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GRASP News, Volume 6, Number 1

Abstract

A report of the General Robotics and Active Sensory Perception (GRASP) Laboratory, edited by Gregory Long and Alok Gupta.

Comments

University of Pennsylvania Department of Computer and Information Science Technical Report No. MS-CIS-90-15.

GRASP NEWS
Volume 6 / Number 1

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GRASP LAB 207

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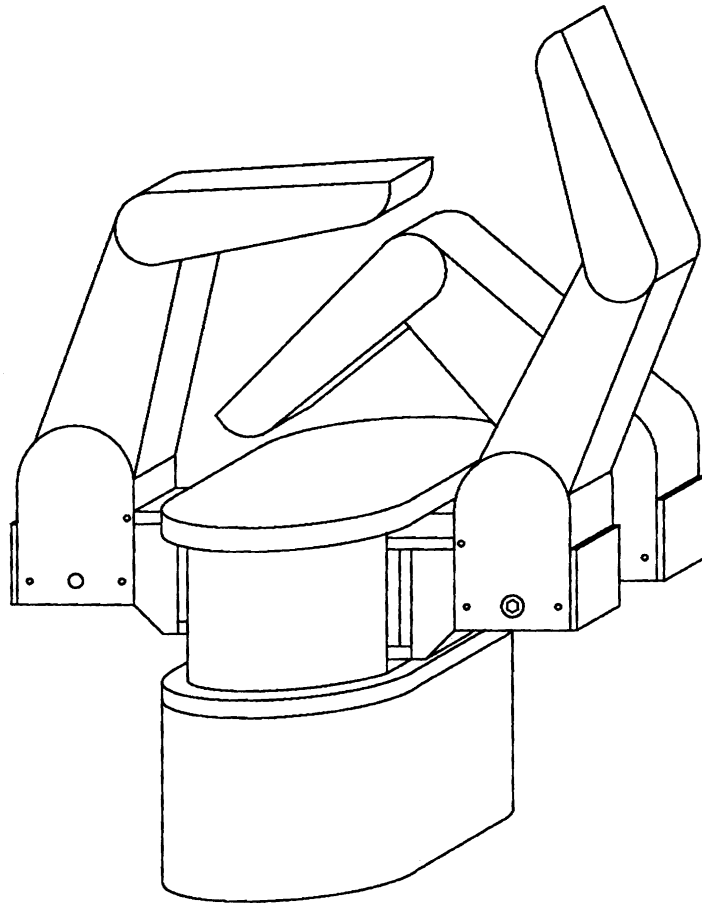
March 1990



GRASP News

Volume 6, Number 1

Fall 1989



UNIVERSITY OF PENNSYLVANIA

*GraspNews*¹ is published twice a year by the Department of Computer and Information Science, University of Pennsylvania, Philadelphia, Pennsylvania 19104-6389. This edition of the *GraspNews* was edited by Gregory Long and Alok Gupta.

Shown on the cover is an isometric drawing of Version Two of the Penn Hand, at approximately one-half scale. The Penn Hand is a medium-complexity end-effector designed for research in active sensing, grasping, and manipulation. Cover layout was designed by Nathan Ulrich using Macintosh software.

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1 Forum

Editors' Foreword

The Volume 6, Number 1 edition of the *GraspNews* marks the revival of a longstanding tradition. Since its beginning in 1983, the *GraspNews* has chronicled the research efforts of the Grasp Laboratory. This edition, which covers developments for the year 1989, follows the format of previous editions. The Feature Article, which highlights the research of Raymond McKendall, Gerda Kamberova, and Professor Max Mintz, is entitled *Robust Fusion of Location Data: A Decision-Theoretic Approach*. The research abstracts summarize the progress of students, postdoctoral fellows, visiting professors, and faculty. The *Vision Research* sections cover topics specifically related to vision, while the *Robotics Research* sections cover subjects such as the kinematics and dynamics of mechanical systems and real-time processing. There is also a section on laboratory *Software and Hardware Developments*. This edition comprises over 33 articles from 48 contributors, which makes it the largest *GraspNews* ever! We hope you enjoy this edition.

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Director's Note

One major objective of our research is to extract and recover physical/substance and geometric properties of the environment with minimal a priori knowledge or assumptions. The rationale behind this strategy is to investigate how far one can go in a bottom-up approach. Practical applications of this situation are when a robotic system explores unknown regions in outer space, underwater, and in general in unknown or unstructured environs. This approach is important even if one knows a great deal about the environment because it allows for variations due to illumination, camera position, sensor errors, and variability in the geometry of objects.

Thus we are systematically developing a theory of Machine Perception, the Components of the which are: 1) the primitives, their choice (uniqueness and completeness) and the ease in extracting them from the data (computability); 2) the Exploratory Procedures that perform the exploration, sensory data reduction, and control strategies; and 3) models of sensors and manipulators, of the operating environment and a representation of the task.

While the models of the sensors and manipulators determine the resolution and the accuracy of the information we extract of the properties of the environment, the model of the task will determine how much information we need to extract. So the models of the sensors and manipulators give the upper boundary, while the model of the task determines the lower boundary of the desired extracted information.

The choice of primitives is the representational issue in Machine Perception. There are several approaches to this problem, though, we feel the primitives should be as close to the physical entity as possible. While we recognize that any sensory measurement is not reality but only a partial reflection of it, we believe that if we have a proper model of the sensor, we can apply an inverse transform and recover the physical reality modulo the resolution, accuracy, and other limitations of the sensor.

There is some concrete work that supports this premise, like two dimensional image segmentation using color and multiscale spatial resolution, as also three dimensional image segmentation and representation. We believe that vision as one modality is insufficient to perceive all the physical properties of the world, since in addition we would require measures of force, temperature, and kinematics to get the complete picture.

Ultimately, we hope to learn the best representation for a given world. We believe that the robotic system should be able to derive such a representation by learning from its environment, just as children do in their early infancies.

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2 Feature Article

Robust Fusion of Location Data: A Decision-Theoretic Approach

Researchers: Raymond McKendall,² Gerda Kamberova, Max Mintz³

This research studies robust fusion of location data. *Location data* are sensors' measurements of the position of an object. *Fusion* is the combination of location data from different sensors. *Robust fusion* accounts for uncertainty in the description of the underlying system. The goals of this research are to model sensor fusion as a statistical problem, to analyze the model with statistical decision theory, and to develop mathematical statistics for the analysis.

Sensor-Fusion Problem

The location-data paradigm consists of a measurement Z of a parameter θ containing statistical uncertainty, noise due to the environment or to the sensor itself. A location model of a measurement assumes that the parameter governs only the location of the noise but not its shape; the model assumes that the shape of the noise is independent of the parameter — such noise is called additive. For example, a measurement Z of a parameter θ may be modeled as a Gaussian or normally distributed random variable with mean θ : $Z \sim \mathcal{N}(\theta, \sigma^2)$. Then the shape of the noise is $\mathcal{N}(0, \sigma^2)$ regardless of the location θ of the mean.

The sensor-fusion problem has multiple measurements Z_1, \dots, Z_n of the location θ in additive noise. These measurements originate from different sensors. The fusion problem is to combine these data into a single value for the location θ . This problem subsumes two additional problems, estimation and consistency. The estimation problem determines an estimate of θ from a single observation, and the consistency problem determines if the data Z_1, \dots, Z_n are measurements of the same location.

• **Example** Figure 1 (p. 4) illustrates a sensor-fusion problem with three sensors. The sensors S_1 , S_2 , and S_3 may be different kinds of sensors. For example, S_1 may be a laser sensor, S_2 may be a sonar sensor, and S_3 may be a camera. The output of each sensor S_i is a measurement Z_i of the distance θ of the object T from the horizontal axis. The dashed box around each sensor represents the noise associated with the sensor's measurement. For example, there may be uncertainty in the exact position of each sensor. The box around the object T represents the prior information about the location of the object. For example,

² Author

³ Principal investigator

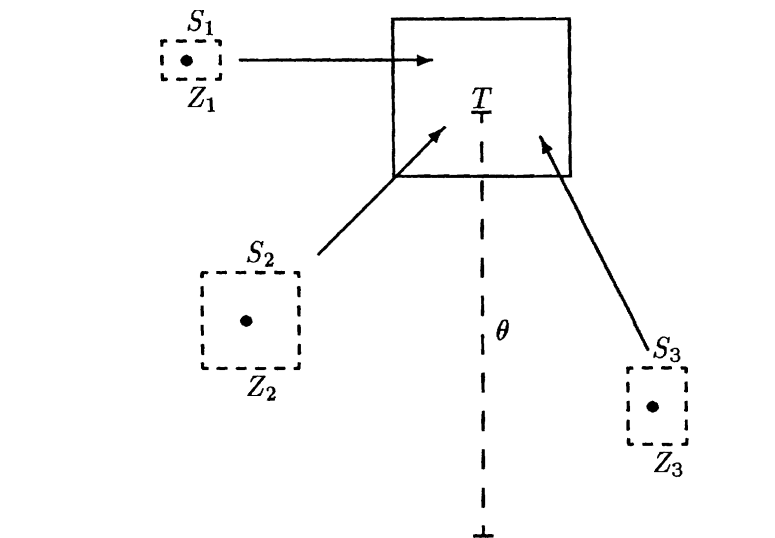


Figure 1: Sensor-fusion paradigm

the object may lie on a table with known position. The fusion problem is to combine the three measurements Z_1 , Z_2 , and Z_3 of the distance θ into a single estimate. Fusion of data requires that the data are consistent: The consistency problem is to verify that Z_1 , Z_2 , and Z_3 are in fact measurements of the same parameter. The test for consistency, in turn, requires the estimate of θ from the individual measurement Z_i , $i = 1, 2, 3$. The estimation problem is to find this estimate. \square

Statistical Problem

The underlying statistical model has multiple measurements Z_i consisting of a location parameter θ_i in additive noise V_i :

$$Z_i = \theta_i + V_i, \quad i = 1, \dots, n$$

The random variable V_i is the statistical uncertainty in the measurement Z_i . The scalar θ_i is a location parameter for the distribution function F_{Z_i} of Z_i : For all $\theta_i \in \Theta$,

$$F_{Z_i}(z|\theta_i) = F_{V_i}(z - \theta_i), \quad \forall z.$$

The set Θ represents the prior information about the location parameter. The principal problem is to estimate the location parameter θ_i of an observation Z_i . The estimator is used to construct a test of hypothesis that $\theta_i = \theta_j$: The data are consistent if $\theta_i = \theta_j$ within statistical uncertainty for all i and j . Consistent data are combined by transforming the observations to a single statistic and estimating the common location from this statistic.

The canonical research problem motivated by this paradigm is to estimate the location parameter $\theta \in \Theta$ of a single observation Z in the model

$$Z = \theta + V.$$

There are two versions of this problem, standard estimation and robust estimation. In a *standard-estimation* problem, the distribution function F_V of the additive noise V is known. An example is to estimate the mean θ of $Z \sim \mathcal{N}(\theta, 1)$; in this case $F_V \sim \mathcal{N}(0, 1)$. In a *robust-estimation* problem, the distribution F_V is uncertain: It is an unknown member of a given class \mathcal{F} of distribution functions, an uncertainty class. An example is to estimate the mean θ of $Z \sim \mathcal{N}(\theta, \sigma^2)$ when $\sigma \in (0, 1)$ is unknown; in this case $F_V \in \mathcal{F}$ where \mathcal{F} is the set of $\mathcal{N}(0, \sigma^2)$ distribution functions with $\sigma \in (0, 1)$. Robust estimation accounts for inexact characterizations of the noise. Many problems in robust estimation reduce to problems in standard estimation.

This formulation of the sensor-fusion permits flexibility in modeling the noise. For example, the distribution of the noise may be asymmetric, multi-modal, or uncertain. In particular, there is no restriction to Gaussian noise. Also, the model allows measurements from sensors with different noise distributions.

Uncertainty Classes

Uncertainty classes model a variety of problems in which the noise distribution is not exactly known. Examples are uncertainty in origin, uncertainty in scale, and ϵ -contamination.

- **Example** A model for uncertainty in the origin of a sensor is

$$Z = \theta + V' + \eta, \quad \eta \in [\eta_1, \eta_2].$$

Here, the distribution $F_{V'}$ of V' is known, but the shift in origin η is unknown. With $V := V' + \eta$, this problem becomes a robust-estimation problem with

$$F_V \in \{F : F(x) = F_{V'}(x - \eta), \eta_1 \leq \eta \leq \eta_2\}.$$

(See figure 2, p. 6.) This set extends to an uncertainty class \mathcal{F} with

$$\mathcal{F} \subseteq \{F : F_{V'}(x - \eta_2) \leq F(x) \leq F_{V'}(x - \eta_1), \eta_1 \leq \eta \leq \eta_2\}.$$

- **Example** A model for uncertainty in the scale of a sensor's precision is

$$Z = \theta + \sigma V' \quad \sigma \in (0, \sigma_m].$$

Here, too, the distribution $F_{V'}$ of V' is known, but the scale σ is unknown. With $V := \sigma V'$, this problem becomes a robust-estimation problem with

$$F_V \in \{F : F(x) = F_{V'}(x/\sigma), 0 < \sigma \leq \sigma_m\}.$$

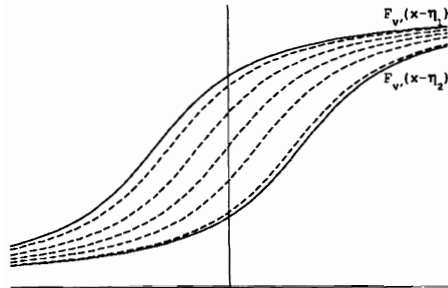


Figure 2: An uncertainty class for origin

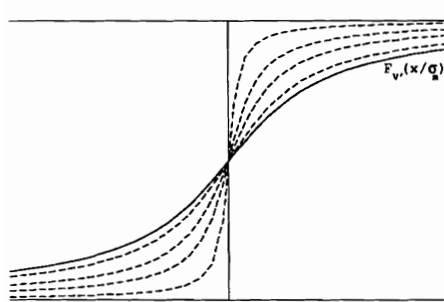


Figure 3: An uncertainty class for scale

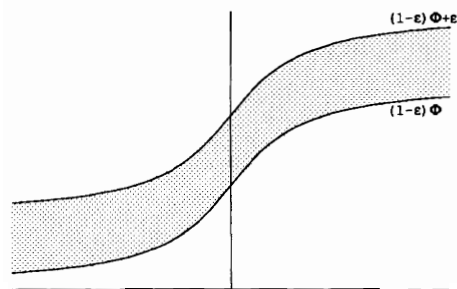


Figure 4: An uncertainty class for ϵ -contamination

(See figure 3, p. 6.) This set extends to an uncertainty class \mathcal{F} with

$$\mathcal{F} \subseteq \{F : F(x^-) \leq F_{V'}(x/\sigma) \text{ for } x < 0 \text{ and } F(x^-) \geq F_{V'}(x/\sigma) \text{ for } x \geq 0\}.$$

• **Example** The distribution function of ϵ -contaminated noise V is

$$F_V = (1 - \epsilon)\Phi + \epsilon\Psi,$$

where Φ is a known distribution function, Ψ is an unknown distribution function, and $\epsilon \in (0, 1)$ is known: With probability $1 - \epsilon$ the distribution of V is the known distribution Φ , but with probability ϵ the distribution of V is contaminated by an unknown distribution Ψ and is thus uncertain. The corresponding uncertainty class for F_V is

$$\mathcal{F} = \{F : (1 - \epsilon)\Phi(x) \leq F(x) \leq (1 - \epsilon)\Phi(x) + \epsilon\}$$

(See figure 4, p. 6.)□

Decision-Theoretic Problem

The tool for the analysis of the location-estimation problem is statistical decision theory. A decision problem is a quadruple $(\Omega, \mathcal{A}, L, Z)$ consisting of a parameter space Ω , an action space \mathcal{A} , a loss function L , and an observable Z . The *parameter space* is the set of possible values for the unknown statistical parameters. For standard estimation, the parameter space is $\Omega := \Theta$. For robust estimation, the parameter space is $\Omega := \Theta \times \mathcal{F}$. The *action space* is the set of available decisions. The action space of an estimation problem is $\mathcal{A} := \Theta$; an action $a \in \mathcal{A}$ is an estimate of θ . The *loss function* is a scalar function on $\Omega \times \mathcal{A}$. The loss $L(\omega, a)$ for $\omega \in \Omega$ is the cost of the estimate a of θ . This research uses the *zero-one* (ϵ) *loss function*, L_ϵ :

$$L_\epsilon(\omega, a) := \begin{cases} 0 & \text{if } |\theta - a| \leq \epsilon \\ 1 & \text{if } |\theta - a| > \epsilon \end{cases}$$

The *observable* is a random variable whose distribution depends on the unknown parameters and thus contains information about them. For the location-estimation problem, the observable is $Z = \theta + V$.

The goal of a decision problem is to gain information about the unknown parameters from the observable. The objective is to find a decision rule δ that maps the sample space of the observable Z to the action space \mathcal{A} ; a decision rule $\delta(Z)$ in an estimation problem is an estimator of θ . The decision rule is chosen according to an optimality criterion. This research constructs minimax decision rules: Under zero-one loss, an estimator $\delta^*(Z)$ of the location parameter θ is minimax if

$$\sup_{\omega} P_{\omega}\{|\delta^*(Z) - \theta| > \epsilon\} = \inf_{\delta} \sup_{\omega} P_{\omega}\{|\delta(Z) - \theta| > \epsilon\}.$$

Thus, a minimax estimator based on zero-one (e) loss minimizes the maximum probability that the absolute error of estimation is greater than e .

This decision-theoretic formulation of the location problem has several features. First, standard estimation and robust estimation coincide within the framework of statistical decision theory. The only difference is the specification of the parameter space: $\Omega = \Theta$ or $\Omega = \Theta \times \mathcal{F}$. The tools of statistical decision theory, however, apply to either specification. Second, decision theory incorporates the prior information about the location parameter through the minimax criterion by optimizing over $\theta \in \Theta$. Third, a decision problem accounts for the consequences of the estimate through the loss function. With zero-one loss, in particular, an estimate within e of θ is sufficiently close and so incurs no penalty, and an estimate greater than e from θ is too far and thus incurs full penalty. Also, there is no difference between under-estimation or over-estimation of the parameter, and the loss is independent of F_V . Finally, a minimax estimator $\delta^*(Z)$ based on zero-one (e) loss induces an optimal fixed-size ($2e$) confidence procedure that maximizes the confidence coefficient among all fixed-size ($2e$) confidence procedures. The confidence procedure induced by an estimator δ of θ is

$$C_\delta(Z) := [\delta(Z) - e, \delta(Z) + e].$$

The confidence coefficient of $C_\delta(Z)$ is

$$\inf_{\omega} P_{\omega}\{C_\delta(Z) \ni \theta\},$$

where $P_{\omega}\{C_\delta(Z) \ni \theta\}$ is the probability under ω that the confidence interval covers θ . If δ^* is a minimax rule, then

$$\inf_{\omega} P_{\omega}\{C_{\delta^*}(Z) \ni \theta\} = \sup_{\delta} \inf_{\omega} P_{\omega}\{C_{\delta}(Z) \ni \theta\}.$$

This confidence procedure is the foundation for the test of hypothesis that two measurements Z_1 and Z_2 are consistent.

Research Problems

The current emphasis of this research is the third goal — to develop mathematical statistics suggested by the sensor-fusion paradigm. The research problems are decision problems in which Θ is a finite interval $[-d, d]$ or its discrete analog $\{0, \pm u, \dots, \pm Nu\}$. In standard-estimation problems, the minimal assumptions on the noise are that V has a continuous, increasing distribution function and a continuous, positive density function. The uncertainty classes \mathcal{F} in robust-estimation problems are uncertainty classes for origin, scale, or ϵ -contamination. Different assumptions about the parameters e , d or N , and F_V or \mathcal{F} define the specific research problems studied. The next section summarizes this research.

Future work will pursue the other goals of this research — to model sensor fusion as a statistical problem and to analyze the model with statistical decision theory. The linear location-data model $Z = \theta + V$ will be extended to the non-linear model $Z = h(\theta) + V$, where

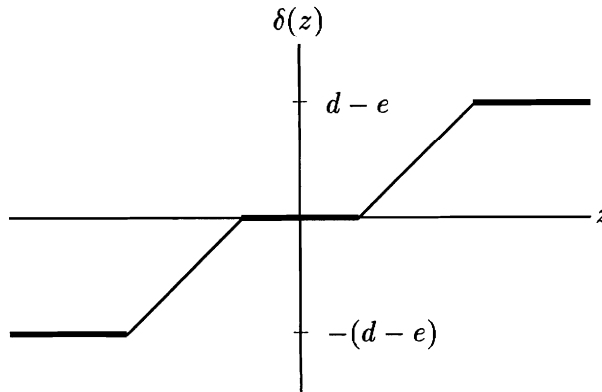


Figure 5: A minimax rule of [ZM84]

the function h on Θ may be uncertain. Possible transforms are truncation and saturation functions. Models with the general structure $Z = h(\theta, V)$ will be studied, too. Development and testing of these models for specific sensors will include acquisition and analysis of data. Also, future work will analyze decision problems motivated by these investigations.

Summary of Results

This section summarizes results of research in decision problems relevant to the sensor-fusion paradigm. It is a synopsis of [ZM84], [ZM88], [MM87], [KM89], and [McK90].

The standard-estimation problem of [ZM84] has parameter space $[-d, d]$. The noise distribution has a unimodal, symmetric density function and a monotone likelihood ratio.⁴ The minimax rule δ is an odd, continuous, non-decreasing, piecewise-linear function. Its linear elements alternate between segments of unit slope and segments of zero slope. (See figure 5, p. 9.) The changes occur at points determined by the solution of a nonlinear system of equations in the noise distribution F_V . Without the assumption that F_V has a monotone likelihood ratio, the decision rule δ is at least minimax within the class of odd, non-decreasing, non-randomized decision rules.

In [ZM88], the standard-estimation problem of [ZM84] is extended to robust estimation. The uncertainty class is a generalized uncertainty class for scale,

$$\mathcal{F} \subseteq \{F : F(x^-) \leq \Phi(x) \text{ for } x < 0 \text{ and } F(x) \geq \Phi(x) \text{ for } x \geq 0\},$$

where Φ has a symmetric, unimodal density with a monotone likelihood ratio. If e exceeds a bound e^* depending on d/e and Φ , then the decision rule δ of [ZM84] with $F_V = \Phi$ is minimax. Without the assumption that Φ has a monotone likelihood ratio, the rule δ is at least minimax within the class of odd, non-decreasing, non-randomized decision rules.

⁴A random variable Z with a density function $f_Z(\cdot|\theta)$, for $\theta \in \Theta$, has a *monotone likelihood ratio* if the ratio $f_Z(\cdot|\theta_1)/f_Z(\cdot|\theta_2)$ is non-decreasing for all $\theta_1 > \theta_2$.

In [MM87], the robust-estimation problem of [ZM88] with $e < e^*$ is studied through a specific example in which $d/e = 3$ and Φ is the standard normal distribution, $\mathcal{N}(0, 1)$. The uncertainty class is

$$\mathcal{F} := \{F : F \sim \mathcal{N}(0, \sigma_1^2) \text{ or } F \sim \mathcal{N}(0, \sigma_2^2), \sigma_1 < \sigma_2\}.$$

The minimax rule for this problem is a randomized decision rule that places a probability distribution on translations of the minimax rule obtained in [ZM84] with $F_V = \Phi$.

In [KM89], the results of [ZM84] and [ZM88] are extended to include any noise distribution F_V that is continuous and increasing on the set $\{x : 0 < F_V(x) < 1\}$. In particular, the restrictions that F_V have a unimodal and symmetric density function are removed.

The decision problems of [McK90] extend the problems of [ZM84] and [ZM88] to the discrete parameter space $\{0, \pm u, \dots, \pm Nu\}$, where N is a positive integer and u is a positive unit. There are two standard-estimation problems, in which the distribution function F_V is continuous and increasing on \mathfrak{R} and has a continuous density function. In the first F_V has a monotone likelihood ratio. The corresponding minimax rules are non-decreasing step functions whose jumps have magnitude u . (See figure 6, p. 11.) In contrast, the second problem assumes that F_V is the standard Cauchy distribution, which does not have a monotone likelihood ratio. The minimax rules for this problem are also step functions with unit jumps, but they are not monotonic. (See figure 7, p. 11.) In both cases, the steps in the decision rules occur at points determined by the solution of nonlinear systems of equations in the noise distribution F_V . There are also two robust-estimation problems, similar to the problems of [ZM88] and [MM87]. The uncertainty class is the generalized uncertainty class for scale in which Φ has a monotone likelihood ratio. If u exceeds a bound u^* depending on N , e and Φ , then the decision rule δ of the first standard-estimation problem with $F_V = \Phi$ is minimax. The case $u < u^*$ is studied through specific examples in which $N = 1$, $e = 0$, and \mathcal{F} is an uncertainty class for scale. The minimax rules for these examples are step functions with unit jumps, but they are not monotonic. (See figure 8, p. 11.)

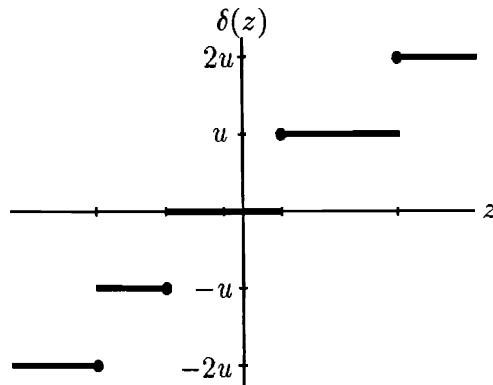


Figure 6: A minimax rule of [McK90] when F_V has a monotone likelihood ratio

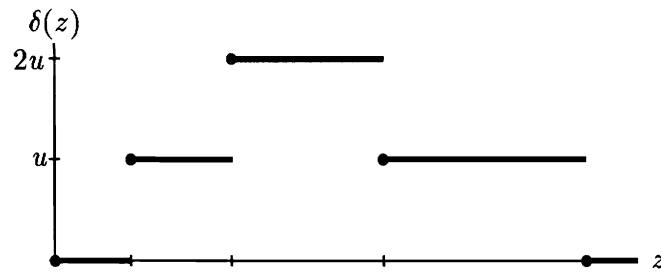


Figure 7: A minimax rule of [McK90] when F_V is standard Cauchy ($z \geq 0$)

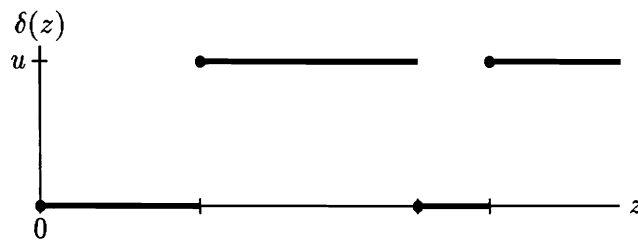


Figure 8: A minimax rule of [McK90] when $u < u^*$ ($z \geq 0$)

References

- [KM89] G. Kamberova and M. Mintz. Decision theory for robust multi-sensor fusion. 1989. Research notes, GRASP Lab, Department of Computer and Information Science, University of Pennsylvania.
- [McKa] R. McKendall. Robust fusion of location information: a decision-theoretic approach. Presented to *Workshop on Robust Estimation Techniques for Computer Vision*, University of Maryland, College Park, MD. July 1989.
- [McKb] R. McKendall. Statistical decision theory for sensor integration. Presented to *ARO Short Course on Multisensory Integration*, TACOM (Tank-Automotive Command), Warren, MI. November 1988.
- [McK90] R. McKendall. *Minimax Estimation of a Discrete Location Parameter for a Continuous Distribution*. PhD thesis, Department of Systems Engineering, University of Pennsylvania, (expected) May 1990.
- [MM87] K.E. Martin and M. Mintz. Research on randomized robust confidence procedures. December 1987. Research notes, Department of Systems Engineering, University of Pennsylvania.
- [MM88] R. McKendall and M. Mintz. Robust fusion of location information. In *Proceedings of the 1988 IEEE International Conference on Robotics and Automation*, pages 1239–1255, November 1988.
- [ZM84] M. Zeytinoglu and M. Mintz. Optimal fixed sized confidence procedures for a restricted parameter space. *The Annals of Statistics*, 12(3):945–957, September 1984.
- [ZM88] M. Zeytinoglu and M. Mintz. Robust optimal fixed sized confidence procedures for a restricted parameter space. *The Annals of Statistics*, 16(3):1241–1253, September 1988.

3 Current Research

3.1 Vision Research

3.1.1 Color Image Segmentation and Color Constancy

Ruzena Bajcsy, Sang Wook Lee, Aleš Leonardis

We present an approach to the construction of computational model for color image segmentation based on the physical properties of sensors, illumination lights and surface reflectances. We used the dichromatic model for dielectric materials and develop a metric space of intensity, hue and saturation in order to better interpret light-surface interactions. Using the established model, experimental studies on color image segmentation with detection of small inter-reflections between different objects and highlights were performed. While the spectral distribution of surface reflectance is not changed by shading and shadows, it is affected by highlights, as well as inter-reflections.

Color constancy is the process of discounting spectrally colored illuminations from perceived color images to obtain correct surface reflectances. We have examined many color constancy algorithms based on finite-dimensional linear models of surface reflectance and illumination from a computational point of view. Within finite-dimensional models, formulation and solution of color constancy are determined by: the choice of basis functions, the number of spectral receptors and the spatial constraints.

We have analyzed the computational limitations of color constancy algorithms for applications on real images are analyzed, and are investigating the extensive use of spatial and spectral information for color constancy.

3.1.2 Wavelet Decomposition for Active Vision

Helen Anderson, Ruzena Bajcsy, Howard Choset

A wavelet decomposition for multiscale edge detection is used to separate border edges from texture in an image, toward the goal of a complete segmentation by Active Perception for robotic exploration of a scene. The physical limitations of the image acquisition system and the robotic system provide the limitations on the range of scales which we consider. We link edges through scale space, using the characteristics of these wavelets for guidance. The linked zero crossings are used to identify and remove texture and preserve borders, then the scene can be reconstructed without texture.

Multiresolution representations are very effective for analyzing the information in images. The wavelet representation uses an operator which approximates a signal at a finite resolution. The difference in information between the approximation of a signal at the resolutions 2^{j+1} and 2^j can be extracted by decomposing the signal on a wavelet orthonormal

basis of $L^2(\mathbf{R})$, the vector space of measurable, square-integrable one-dimensional functions $f(x)$. A wavelet orthonormal basis is a family of functions $\left[\sqrt{2^j}\psi(2^jx + n)\right]_{(j,n)\in\mathbb{Z}^2}$ which is built by dilating and translating a unique function $\psi(x)$ called a wavelet. This decomposition defines an orthogonal multiresolution representation called a wavelet representation, based on the work of Stephane Mallat in the GRASP Laboratory. It is computed with a pyramidal algorithm of complexity $n \log(n)$.

Wavelet-based algorithms have been used at the GRASP Lab for stereo matching, edge detection, corner detection and image compression/reconstruction. Current work involves implementing texture identification as a parallel process on the Connection Machine.

3.1.3 Multi-resolution Multi-oriented Edge Detection with the use of Wavelet Decomposition

Laurent Peytavin

The wavelets are functions well-localized in spatial domain and in frequency domain [Mallat, 1988]. Thus the wavelet decomposition of a signal or an image provides outputs in which you can still extract spatial features and not only frequency components. In order to detect edges we use first derivative of smoothing functions as wavelets and decompose the images as many times as we've got directions of detection. We are working for the moment on X-direction and Y-direction only. Each step of the decomposition corresponds to a different scale. We use a discrete scale $s = 2^j$ (dyadic wavelet) and a finite number of decomposed images. Instead of scaling the filters at each step we sample the image by 2 (gain in processing time). Then, we extract the extrema, track and link them from the coarsest scale to the finest one (Canny, IEEE PAMI, 1986). we build a symbolic image in which the edge-pixels are not only localized but labeled too, according to the number of appearance in the different scales and according to some others parameters. Without any arbitrary and continuous threshold we can subsequently classify the edges, focus our interest on the behavior of detected edges through scale space and relate it to the physical properties of the real image.

3.1.4 Image Segmentation Using Multiple Sources of Information

Aleš Leonardis, Ruzena Bajcsy

We are working on image segmentation problems using multiple sources of information. Segmentation is defined as an inference of a symbolic description of the world from one or more images. The symbolic description depends on the type of measurements and on the available knowledge. We have limited ourselves to non-contact visual sensing, where we measure energy flux incident on the image plane (irradiance) which is composed of three terms (energy and spectral distribution of the incident light, reflectance properties of the objects and geometry, which is determined by the orientation of the surface with respect to

the viewer and the light source). Besides having the knowledge about the sensors, we assume the knowledge about how the image domain phenomena reflect scene domain phenomena, which leads us to the physically based segmentation. Primitive elements, which balance the trade-off between data reduction and faithfulness to measured data, correspond to meaningful segments in terms of physical properties of the world (surface reflectance, shading, shadow, highlight), rather than in terms of image attributes. So defined image segmentation balance the trade-off between pure signal segmentation and complete knowledge based segmentation. Knowledge about the constituents of the scene can make the segmentation process less dependent on noisy data, thus more robust, but less general. While the number of different scenes is almost non-countable, the number of different physical phenomena in a scene is relatively small. This enable us to build models and try to find their instances in the scene. One of basic principles of our approach is to use as much information as possible. At this initial stage we try to combine three sources of information (multiresolution information - using wavelet decomposition , region fitting and multispectral information (Bajcsy, Lee and Leonardis, 1989)). Color information is combined with multiresolution edge detection in order to get the classification of the discontinuities. Edge information determines the seeds for region fitting. Regions, as primitive elements, are complementary to edges. They provide a compact description of the signal between discontinuities which is not sensitive to partial information. Region fitting has a role of perceptual grouping, since it contains a global information about the scene. Parametric descriptions of the regions enable us to derive parameters which are invariant to translation and rotation. Certain features in the image can only be detected when both, edge detection and region fitting, are used together. All the interpretive processing of the data is bound to the original stimulus in each stage of processing to reduce the probability of data interpretation error. Future work is directed toward exploration how parametric descriptions can be used for solving middle-level vision problems. We would like to add some additional features on static image analysis (for example: texture) and put this segmentation in the framework of active perception, where additional information can be obtained via active camera (observer) in order to resolve the ambiguities that remain after the initial stages of segmentation.

3.1.5 Shape from Highlight

Gerda Kamberova

The object of this research is to explore the shape information which a highlight of a specular surface carries. The goal is to estimate the Gauss curvature at a highlighted point, using just the image of the highlighted region and its change with the change of the viewing position. The assumptions made are: i) regular surfaces; ii) fixed point light source, relatively far; iii) orthogonal projection. The theoretical study for the qualitative classification of the surfaces is done. Under the General Position Assumption the image of the highlighted region from one view is enough to classify the surface locally - planar, parabolic,hyperbolic. If the General Position Assumption is dropped, two pictures from different views are enough to resolve possible ambiguities. If the direction of the light is

known, by looking at the change of the highlight in two image frames, when a motion with known parameters is done, the principal curvatures of cylindrical and spherical surfaces are derived quantitatively. Next step is to test these results. Also, rather than continuing the work on quantitative curvature estimation for any regular surface (which we believe can be done), we focus our research on relaxing some of the assumptions and intergating the highlight information with 'shape from' techniques. Our view is that though the highlight does not carry enough shape information by itself, it can be used to increase the efficiency or to resolve ambiguities especially in 'shape from shading' and 'shape from contour'. This research is done together with professor K. Wohn.

3.1.6 Estimating Structure from Motion

Siuleong lu

The focus of our research is on estimating the 3-D motion and/or structure of objects in space from video camera images. This research may play an important role in building intelligent robot, tracking moving objects and autonomous navigation. Our approach to this problem relies on the temporal information instead of the spatial information. Experimental results show that the estimation performance of this approach is much better than that of the conventional approaches which use two or a few frames but require many features on the object.

Two of the main contributions of the above approach are as follows: We have invented a new filter called 'Finite Lifetime Alternately Triggered Multiple Model Filter' (FLAT MMF) to overcome the problems of model mismatch. Ours is the first work to formulate and solve the estimation of rigid body motion with arbitrary order translation and rotation. Currently, we are working on analyzing the statistical behavior of FLAT MMF and applying it to the real images.

3.1.7 Recovery of 3-D Motion and Structure by Temporal Fusion.

Tarek Sobh, Kwangyoen Wohn

In this work, we discuss the problem of recovering the 3-D motion of camera and the orientation of planar surface. First, we develop an algorithm which iteratively improves the solution given two successive image frames. The algorithm utilizes the image flow velocities in order to recover the required parameters .

The solution space is divided into three subspaces - the translational motion, the rotational motion and the surface slope. The solution of each subspace is updated by using the current solution of the other two subspaces. Each update involves solving a linear system, thereby it requires to solve three linear systems to complete a single iteration. This process continues until the solution converges, or until no significant improvement is made. We

report some experimental results conducted on real images to demonstrate the soundness of this approach. However, the algorithm is shown to be sensitive with respect to input noise as other existing algorithms .

Second, we further improve the solution progressively by using a large number of images. The ordinary differential equations that describe the evolution of motion and structure parameters are used to find an expression for the expected change given the previous values for the parameters. The expected change and the old values are then used to produce an estimate of the values of the current motion and structure parameters. Our algorithm uses a weighted average of the expected parameters at time $t + dt$ and the calculated parameters using the 2-frame iterative algorithm as the solution at time $t + dt$ and continues in the same way till the end of the frame sequence. Thus it keeps track of the past history of parametric evolution .

The robustness of the entire process is demonstrated by the experiment with a moving camera which “flies” over a terrain model. The solution can be further improved by exploiting the temporal coherence of 3-D motion. We can develop the ordinary differential equations which describe the evolution of motion and structure in terms of the current motion/structure and the measurements (the 2-D motion vectors) in the image plane and as an initial step we can assume that the 3-D motion is piecewise uniform in time. The extended Kalman filter can then be used to update the solution of the differential equations .

The recovery method described have a variety of applications. It can be useful in vision - guided applications such as autonomous landing and navigation. It may be a starting point for determining global structure - motion analysis of entire polyhedra, making it suitable for robotics applications in the “moving blocks world.”

3.1.8 Coordination and calibration of television cameras for visual active sensing

Alberto Izaguirre

We are investigating coordination for different camera coordinate systems for Visual Active Sensing. We define active sensing as the process of controlling perception at a given time by using knowledge gained through perception at a previous time.

This coordination permits us to control the motion of a small angle camera as a function of the image seen by a wide angle camera. The wide angle camera can be considered as the guidance that allows the small camera to gain information in a particular part of the image field.

The results in this area are very encouraging. We calibrated both cameras relative to the tip of a PUMA 560 robot, the cameras being attached to the tip. We used an Extended Kalman Filtering technique that has been proven very convenient for the estimation of the parameters related to the transformation. We also experimented with the problems

of orientation of the small angle camera by providing information given by the wide angle camera. The error in orientation are very small (in the order of 1 degree), and correlation between the visual informations provided by both cameras is made in order to validate the motion.

We are investigating at this moment the problem of the correction of the internal parameters of the PUMA 560 by using visual information given by the cameras. A simulation of the system has been made, to test the approach. We are currently performing real experiments in order to validate the method.

Parallel to this research, We are interested in the creation of Object Oriented software for Image Processing. We are currently implementing classes of objects (e.g. Images, Masks for Convolution, Matrices, etc.). Using these classes, we can easily implement algorithms for Image Processing and Robotics. The implementation is still in an early stage, and we are using C++ version 2.0 as well as X11 version 3 of the Xwindows system in order to visualize our implementation.

3.1.9 Segmentation, Modeling and Classification of the Compact Objects in a Pile Using a Single Range Image

Alok Gupta, Gareth Funka-Lea, Kwangyoen Wohn

We have been looking at the problem of interpreting dense range images obtained from the scene of a heap of man-made objects. The postal domain (mail pieces) has served as our test-bed, but our approach is not confined to such a domain only. The system we have developed is model-base and consists of segmentation, modeling, verification, and classification procedures.

First, the range image is segmented into regions and reasoning is done about the physical support of these regions. Second, for each region several possible 3-D interpretations are made based on the partial knowledge. Finally each interpretation is tested against the data for its consistency.

We have chosen the *superquadric* model as our 3-D shape descriptor, plus deformations such as tapering and bending along the major axis. The superquadric model is an analytic representation of volume for which a cross-section is one of a class of curves varying between rectangular to elliptical shaped. Superquadric parameters are recovered by minimizing the least-squares error between the superquadric surface and the range data. The system recovers position, orientation, shape, size and class of the object. Using the goodness of fit and Euclidean distance measures, and the shape and size parameters of the recovered model, objects are classified into one of the following broad categories: flat (letters), box (parcels), roll (circular and elliptical cylinders), and irregular (film mailers etc.).

The overall approach to this problem has been to find the most general yet computationally economical method to interpret the data. Current work has focussed on techniques

to handle cases of one object obstructing the view of another in a pile. Further issues of concern are using multiple range images of the same scene and improving the way we reason about the physical stability of the objects in a pile.

3.1.10 An Integrated Approach for Part Description and Segmentation of Range Images

Alok Gupta, Ruzena Bajcsy

The problem of part definition, description, and decomposition is central to the shape recognition systems. The ultimate goal of segmenting range images into meaningful parts and objects has proved to be very difficult to realize, mainly due to the isolation of the *segmentation* problem from the issue of *representation* [10]. We have proposed a paradigm for part description and segmentation by integration of contour, surface, and volumetric primitives. Unlike previous approaches, we have used geometric properties derived from both boundary-based (surface contours and occluding contours), and primitive-based (quadric patches and superquadric models) representations to *define* and *recover* part-whole relationships, without *a priori* knowledge about the objects or object domain. The object shape is described at three levels of complexity, each contributing to the overall shape. Our approach can be summarized as answering the following question: Given that we have all three different modules for extracting volume, surface and boundary properties, how should they be *invoked*, *evaluated* and *integrated*? Volume and boundary fitting, and surface description are performed in parallel to incorporate the best of the coarse to fine and fine to coarse segmentation strategy. The process involves feedback between the segmentor (the Control Module) and individual shape description modules. The control module *evaluates* the intermediate descriptions and formulates hypotheses about parts. Hypotheses are further tested by the segmentor and the descriptors. The descriptions thus obtained are independent of position, orientation, scale, domain and domain properties, and are based purely on geometric considerations. They are extremely useful for the high level domain dependent symbolic reasoning processes, which need not deal with tremendous amount of data, but only with a rich description of data in terms of primitives recovered at various levels of complexity. Our proposed approach and the preliminary results are presented in Gupta [1989] and Gupta and Bajcsy [1989,1990].

3.1.11 Evaluation of Superquadric Models

Alok Gupta, Luca Bogoni, Ruzena Bajcsy

Superquadrics being part models, it is imperative to have a set of criteria to completely evaluate the models recovered for arbitrary objects in the scene. *Evaluation* is described as studying both quantitatively and qualitatively, the description of the input range data by the given superquadric model. We have identified two quantitative (global numerical

value) and three qualitative (local patches) measures that are useful in both object modeling [Gupta, Lea and Wohn, 1989] as well as object segmentation [Gupta and Bajcsy, 1990]. The motivation for this work comes from the simple fact that while an object in the superquadric vocabulary will result in acceptable global fitting error, the converse is not true in general.

We introduced the concept of superquadric contraction and dilation and used it to derive a novel interpretation of the modified superquadric inside–outside function in terms of contraction/expansion factor. The same concept also gives a close initial guess for the numerical procedure computing the minimum Euclidean distance of a point from a superquadric model. The minimum Euclidean distance map is introduced as a qualitative criterion for interpretation of fit. View-dependent qualitative measures like the contour-difference map and the z-distance map are shown to be essential for the complete evaluation of the models, and at the same time useful for further description and segmentation of the object. A closed-form analytical solution for the contour generator on non-deformed superquadrics was derived. Techniques for the computation of qualitative measures for the deformed models are presented. These measures and the Results for range images of real objects are presented in Gupta, Bogoni and Bajcsy [1989].

3.1.12 Acquiring Scene Information from Multiple Views

Jasna Maver, Ruzena Bajcsy

We are working on the problem of acquiring scene information from multiple views. We use range images which are dense depth maps. These images are obtained by using the range scanner system which contains a laser and a CCD camera, both of which are mounted on a robot arm. We would like to minimize the number of scanning directions, but still maximize the amount of spatial information about the scene under consideration.

The problem of multiple views is determining the spatial layout. This can be decomposed into three sub-problems

- combining multiple scans into one coordinate frame, identifying the transformation between two scanning positions and understanding how errors propagate as a result of uncertainty of the computed point position and uncertainty of the applied transformations;
- developing the strategy for choosing the scanning direction which uncovers the biggest part of the unseen scene, finding out the areas which can not be seen from any direction;
- representing the object in the scene in 3-D space.

3.1.13 Projection Correction for Range Scanners

Howard Wang, Alok Gupta

Howard Wang has been working with the range scanners in the lab in addition to developing an integrated package for the superquadric model recovery procedure. He completed the interface between the Technical Arts White Laser Scanner and the MicroVax-II (index), that allows the host to control all the functions of the scanner. He modified the control program for the Range Imaging System to interactively save a part of the range image from the Data Translation buffer. Most importantly, he discovered and provided algebraic solution to the problem of perspective projection in the range scanners that results in the spatial distortion in range images. He is now working on acquiring a complete range image from the White Scanner and applying the solution to the projection problem to the mobile scanner.

3.1.14 High Level Vision: Study of Object Properties and their Relations to Task's Functionality

Luca Bogoni

In considering object representation and modeling, one must take into account both physical and functional properties. This study is focused on analyzing object representations, in particular relating their physical and functional description to tasks, such as manipulation and classification (using EP). The aim of such pursuit is that of understanding and bridging the gap between data and its symbolic interpretation by incorporating functional description in the object representation. The general philosophy underlying the process is that one needs to recover functional specifications of the object if he is to perform a task. Thus, one would like to consider information about the object, data driven, well as knowledge about the object to be operated upon, symbol/task driven. Furthermore, as partial and insufficient information may have been recovered, it is necessary to define some subtask, E.P., whose primary responsibility is that of either obtain further information or corroborating hypothesis. Thus, one can observe that if the object's functional description is recovered, *inherent* functionality, then for any given task whose functionality applied to the object, *imposed* functionality, matches that of the object will yield optimal, or good, task performance.

3.1.15 Picture Manipulation on Frame Buffers

Helen Anderson, Arup Mukherjee, Gaylord Holder, Dmitry Cherkassky

PMFB is an extension to the PM (Picture Manipulation) library that allows the display of images and the execution of simple geometric drawing operations on a generic frame buffer device, serving to expedite the development of device-independent display software

for image processing applications in the GRASP Laboratory.

An output device corresponding to a given generic framebuffer is specified at run time through the use of an environment variable, which PMFB routines use to map PMFB function calls to device specific calls. Display of bitmap images is supported for grayscale images only, while geometric operations (line drawing, box drawing, etc) support both color and grayscales. PMFB offers its user a way to write code that will produce output on a variety of output devices without requiring any rewriting or recompilation. The supported devices include X11/R3 on Suns, MicroVaxes and HP's, PostScript, Adage (Ikonas) Framebuffer and Data Translation (DT2651) Framebuffer. The X11 server is implemented as an inetd client acting upon a simple, text-oriented protocol that does not suffer from byte-order problems, and works at a reasonable speed between hosts networked together by 1 Mbit ethernet.

3.2 Robotics Research

3.2.1 What Do Distributed Systems Offer Us for Dextrous Manipulation?

Sanjay Agrawal, Ruzena Bajcsy, Vijay Kumar

An important aspect of manipulation is the extraction and use of perceptual information. By using tactile sensors mounted on the fingers of an articulated gripper, we extract information about objects to be manipulated and the environment they lie within. The tactile sensors, in conjunction with the force and position sensors available in the hand, will give us sufficient information to both create a structural model of the object, as well as infer a set of possible motions that could provide us with functional properties about the object. By functional, we refer to properties which tell us about possible uses of the object that cannot solely be derived from the structure, like degrees-of-freedom and moving parts. We use both heuristics and geometric analysis for motion planning. This work is being done in the larger context of a hand/arm coordination system.

3.2.2 Exploratory Procedures for Extraction of Mechanical Properties of Manipulable Objects

Mario Campos, Ruzena Bajcsy, Vijay Kumar

The primary goal of this research is to extract mechanical properties from objects. The fundamental question is: given an unknown object in an unstructured environment, determine the minimum set of properties, and the sequence which they should be determined.

Without a priori knowledge of the object's composition, it is difficult to determine if it can be held, lifted, or even manipulated. Psychologists have observed that subjects, when asked to classify and explore objects according to specific cues or dimensions, would follow

standard manipulatory actions. These manipulatory actions, also known as *Exploratory Procedures*, or EP's, are in fact stereotypical hand movements humans perform when they explore unknown objects. For instance, when subjects were asked to determine the texture of a given object, almost invariably they would proceed in their exploration by rubbing (lateral motion) one or more fingers on the surface of that object. Likewise, if subjects were asked to determine the hardness of an object, they would exert forces perpendicular to the object's surface. It has been observed that subjects would perform some type of hand pre-shaping (hand configuration before the actual grasping occurred) which could be related to the object's volume and shape.

We propose a paradigm for exploratory procedures (EP's) that will enable the system to determine mechanical properties of objects that can be held either by an enveloping grasp, or by holding part of the object.

3.2.3 Modeling and Analysis of Two-hand Grasps

José-Antonio Caraza, Xiaoping Yun

A two-arm robotic system has many advantages over a one-arm robotic system, among them: larger payload and more dextrous manipulation. Although a two-arm robotic system has advantages over a one-arm robotic system, these advantages cannot be exploited until two-hand grasping is fully understood. Our research concerns the development of grasping strategies for two-arm/two-hand robotic systems.

Grasping is an active area in robotics. Current research in this area has focused on the determination of grasp stability given all the parameters (such as weight, size, and shape of the object, contact points between fingers and the object, the coefficient of contact friction, and the model of the hand). However, in most practical applications, all the parameters, except the model of the hand, are either unknown or partially known. In this research, we assume the size of the objects are known within a range, the coefficient of friction is known within a range (or in terms of symbolic values, such as small, medium or large friction), and the exact contact points are unknown — only contact or non-contact of the object with each finger is known. No assumptions are made about the shape of objects.

3.2.4 Exploration of Unknown Mechanical Systems through Manipulation

Weili Chen, Vijay Kumar, Xiaoping Yun

If robots are to function in unstructured environments, they must possess the ability to acquire information and construct appropriate models of the unknown environment. In most cases, we have complete models of the robot(s), controller(s), and sensor(s). However, to implement effective control and planning schemes, appropriate models of the unknown environment must be constructed. Our work deals with the automatic generation of kine-

matic models of unknown objects with movable parts by two handed manipulation. The basic objective is to design an exploratory motion that is sufficiently exciting so that the mobility and the unknown kinematic parameters can be determined through an off-line or on-line estimation. At the same time, the exploration must not damage the robot-object system.

3.2.5 Explorations through Two-arm Manipulation

Wallace Ching, Ruzena Bajcsy, Xiaoping Yun

The coordination of two robot arms in a distributed computing environment is investigated. Control algorithms for two-arm motion primitives, like pulling, pushing, and twisting, are being developed. From these primitives, algorithms will be developed for more sophisticated tasks. A long-range goal is to explore and identify features of an unknown object using combinations of these primitives.

Experiments will be conducted with the two PUMA 560 robots in the Grasp Laboratory. Communication between the two manipulators is achieved through Timix, a real-time operating system developed in the Grasp Laboratory by Robert King and Insup Lee.

3.2.6 Teleoperation in the Presence of Communication Delays

Janez Funda, Nicola Simeon, Richard Paul

This research addresses two key issues in teleoperation: 1) how to provide an operator with realistic kinesthetic feedback despite communication delays between the master and the slave, and 2) the automatic generation of symbolic robot instructions based on an operator's motions. We propose to model the remote slave environment with a graphical simulator/display and compute the kinesthetic feedback parameters with information about the slave's geometric constraints. As the task progresses, the force and positional information provided by the operator is recorded and analyzed on-line. This force and positional information is then used to produce a sequence of parameterized guarded and compliant motion commands sent to the slave. Some high-level knowledge about the task at hand may be necessary to aid the interpretation process.

3.2.7 Force and Motion Control of Redundantly Actuated Robotic Systems with Closed Kinematic Chains

Michael Johnson, Vijay Kumar

Examples of mechanisms in which closed kinematic chains arise include cooperating robot manipulators, walking machines, and multifingered grippers. In all these examples, the linkages can form a closed loop. If the number of available joint torque inputs exceeds the

number of motion degrees of freedom, redundancy exists in the actuation of the mechanism. The objective of this research has been to examine methods of exploiting this redundancy for motion and force control. In this work, the case of multiple robot arms manipulating a common object was specifically addressed. The principle of virtual work and the methods of linear algebra were applied to rigid cooperating manipulators with massless links in order to investigate the singularities which arise and illustrate the duality of the instantaneous kinematics and statics of such mechanisms. The remainder of the research dealt with the case of two rigid two-link planar manipulators with non-zero mass which manipulate a common object with non-zero mass. The derivation of the dynamic equations for this system was done twice, once with a Lagrangian and once with a Newton-Euler approach, so that the Lagrange multipliers could be interpreted in terms of physical forces.

3.2.8 Timix: A Real-Time Kernel for Distributed Applications

Robert King, Insup Lee

Timix is a real-time kernel developed to support distributed applications which require predictable timing behavior. Timix executes on DEC MicroVAX II processors connected by Ethernet and, optionally, ProNET-10 (Proteon token ring). The host machine for system development is a VAXstation II/GPX running Ultrix.

Timix supports processes with independent address spaces that execute, communicate, and handle devices within timing constraints. A preemptive priority-based scheduler schedules processes for execution first according to its type and second according to the process order technique used within that type: *urgent* is first-come-first-serve, *hard real-time* and *soft real-time* are earliest deadline first, and *non real-time* and *background* are both first-come-first-serve. Two basic communication paradigms are provided: *signals* and *asynchronous message passing*. Signals are the most basic way to communicate and are used by various other components of the kernel such as asynchronous messages, alarms, scheduling, devices, and system error reporting. Our asynchronous message passing technique extends the notion of ports for real-time communication by allowing the receiver to control message queuing and reception strategies. New devices can be directly controlled by application processes and can be integrated into the system without changing the kernel.

A set of library routines that mimic the functionality of RCI (Robot Control Interface) have been implemented for Timix. This package requires no modifications to the kernel as was required to implement RCI on UNIX: each process is always resident in memory and the device interface allows new applications to be easily added. The same communication program that runs on the PUMA controller for RCI on UNIX is used for RCI on Timix.

3.2.9 Useful Work and Telerobotics

Tom Lindsay, Richard Paul

Much of robotics deals with assembly tasks, where the environment is rigid and positions are known accurately. In unstructured environments, rigid control schemes are difficult if not impossible. Until there are major advances in artificial intelligence, work in unstructured environments requires human intervention. However, human abilities are limited — machine accuracy cannot be achieved, and complex movements must be broken into subtasks.

Two examples of useful work in unstructured environments are underwater salvage work and the repair of satellites in space. In both of these cases, the advantage of telerobotics is clear: the use of human intelligence without an actual presence.

Development of hardware and software for use in unstructured environments are important areas of research. One topic in hardware development is the design of an impact wrench which is used by a robot manipulator. A topic in software development concerns the creation of a telerobotic language to help operators do useful work. The combination of the impact wrench and the telerobotic language will demonstrate that useful work can be done by a human operator in unstructured environments.

3.2.10 The Kinematic Control of an Eight-revolute-joint Robot Manipulator

Gregory Long, Richard Paul

Current general purpose robot manipulators consist of six-axis serial-chain structures, where the kinematic intent is to map the six axes' freedoms to six Cartesian freedoms. In practice this kinematic mapping breaks down, as there are manipulator configurations where the six axes' freedoms do not map to six Cartesian freedoms — these configurations are *singular*. Singular configurations limit a manipulator's workspace and dexterity. To utilize the full potential of a general purpose six-axis robot manipulator requires the addition of more joints to its structure.

A "geometrically optimum" six-revolute-joint robot manipulator is used as the foundation for a singularity avoiding eight-revolute-joint robot manipulator. An algorithm is given to coordinate the eight-revolute-joint manipulator such that its joint-screws belong to a sixth-order screw system, and its joint velocities are bounded and well-conditioned. The algorithm is a rate controlled method which depends on the required angular velocity of the end-effector, as well as the required linear velocity of the wrist coordinate center. The algorithm can be implemented in real-time.

3.2.11 Coordinated Control of Two Robotic Manipulators

Eric Paljug, Xiaoping Yun

This research is centered around the development of a workcell for the investigation of coordinated control of two robot manipulators. The manipulators will be required to perform tasks such as complicated assembly and identification of an object's characteristics under minimal environmental assumptions. Coordination, compliance (force control), integration of sensory data, and collision avoidance are among the areas to be investigated. A single central processor capable of operating in a critical real-time environment is required, as the control of both manipulators must be calculated at the servo rate. The planned physical implementation includes two Puma 250 manipulators and their associated controllers, an IBM PC-AT host computer, and an AMD 29000 based processor board that is compatible to the PC-AT bus.

3.2.12 Design and Control of a Parallel Actuated Micro-manipulator/Wrist

George Pfreundschuh, Vijay Kumar

A three degree-of-freedom parallel-actuated micromanipulator/wrist is being constructed for use on a PUMA 560; both high-performance force and velocity operations will be explored. The research involves investigating the manipulator's kinematics, designing the micromanipulator, controlling the manipulator's actuators, and lastly investigating the performance of the micro/macro system in an assembly task, such as the peg-in-hole insertion.

The uniqueness of the project lies in the use of pneumatic actuators and parallel actuation. Pneumatic actuation is attractive because of their large power output to weight ratios, their "direct-drive" capability, and their "built-in" compliance. The merits of parallel actuation include high accuracy, high manipulator rigidity, and high manipulation force to actuation force ratios. Thus the merits of parallel actuation and pneumatic actuators complement each other; these features will enable a versatile high-performance micromanipulator to be constructed which will be light enough to allow the system to perform useful operations.

3.2.13 How Does a Robot Know Where to Step? Robotic Exploration of Surfaces

Pramath Raj Sinha, Ruzena Bajcsy, Vijay Kumar

The objective of this research is to design a robotic system that will be able to adapt to and explore an environment that is unknown and unconstrained. We are investigating the necessary components/modules that must be embedded into a robot for it to have ex-

ploratory capabilities. Based on our experiments in the GRASP Lab, we will show what sensors, exploratory procedures, data processing, data reduction, and interpretation capabilities a robot must have to be able to explore surface properties for mobility purposes. The investigation is limited to surfaces composed of materials such as dirt, soil, sand, rocks, pebbles, gravel, and mud. We are designing and implementing exploratory procedures to recover physical properties (like relative hardness, deformability, compressibility, penetrability) given minimal a priori information so that a robot or a vehicle can decide whether to move on this surface. We are using a six degree-of-freedom compliant wrist device mounted on a PUMA 560 arm for our experiments. We plan to mount a model of a foot on to the wrist to implement our application to mobility of robots. At the same time, the model foot will serve as the probe for the implementation of our exploratory procedures and the data from the sensing mechanism will help us evaluate the attributes we are trying to recover.

3.2.14 The Penn Hand

Nathan Ulrich, Richard Paul, Ruzena Bajcsy, Vijay Kumar, Filip Fuma

A three-fingered mechanical hand has been developed for use in the Grasp Laboratory. The Penn Hand has four actuators: one for each finger and a fourth for a movement of the fingers relative to the palm, which gives the hand the ability to change its grasping mode in response to various object shapes and sizes. For example, the hand can grasp objects such as spheres and cylinders in an enveloping-type grasp, as well as being capable of grasping large objects from one side and small objects in its fingertips. Each finger has two joints which are compliantly coupled (allowing adaption to object shape) and driven by one actuator. The simplicity of the hand allows it to be lightweight and completely self-contained (therefore making the hand easy to mount and dismount, requiring no remote actuation or transmission linkages, and maximizing the payload of the robot/hand combination). The control and planning of the hand are also facilitated by its few degrees of freedom and by the ability of the hand to comply to object shape. The first prototype is mechanically complete and control hardware and software is under development.

3.2.15 Language Constructs for Distributed Real-time Computing

Victor Wolfe, Susan Davidson, Insup Lee

Language constructs for distributed real-time computing are being developed. The model consists of resources, processes and a global scheduler. Using this model, language constructs have been developed to specify the functional and timing constraints inherent in the underlying application. The constructs explicitly express information to the run-time system and include timing constraints on resource use, allowable preemptions of resources that maintain functional consistency, sets of actions that must be scheduled simultaneously, sets of actions that must be scheduled exclusively, and sets of actions that must be atomic.

A major focus in 1989 was on the definition and solution of *timed atomic commitment*. In a large class of hard-real-time control applications, such as robot control, components execute concurrently on distributed nodes and must coordinate, under timing constraints, to perform the control task. As such, they perform a type of *atomic commitment*. Traditional atomic commitment differs, however, because there are no timing constraints; agreement is eventual. Therefore, the *timed atomic commitment* (TAC) has been defined which requires the processes to be functionally consistent, but allows the outcome to include an exceptional state, indicating that timing constraints have been violated. Centralized and decentralized protocols have been developed to implement TAC and a high-level language construct which facilitates its use.

These distributed real-time language constructs are being implemented as an extension to the C language executing on the Timix real-time kernel.

3.2.16 Hybrid Position Force Control With an Instrumented Compliant Wrist

Yangsheng Xu, Richard Paul, Xiaoping Yun

Most industrial robots are utilized to perform tasks in which the end-effectors are in contact with the environment. It is becoming increasingly clear that robots require more sophisticated compliant motion. A new compliant motion methodology combining both passive compliance and active control has been developed.

The compliant wrist installed between the end-effector and the robot was developed in the Grasp Laboratory. The wrist consists of a passive compliance element and a sensing mechanism. The passive compliance provides an adaptation for assembly operation and manufacturing process so that the positioning tolerances are relaxed and the high force normally produced in jamming or wedging is reduced. The sensing information is used two ways. In position control, the sensed information is utilized to compensate deflection of the wrist, due to the load or external forces, so as to increase apparent stiffness of the manipulator wrist system. In force control, the wrist sensor is used as a force sensor by which means the manipulator is driven in the same direction as the sensed force and the desired contact force is maintained. Various experiment in force and position control has demonstrated its applicability.

4 Software and Hardware Developments

4.1 Software Developments

John Bradley

XV – a new X program that combines all features of 'xpmload', 'xgif', and 'xpmmono' into one program. In short, XV allows you to view PM pictures and GIF pictures on an X display. XV opens up a window on the X display with your picture in it. If you resize the window, your picture is scaled to fit. You can zoom the picture up to the size of your screen. You can 'crop' unwanted portions of the picture (can't write it back out yet, but that'll be in the next release). You can stretch any portion of the picture up to the full size of your screen.

XV currently works on 1-bit and 8-bit displays, which covers nearly everything in the lab. In future versions, XV will work on all types of displays. On 8-bit color displays (robo, touch, hand, dps1, oldphila, hersheys, wynnewood, and nmos), XV runs a 24-to-8-bit color-compression algorithm (on 24-bit PM images) which does a very nice job of displaying full color images on your workstation. It's pretty quick, too. Any other types of images (GIF, or grayscale PM) display perfectly — particularly if you specify the '-p' option ('man xv' for details).

If you're using XV on an 8-bit grayscale display — the 'alternate' screens on anchovy, bass, and cod, eg, anchovy:0.1 — color pictures will automatically be converted to grayscale before being displayed.

And finally, if you're using XV on a 1-bit monochrome display (cummings, starfish, grope, and the 'primary' screens of anchovy, bass, and cod), XV will do a surprisingly nice job of B/W stippling.

Also of some note: XV will automatically uncompress compressed PM files. This way, you can view PM pictures you haven't looked at in a while without going to the trouble of uncompressing them first.

GIF2PM – also of some note is this program, which, as the name suggests, converts GIF pictures to PM. There is a large collection of publicly-accessible GIF pictures in /pic/gif on grip. While you can view these pictures as-is, using XV, you may want to do some further processing on them. GIF2PM will convert a GIF picture into a 1-plane PM.I format PM picture, which you can then process just like any other picture.

Both of these programs are currently installed on grip and grasp. See their respective man pages for further details.

XWPS – also, installed on grip, there is a program called 'xwps' that will take any window you have on your X display, and convert it to a PostScript image. This means that anything you can get on the screen, you can get in your TEX/LATEX documents.

Developed by several members of the MIT X Consortium.

4.2 Hardware Developments

John Bradley

Several changes have recently taken place, regarding the LaserWriters and the Macintosh. The most obvious change is that we now have a second LaserWriter on-line. It's located in the receptionist's area, near the copying machine. It's called 'lw-grasp2', and you can print to it from any of the machines in the Grasp Lab (except for the HPs). However, 'lw-grasp' (the LaserWriter II NTX in the terminal room) will remain the default printer.

A less obvious change is that 'lw-grasp' and the Macintosh are no longer connected serially to anything. We've recently acquired a Kinetics Fastpath 4, which is a device that serves as a bridge between AppleTalk and Ethernet networks.

This means several things:

1. communications to the LaserWriter are no longer limited by a 9600 baud serial line. As you know, in the past, printing PM images could tie up the LaserWriter for very long times (10 minutes or so). This was almost entirely due to the limitations of a 9600 baud line. You simply can't transfer 500k of data to the LaserWriter very fast at 9600 baud. Now, however, communications is limited by the speed of an AppleTalk network, which, while not incredibly fast itself, is a good 20-25 times faster than 9600 baud. As a result, 500k PostScript files can now be printed in under a minute.
2. the Macintosh and the LaserWriters are connected via AppleTalk. This means that if you just want to create something on the Macintosh and print it, (and you're not interested in generating PostScript files to be included in one of your TEX files), you just select 'Print' from your application's menu and wait for your results to come out of the printer. That's it. No more annoyance of generating PostScript files, exiting your application, transferring the PostScript to a Unix machine via kermit (possibly the slowest thing in the world), and 'psprint'-ing the file. Not only is it far easier, it's much, much faster, as well.
3. the Macintosh is now hooked up to the network. This means that run 'kermit' and log in to 'bass' to get to the rest of the world. Instead, you run 'NCSA Telnet', and you can go directly to any machine on the Internet. Also, can now use 'ftp' to transfer files between the Macintosh and the Rest of The World. The major feature here is increased transfer speed. You'll be able to transfer files at roughly 10k bytes per second, which is about 40 times faster than kermit at 9600 baud.

See the document 'Using the Macintosh' in the terminal room for more information about file transfer.

Future Soon to come: AUFS, the AppleTalk to Unix FileSystem 'thing'. This will make your home directory on grip (or wherever) appear as a 'disk' when using the Macintosh. Two features of this are: you'll never need 3.5" diskettes again, and transferring a file between the Mac and grip will be as simple as copying a file from one Mac disk to another. Just drag the icon...

4.3 Mechanical and Electrical Hardware

4.3.1 Tactile Sensor Interface Board

Balaji Srinivasan

The Tactile Sensor interface board is designed to interface the ATT Interlink sensor to a standard parallel port. The Sensor is a 16x16 array with the rows and columns connected at each row and column intersection by a piezoresistive material which varies exponentially in resistance with applied normal force. The board varies the resolution by combining sites by multiples of two; it can look at the sensor as a 16x16, 16x8, 8x16,... 2x1, 1x2, 1x1. By varying the resolution, the TSI board can scan the 256 sites of the sensor array individually, or it can be used to look for contact, pattern of contact, or to characterize the contact pressure. The final version of the board is expected to be used to get tactile feedback from a sensor mounted on a finger.



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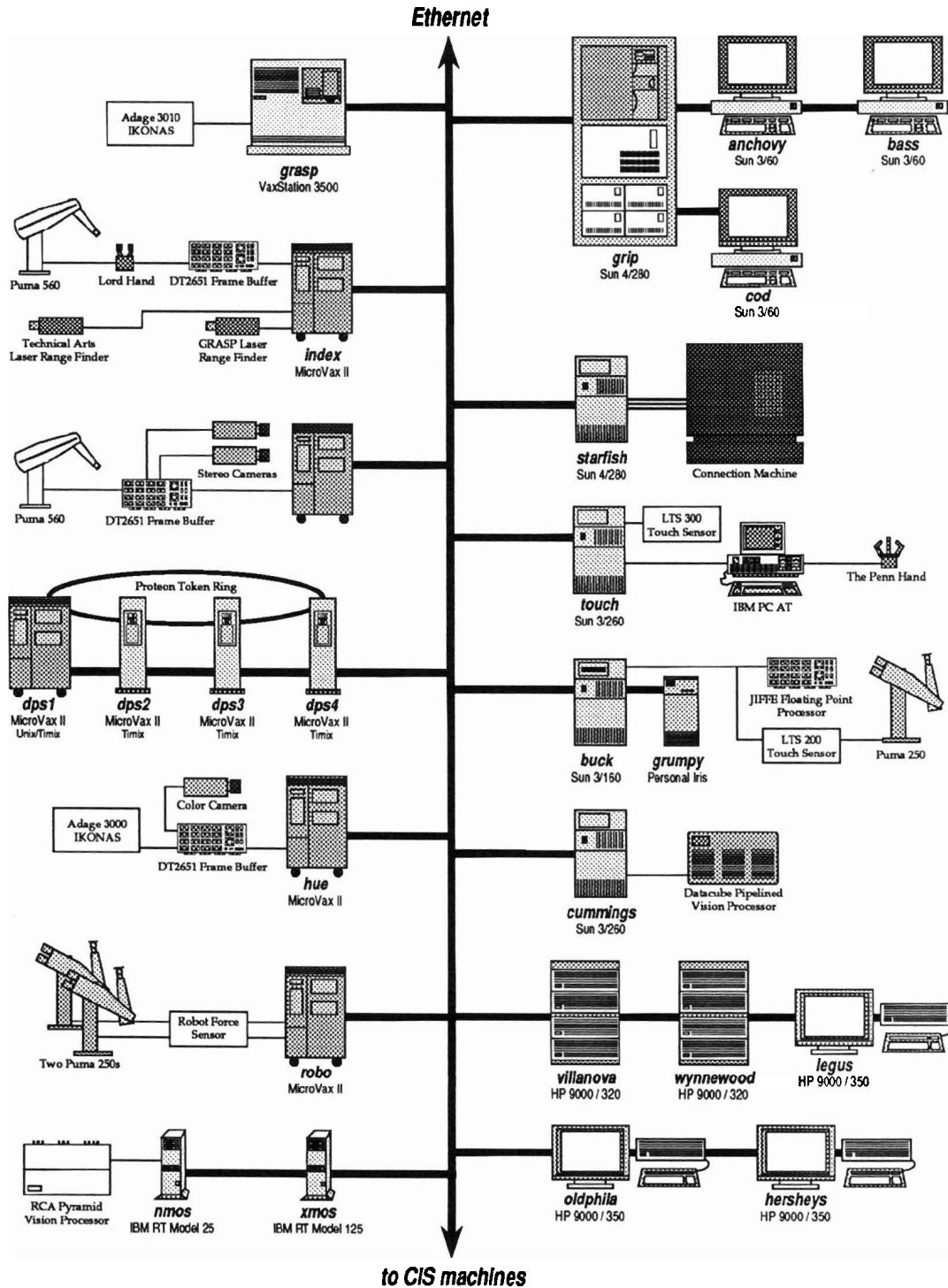


Figure 9: Grasp Laboratory Systems Layout

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

6 Laboratory Publications

- [1] Sanjay Agrawal. *Control Framework For Hand/Arm Coordination*. Technical Report MS-CIS-89-70. GRASP Laboratory, University of Pennsylvania.
- [2] Helen Anderson. *GRASP Lab Camera Systems and their Effects on Algorithms*. Technical Report MS-CIS-88-85. GRASP Laboratory, University of Pennsylvania.
- [3] Helen Anderson, Ruzena Bajcsy, and Max Mintz. *Adaptive Image Segmentation*. Technical Report MS-CIS-88-26. GRASP Laboratory, University of Pennsylvania.
- [4] Ruzena Bajcsy, "Active Perception", *Proceedings of the IEEE*, August 1988.
- [5] R. Bajcsy, "Active Perception and Exploratory Robotics", *5th International conference on Artificial Intelligence and Information-Control systems of Robots*, Czechoslovakia, November 1989 (invited paper).
- [6] R. Bajcsy, S.W. Lee, and A. Leonardis, "Image Segmentation with Detection of Highlights and Inter-reflections Using Color", *GRASP Laboratory Technical Report MS-CIS-89-39*, University of Pennsylvania, June, 1989. Also in *Image Understanding and Machine Vision, 1989 Technical Digest Series, Volume 14*, North Falmouth, Cape Cod, MA, June 12-14, 1989. Submitted to the *International Journal of Computer Vision*
- [7] R. Bajcsy, S.W. Lee, and A. Leonardis, "Computational Aspects of Color Constancy", *GRASP Laboratory Technical Report MS-CIS-89-50*, University of Pennsylvania, September, 1989.
- [8] R. Bajcsy, S.W. Lee, and A. Leonardis, "Color Image Segmentation and Color Constancy", *Presented at SPIE/SPSE Symposium on Electronic Imaging Science and Technology*, Santa Clara, Feb, 1990.
- [9] R. Bajcsy, S.W. Lee, and A. Leonardis, "Color Image Segmentation with Detection of Highlights and Local Illumination Induced by Inter-reflections", *Submitted to the 10th International Conference on Pattern Recognition, Atlantic City, NJ - June 17-21, 1990*
- [10] Ruzena Bajcsy, Franc Solina, and Alok Gupta, "Segmentation versus Object Representation - Are they Separable?" *Technical Report MS-CIS-88-58*. Revised version published as a Book Chapter in *Analysis and Interpretation of Range Images*, edited by Ramesh Jain and Anil Jain. Springer-Verlag 1990.
- [11] Ruzena Bajcsy and Alok Gupta, "Part Description and Segmentation of Range Images by integration of Contour, Surface, and Volumetric Primitives." *Topical meeting on Image Understanding and Machine Vision*, June, 1989. Cape Cod, Massachusetts. Technical Digest Series, Vol. 14, (Optical Society of America, Washington, D.C. 1989) pp. 100-103.

- [12] Ruzena Bajcsy and Alok Gupta, "Segmentation of Range Images using Geometric Properties." *4th Int. conf. on CAD/CAE Robotics and Factories of Future*, IIT, New Delhi. Organized by ISPE. Dec 19-22, 1989
- [13] Ruzena Bajcsy, Alok Gupta, and Max Mintz, "Research on Symbolic Inference in Computer Vision." *Invited paper at the Robotics Conference, Arizona, May, 1989*. Technical Report MS-CIS-89-41.
- [14] Ruzena Bajcsy, Alok Gupta, and Helen Anderson, "Scene Segmentation in the Framework of Active Perception." *Presented at the NATO Advanced Studies Institute, Maratea, Italy, July, 1989*. Technical Report MS-CIS-89-69.
- [15] Ruzena Bajcsy, Kwangyoen Wohn, Franc Solina, Alok Gupta, Pramath Sinha, and Constantine J. Tsikos, *Second Interim Technical Report For Advanced Research in Range Image Interpretation for Automated Mail Handling*, MS-CIS-88-43, GRASP LAB 146.
- [16] R. Bajcsy and C. J. Tsikos, "Physical Scene Segmentation via Vision and Manipulation", *Proceedings of the Third Advanced Technology Conference*, Washington, D.C., May 3-5, 1988
- [17] R. Bajcsy and C. J. Tsikos, "Redundant Multi-Modal Interaction of Machine Vision and Programmable Mechanical Manipulation for Scene Segmentation", *NATO ARW on Robots with Redundancy*, Antol K. Bejczy (editor), Verona, Italy, June 27-30, 1988.
- [18] Ruzena Bajcsy and Stane Kovacic, "Multi-resolution elastic matching", *Computer Vision, Graphics and Image Processing*, 1988.
- [19] Ruzena Bajcsy, Robert Dann, John Hoford, Stane Kovacic, and Martin Reivich, "Preliminary Clinical Evaluation of Multi-Resolution Elastic Matching Software," *Journal of Computer Assisted Tomography*, 1989.
- [20] R. Bajcsy, R. Dann, J. Hoford, S. Kovacic, and M. Reivich, "Three-dimensional computerized brain atlas for elastic matching: creation and initial evaluation", *SPIE Proceedings, Medical Imaging II*, Newport Beach, CA., (.) 1988.
- [21] R. Bajcsy and C. J. Tsikos, "How do robots take two parts apart?", *NASA Conference on Space Telerobotics*, 1988.
- [22] R. Bajcsy and C. J. Tsikos, "Assembly via Disassembly: A Case in Machine Perceptual Development" *Proceedings of the Fifth ISRR*, Tokyo, Japan, August 1989. Also available as Technical Report: MS-CIS-89-04, GRASP LAB 173.
- [23] R. Bajcsy, S. Lederman, and R. Klatzky, *Machine System for Exploration and Manipulation: A Conceptual Framework and Method of Evaluation*, Technical Report: MS-CIS-89-03, GRASP LAB 172.

- [24] R. Bajcsy, K. Wohn, and S. W. Lee, *Exploratory Procedures for Computer Vision*, Technical Report: MS-CIS-88-92, GRASP LAB 165.
- [25] R. Bajcsy, M. Reivich, and S. Kovacic, *Evaluation of Registration of PET Images with CT Images*, Technical Report: MS-CIS-88-89, GRASP LAB 163.
- [26] R.K. Bajcsy and P.R. Sinha. Exploration of Surfaces for Robot Mobility. December 1989. *Fourth International Conference on CAD, CAM, Robotics and Factories of the Future*, IIT, New Delhi, India. December 1989.
- [27] W. Chen and V. Kumar. Grasping with mechanical intelligence. In *Proceedings of the 1989 ASME Winter Annual Meeting*, San Francisco, CA, December 1989.
- [28] D. Cheng and Xiaoping Yun. Linearization of time-varying affine nonlinear systems. *Journal of Systems Science and Mathematical Sciences*, 1(2):119–130, 1988.
- [29] Howard Choset, Ruzena Bajcsy, and Helen Anderson, “Active Vision with Multiresolution Wavelets,” *submitted to 10th International Conference on Pattern Recognition, 1990. Technical Report MS-CIS-89-73*
- [30] Peter Corke and Helen Anderson, “Fast Image Segmentation” *Technical Report MS-CIS-89-46. submitted to Australian Robotics Conference 1990*
- [31] Susan Davidson, Insup Lee, and Victor Wolfe. A protocol for timed atomic commitment. In *Ninth International Conference on Distributed Computing*, IEEE Computer Society, June 1989.
- [32] Susan Davidson, Insup Lee, and Victor Wolfe. Language constructs for timed atomic commitment. In *19th International Symposium on Fault-Tolerant Computing*, June 1989.
- [33] Susan Davidson, Insup Lee, and Victor Wolfe. *Timed Atomic Commitment*. Technical Report MS-CIS-88-80, University of Pennsylvania, Department of Computer and Information Science, October 1988. Submitted for publication to IEEE Transactions on Computers.
- [34] Filip Fuma and Ruzena Bajcsy, *Comparative Studies Between Mechanical and Biological Sensors*, Technical Report: MS-CIS-88-98, GRASP LAB 169.
- [35] J. Funda. *A Computational Analysis of Line-Oriented Screw Transformations in Robotics*. Technical Report, University of Pennsylvania, 1988. MS-CIS-88-83.
- [36] J. Funda. *Quaternions and Homogeneous Transforms in Robotics*. Master’s thesis, University of Pennsylvania, 1988. MS-CIS-88-06.
- [37] John F. Gardner, Vijay R. Kumar, and J.H. Ho. Kinematics and control of redundantly actuated closed chains. In *Proceedings of the IEEE International Conference on Robotics and Automation*, Scottsdale, AZ, May 1989.

- [38] Alok Gupta, Gareth Funka-Lea, and Kwangyoen Wohn, "Segmentation, Modeling and Classification of the Compact Objects in a Pile." *SPIE's Intelligent Robots and Computer Vision VIII conference*, Nov. , 1989. Philadelphia.
- [39] Alok Gupta, Luca Bogoni, and Ruzena Bajcsy. "Quantitative and Qualitative Measures for the Evaluation of the Superquadric Models." *Proceedings of the IEEE Workshop on Interpretation of 3D Scenes*. Austin, TX. November, 1989.
- [40] Alok Gupta and Ruzena Bajcsy. "Part Description and Segmentation Using Contour, Surface, and Volumetric Primitives," *Sensing and Reconstruction of 3D Objects and Scenes*, Bernd Girod, Editor, Proceedings of the SPIE conference 1260. Santa Clara, CA. February, 1990.
- [41] Alok Gupta. "Part Description and Segmentation Using Contour, Surface, and Volumetric Primitives." *Dissertation Proposal*. Technical Report MS-CIS-89-33.
- [42] Gregory D. Hager, *Active Reduction of Uncertainty in Multi-Sensor Systems*, Ph.D. Dissertation. Technical Report MS-CIS-88-47.
- [43] J. Hoford, H. Choset, S. Kovacic, J. Gee, and R. Bajcsy, *CUBE ANALYZER: A Medical Image Analysis Program User's Manual*, Technical Report: MS-CIS-88-101, GRASP LAB 170.
- [44] S.-L. Iu and K. Wohn, "Estimation of 3-D motion and structure based on a temporal-oriented approach with the method of regression", *IEEE Workshop on visual motion, March 1989, pp. 273-281*.
- [45] S.-L. Iu and K. Wohn, "Recovery of 3-D motion of a single particle", *SPIE Symposium on Machine Vision, Philadelphia, November 1989*.
- [46] S.-L. Iu and K. Wohn, "On the effects of model mismatch in particle motion analysis", *submitted to the 10th International Conference on Pattern Recognition, 1990*.
- [47] S.-L. Iu and K. Wohn, "Estimation of general rigid body motion from a long sequence of images", *submitted to the 1st European Conference on Computer Vision, 1990*.
- [48] A. Izaguirre, M. Hashimoto, R.P. Paul, and V. Hayward, "A new Computational Structure for Real Time Dynamics", to appear in Special Issue on Dynamics in *International Journal of Robotics Research*.
- [49] A. Izaguirre, P. Pu, and J. Summers, "A new development in camera Calibration : Calibrating a Pair of Mobile Cameras", *International Journal of Robotics Research*, vol 6, n 3, 1987.
- [50] Gerda Kamberova and Max Mintz. Robust multi sensor fusion: decision theoretic approach. In *Proc. SPIE symp. on Advances in Intelligent. Robotics*, 1989.

- [51] Robert King. Real-time systems for multi-sensor applications. Presented to *ARO Short Course on Multisensory Integration*, TACOM (Tank-Automotive Command), Warren, MI. November 1988.
- [52] Hiroaki Kobayashi, Xiaoping Yun, and Richard Paul. On the stability of distributed robotic systems with random communication rates. In *NASA Conference on Space Telerobotics, Jet Propulsion Laboratory*, California Institute of Technology, Pasadena, California, February 1989.
- [53] Vijay R. Kumar, Benjamin P. Meyer, and Nathan Ulrich. Mechanics and design of a planar parallel manipulator. In *National Applied Mechanisms and Robotics Conference*, Cincinnati, Ohio, November 1989.
- [54] Vijay R. Kumar, Xiaoping Yun, and Ruzena Bajcsy. Exploration of unknown mechanical assemblies through manipulation. In *Advances in Intelligent Robotics Systems Symposium, SPIE*, Philadelphia, PA, November 1989.
- [55] Insup Lee, Susan Davidson, and Victor Wolfe. Maintaining consistency over a network in real-time applications. In *American Control Conference*, June 1989.
- [56] Insup Lee and Robert King. Timix: a distributed real-time kernel for multi-sensor robots. In *Proc. of 1988 IEEE International Conference on Robotics and Automation*, pages 1587–1589, IEEE Council on Robotics and Automation, IEEE Computer Society Press, April 1988.
- [57] Insup Lee, Robert King, and Richard Paul. *RK: A Real-Time Kernel for a Distributed System with Predictable Response*. Technical Report MS-CIS-88-78/GRASP LAB 155, Department of Computer and Information Science, University of Pennsylvania, October 1988.
- [58] Insup Lee, Robert King, and Xiaoping Yun. A real-time kernel for distributed multi-robot systems. In *Proc. of the 1988 American Control Conference*, pages 1083–1088, American Automatic Control Council, June 1988.
- [59] Insup Lee, Robert B. King, and Richard P. Paul. A predictable real-time kernel for distributed multi-sensor systems. *IEEE Computer*, 22(6):78–83, June 1989.
- [60] Gregory L. Long and Richard P. Paul. Avoiding orientation singularities with a four-revolute-joint spherical wrist. In *IARP - 2nd Workshop on Manipulators, Sensors and Steps Towards Mobility. Manchester, UK*, 1988.
- [61] Gregory L. Long, Richard P. Paul, and William D. Fisher. The hamilton wrist: a four-revolute-joint spherical wrist without singularities. In *Proceedings, 1989 IEEE International Conference on Robotics and Automation*, pages 902–907, 1989.
- [62] Gregory L. Long, Richard P. Paul, and William D. Fisher. The kinematic control of an eight-revolute-joint robot manipulator. In *Eighth CISM-IFTOMM Symposium*

- on the Theory and Practice of Robots and Manipulators: Ro.man.sy. '90*, Cracow, Poland, July 1990. (to appear).
- [63] Stephane Mallat, *Multiresolution Representations and Wavelets*, Ph.D. Dissertation. Technical Report MS-CIS-88-68.
- [64] R. McKendall. *Minimax Estimation of a Discrete Location Parameter for a Continuous Distribution*. PhD thesis, Systems Engineering, (expected) May 1990.
- [65] R. McKendall. Robust fusion of location information: a decision-theoretic approach. Presented to *Workshop on Robust Estimation Techniques for Computer Vision*, University of Maryland, College Park, MD. July 1989.
- [66] R. McKendall. Statistical decision theory for sensor integration. Presented to *ARO Short Course on Multisensory Integration*, TACOM (Tank-Automotive Command), Warren, MI. November 1988.
- [67] R. McKendall and M. Mintz. Robust fusion of location information. In *Proceedings of the 1988 IEEE International Conference on Robotics and Automation*, pages 1239–1255, November 1988.
- [68] R. P. Paul, Y. Xu, and Xiaoping Yun. Hybrid position and force control in the presence of passive compliance. In *The 5th International Symposium of Robotics Research*, pages 9–16, Tokyo, Japan, September 1989.
- [69] Richard P. Paul, Yangsheng Xu, and Xiaoping Yun. Terminal link force and position control of a robot manipulator. In *Proceedings of Seventh CISM-IFTOMM Symposium on Theory and Practice of Robots and Manipulators*, Udine, Italy, September 1988.
- [70] Richard P. Paul, Yangsheng Xu, and Xioping Yun. The implementation of hybrid control in the presence of passive compliance. In *Proceedings of the Fifth International Symposium on Robotics Research*, 1989.
- [71] Marcos Salganicoff. Learning to compute the slant of uniformly textured surfaces using gabor filters and receptive fields. In *Optical Society of America 1989 Annual Meeting Technical Digest*, page 97, October 1989. Poster Paper.
- [72] P.R. Sinha. *A Contact Stress Model for Determining Forces in an Equilibrium Grasp*. Master's thesis, University of Pennsylvania, Department of Mechanical Engineering and Applied Mechanics, 279 Towne Building, 220 South 33rd Street, Philadelphia, PA 19104-6389, August 1989.
- [73] Tarek M. Sobh and K. Wohn "Recovery of 3-D Motion and Structure by Temporal Fusion." *SPIE Conference on Advances in Intelligent Robotics Systems*. Nov. 1989. Philadelphia.
- [74] Franc Solina *Shape Recovery and Segmentation with Deformable Part Models*, Ph.D. Dissertation. Technical Report MS-CIS-87-111.

- [75] Franc Solina and Ruzena Bajcsy, "Recovery of Mail Piece Shape from Range Images Using 3-D Deformable Models", *International Journal of Postal Research and Engineering*, 1989. Also available as a technical Report: MS-CIS-88-57.
- [76] Franc Solina and Ruzena Bajcsy, "Recovery of parametric models from range images: the case for superquadrics with global deformations", *IEEE Transactions on PAMI*, Volume 12, Number 2, February 1990.
- [77] T. J. Tarn, A. K. Bejczy, and X. Yun. New nonlinear control algorithms for multiple robot arms. *IEEE Transactions on Aerospace and Electronic Systems*, 24(5):571-583, September 1988.
- [78] T. J. Tarn, A. K. Bejczy, and X. Yun. Robot arm force control through system linearization by nonlinear feedback. In *Proceedings of 1988 IEEE International Conference on Robotics and Automation*, Philadelphia, Pennsylvania, April 1988.
- [79] N. Treil, S. Mallat, and R. Bajcsy, *Image Wavelet Decomposition and Applications*, Technical Report: MS-CIS-89-22, GRASP LAB 177.
- [80] C. J. Tsikos and R. Bajcsy, *Redundant Multi-Modal Integration of Machine Vision and Programmable Mechanical Manipulation for Scene Segmentation*, Technical Report: MS-CIS-88-41, GRASP LAB 144.
- [81] Mark Turner, Marcos Salganicoff, George Gerstein, and Ruzena Bajcsy. Receptive fields for the determination of textured surface inclination. *IEEE proceedings*, 1990. submitted for publication.
- [82] M. Turner, M. Salganicoff, G.L. Gerstein, and R. Bajcsy, *Receptive Fields for the Determination of Textured Surface Inclination* Technical Report MS-CIS-89-48.
- [83] M.R. Turner, R. Bajcsy and G.L. Gerstein, *Estimation of Textured Surface Inclination by Parallel Local Spectral Analysis*, Technical Report, MS-CIS-89-42.
- [84] Nathan Ulrich. *Grasping with Mechanical Intelligence*. Master's thesis, University of Pennsylvania, Department of Mechanical Engineering and Applied Mechanics, December 1988. Technical Report MS-CIS-89-51.
- [85] Nathan Ulrich. The penn hand: a mechanical approach to grasping. In *Proceedings of the 1990 IEEE International Workshop on Intelligent Robots and Systems*, Tsuchiura, Japan, July 1990. (to appear).
- [86] Nathan Ulrich and Vijay Kumar. Grasping stability using fingers with coupled joints. *ASME Journal of Mechanical Design*, 1990. (to appear).
- [87] Nathan Ulrich and Vijay Kumar. Grasping using fingers with coupled joints. In *Proceedings of the 1988 ASME Mechanisms Conference*, Orlando, Florida, September 1988.

- [88] Nathan Ulrich, Richard Paul, Ruzena Bajcsy, and Vijay Kumar. Grasping with mechanical intelligence. In *Proceedings of the 1990 International Conference on Robots, Manipulators and Systems*, Cracow, Poland, July 1990. (to appear).
- [89] Nathan Ulrich, Richard P. Paul, and Ruzena Bajcsy. *A Medium-Complexity Compliant End Effector*. Technical Report MS-CIS-87-82, University of Pennsylvania, Department of Computer and Information Science, September 1987. Grasp Laboratory Technical Report.
- [90] Nathan Ulrich, Richard P. Paul, and Ruzena Bajcsy. A medium-complexity compliant end effector. In *Proceedings of the IEEE Conference on Robotics and Automation*, April 1988.
- [91] Yangsheng Xu. *Compliant Wrist Design and Hybrid Position/Force Control of Robot manipulators*. Technical Report MS-CIS-89-67, Department of Computer and Information Science, University of Pennsylvania, October 1989.
- [92] Yangsheng Xu. *Control Software of Robot Compliant Wrist System*. Technical Report MS-CIS-89-66, Department of Computer and Information Science, University of Pennsylvania, October 1989.
- [93] Yangsheng Xu and Richard P. Paul. Decoupling compliance mechanisms of robot manipulators. Submitted to the International Journal of Robotics and Computer-Integrated Manufacturing.
- [94] Yangsheng Xu and Richard P. Paul. On position compensation and force control stability of a robot with a compliant wrist. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 1173–1178, 1988.
- [95] Yangsheng Xu and Richard P. Paul. Orthogonal jacobian matrix and compliance of robots manipulators. In *Proceedings of International Conference on Advances in Robot Kinematics*, pages 26–35, Ljubljana, Yugoslavia, 1988.
- [96] Yangsheng Xu and Richard P. Paul. Robot compliant wrist system for automated assembly. Submitted to IEEE International Conference on Robotics and Automation, 1990.
- [97] Yangsheng Xu, Richard P. Paul, and Peter I. Corke. Hybrid position force control of robot manipulator with an instrumented compliant wrist. In *Proceedings of the First International Symposium on Experimental Robotics*, page , 1989.
- [98] Yangsheng Xu, Richard P. Paul, and Peter I. Corke. Hybrid position force control of robot manipulator with an instrumented compliant wrist. Submitted to IEEE Journal of Robotics and Automation, 1990.
- [99] Yangsheng Xu, Xiaoping Yun, and Richard P. Paul. Nonlinear feedback control of robot manipulator and compliant wrist. Submitted to ASME International Conference on Computers in Engineering, 1990.

- [100] Xiaoping Yun. Dynamic state feedback control of constrained robot manipulators. In *Proceedings of the 27th IEEE Conference on Decision and Control*, pages 622–626, Austin, Texas, December 1988.
- [101] Xiaoping Yun. Nonlinear feedback control of two manipulators in the presence of environmental constraints. In *1989 International Conference on Robotics and Automation*, Scottsdale, Arizona, May 1989.
- [102] Xiaoping Yun, Robert B. King, Insup Lee, and Vijay R. Kumar. A two-arm exploratory system for identifying movable and removable parts. In Y. Youcef-Toumi and H. Kazerooni, editors, *Robotics Research - 1989*, pages 125–130, The Robotics Technical Panel of the Dynamic Systems and Control Division, The American Society of Mechanical Engineers, December 1989.
- [103] Xiaoping Yun and Vijay R. Kumar. An approach to simultaneous control of trajectory and interaction forces in dual arm configurations. In *Fourth International Conference on Advanced Robotics*, Columbus, Ohio, June 1989.
- [104] Xiaoping Yun, T.J. Tarn, and A.K. Bejczy. Dynamic coordinated control of two robot manipulators. In *The 28th IEEE Conference on Decision and Control*, Tampa, Florida, December 1989.