysis of Multiple Reflection Components – Separation of Specular and Lambertian Reflection

Sang Lee and Ruzena Bajcsy

Visual measurement of surface reflectance properties is an important issue both in basic and in applied computer vision research. Surface reflectance gives a reliable cue for image segmentation and object recognition. The goal of the research is to detect and separate specularity from Lambertian reflectance based on physical models. In order to provide enough information to extract various properties of reflectance, we generally need more than one frame of images. One direction is to use color information and another is to use multiple images with different views.

We have proposed a computational model using color for image segmentation and for separating specular and Lambertian reflection based on the physical properties of sensors and surface reflectances. The fact that the interface and Lambertian reflections are often spectrally different is key to separation by color. Our model allows us to separate diffuse as well as sharp specularities from Lambertian reflections. Therefore inter-reflections between adjacent objects (which are usually diffused) can also be detected. In addition to the use of color, we have also proposed the use of different views to differentiate specularity from Lambertian reflectance and to obtain object structure. The algorithm is based on the fact that the appearance of specularity varies depending on viewing direction while that of Lambertian does not. In order to build a even more robust and reliable vision system, we will work on the low-level integration of information by color and multiple views.

3.1.2 Empirical Studies of Minimum Description Length Modeling

Kevin Atteson and Max Mintz

Minimum description length modeling is a criteria for statistical inference which has applications in many areas of machine perception and learning. Statistical inference is the problem of choosing a model from some set of observations. There is a large body of literature on different criteria for choosing such a model. Rissanen has recently proposed the Minimum Description Length (MDL) criterion for model selection. With the MDL criterion, we choose the model which allows the data to be described with the shortest possible sequence, assuming that the description language must be designed without knowledge of the observed data. MDL can be applied to parametric problems in which there is a well defined parameter space associated with the set of models. However, MDL requires discretization of both the parameter space and the data space and it is not clear that the
results are invariant to the method of discretization chosen.

We have performed an empirical study of the effectiveness of the MDL procedure and are in the process of a second study. The first involved autoregressive (AR) and moving average (MA) models. In selecting an AR process to model a sequence which is actually generated by some AR process, the MDL procedure demonstrated rapid convergence of the model to the actual process in all cases. When attempting to model a sequence from an MA process with an AR model, the MDL procedure seemed to choose a model appropriate to the data available at any given time. The second experiment which is still be implemented involves the MDL approach to image segmentation as formulated by LeClerc. The approach is designed so that it can be implemented effectively on a data-parallel machine and is being implemented on the massively parallel Connection Machine. Results are available for a simplified version of the model space. The procedure does reasonably well but it appears that the minimization procedure converges to a sub-optimal local minimum.

3.1.3 Segmentation as the Search for the Best Description of the Image in Terms of Primitives

Aleš Leonardis, Alok Gupta, and Ruzena Bajcsy

Segmentation of images has long been considered in computer vision as an important but extremely difficult problem. We develop a new paradigm for the segmentation of images into piecewise continuous patches. Data aggregation is performed via model recovery in terms of variable-order bi-variate polynomials using iterative regression. All the recovered models are potential candidates for the final description of the data. Selection of the models is achieved through a maximization of quadratic Boolean problem. The procedure can be adapted to prefer certain kind of descriptions (one which describes more data points, or has smaller error, or has lower order model). We have developed a fast optimization procedure for model selection. The major novelty of the approach is in combining model extraction and model selection in a dynamic way. Partial recovery of the models is followed by the optimization (selection) procedure where only the "best" models are allowed to develop further. The results obtained in this way are comparable with the results obtained when using the selection module only after all the models are fully recovered, while the computational complexity is significantly reduced. We test the procedure on real range and intensity images.

3.1.4 Judging Texture Coarseness based on Edges

Gareth Funka-Lea and Ruzena Bajcsy

At present we are investigating techniques to analyze images of scenes of textured surfaces. The texture in an image is considered to be those regions where edges frequently occur (i.e. there is a lot of variation in the image values). The application we are interested
in is determining the smooth surfaces in the observable world in front of a mobile robot. A visually smooth surface is one where there is no texture or the texture consists of suitably weak edges. The strength of edges is judged based on statistics of the local distribution of edge magnitude. Exact criteria would depend on the robot's capabilities and the task. In effect, what we are using is a measure of texture coarseness. We are particularly interested in how this measure varies with observed distance. Consequently, we are interested in scenes where surfaces extend into the distance and perspective distortions are an important consideration. We hope to be able to segment images of such scenes in a meaningful way based on the coarseness of the texture.

3.1.5 Volumetric Segmentation Of Complex 3-D Scenes Using Parametric Shape Models

Alok Gupta and Ruzena Bajcsy

The problem of part definition, description, and decomposition is central to the shape recognition systems. In this thesis, we develop an integrated framework for segmenting dense range data of complex 3-D scenes into their constituent parts in terms of surface and volumetric primitives. Unlike previous approaches, we use geometric properties derived from surface, as well as volumetric models, to recover structured descriptions of complex objects without a priori domain knowledge or stored models. The guiding principle to obtain an optimal segmentation is that the recovered models must account for only the given data (within the specified tolerance). However, the models can predict data not visible from the given viewing direction.

To recover shape descriptions, we use bi-quadric models for surface representation and superquadric models for object-centered volumetric representation. The surface segmentation uses a novel approach of searching for the best piecewise description of the image in terms of bi-quadric \((z = f(x, y))\) models. It is used to generate the region adjacency graphs, to localize surface discontinuities, and to derive global shape properties of the surfaces. A superquadric model is recovered for the entire data set and residuals are computed to evaluate the fit. The goodness-of-fit value based on the inside-outside function, and the mean-squared distance of data from the model provide quantitative evaluation of the model. The qualitative evaluation criteria check the local consistency of the model in the form of residual maps of overestimated and underestimated data regions.

The control structure invokes the models in a systematic manner, evaluates the intermediate descriptions, and integrates them to achieve final segmentation. 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 model evaluation criteria determine the dimensionality of the scene, and decide whether to terminate the procedure, or selectively refine the segmentation or generate constructive solid geometry (CSG) descriptions. The control module generates hypotheses about superquadric models at individual regions or a collection of regions. The hypothesized superquadric models are grown to include more
data within the constraints imposed by the already accepted data, the error tolerance, and the bi-quadric surface segmentation. The control system can be tailored to suit the requirements of a particular domain by making it prefer certain descriptions to others.

We present results on real range images of scenes of varying complexity, including overlapping objects, and scenes where surface segmentation is not sufficient to guide the volumetric segmentation. We analyze the issue of segmentation of complex scenes thoroughly by studying the effect of missing data on volumetric model recovery, generating object-centered descriptions, predicting and verifying additional information needed to obtain position, orientation and scale invariant segmentation. Our approach has applications in data reduction, 3-D object recognition, geometric modeling, automatic model generation, object manipulation, and active vision.

3.1.6 Qualitative and Quantitative Criteria to Evaluate and Analyze a Recovered Superquadric Model

Luca Bogoni, Alok Gupta, and Ruzena Bajcsy

The relations between different criteria are used to evaluate the recovered superquadric model. These criteria are derived from various measures which relate the model to the data. The evaluation is obtained by verifying that the qualitative and quantitative measures satisfy the following modeling principle:

\[ \text{data points} \iff \text{model} \]

which can be stated as follows:

\emph{Any model in order to optimally represent some data must account for all and only the data which it is trying to describe.}

This relation enforces the requirement that data points be described by the model and, at the same time, that the model be representative only of data present. Thus, the developed criteria must guarantee that the principle is satisfied in order to qualify the model as descriptive of the data and vice-versa. These criteria are also used to gain insight on alternative routes to be considered. As a result, one may be able to

- perform object segmentation to try to recover the parts.
- reject the current modeling schema and suggest others which, upon analysis of the residuals may result more plausible.

This work is to be submitted to the Journal of Computer Vision.
3.1.7 Resource-Bounded Sensor-Based Decision Making in Unconstrained Environments

Greg Hager

A central problem in sensor data fusion is the recovery of complex, multi-component models from various sensory modalities. We argue an essential component of this process is a description of what decision must be made from the recovered model. We refer to this description as the sensing task. The goal of this research project is to develop and analyze techniques for recovering the minimal or least detailed model required to make a satisfactory decision for a given sensing task. In particular, we are focusing on the task-directed recovery of composite models (models composed of several components).

Our model recovery method is based on the numerical solution of systems of nonlinear constraints using interval bisection. Previous work, based on making decisions about objects modeled by a single parametric form, showed that these methods are general, natural, simple to implement, and computationally effective. In addition, we were able to incorporate notions of the cost of computation and the value of information into the recovery process, and to terminate the recovery process when the model with the highest net value (decision payoff minus computational cost) was reached. We are now extending the underlying recovery method by incorporating model refinement and data segmentation in a manner that also exploits information about the sensing task.

We expect our results to have particular impact in application areas where good a priori models are not available. Examples of these domains include classification and sorting of irregular (naturally occurring) objects, supervisory control, and partially or fully autonomous vehicles.

3.1.8 Multivariate Sensor Fusion

G. Kamberova, R. McKendall, and M. Mintz

The successful design and operation of autonomous or partially autonomous agents which are capable of traversing and exploring uncertain environments requires the application of multiple sensors for tasks such as: local motion, environmental evaluation, and feature recognition. In applications which include a teleoperation mode, there remains a serious need for local data reduction and decision-making to avoid the costly or impractical transmission of vast quantities of sensory data to a remote operator. There are several reasons to include multi-sensor fusion in a system design: (i) it allows the designer to combine intrinsically dissimilar data from several sensors to infer some property or properties of the environment, which no single sensor could otherwise obtain; and (ii) it allows the system designer to build a robust system by using partially redundant sources of noisy or otherwise uncertain information.
At present, the epistemology of multi-sensor fusion is incomplete. Basic research topics include the following task-related issues: (i) the value of a sensor suite; (ii) the layout, positioning, and control of sensors (as agents); (iii) the marginal value of sensor information; the value of sensing-time versus some measure of error reduction, e.g., statistical efficiency; (iv) the role of sensor models, as well as a priori models of the environment; and (v) the calculus or calculi by which consistent sensor data are determined and combined.

In our research on multi-sensor fusion, we have focused our attention on several of these issues. Specifically, we have studied the theory and application of robust fixed-size confidence intervals as a methodology for robust multi-sensor fusion. This work has been delineated and summarized in Kamberova and Mintz (1990) and McKendall and Mintz (1990a, 1990b). As we noted, this previous research focused on confidence intervals as opposed to the more general paradigm of confidence sets. The basic distinction here is between fusing data characterized by an uncertain scalar parameter versus fusing data characterized by an uncertain vector parameter, of known dimension. While the confidence set paradigm is more widely applicable, we initially chose to address the confidence interval paradigm, since we were simultaneously interested in addressing the issues of: (i) robustness to nonparametric uncertainty in the sampling distribution; and (ii) decision procedures for small sample sizes.

Recently, we have begun to investigate the multivariate (confidence set) paradigm. The delineation of optimal confidence sets with fixed geometry is a very challenging problem when: (i) the a priori knowledge of the uncertain parameter vector is not modeled by a Cartesian product of intervals (a hyper-rectangle); and/or (ii) the noise components in the multivariate observations are not statistically independent. Although it may be difficult to obtain optimal fixed-geometry confidence sets, we have obtained some very promising approximation techniques. These approximation techniques provide hyper-rectangular confidence set approximations to given hyper-ellipsoidal confidence procedures, as well as tight upper and lower bounds to the optimal confidence coefficients in the presence of both Gaussian and non-Gaussian sampling distributions.

The goal of this research is the delineation of good approximations to fixed-geometry confidence procedures with application to multivariate sensor fusion.

### 3.1.9 Sensor Fusion

**Raymond McKendall and Max Mintz**

The analysis of statistical decision problems motivated by the sensor fusion paradigm is now addressing estimation of two-dimensional location parameters. An example problem is to estimate the position of some object in a planar area from a noisy measurement of the position. This analysis is the first step in extending previous results to multi-dimensional settings required by applications.

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The general statistical problem is to estimate a parameter \( \theta = (\theta_x, \theta_y) \) from an observation \( Z = (Z_x, Z_y) \) for which \( \theta \) is a location parameter. The problem assumes that the possible values of the parameter \( \theta \) are elements of a known set \( \Theta \). The set \( \Theta \) may be a planar region, such as a square or circle, or it may be a planar lattice. The goal is to find a minimax estimator that minimizes that maximum probability that the absolute error of estimation exceeds a specified threshold. This framework extends previous work in which \( \theta \) and \( Z \) are one-dimensional.

The two-dimensional problem introduces new research issues that are not present in the one-dimensional problem. One issue is stochastic dependence between the components \( Z_x \) and \( Z_y \) of the observation \( Z \). For example; the observation \( Z \) may be a bivariate normal random variable having non-zero coefficient of correlation. A second issue is algebraic dependence between the components \( \theta_x \) and \( \theta_y \) of the parameter \( \theta \). For example, if \( \Theta \) is a disk with radius \( r \) centered at the origin, then \( \theta_x \) and \( \theta_y \) are related through the inequality \( \theta_x^2 + \theta_y^2 \leq r^2 \). In addition to direct analysis, a promising direction of analysis is to approximate the exact solution of a problem by solving a similar problem in which there is no dependence. For example, a problem in which \( \Theta \) is a disk of radius \( r \) may be approximated through the problems in which \( \Theta \) is the largest square region inscribed in the circle and in which \( \Theta \) is the smallest square region circumscribed around the circle. Research issues in this approach are appropriate simplifications of assumptions and subsequent performance of approximations.

The methodology of our analysis continues to embrace both traditional mathematical analysis and computational investigation. In both approaches, Mathematica and the Connection Machine are important new tools in the lab for exploration of solutions and verification of ideas.

Further research in sensor fusion will address other extensions of previous results. These include robust estimation, multiple sample problems, different assumptions about the noise distribution, and different models of sensor measurements. Also, recent work in the decision-theoretic formulation of machine learning offers a promising new direction this work in statistical decision theory; future research will pursue this direction.

### 3.1.10 Scene Segmentation from Visual Motion Using Spatio-Temporal Filters

**George Chou, Aleš Leonardis, and Ruzena Bajcsy**

Visual motion offers an abundance of information necessary to disambiguate uncertainties about the visual world. We are currently working on the task of static scene segmentation based on motion information. Our model involves two stages of processing. The first stage measures the normal components of motion in the image; the second stage utilizes this information to perform object-based segmentation of the scene. We are taking an active approach in generating visual motion by translating the camera in orthogonal directions. The translation induces a radial, depth-dependent optical flow that form the input to our
analysis.

For the task of motion sensing we have implemented a system of 3D (space-time) Gabor filters that can extract separate normal motion components. Gabor decomposition of an image sequence is well-localized in space-time and frequency domains. The flow field represented by multiple maps corresponding to various velocities are grouped spatially within each map under the assumption that they are induced by a single rigidly moving object. The hypotheses are tested in space and time by a region-growing process that imposes both spatial and temporal coherence on the segmentation of motion flow. Hypotheses that remain at the end form a depth-dependent segmentation of the scene. The region-growing and hypothesis testing procedure is based on the segmentation paradigm formulated earlier by Leonardis, Gupta, and Bajcsy.

Since the evolution of image pattern through time forms a direct relationship with the geometry of the scene, undesirable optical effects such as specularity and shadow could be overcome. In the future we plan to apply and extend our model for the recovery of structure from motion.

3.1.11 Estimation Of Three-Dimensional Motion And Structure From Images By Using A Temporally-Oriented Approach

Siu-Leong Lu

This dissertation explores the problem of estimating the 3-D motion and the structure of an object from video images using a new approach which looks for the temporal information prior to the spatial information. Since motion is observed over an extended period of time, we can reduce the number of features required by the conventional approach and improve significantly the estimation performance.

In recovering the motion of a single particle or a rigid body, we prove that, under some conditions, the solution is unique. Regression relations between the unknown motion parameters and the projective trajectories are obtained for general particle motion and constant rigid motion. The method of maximum likelihood is used to estimate the motion. Using the non-linear state estimation formulation, the extended Kalman filter is applied to obtain the estimate recursively.

We propose an approach to estimate a general non-constant rigid motion in which the orders of translation and rotation can be arbitrary. We also show that for some special angular velocities, non-constant rigid motion has closed-form evolution, and discuss how to reduce the number of unknowns if all the points lie on a planar surface.

We have addressed the problem of model mismatches for parameter jumping, under-modeling and over-modeling. We find that the model error makes the conventional approach break down. In order to solve this problem, we develop a new filter called Finite Lifetime Alternately Triggered Multiple Model Filter (FLAT MMF) is a filter composed of a number
of identical conventional state estimation filters, each triggered alternately. After the last filter is triggered, the oldest one is triggered again and, so on. Experiments on the simulated trajectory and the real images show the FLAT MMF is quite effective in suppressing the model errors. For the particle motion without a depth change, we obtain the analytic, closed-form estimate for cases of model match and mismatch. We show that the filter that provides the best estimates dominates the final estimate. Finally, we show the potential of FLAT MMF for real-time object tracking.

3.1.12 The Role of Vergence Micromovements on Depth Perception

Antônio Francisco Júnior

A new approach in stereo vision is proposed which recovers 3D depth information using continuous vergence angle control with simultaneous local correspondence response. This technique relates elements with the same relative position in the left and right images for a continuous sequence of vergence angles. The approach considers the extremely fine vergence movements around a given fixation point within the depth of field boundaries. It allows the recovery of 3D depth information given the knowledge of the system's geometry and a sequence of tuples \([a_i, C_i]\), where \(a_i\) is the \(i^{th}\) vergence angle and \(C_i\) is the \(i^{th}\) matrix of correspondence responses. The approach has several advantages over the current ones. First, due to its local operation characteristics, the resulting algorithms can be implemented in a modular hardware scheme. Secondly, unlike currently used algorithms, there is no need to compute depth from disparity values; at the cost of the acquisition of a sequence of images during the micromovements. Also, the approach greatly reduces the errors in stereo due to the sensor quantization. Lastly, and most important of all, the approach is supported on experimental results from physiology and psychophysics. Physiological results shows that the human eye performs fine movements during the process of fixation on a single point, which are collectively called physiological nystagmus. One such movement, called binocular flicks, happens in opposing directions and produces convergence/divergence of the eyes. These are the micromovements that we suppose are the basis for depth perception. Therefore, the approach proposes a functional correlation between these vergence micromovements, depth perception, stereo acuity and stereo fusion.

3.1.13 Coordination of Two TV Cameras Using Vision

Alberto Izaguirre

An algorithm to fit the Denavit Hartenberg parameters for the PUMA 560 has been implemented. A TV camera attached to the tip of the Robot is used to do the fitting. The algorithm is based on non-linear minimization similar to the method of steepest descent. The Levenberg Marquant method is used to prevent the occurrence of near singularity positions. It contains a parameter \(\alpha\) that prevents the solution from diverging.
The simulation results for this system give the original exact solution. In the real experiments we found an average error of 2mm in the close loop by vision. The recovered Denavit-Hartenberg parameters are also close to the ones specified by Unimation. In the future, we would like to compare the results obtained by two different cameras attached to the same robot.

Also, the FFT algorithm has been programmed on the Connection machine. The algorithm for a double[1024][1024] gives the correct answer in a time of the order of 10 milliseconds. The bottleneck is the download of the memory from the front end (a Sun 4/280) to the elements in the connection machine.

3.1.14 Constructing an Observer for a Moving Agent

Tarek Sobh and Ruzena Bajcsy

In this work, we address the problem of observing a moving agent. In particular, we propose a system for observing a manipulation process, where a robot hand is manipulating an object. A discrete event dynamic system (DEDS) framework was developed for the hand/object interaction over time and a stabilizing observer was constructed for a grasping action. Low-level modules were developed for recognizing the "events" that causes state transitions within the dynamic manipulation system. The system utilized different tracking mechanisms in order to observe the task in an efficient and stable manner. Using DEDS as a high-level structuring technique to model the tasks utilizes the existing knowledge about the hand and/or the manipulation domain in order to achieve a stable and efficient solution to the observation problem. The process uses a coarse quantization of the manipulation actions in order to attain an active, adaptive and goal-directed sensing mechanism.

The current work examines closely the possibilities for errors, mistakes and uncertainties in the manipulation system, observer construction process, and event identification mechanisms. We divide the problem into six major levels for developing uncertainty models in the observation process. The sensor level models deal with the problems in mapping 3-D features to pixel coordinates and the errors incurred in that process. We identify these uncertainties and suggest a framework for modeling them. The next level is the extraction strategy level, in which we develop models for the possibility of errors in the low-level image processing modules used for identifying features that are to be used in computing the 2-D evolution of the scene under consideration. In the third level, we utilize the geometric and mechanical properties of the hand and/or object to reject unrealistic estimates for 2-D movements that might have been obtained from the first two levels.

After having obtained 2-D models for the evolution of the hand/object relationship, we transform the 2-D uncertainty models into 3-D uncertainty models for the structure and motion of the entire scene. The fourth level uses the equations that govern the 2-D to 3-D relationship to perform the conversion. The fifth level rejects the improbable 3-D uncertainty models for motion and structure estimates by using the existing information.
about the geometric and mechanical properties of the moving components in the scene. The sixth and highest level is the DEDS formulation with uncertainties, in which state transitions and event identification is asserted according to the 3-D models of uncertainty that were developed in the previous levels.

3.1.15 Real-time Visual Tracking for Agent Observation

Robert Potter

This is a project on visually tracking a known target in real time. It is in support of Tarek Sobh's research on observing and understanding the actions of an external agent. In order to understand the actions of the agent, a visual system is needed that can follow the agent (in this case a Lord gripper mounted on a PUMA 560 arm) as it moves about the workspace. Moreover, the visual system must be capable of moving so as to maintain a good point of view. This movement capability is provided by a second PUMA 560, upon which the camera is mounted.

The low level vision is done on the MaxVideo pipelined video processor. This subsystem can track four markings on the gripper at frame rate (30 Hz). The 3D position of the gripper is calculated from the image positions of these markings, and the camera is moved so as to keep a constant viewing position relative to the gripper. This position update cycle runs at 3 Hz. The system is currently being extended to detect and compensate for target rotations as well as translations.

Future work is directed at research in task-directed control of focus of attention. When computational resources are limited and time is critical, visual processing must be concentrated on the data that are most relevant. Therefore, a mechanism for identifying interesting portions of the incoming data stream is essential. This "attentional reflex" system must function continuously over the entire field of view, and thus must be computationally inexpensive. A simple way of reducing computational expense is to tailor the system to the task at hand. Of particular interest will be the discovery of triggering mechanisms that are appropriate for various specific visual tasks.

3.1.16 How to Decide from the First View where to Look Next

Jasna Maver and Ruzena Bajcsy

The task of constructing a volumetric description of a scene from a single image is an underdetermined problem, whether it is a range or an intensity image. To resolve the ambiguities that are caused by occlusions in images, we need to take sensor measurements from several different views. We have limited ourselves to the range images obtained by a laser scanning system. It is an active binocular system which can encounter two types of occlusions. An occlusion arises either when the reflected laser light does not reach the
camera or when the directed laser light does not reach the scene surface. The task of 3-D data acquisition is done in two steps. First, we acquire the depth information from different directions in one plane to build the complete 2½-D image of the scene and then from the complete 2½-D image the directions of the next scanning planes are computed. The first kind of occlusions (range shadows) are easily detected and can be used in designing an efficient algorithm. We develop a strategy to determine the sequence of different views using the information in a narrow zone around the occluded regions. Occluded regions are approximated by polygons. Based on the height information of the border of the occluded regions and geometry of the edges of the polygonal approximation, the histogram is constructed. It represents the number of pixels in occluded regions which can be observed from all directions. From the histogram maxima we select the minimum number of directions such that all pixels in occluded regions can be observed. In the range image of the first plane the second type of occlusions are located. From their geometry, the directions of the next scanning planes for further data acquisition are determined.

3.1.17 Functionality in Goal Oriented Task as a means for Interpretation and Recognition of Objects

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 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 associate suitable interpretation to them. Thus, we are going to recognize whether within a group of objects anyone possesses the appropriate functionality to perform a task. Functionality is seen as key factor for object interpretation in the context of performing a goal. Currently we are investigating the fundamental aspects involved in the formulation and specifications of this process. Later we would like to analyze interaction/manipulation tasks as goal oriented recognition processes. These considerations will allow us to identify/classify suitable objects for given applications.

3.1.18 Implementation of Algorithms on the Connection Machine

Dmitry Cherkassky

The Connection Machine is ideal for modeling stochastic processes in which interactions are limited to relatively small neighborhoods. Markov random fields is an example of such a process. A Gibbs sampler - a highly parallel algorithm that exploits the equivalence between Gibbs distributions and Markov random fields has been implemented. This algorithm samples from Gibbs distribution which determines an MRF image model. The algorithm can also be used to perform image recovery by computing the maximum a posteriori estimate of
the image given observations degraded by blurring and noise. This program can be used in research on how to select the MRF parameters, namely potential functions that determine the energy function and neighborhood systems, for a given image.

A sequential program (see MS-CIS-90-30) that performs segmentation by region growing has also been ported to the Connection Machine. Aggregation of data is performed via model recovery in terms of variable-order bi-variate polynomials using iterative regression. This is followed by an optimization procedure. The parallel version runs faster than sequential one (a 10 to 12 times speed up was achieved).

CM is a Connection Machine version of PM (Picture Manipulation). It performs the same operations on images as PM, but runs on the Connection Machine. CMFB, an extension of PMFB to the Connection Machine frame buffer, will be implemented as well.

Work is also being done on implementing time consuming functions of wavelet and superquadric software on the Connection Machine.

3.2 Robotics Research

3.2.1 Machine Perceptual Development – A Conceptual Framework and Experimental Robotic System for Acquiring Sensorimotor Strategies

Marcos Salganicoff and Ruzena Bajcsy

It is interesting to explore what is innate and what can be learned in the context of perceptual development, especially as it relates to vision driven grasping. A motivation for this investigation is the belief that future autonomous systems must be capable of adapting to different environments and learning from new experiences.

Adopting the formalism of situated automata, we may think of the process of successful task completion as traversing some states of an automaton where each state encodes a state of affairs in the environment and each action emitted in that state leads to a state transition by having some effect on the world. A successful action in a state is one which leads the system closer to the desired goal state. Actions associated with a state are a function of sensed perceptual attributes. The relevant perceptual attributes must first be identified, and then a relation between these attributes and controllable attributes must then be found. This relationship, once determined, allows for the system to have a mechanism of attention and also to generalize from its previous results. We define this relationship in terms a multivariate statistical regression using weighted evidence from previous trials. This weighting is based on the reinforcement achieved in previous trials. We may also weight empirical evidence according to how recently they have been executed yielding a system that tracks changes in actuators and in expected world behavior.

We propose that learning of prehension (and sensorimotor tasks in general) can be divided into three inter-related processes. A state learning and recognition process attempts
to identify system states and the sensory events that characterize them. The strategic learning process involves the unsupervised identification of pertinent perceptual and motor attributes and their characteristic relationships which mark successful subtask execution. Finally, action learning attempts to determine the relationships between intentional actions and their effect on perceptual parameters. Once this relationship is known, the actions can be used to satisfy preconditions identified by the strategic learning process to achieve a goal.

These ideas will be illustrated in the context of a dual arm robotic system with mobile vision sensing and a dextrous sensorized hand which allows for the evaluation of learning strategies by repeated interactions with the environment. Several sensorimotor axioms are defined and implemented using this system and may be thought of as the innate perceptual and motor abilities of the system. By varying the competence and initial structure imposed on these innate abilities we can investigate effects on convergence rates for the respective learning process in finding new states and relations.

3.2.2 Grasping using Hand Arm Coordination

Sanjay Agrawal and Ruzena Bajcsy

In building a hand-arm system, coordination between the hand and the arm is established at two levels. At the higher or task level, a task framework is setup that incorporates both the motions of the hand and arm. A task framework consists of a goal state, which determines all the substates that must be accomplished in order to achieve the goal state. Each substate initializes a set of motions the arm must accomplish to complete the task, and for each arm motion, a corresponding hand motion is initialized. Dependencies between the individual motions are established between the substates. Substates are exited either by achieving the exit condition, specified as a set of desired forces and positions, or by entering an undesired condition such as a joint limit or excessive forces.

At a lower level, the forces from the sensors on the hand are mapped back into the tool frame of the arm. By using the Jacobian to transform the forces into a set of displacements the arm can either move to comply with these force and moment vectors or modify the forces and moments being applied. The hand control is based on a quasi-force/position control strategy whereby each joint has a desired force and position as well as force and position limits. This control scheme enables the fingers to comply individually to forces or to exert a net desired force on a grasped object. A contour following algorithm has been designed to allow the hand and arm to trace large contours, detect changes in the slopes or discontinuities, and map the local terrain. This contour following strategy is useful in identifying obstructions in the workspace that can then be grasped by the hand and removed.

A compliant control strategy has been designed for coordinating the hand and arm motions to avoid fatal collisions. This is a two tiered control scheme, whereby the fingers on the hand comply to forces at a very high bandwidth, and the arm reacts to the same
forces at a lower bandwidth.

The hand-arm system implemented consists of the Penn Hand mounted at the end of a Puma560 arm. Each finger of the Penn Hand carries four tactile pads, and the entire palmer area is covered by two pads. One of the four finger pads, cover the inward facing area of the proximal link, while the other three pads entirely cover the distal link, arranged such that one pad covers the palmer side of the link, another pad covers the tip, and the third pad covers the back of the link. This arrangement of sensors is designed to allow exploration even while maintaining a stable grasp, by decoupling the internal forces, from those detected while contacting the environment. All the sensors are entirely covered by a molded silicon elastomer that provides both compliance and friction, while at the same time protecting the sensors. The arm is controlled using an Unimate controller at the servo level. The hand is controlled by a PC at the joint level, and at the kinematic or task level the hand and arm are controlled by a Sun3. An additional component of this system is a laser-range finder mounted on another Puma560 placed such that there is a substantial overlap in the workspace of the two robots. Range data from this scanner is used to extract the position and orientation of the object, and obtain a volumetric description of the object.

This information is used to preshape the fingers of the hand. The hand approaches towards the expected object position, complying with any obstacles and modifying its trajectory until the object is contacted by the palm or fingers. On contact a \textit{wrap} algorithm is used, which attempts to bring opposing fingers around the object, by spreading them open and reorienting the arm, till both the palmer facing sensors of the fingertip are in contact with the object. At this point the hand closes around the object with the desired force. On squeezing the object, the compliant polymer is stretched around the object, causing both frictional and adhesive forces to hold the object in the grip.

### 3.2.3 Autonomous Grasp Planning using Superquadric Modeling

Michael Chan

A mobile laser range finder mounted on a Puma 560 robot was employed to acquire range information of a scene. Robot software was developed to allow scanning from different positions and directions covering an arbitrarily large area within the robot's work space. The object, recovered as range points, is modeled by superquadrics, and the PENN hand is used for the grasping task. Based on parameters of the superquadric model recovered, physical constraints of the robot and some heuristics, a program was developed which can decide how to approach an object and which grasping primitive to use. A stereo camera pair is currently being incorporated as an extra "agent" for sensing in the current robotic system. The long term goal is to study how these "agents" can be coordinated in an integrated system to execute specified tasks.
3.2.4 Coordinated Control of Two Robotic Manipulators

Eric Paljug and Xiaoping Yun

A dynamic coordinated controller of two robotic arms is being developed to perform manipulation and grasping of objects by using flat surface open palm end-effectors. The open palms enable the arms to grasp large, arbitrarily shaped objects, much like humans lift large objects. The open palms constrain the system because the palms can only produce a pushing force against the object, they cannot pull. Additionally, the interaction force, the force applied to the object that does not result in motion, must be controlled so the object is not dropped nor crushed and the manipulators do not exceed their torque limits.

In the past year, the hardware for the Two Robotic Arm Coordination System (TRACS) has been completed. This system will be used to perform research experiments in coordinated control. The system consists of 2 Puma 250 robots, an IBM PC-AT host computer, and an AMD 290000 high speed floating point processor based board.

Future research will address the contact conditions of the end-effector surface with the object, in particular the case of rolling contacts. The system should be able to control rolling so as to not only recover from unintentional rolling but to actively roll. The goal of active roll can be the maintenance of a grasp that keeps the applied force centered within the friction cone of the contact or task specific rolling.

3.2.5 Control of Contact Conditions in Multiple Robotic Systems

Nilanjan Sarkar, Vijay Kumar, and Xiaoping Yun

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 rigidly grasp the object 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 arm(s). The objective of this research is to investigate the modeling and control of multiple robotic systems in coordination with special emphasis on contact interactions within the system and non rigid grasps.

There are two approaches to modeling the contact interactions. In the first approach, the dynamic equations of motion are derived from rigid body models for the effectors and the object. In the second approach, the contact phenomenon is modeled as an elastic contact and the dynamic model is based on continuum mechanics. In both cases, the primary goal is to control not only the position and orientation of the object but also the interaction forces and moments that the effectors apply on the object. Additionally, explicit control of contact conditions, namely rolling and sliding at each contact point, are investigated in order to improve dexterity.
Multiple manipulators together with the grasped object form a closed kinematic chain. In such a situation, the cooperating manipulators are kinematically and dynamically constrained and the resulting dynamic equations of motion are extremely nonlinear and coupled. In order to control such a system effectively, we linearize and decouple the equations using nonlinear feedback derived from differential geometric control theory. We develop second order kinematics for the contact points which are used to control the relative motion at each contact position. Again, the relative motion can be either rolling or sliding. By controlling the contact motion and the loci of the contact points, we can control the object motion and also maneuver it to a different grasp - possibly to the optimal grasp - without releasing and regrasping.

The verification of the dynamic models, and the testing and evaluation of the control scheme will be achieved through computer simulation as well as experiments. The experiments will be performed on a test-bed of two robotic manipulators (TRACS) which has been developed in the laboratory.

Our ultimate goal is to develop truly autonomous systems capable of exploiting all parts of the robot system (palm, forearm etc.) in manipulation or locomotion tasks. At the end of this project, we will have made significant scientific contributions in the area of dynamic coordination of multiple robots. This research will lead to an improved understanding of manipulation with compliant effectors and will impact research on motor control in biological systems. In addition, the implementation of the control algorithms, and experiments on a multi-robot manipulation system will be of considerable engineering significance.

3.2.6 Two-Handed Grasping

José-Antonio N. Caraza and Xiaoping Yun

The problem of two-handed grasping is studied in this project. Although single-handed grasping has been studied intensively by many researchers, there is barely any work on two-handed grasping in the literature. In this study, grasping an object is considered as a process of five steps: (1) approaching the object, (2) detecting contacts, (3) evaluating the initial contact configuration, (4) determining the appropriate grasping forces, and, (5) applying the grasping forces. While all the steps are being investigated, the current focus is on the third step. The purpose for evaluating the initial contact configuration is to rule out configurations that would lead to unstable grasping. This step is important since certain tasks can not afford the consequence of unstable trial grasping, e.g., lifting an open-ended liquid container.

The hands considered in this study are two-fingered angular-motion grippers with palms. Unlike two-fingered grippers used in single-handed grasping whose fingers normally possess a motion range of less than 15 degrees, the fingers in this study can rotate in a range of more than 90 degrees. This is particularly suitable for grasping large objects by using an open-palm configuration. The hand may have contacts with an object at all or any of the
three locations: at the first finger, the second finger, or the palm. To reduce the complexity of the problem, the contact area on the fingers and palm is a flat surface, and the objects considered are assumed to be rigid. Each surface is instrumented with a tactile sensor capable of measuring normal contact forces.

The initial step of the analysis was to consider grasping of an object by only using two palms. In the research performed, the two palms under consideration were assumed to be respectively installed on two robotic manipulators capable of motion and force control. The analysis developed led to a basic condition which, whenever satisfied, guarantees that the configuration of the two hands at the initial contact with the object allows a stable grasp. For the grasp with two palms, this condition can be defined in terms of the positions and orientations of the two palms, and the friction coefficient between palms and object. Shape, orientation and location of the object, and position of the contact points are not assumed in this condition. Basically, the condition states that each plate must be included in the friction cone of all the points of its opposite plate. A configuration of two palms in contact with the object satisfying this condition is called a proper grasping configuration.

The work was subsequently extended to the study of grasping an object with two two-fingered hands. The hands were assumed to be respectively installed on two robotic manipulators with similar capabilities to those used for the grasp with two palms. A detailed study of the properties of contacts with the two fingers of a hand, and a method to determine if a proper grasping configuration has been reached by the two hands, was also developed under similar considerations as those of grasping with two palms.

The results obtained are readily applicable to grasping lightweight objects. The simplicity of the conditions and the practical assumptions make it feasible to implement these results in real time. The implementation of a grasping strategy for rigid objects will follow the results obtained from the theoretical analysis. The two-fingered angular-motion grippers with palms described previously, will be the hands used for this purpose. The grasping strategy will be especially valuable in tasks such as holding and picking up objects in an unstructured environment, and using only low resolution, simple sensing components.

3.2.7 Simulation of Manufacturing Processes Involving Multiple Frictional Contacts

Yintien Wang and Vijay Kumar

In manufacturing processes such as assembly of mechanical components, gripping, fixturing and part feeding, there are situations in which normally rigid objects are subject to multiple frictional contacts with other objects. It is proposed to use computer simulation as an engineering design tool to evaluate designs of mechanical components and analyze the behavior of such systems. There are two key factors that make this a challenging research problem. Firstly, since the mechanical system is characterized by unilateral, frictional constraints, the topology of the system varies with time. Secondly, frictional laws, such as
Coulomb's law, engender inconsistencies and ambiguities with rigid body mechanics. It is proposed to develop an efficient computer simulation for mechanical systems with changing topologies and unilateral frictional constraints. The approach to simulation involves the integration of rigid body models with contact stress models and nonlocal frictional laws in order to resolve inconsistencies. The simulation will be interfaced with a three-dimensional graphical display on a high-resolution workstation. A planar experimental test-bed will be constructed in order to study cases with inconsistencies and to experimentally validate the results of the simulator. Finally, the integration of the simulation with CAD databases will be investigated. At the completion of the project, a CAD tool which will allow concurrent consideration of the design of the mechanical component as well as the manufacturing process, will be available.

3.2.8 Instrumented Compliant Wrist and Telerobotics

Thomas Lindsay and Richard Paul

A new and improved compliant instrumented wrist has been developed. The wrist is designed to surround the tool being used in order to reduce the distance between the robot and the tool tip. The new wrist also has improved compliance characteristics and has a simplified and more protected sensing mechanism. Current work includes a redesign of the electronic sensing system, and more accurate calibration of the wrist.

The wrist is being used as the main sensor in ongoing research in teleoperation with significant time delays. Recently, the first iteration of the completed system has been tested. Commands generated at the master site are sent to the slave site, with a communication delay. The slave system has been shown to successfully follow these commands and report back to the master when an error occurs. The master then sends new commands, which correct the error.

Current and future work includes studying the boundedness of the time lag between master and slave, studying contact motions to gain insight in moving with unknown friction parameters, and increasing the accuracy of the slave system.

3.2.9 Teleprogramming: Towards Delay-Invariant Remote Manipulation

Janez Funda, Thomas Lindsay, and Richard Paul

Our 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 with untethered submersibles when acoustic communication links are involved. The delay in obtaining position and force feedback from the remote slave arms makes direct teleoperation infeasible.

We are proposing a control methodology, called teleprogramming, which is based on a
A novel combination of computer graphics, virtual reality, and automatic generation of manipulator programs, coupled with a modest degree of remote site autonomy. 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 symbolic instructions. These instructions are at the level of guarded and compliant motions and are generated automatically by the operator’s station software in real time as the task progresses. The slave robot executes these symbolic commands delayed in time and, should an error occur, reports the relevant information back to the operator’s station, where the world model is properly updated to reflect the error state and the operator resumes by teleprogramming the necessary corrective actions.

Experimental results using our Experimental Teleprogramming System have successfully demonstrated the validity of the teleprogramming concept. So far we have been experimenting with an artificially introduced transmission delay of 3 seconds, and have confined ourselves to the simple task domain of kinesthetically exploring the inside of an open box. Tests show that the real-time kinesthetic feedback, generated artificially on the basis of the simulator contact geometry, feels natural and contributes dramatically to the operator’s ability to perform contact tasks quickly and efficiently. The tests have also confirmed that the automatically generated symbolic language provides a sufficiently detailed description of the slave’s activity to ensure stable and robust execution at the remote site. A preliminary implementation of error recovery allows us to recover from execution errors and continue with the task. Research is under way to provide for a more comprehensive error recovery, where the slave workcell would be able to gather detailed information about its error configuration and report this to the ground station. We are also currently investigating the design of an execution protocol at the remote workcell to provide for efficient parsing and scheduling of the incoming instructions so as to ensure non-increasing time lag between the master and the slave manipulators as the task progresses.

3.2.10 Exploratory Procedures for Material Properties: The Temperature Perception

Mario Campos, Ruzena Bajcsy, and Vijay Kumar

Whenever there is a need to physically interact with the external world in an unstructured environment, a robotic system must be able to extract physical, geometric, and substance properties of that environment. We use, and further define, the paradigm of Exploratory Procedures (EP’s). The EP’s are stereotypical motoric procedures executed by humans when exploring an object. In our work we adapt these for use in the robotics domain. Recently, we have been concentrating on one specific case: the EP that returns the temperature property of an unknown object. To accomplish that, a model of a thermal sensor was developed and its validity was experimentally verified with different objects.

According to Katz, the temperature perception in humans is fundamental for material
properties evaluation. He has shown in many of his experiments, that it seems that the thermal conductivity and the specific heat play a major role in the recognition process. We have found out from a mathematical model we built for the sensor, that the material property is related to the product \( kpc \), that is the product of the thermal conductivity, the mass density, and the specific heat. Therefore, when the human finger touches objects at, say, room temperature, heat will flow from the finger (usually at higher temperature) to the object. What is most interesting, is that the “coldness” or “warmness” sensation will depend on that product \( kpc \). From our model, it is also easy to see the reason for what Katz calls the inversion phenomena, that is, if the objects are kept at a higher temperature than the finger, the “coldness” and “warmness” effect will invert for a given object. In other words, an object which at room temperature provided the sensation of being colder, with the inversion, is going to feel warmer. Also, objects kept at the same temperature as the finger, will feel the same. The temperature difference is also important in the perception process.

To test our model, we first built a prototype similar to Russell’s temperature sensor. We observed, however, that enhancements were needed. One of the most important points was the need for a better model, so that upon the measurement of the temperature variation over time, one would be able to determine the thermal characteristics of the object being touched.

We come up with a new approach for the design and modeling of a novel thermal sensor. We are currently in the process of building that temperature sensor, which is based on a Peltier module, which is able to either sink or source heat to the external object. This capability is desirable, since it extends dramatically the operating range of the sensor. Thermistors of very small size are being used as the temperature sensor, with the purpose of reducing the time lag in the measurement. The reference slab is of standard Silicone RTV 732 elastomer. The Silicone is attractive for two main reasons: its inherent flexibility (compliance) and its not so high thermal conductivity. This allows for a more compact design, which will imply a faster sensor. A more detailed exposition of the model and the design can be found in the paper “Exploratory Procedures for Material Properties: The Temperature Perception”.

3.2.11 Robotic Exploration of Surfaces to Recover Material Properties and its Application to Legged Locomotion

Pramath Raj Sinha and Ruzena Bajcsy

This research is an investigation of the necessary components and modules that must be embedded into a robotic system for it to have the exploratory capabilities required to recover material properties from a surface, given minimal a priori information. The measured properties are used to control foot forces that will enable a robot to stand and walk stably in an environment that is unknown and unstructured. To this end, exploratory procedures (ep’s) have been designed and implemented to recover penetrability, material
compliance and surface roughness by exploring the surface using a compliant wrist sensor. A six degree-of-freedom compliant wrist sensor, which combines passive compliance and active sensing, is implemented under a hybrid control scheme to provide the necessary flexibility for force and contact control during the exploration and the simulation of legged locomotion. The leg-ankle-foot system is simulated by a PUMA arm-wrist-foot system which behaves both as a probe as well as a foot for a robotic system. During walking the foot is stabilized against sinking and slipping by incorporating the information that is recovered simultaneously from the terrain about its material properties. An accelerometer on the foot detects slippage and the wrist sensor detects sinking as well as acts as the primary sensor that recovers the material properties during locomotion. Current research is aimed at creating an analytical model to better understand the foot-terrain interaction during legged locomotion, particularly when walking on soils and sands. Using concepts from soil mechanics and solid mechanics, the terrain behavior under the influence of foot forces is being examined. Finite element techniques are being used to simulate the foot-terrain interaction. It is also intended to extend this model to terrains composed of rocks and pebbles.

3.2.12 Mechanical Design Optimization Of Robot Manipulator Performance

Nathan Ulrich

This dissertation presents mechanical design techniques of improving the performance of robot manipulators. Although measures of robot performance for conventional applications—such as payload, dynamic response, accuracy, economy and reliability—are considered, this research is especially concerned with the behavior of robots in unstructured environments. In such a setting, the total system mass, the energy efficiency, and the ability of a manipulator arm to interact positively with its surroundings are also important. Included here are three methods of overcoming performance limitations.

Gravity-induced joint torques can seriously degrade manipulator performance. A method of passive and energy-conservative mechanical gravity compensation is developed which can be applied to a wide range of manipulator geometries, two examples of which are presented. Experimental verification of compensation performance for one- and two-link implementations is reported, which shows the method to be accurate to well within one percent, and to be stable under a wide range of dynamic and static loading conditions. This approach to gravity compensation is also economical and easily applied.

Another method is a means of modifying the transmission characteristics of a robot manipulator to improve the predictability of actuator response. This is accomplished by optimizing the transmitted inertia matrix relating actuator inputs to joint outputs. Included is an application of this technique to a two-joint planar manipulator. Also discussed are methods of regenerating the energy expended in accelerating members to reduce energy consumption.
Finally, a new robot arm design is presented as an example of the use of mechanical design ideas to improve the performance of robot manipulators. The design is a demonstration of the benefits of applying these research results: in comparison to an advanced conventional arm, the new design uses less than a tenth as much energy, has better dynamic and static performance, and has lower mass and inertia.

3.2.13 Design and Control of a 3DOF in–Parallel Actuated Manipulator

Thomas Sugar, George Pfreundschuh and Vijay Kumar

Most present day robots are very rigid and stiff, and consequently, quite unsuitable for operating in unstructured environments in which unexpected collisions and impacts with rigid objects are possible. We have developed an active, pneumatic, compliant end-effector which can absorb energy from unforeseen impacts and can comply to partially known constraints. The end-effector is a three degree of freedom in-parallel, pneumatically actuated manipulator which is designed to function as a wrist for a robot arm or an ankle for a leg of a walking machine. The three degrees of freedom are precisely those that are required to accommodate constraints or for hybrid control - translation along the approach direction and rotation about axes perpendicular to this direction. The manipulator has a payload of 30 pounds and its 5 pound weight gives it a remarkable strength to weight ratio of 6. Pressure and position sensing on each actuator allows force and position control. Experiments with a dynamic spectrum analyzer have demonstrated bandwidths of approximately 10 Hertz. In addition, the system’s response to impacts was found to be desirable. Current work is directed towards the use of high performance, low friction, graphite glass actuators. The high performance actuators will allow better performance and the ability to model a higher order system. A new Dynamic Valve servovalve and an Atchley flow control valve will be used to power the graphite glass actuators.

3.2.14 Singularity Avoidance and The Kinematics Of An Eight-Revolute-Joint Manipulator

Gregory Long

Many general purpose robot manipulators consist of six serially connected actuators whose functional intent is to provide six Cartesian degrees-of-freedom to an end effector. This kinematic mapping of actuator freedoms to Cartesian freedoms is valid only when the six actuator-screws are linearly independent. When the six actuator-screws become linearly dependent, the manipulator has lost full freedom and the end-effector is unable to follow arbitrary Cartesian trajectories with finite actuator speeds.

We begin our study with a geometrically “optimum” six-revolute-joint robot manipulator, which is decoupled into a regional structure and an orientation structure. Since the 6R manipulator is kinematically decoupled, the regional and orientation structures comprise
two separate screw systems, both of third order. When the order of either of these systems falls below three, the 6R manipulator will be at a configuration singularity.

With the three actuator-screws of the orientation structure placed in a configuration singularity, we find the screw which is instantaneously reciprocal to this system. With this reciprocal screw we locate a fourth "redundant" actuator-screw "best" suited for returning freedom to the orientation structure. With the regional structure placed in its configuration singularity, we do likewise by adding to it the actuator-screw "best" suited for returning the lost freedom. Hence, the orientation and regional structures form two separate 4R structures, taken together forming an 8R manipulator.

Conceptually, the algorithms to control both the 4R orientation and 4R regional structures begin in primary mode with three actuator-screws apiece. In primary mode we use the traditional position kinematics approach. Whenever either of the orientation or regional structure has difficulty following its Cartesian trajectory, control for the structure goes into secondary mode, where the redundant actuator is then called upon.

The algorithms maintain a sixth-order screw system for an 8R manipulator with bounded actuator rates and well-behaved actuator values. The numerical computations for an 8R manipulator are comparable to those for the "optimum" 6R manipulator and can be implemented in real-time.

### 3.2.15 The Hughes Systolic Array Co-Processor and its Applicability to Robotics

**Craig Sayers and Richard Paul**

The Hughes systolic array is the result of a joint effort between Hughes Research Laboratories and the University of Pennsylvania. The hardware was developed at Hughes by Ted Carmely, Lap Wai Chow, Charles Martin, J. Greg Nash, K. Wojtek Pryztula and Dale Simpa. Software to operate the system was developed at the University of Pennsylvania GRASP Lab under the supervision of Richard Paul by Miriam Hardboltz (assembler), Janez Funda (simulator) and Craig Sayers (run-time system). Current research is aimed at continuing the investigation into robotic applications for this processor which was begun by Yehong Zhang.

The Hughes co-processor is composed of 256 processing elements configured in a square 16x16 array. Systolic architectures of the type originally proposed by Kung are typically made up of a number of simple processing elements - each of which is dedicated to a simple task. Data is manipulated by feeding it into the array at the array boundaries. The data is then continuously processed as it moves through the array with the results appearing at the output of boundary processing elements on the far side of the array. The Hughes processor differs a little from this definition in that each processing element is a programmable arithmetic logic unit. In effect this makes the processor into a re-configurable
systolic architecture. While this will clearly not be as efficient as a dedicated system it does have the significant advantage of allowing the same hardware to be used for a number of applications.

At present there are several areas in robotics where the computationally-intensive nature of the calculations makes it difficult to perform real-time evaluation. These include "optimal" trajectory planning, obstacle avoidance and the control of redundant manipulators. The application of the array co-processor to these areas will, in some cases, allow existing algorithms to be executed more quickly. However, a more significant advantage is that it may enable the application of simpler, but more computationally demanding, solutions.

A current area of research is the application of the array co-processor to the task of trajectory planning. At present path-planning is typically performed by calculating an "optimal" path off-line and then tracking that path on-line. It is anticipated that the application of the array processor to the path-planning problem will allow for dynamic path planning where the desired trajectory may be continuously re-evaluated as the robot moves.

3.2.16 Redundancy Control of A Robot Manipulator Using A Systolic Array Processor

Yehong Zhang

This thesis provides an approach to the solution of a number of key problems in Robotics, namely planning, force and motion control of a highly redundant manipulator system by means of a special computer architecture.

Robotic control is a computationally intensive task. The real time requirement makes many control formulations impractical. In particular, planning and redundancy control require so much computation that they are performed off-line. Planning algorithms are global in nature and are carried out before motion starts. Redundancy control involves the computation of a pseudoinverse of 6xn matrix which is computationally expensive and thus real time control is very difficult.

In this thesis, the motion and force control of a highly redundant robotic system is studied. A local, time optimal planning algorithm is formulated to provide the robot with a time optimal trajectory. A hybrid motion/force control method for a highly redundant system using joint space partition and compensation is also presented. At the same time, a special purpose Systolic Array Processor is studied and is applications in Robotics are explored. Because of the matrix nature of control formulations, a matrix engine based on the systolic computational structure greatly enhances the computational power of the robot controller making real time planning and control possible.
3.2.17 An Ultrasonic Ranging Array

John Mulhern III, Fil Fuma, and Max Mintz

The research covers the design, assembly, and application of an ultrasonic ranging system. The goal of this project is to evaluate the effectiveness of a small sonar sensor array in an integrated robot sensor system.

The sonar transducer in use is a small (approximately 1 inch diameter) electrostatic transducer which transmits and receives 50 kHz pulses. This transducer has an effective range of approximately 35 feet.

An analysis of array types has shown the triangular shaped array to be the best compromise available in order to achieve the project goals, given the use of this particular electrostatic transducer. Each of the three square transducer housings (the transducers themselves are circular) is placed at a 120 degree interval from the other two transducer housings in order to increase the symmetry of transmission and reception. The transducer assembly will be held in an anechoic mount composed of either plastic or foam. This particular triangular array design also allows separate software controlled firing of individual transducers.

The construction of the ultrasonic ranging array is currently in progress.

3.2.18 RS: Robot Software Package

Sanjay Agrawal and Robert King

We have built a modular Robot Software package (RS) for a Puma560 that provides user support at the control level as well as at the task level. RS is built in a hierarchical fashion, in order to distinguish and decouple the different levels of interaction between the controller, the programmer, and the user. At the controller level, an interface is provided for RCI, which is the MicroVAX interface to the Unimate controller. Other interfaces may be substituted without affecting the other sections of the library. At the programmer level, a variety of real time functions and hooks are provided to allow for dynamic modification of parameters, input from sensors, and adaptive control routines to be programmed. A set of standard kinematic and Jacobian functions are also provided. At the user level, a set of routines can be invoked to perform joint motion or Cartesian motion. To assist the user and programmer, a set of I/O and conversion routines as well as error checking routines have been provided. On VAXs and Suns a simulation mode can be used to test programs, or debug control algorithms. A graphical interface to the IRIS workstation is currently being implemented to provide visual feedback in the simulation mode. Many of the ideas and concepts have been borrowed from RCCL (John Lloyd, McGill University) and MO (Gaylord Holder, University of Pennsylvania).
3.3 Distributed Real-Time Systems Research

3.3.1 TimixV2: A Real-Time Kernel for Distributed Robotics

Robert King and Insup Lee

A new real-time kernel has been developed to support distributed real-time applications. We developed a model for the real-time system to support distributed applications. Using this model, a real-time distributed kernel, TimixV2, was designed and implemented. A distributed robotics control application is being implemented to demonstrate the effectiveness of the kernel. The work described here differs from our earlier version of the Timix real-time kernel in two ways: first, the real-time system model uses threads instead of processes and second, the new kernel has been completely rewritten to reflect the new model.

In the real-time system model, each thread represents a logically independent execution element of control with dynamic timing constraints. A thread can suspend its execution by waiting for an event to be triggered. An event is triggered when a message arrives at a port, when a specified time arrives (alarm), or when a device interrupts. The real-time system model employs a single, application-definable, scheduling algorithm that is applied to each thread in a consistent manner to attain a predictable response to external events. To remove the unpredictability from interrupt overhead often found in real-time systems, all interrupts, except clock interrupts, are converted into events and the interrupt handlers become threads to be scheduled as any other thread. Based on this model, the TimixV2 kernel is implemented on a distributed real-time testbed consisting of DEC MicroVAX IIs connected through an Ethernet and a Proteon token ring.

To evaluate the real-time system model and our kernel implementation, a distributed robotics application is being developed. This application consists of two manipulators coordinating to search a space and lift an object found in that space. The underlying robot support software for TimixV2 consists of two basic levels: the Robot Software (RS) package and the Robot Control Interface (RCI). RS3, software originally designed and implemented by Robert King and Sanjay Agrawal for UNIX, is a derivative of MO (designed by Gaylord Holder). RCI provides a common interface to the PUMA controllers since RCI on TimixV2 and RCI on UNIX use the same communication program.

We are currently finishing the implementation of the distributed robotics application. Once we complete the implementation, we will examine the effects that time granularity, network type and protocol, and the handling of external event using interrupts versus polling has on the system.

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3See description elsewhere in this GRASP News.
3.3.2 Design and Implementation of User Datagram Protocol/Internet Protocol over TimixV2

Hanéne Ben Abdallah and Insup Lee

We designed and implemented the two highest layers of a hierarchical network over TimixV2. This communication software allows TimixV2 applications to communicate with other applications that may be running over TimixV2 or another kernel (e.g., Unix) in a remote host connected to the same network.

This TimixV2 network architecture consists of four layers. A physical layer, the lowest, consisting of a device driver interface (Deqna device driver) for a high-speed local area network (Ethernet.) On the physical layer is built the internet protocol software which provides an address resolution scheme. Higher up comes the user datagram protocol software layer which extends the internet protocol layer by adding a remote interprocess communication mechanism. Finally at the highest level, comes the application layer as a user interface.

Using TimixV2 approaches and features, we implemented the user datagram protocol and internet protocol software following the protocol definitions outlined in the [RFC 768] and [RFC 791]. Also to facilitate the user interface with this layered network, we implemented library primitives for the application layer.

Each of the two layers consists of two transmitting threads for which synchronous TimixV2 reception ports are reserved. Dealing with foreign messages (i.e., messages exchanged between an application running over TimixV2 and another one running over a different kernel) is done at the UDP protocol layer. Also in this layer, a UDP port database used to distinguish between multiple applications within a single host is managed by a UDP port server thread. This thread accepts requests from TimixV2 applications to reserve, associate, or delete UDP ports.

All the transmitting threads are currently running as non-real-time threads. Future research issues include the support of scheduling propagation. That is, scheduling parameters carried by messages arriving at the reception ports will be used to schedule the execution of these threads so that they meet the "urgency" of the messages. Including the scheduling propagation feature in all the transmitting threads of this communication software could be an attempt to make remote communication using this network architecture meet application-specified timing constraints.

3.3.3 Language Support For Real-Time Concurrency

Victor Wolfe, Insup Lee, and Susan Davidson

Victor Wolfe, Insup Lee, and Susan Davidson have developed programming language constructs for distributed real-time programming. The programming paradigm combines an object-based paradigm for the specification of shared resources, a distributed transaction-
based paradigm for the specification of application tasks, explicit timing constraint expression, and specification of recovery from timing and concurrency violations. A program consists of resources and processes. Resources provide abstract views of shared system entities, such as devices and data structures. Each resource has a state and defines a set of actions that can be invoked by processes to examine or change its state. A resource also specifies scheduling constraints on the execution of its actions that preserve its state’s consistency. Processes access resources using action invocations, and express timing constraints as well as concurrency constraints: exclusive execution, simultaneous execution, atomic execution, and predictable execution. The run-time support of the language constructs uses real-time scheduling and locking for concurrency control.

We have embedded the constructs in the C language and implemented the resulting language on the TimixV2 real-time kernel. The language has been used to create a program that executes on three distributed MicroVax II TimixV2 processors to drive a computer graphics simulation on an IRIS workstation. The control program coordinates two graphic models of Puma 560 robot arms, which are shared resources in our application, to pick up a moving object under timing constraints.

We are currently improving error checking and fault-tolerance capabilities in the language. Once completed, we will evaluate exact timing properties.
4 Software and Hardware Developments

Helen Anderson, John Bradley, and Filip Fuma

XV, a program for display of images using X windows:
XV, written at the GRASP Lab by John Bradley, allows the display of color images on X devices with parameters which are not known in advance. In general, X displays do not have enough bit planes to display 24 bit color images. Though X is intended to be device independent, this feature may not be preserved when images are displayed on different devices. This program automatically selects a color map which solves this problem. A new color selection algorithm used in XV balances both the diversity of colors selected and the number of pixels with the correct color value. This preserves both color details and overall color balance. Also, this program builds on existing techniques, such as the Floyd-Steinberg dithering algorithm for the display of grayscale images on one bit plane displays. In addition, this algorithm allows the user to perform several tasks under mouse control. These tasks include change the contrast and brightness of the image by creating a new color mapping, application of the color mapping that to the image and saving the result, cropping, enlargement, and others. This program can run on X based workstations directly, or on X terminals. XV uses either PM or GIF image formats. XV is already in national distribution and is being used by X terminal manufacturers and in hundreds of educational and industrial locations.

Picture Manipulation libraries for image processing:
A new PM manual, including more introductory information, has been released. On an experimental basis, these libraries have been extended to use the Connection Machine. The software format is slightly different, since the efficiency of using the CM would be defeated if the images were read in and out each time, as they are in Unix pipes. Programs available include cm_read, cm_write, cm_conv (convolve), cm_hist (histogram), cm_bthresh (binary threshold) and many more.

Mathematica™, a mathematical computation package:
This purchased package includes graphical, numerical and symbolic capabilities. It includes a full programming environment and programming language, supporting object-oriented, rule-based and iterative/procedural programming. Graphics can be rendered in PostScript for printing. This package is available on tuna.

ABAQUS™, a FEM package:
This purchased package includes numerical and graphical capabilities for finite element (FEM) analysis. This package is also available on tuna.

A Sun SparcStation 1 (halibut), a Sun SparcStation 1+ (tuna), a Personal Iris (grumpy), a Sun 3/160 (flounder) two Tektronics X terminals, a Macintosh II, two Sony XC-77 cameras and two Sony XC-77RR miniature cameras have recently been added to the GRASP Lab hardware.
Perception Laboratory
The General Robotics and Active Sensory

Figure 1: Grasp Laboratory Systems Layout
## 5 Contributors

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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


49. N. Ulrich and V. Kumar, "Design Methods of Improving Robot Manipulator Performance," submitted to the ASME Journal of Mechanical Design.


7 GRASP Lab Technical Reports

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5. Kevin Atteson. Descriptive Complexity Approaches To Inductive Inference. MS-CIS-91-08. GRASP LAB 253.


8. Ruzena Bajcsy. Image Understanding at the GRASP Laboratory MS-CIS-90-52. GRASP LAB 225.


