An Annotated Bibliography of Multisensor Integration[1]

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Abstract

In this paper we give an annotated bibliography of the multisensor integration literature.

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An Annotated Bibliography of Multisensor Integraton

[1] **Alami**, R. NNS: A lisp-based environment for the integration and operation of complex robotics systems. In *Proc. IEEE International Conference on Robotics and Automation* (Atlanta, March 1984), pp. 349-353.

This paper addresses issues of integration and programming of complex robotics systems. It describes the underlying approach, the design and implementation of the NNS system, an interactive LISP-based environment for the integration and setting up of Flexible Assembly Cells. Programming, debugging, parallelism managing and interaction with decision processes are carried out in the same environment. NNS provides a suitable framework for the design of highly adaptive robotics systems and their use in the experiment of complex manipulation tasks.

[2] **Alami**, R., and Chochon, H. Programming of a flexible assembly cell: task modeling and system integration. In *Proc. IEEE International Conference on Robotics and Automation* (St. Louis, March 1985), pp. 901-909.

This paper is divided into four sections. The first section discusses Flexible Assembly Cell (FAC) programming requirements. Sections 2 and 3 present an approach to FAC modeling and programming. The intended objective is to build a programming and decisional environment which allows construction of assembly applications and to endow the on-line system with decision-making capabilities. The last section describes the current state of an actual system which is a first approach to meeting the discussed requirements.

[3] **Albus**, J. *Brains, Behavior and Robotics.* BYTE Books, Peterborough, New Hampshire, 1981.

The basic elements of the brain and the sensory input system are discussed. The central nervous system is described and then a neurological model, called the CMAC (the Cerebellar Model Arithmetic Computer) is presented. It describes the modeling of higher order functions, e.g., writing, speech, belief, etc. It also describes robots and hierarchical robot-control systems.

[4] **Allen**, P. Surface descriptions from vision and touch. In *Proc. of the IEEE Conf. on Robotics and Automation* (March 1984), pp. 394-397.

Machine vision systems presently do not have the capability of creating the 2 1/2 D sketch from the visual information alone, especially for curved surface. By using tactile data in cooperation with vision, a method is proposed for creating a surface description of an object. This surface description uses bicubic surface patches as a primitive.

[5] **Allen**, P., and Bajcsy, R. Object recognition using vision and touch. In *Proc. of the 9th*

International Joint Conference on Artificial Intelligence (Los Angeles, August 1985), pp. 1131-1135.

A system is described that integrates vision and tactile sensing in a robotics environment to perform object recognition tasks. It uses multiple sensor systems (active touch and passive stereo vision) to compute three dimensional primitives that can be matched against a model data base of complex curved surface objects containing holes and cavities. The three dimensional nature of the sensed data makes the matching process more robust as does the system's ability to sense visually occluded areas with touch. The model is hierarchic in nature and allows matching at different levels to provide support or inhibition for recognition.

[6] **Allen**, P. Sensing and describing 3-D structure. In *Proc. of the IEEE Conf. on Robotics and Automation* (San Francisco, April 1986), pp. 126-131.

Discovering the three dimensional structure of an object is important for variety of robot tasks. Single sensor systems such as machine vision systems cannot reliably compute three dimensional structure in constrained environments. Active, exploratory sensing can be used to complement the passive stereo vision data to derive robust surface and feature descriptions of objects. The control for tactile sensing is provided by the vision system which provides regions of interest that the tactile system can explore. The descriptions of surfaces and features are accurate and have been used in a later matching phase against a model data base of objects to identify the object and its position and orientation in space.

[7] **Andress**, K.M., and Kak, A. C. A production system environment for integrating knowledge with vision data. In *Proceedings of the 1987 Workshop on Spatial Reasoning and Multi-Sensor Fusion* (St. Charles, Illinois, October 1987), pp. 1-11.

A description of work-in-progress on PSEIKI is presented. PSEIKI is a computer vision system designed to use multiple sources of knowledge to aid in the image understanding task. In this paper the incorporation of world knowledge can be used to make PSEIKI expectation driven is described. The world knowledge in the system is represented as a line drawing of the expected scene. The system is implemented as a 2 panel/6 level blackboard and uses the Dempster-Shafer formalism to accomplish inexact reasoning in a hierarchical space.

[8] **Authors**, Numerous. Diverse papers. In *Proceedings of the IEEE Conference on Solid-State Sensors and Actuators* (Philadelphia, PA, June 1985).

[9] **Bajcsy**, R. GRASP:News quarterly progress report. Tech. Rep. Vol. 2, No. 1, The University of Pennsylvania, School of Engineering and Applied Science, 1st Quarter 1984.

Quarterly newsletter of the General Robotics and Active Sensory Processing Group (GRASP).

Gives a summary and status of all the projects.

[10] **Bajcsy**, R. GRASP:News quarterly progress report. Tech. Rep. Vol. 2, No. 2, The University of Pennsylvania, School of Engineering and Applied Science, 2nd Quarter 1984.

This issue describes the IPON project which is directed at investigating approaches to solve the problems involved in the manipulation of extremely large data sets which is required for real-time machine perception, object tracking, etc. It also gives a summary of the status of all the projects.

[11] **Bajcsy**, R., McCarty, M. J., and Trinkle, J. C. Feeling by grasping. In *Proc. of the IEEE Conf. on Robotics* (March 1984), pp. 461-465.

This paper specifies constraints based on geometry of the grasped object, on geometry of the hand and kinematics of the constrained object which determine how to grasp an object.

[12] **Barbera**, A., Fitzgerald, M., Albus, J., and Haynes, L. RCS: the NBS real-time control system. In *Proc. of Robots 8* (Detroit, June 1984).

[13] **Bixler**, J. P., and Miller, D. P. A sensory input system for autonomous mobile robots. In *Proceedings of the 1987 Workshop on Spatial Reasoning and Multi-Sensor Fusion* (St. Charles, Illinois, October 1987), pp. 211-219.

In order to accomplish navigation in an unfamiliar world a robot must be able to build and update its own world map continuously and in real time. This paper proposes a sensory input system based on the fusion of simple low-resolution vision with directed high-resolution sonar. The basic idea is to use a simple vision system to locate the direction in which an obstacle lies, and then use an ultra-sonic rangefinder to determine the depth of the and to gain clues about its shape. By fusing two simple systems, the strengths of each while maintaining an acceptable computation cost is exploited. An idealized example is given and some problems are discussed.

[14] **Boff**, Kaufmann, and Thomas. *Perception and Human Performance.* Wiley-Interscience, New York, 1986.

[15] **Bolles**, R.,and Cain, R. Recognizing and locating partially visible objects: the local-feature-focus method. *Robotics Research* 1, 3(1982), 57-82.

A new method for locating partially visible two-dimensional objects is presented. The method is used to locate complex industrial parts that may contain several occurrences of local features, such as holes and corners. The matching process utilizes clusters of mutually consistent features to hypothesize objects and also uses templates of objects to verify these hypotheses. The technique is fast because it concentrates on key features that are automatically selected on the basis of a detailed analysis of CAD models of the objects.

[16] **Bolles**, R., and Horaud, P. 3DPO: a three-dimensional part orientation system. *Robotics Research* 5, 3 (1986), 3-26.

In this paper a system is presented that recognizes objects in a jumble, verifies them and then determines some essential configurational information, such as which ones are on top. The approach is to use three-dimensional models of objects to find them in range data. The matching strategy starts with a distinctive edge feature, such as the edge at the end of a cylindrical part, and then grows a match by adding compatible features one at a time. Experimental results of the system's performance in recognizing and locating castings in a bin are also presented.

[17] **Borky**, J. M., and Wise, K. D. Integrated signal conditioning for silicon pressure sensors. *IEEE Transactions on Electron Devices* (December 1979), 1906-1910.

The design of a silicon-diaphragm containing on-chip circuitry for signal conditioning for biomedical applications is presented. The device exhibits 1-percent resolution and accuracy over the physiological pressure and temperature ranges.

[18] **Brooks**, R. Symbolic reasoning among 3-D and 2-D images. *Artificial Intelligence* 17 (1981), 285-349.

Model based vision systems are described in terms of four components: models, prediction of image features, description of image features, and interpretation which relate image to models. The details of the modeling, prediction, and interpretation in an implementation (ACRONYM) are described. Both generic object classes and specific objects are represented by volume models which are independent of viewpoint. New approaches to prediction and interpretation based on propagation of symbolic constraints are presented.

[19] **Brooks**, R. A layered intelligent control system for a mobile robot. In *Proc. 3rd Robotics Research Symposium* (Gouvieaux, France, October 1985).

A new architecture for controlling mobile robots is described. Layers of control system are built to let the robot operate at increasing levels of competence. Layers are made up of asynchronous modules which communicate over low bandwidth channels. Each module is an instance of a fairly simple computational machine. Higher level layers can subsume the roles of lower levels by suppressing their outputs. However, lower levels continue to function as higher levels are added. The result is a robust and flexible robot control system. The system is intended to control a robot that wanders around building maps of the surroundings.

[20] **Brown**, R. B. *An Integrated Multiple-Sensor Chemical Transducer.* PhD thesis, University of Utah, Salt Lake City, Utah, June 1985.

The main goal of this work is to improve transducer accuracy. This is accomplished by replacing the single transistor of CHEMFETs with an on-chip voltage-follower amplifier, and by integrating eight of these circuits onto a multiple-sensor transducer. Among the features are: eight transducers and control circuitry on a 54 x 140 mil chip, matched input transistors to provide inherent compensation for variations in temperature, internal feedback, etc.

[21] **Cameron**, A., Daniel, R., and Durrant-Whyte, H. Touch and motion. In *Proc. IEEE International Conference on Robotics and Automation* (Philadelphia, April 1988), pp. 1062-1067.

A new tactile sensor has been developed which uses a layer of photoelastic material as its primary sensing element. This sensor has several desirable characteristics including very high resolution, adaptable shape, and edge enhancement. Interestingly, the sensor has a similar sensing mechanism to human skin. A mathematical model has been developed for the sensor in an attempt to better understand its operation and to optimize its performance. The model draws heavily on established fields of continuum mechanics and photoelastic stress analysis. The results of this analysis provide several important insights into tactile sensing and human touch, including an explanation of importance of motion to touch, and the enhanced sensitivity of the sensor in detecting edges.

[22] **Cheeseman**, P. In defense of probability. In *Proc. of 9th International Joint Conference on Artificial Intelligence* (Los Angeles, August 1985), pp. 1002-1009.

In this paper it is argued that probability theory when used correctly, is sufficient for the task of reasoning under uncertainty. The definition of probability as a measure of belief rather than a frequency ratio is advocated, since a frequency interpretation of probability drastically restricts the domain of applicability. The interaction of logic and probability is also discussed and it is argued that many extensions of logic, such as *default logic* is better understood in a probabilistic network.

[23] **Chen**, S. An intelligent computer vision system. *Int. Journal of Intelligent Systems* (1986).

[24] **Chen**, S. Multisensor fusion and navigation of mobile robots. *Int. Journal of Intelligent Systems* (1987).

[25] **Chiu**, S., Morley, D., and J .F. Martin. Sensor data fusion on a parallel processor. In *Proceedings of the IEEE Conference on Robotics and Automation* (San Francisco, CA, April 1986), pp. 1629-1633.

A graphical programming environment called the Function Network Programming Environment, for developing and hierarchically organizing the computational modules of complex, asynchronous systems is presented. In this environment, dependencies between modules are described graphically by interconnected function nodes; hence parallelism is expressed naturally. The implementation on the BBN Butterfly parallel processor is also discussed, and a hypothetical development cycle for a multi-sensor integrated robot is described. It is expected that this environment will greatly facilitate the design and development of sophisticated, multi-sensor integrated robotic systems as well as enchance human comprehension of such systems.

[26] **Chun**, K., and Wise, K. A high-performance silicon tactile imager based on capacitive cell. *IEEE Transactions on Electron Devices* (December 1979), pp. 1196-1201.

An 8x8 element silicon-based tactile imager fabricated using integrated-circuit process technology is described.

[27] **Denyer**, P., and Renshaw, D. *VLSI Signal Processing.* Addison-Wesley, Reading, MA, 1985.

This text book is about a design methodology for VLSI signal processing using bit-serial architectures. First, bit-serial architectures and systems are introduced with emphasis on their potential and advantages for VLSI implementation. Then a comprehensive environment of methods, tools, and components within which system designers may design and implement complex VLSI signal processing systems is described. It exclusively deals with nMOS technology.

[28] **Deutsch**, R. *Estimation Theory.* Prentice-Hall, Englewood Cliffs, NJ, 1965.

This book presents an introduction to classical and modern techniques for estimation theory. It uses matrix representation throughout and deals with both discrete and continuous variables. It also gives a historical background of the field. Two chapters are devoted to both liner and non-linear least squares estimators. Recursive estimators and maximum likelihood estimators are also discussed. A chapter on decision theory is also included.

[29] **Dornfeld**, D., and Handy, C. Slip detection using acoustic emission signal analysis. In *Proceedings 1987 IEEE International Conference on Robotics and Automation* (Raleigh, North Carolina, March-April 1987), pp. 1868-1875.

This paper reviews some of the background on the slip detection methods and proposes the use of acoustic emission signal analysis as a slip detection technique. The genesis of acoustic emission during slip is discussed and experimental evidence presented to show the sensitivity of acoustic emission to slip between two surfaces. Preliminary tests are done to demonstrate the feasibility of acoustic emission slip detector.

[30] **Duda**, R., Nitzan, D., and Barrett, P. Use of range and reflectance data to find planar surface regions. *IEEE Transactions on Pattern Analysis and Machine Intelligence* PAMI-1, 3 (July 1979), 259-271.

This paper describes a sequential procedure for processing registered range and intensity data to detect and extract regions that correspond to planer surfaces in a scene. For each significant planer surface region in the scene, a histogramming technique is used to find a starting plane that describes the surface approximately, and it is refined by an iterative procedure.

[31] **Duncan**, J. S., Gindi, G. R., and Narendra, K. S. Low level information fusion: multisensor scene segmentation using learning automata. In *Proceedings of the 1987 Workshop on Spatial Reasoning and Multi-Sensor Fusion* (St. Charles, Illinois, October 1987), pp. 323-333.

As optimization approach to scene segmentation in noisy environments by simultaneously utilizing registered images is obtained from 2 disparate imaging is presented. Segmentation is performed in this dual stochastic environment according to an objective function - based algorithms, modified to include the ability to switch between the sensors' data in order to obtain an optimal result. The proposed algorithm uses a hierarchy of learning automata to first choose which impression of the hill should be used for climbing in a particular part of the underlying scene and secondly in which direction the system should move within that particular domain to most efficiently find the entire object.

[32] **Duncan**, J. S., and Staib, L. H. Shape determination from incomplete and noisy multisensor imagery. In *Proceedings of the 1987 Workshop on Spatial Reasoning and Multi-Sensor Fusion* (St. Charles, Illinois, October 1987), pp. 334-344.

The problem of fusing image-derived information from sensors with differing noise and imaging properties is examined in this paper. The goal is to delineate an object from a scene based on consensus of the incomplete and uncertain information the images have provided about the object. After an initial examination of the images separately, a consensus is achieved by identifying areas of disagreement from the separately generated high level descriptions, then searching for corroboration at a lower level. Processing proceeds from a discrete semantic representation, for model-based analysis of general shape to a continuous representation, for detailed shape characterization and comparison. Uncertainty is tracked probabilistically, using the principle of maximum entropy. A trial contour from the edge segments using the most probable labelings. The shapes of the contours derived by the two sensors are compared and the regions of discrepancy cause adjustments to the model which is reapplied to the segment data. This process is repeated in order to consider alternate segments which could decrease disagreement. The algorithm is being tested on simulated contours and dual modality medical imagery of human hearts.

[33] **Durrant-Whyte**, H. Consistent integration and propagation of disparate sensor observations. In *Proceedings of the IEEE Conference on Robotics and Automation* (San Francisco, CA, April 1986), pp. 1464-1469.

A theory and methodology for integrating and propagating geometric sensor observations is presented. The integration policy task any number of disparate, partial and uncertain observations and optimally combines them into a minimum-risk best estimate consensus views of the state of the environment. These consensus observations are considered to be integrated into a geometric model of the world. A methodology is developed that propagates new observations through this world model, maintaining consistency amongst objects and making maximum use of sensor information.

[34] **Durrant-Whyte**, H. *Integration and Coordination of Multisensor Robot Systems.* PhD thesis, University of Pennsylvania, Philadelphia, Pennsylvania, August 1986.

[35] **Durrant-Whyte**, H. F. Sensor models and multi-sensor integration. In *Proceedings of the 1987 Workshop on Spatial Reasoning and Multi-Sensor Fusion* (St. Charles, Illinois, October 1987), pp. 303-312.

In this paper the world is modeled as a collection of uncertain objects, and describes each sensor by its ability to extract descriptions of these objects from the environment. A sensor model has three components; an observation model which describes a sensor's measurement characteristics, a dependency model which describes a sensor's dependence on information from other sources, and a state model which describes how a sensor's observations are affected by it's location and internal state. Each model is represented as a probability distribution on observed geometric objects. It shown that these sensors models can deal effectively with cooperative, competitive and complementary interactions between different disparate information sources.

[36] **Erman**, L., Hayes-Roth, F., Lessor, V., and Reddy, D. Hearsay-II speech understanding system. *Computing Surveys* 12, 2 (1980), 224-225.

The Hearsay-II system represents both a specific solution to the speech understanding problem and a general framework for coordinating independent processes to achieve cooperative problem-solving behavior. The system reconstructs an intention from hypothetical interpretations formulated at various levels of abstraction. The paper also describes the characteristics of the problem, the special kinds of problem-solving uncertainty, the structure of the system to cope with the uncertainty, and the relationship of the Hearsay-II system with other speech understanding systems.

[37] **Esashi** M., et. al., Fabrication of catheter-tip sidewall miniature pressure sensors. *IEEE Transactions on Electron Devices* (January 1982), 57-63.

The paper gives an approach to improve sensor stability by obtaining a low electrical drift by the use of suitable shielding and guard structure to reduce leakage current, and to eliminate the thermal disturbances by use of thick supporting rim structure and elastic bonding material for its mounting.

[38] **Fai**, W. S. *A Multi-sensor Integration and Data Acquisition System.* Master's thesis, University of Utah, Salt Lake City, Utah, June 1983.

This thesis investigates and implements a framework for multi-sensor integration and data acquisition operating in the context of a robot workstation equipped with both contact and noncontact sensors. An appropriate low-level representation of raw data supplied by various sensors is developed. The spatial proximity graph is proposed as a means to describe spatial relations between features of three dimensional objects. It allows for uniform management of data from a wide spectrum of sensor systems. Two high-level modeling techniques: feature models, and Hough shape transform are also examined.

[39] **Faugeras**, O., Ayache, N., and Faverjon, B. Building visual maps by combining noisy stereo measurements. In *Proceedings of the IEEE Conference on Robotics and Automation* (San Francisco, CA, April 1986), pp. 1433-1438.

This paper deals with the problem of coping with noise disturbing data in stereo, 3-D modeling and navigation. The ideas of Realistic Uncertain Description of the Environment (RUDE) is introduced, which is local, i.e., attached to a specific reference frame, and incorporates both information about the geometry and about the parameters measuring this geometry. This uncertainty is also related to the pixel and it is shown how RUDE corresponding to different frames can be used to relate these frames by a rigid displacement which is described both by a rotation and translation and a measure of their uncertainty. The relations between frames are used to update the associated RUDE and to decrease their uncertainty.

[40] **Faugeras**, O., and Hebert, M. The representation, recognition and locating of 3-D objects. *Robotics Research* 5, 3 (1986), 27-52.

The paper analyzes the task requirements in terms of what information needs to be represented, how to represent it, what kinds of paradigms can be used to process it, and how to implement it. Shape surfaces are represented by curves and patches, which in turn are represented by linear primitives, such as points, lines, and curves. Algorithms to construct this representation from range data are presented. Results are presented for data obtained from a laser range finder, but both the shape representation and the matching algorithm are general and can be used for other types of data, such as ultrasound, stereo, and tactile.

[41] **Faux**, I., and Pratt, M. *Computational Geometry for Design and Manufacture.* John Wiley, New York, 1979.

The book outlines the principal developments in the field of *computational geometry* - the computer representation, analysis, and synthesis of shape of shape information. Among the topics covered are: plane co-ordinate geometry, three dimensional geometry and vector algebra, co-ordinate transformations, three dimensional curves and surface geometry, curve and surface design, composite curves and splines, composite surfaces, and cross-sectional designs, etc.

[42] **Flynn**, A. *Redundant Sensors for Mobile Robot Navigation.* Master's thesis, MIT, Boston, Massachusetts, September 1985.

[43] **Garrett**, P. *Analog Systems for Microprocessors and Minicomputers.* Reston, New York, 1978.

This is a textbook for instrumentation. Topics covered include electrical transducers, instrumentation amplifiers, active fileters, data conversion systems, process controllers, reliability of electronic systems, etc.

[44] **Garrett**, P. *Analog I/O Design Acquisition: Conversion: Recovery.* Reston, New York, 1981.

This book gives a comprehensive approach to the design of analog systems primarily for computer input/output applications. Component and system error analysis are presented to permit evaluation of overall input-to-output system accuracy and thereby the realization of a unified design approach for analog systems. Signal acquisition, conditioning, recovery and distribution are also discussed. Systems for data conversion and measurement sensors are also described.

[45] **Garrett**, P. *Computer Interface Engineering with Model-Based Analysis.* Prentice-Hall, New York, 1987.

[46] **Geschke**, C. A system for programming and controlling sensor-based robot manipulators. *IEEE Transactions on Pattern Analysis and Machine Intelligence* PAMI-5, 1 (1983), 1-7.

This paper describes an approach to programming and controlling robot manipulators which facilitates the use of sensory information. Robot actions are specified by declaring software servo processes which control the robot's various degrees of freedom. These servo processes can involve position, orientation, force, and torque information from the robot itself, or data from external sensors. The robot tasks are programmed by dynamically modifying the servo processes or by changing set points to these processes. Condition monitors which have access to program and sensory information detect the completion of program steps.

[47] **Giralt**, G. Research trends in decisional and multi-sensory aspects of third generation robots. In *Proceedings 2nd Robotics Research Symposium* (Kyoto, Japan, August 1984).

In this paper the issues and trends of robotics research during the late 1980's and early 1990's in view of current needs to develop robots able to operate in a flexible manner and/or in an unstructured environment are presented. Two broad application areas are chosen as a framework for the analysis: multi-robot flexible manufacturing cells and autonomous mobile robots for general purpose tasks.

[48] **Gregory**, R. *Eye and Brain.* McGraw-Hill, London, 1977.

This book discusses the basic features of the visual system and the brain, perception of brightness, movement, color, illusions.

[49] **Grimson**, E.,and Lozano-Perez, T. Model-based recognition and localization from sparse range or tactile data. *Robotics Research* 3, 3 (Fall 1984), 3-35.

This paper discusses how local measurements of three-dimensional positions and surface normals (recorded by a set of tactile sensors, or by three-dimensional range sensors), may be used to identify and locate objects from among a set of known objects. The objects are modeled as polyhedra of having up to six degrees of freedom relative to the sensors. It is also shown that inconsistent hypotheses about pairings between sensed points and object surfaces can be discarded efficiently using local constraints on distances between faces, angles between face normals, and angles (relative to the surface normals) of vectors between sensed points. It is shown by simulation and mathematical bounds that the number of hypotheses consistent with the constraints is small. The algorithm's performance on data obtained from a triangulation range sensor is illustrated.

[50] **Hager**, G., and Mintz, M. Searching for information. In *Proceedings of the 1987 Workshop on Spatial Reasoning and Multi-Sensor Fusion* (St. Charles, Illinois, October 1987), pp. 313-322.

The problem of constructing an intelligent, active sensor is considered in this paper. Such a sensor is able to choose the number and placement of views to gather requested information while contending with noise processes, quantization and limitations of sensor scope. An organization for an intelligent sensing system based on a statistical sensor model is outlined. A data structure similar to Koendrnink and van Doorn's aspect graphs is developed as a local representation for information about the information. Using ideas from decision theory, the tradeoff between the value of information and cost of information is formalized. It is also shown how the game-theoretic techniques can be used to solve the problem of choosing a set of sensor views to maximize the information content of a sensor estimate.

[51] **Harmon**, L. Automated tactile sensing. *Robotics Research* 1, 2(1982), 3-32.

This is a survey aimed at finding out what the researchers and manufacturers of industrial manipulators see as present and future tactile sensing requirements and potentials. The ultimate aim was to identify the device and system parameters and configurations and to match these as far as possible with applications.

[52] **Harmon**, S., Bianchini, G., and Pinz, B. Sensor data fusion through a distributed blackboard. In *Proceedings of the IEEE Conference on Robotics and Automation* (San Francisco, CA, April 1986), pp. 1449-1454.

A computing architecture which supports many different schemes for fusing sensor data is presented. It is the distributed blackboard mechanism implemented on board the USMC Ground Surveillance Robot (GSR). The distributed blackboard has proven to be a very useful and flexible mechanism to accomplish effective sensor data fusion.

[53] **Henderson**, T.C., C. H., and Bhanu, B. A framework for distributed sensing and control. In *Proceedings of IJCAI* 1985 (Los Angeles, CA, August 1985), pp. 1106-1109.

Logical Sensor Specification (LSS) has been introduced as a convenient means for specifying multi-sensor systems and their implementations. This paper demonstrates how control issues can be handled in the context of LSS. In particular, the Logical Sensor Specification is extended to include a control mechanism which permits control information to (1) flow from more centralized processing to more peripheral processes, and (2) be generated locally in the logical sensor by means of a micro-expert system specific to the interface represented by the given logical sensor. Examples are given including a proposed scheme for controlling the Utah/MIT dextrous hand.

[54] **Henderson**, T. The specification of logical sensors. In *Proceedings of the IEEE Intelligent Control Workshop* (Troy, New York, August 1985), pp. 95-101.

Multi-sensor systems require a coherent and efficient treatment of the information provided by the various sensors. This paper proposes a framework, the Logical Sensor Specification System, in which the sensors can be abstractly defined in terms of computational processes operating on the output from other sensors. Issues addressed include: (1) integration of various kinds of sensed data, (2) sensor system reconfiguration for fault tolerance or dynamic context, and (3) the control of sensors. Various properties of such an organization are given, and a particular implementation is described.

[55] **Henderson**, T., Bhanu, B., Hansen, C., and Shilcrat, E. ASP: a sensor performance and evaluation system. In *Proceedings of Pecora IX* (October 1984), pp. 201-207.

This paper describes a methodology which permits (1) the precise characterization of sensors, (2) the specification of algorithms which transform the sensor data, and (3) the quantitative analysis of combinations of algorithms and sensors. Such analysis makes it possible to determine appropriate sensor/algorithm combinations subject to a wide range of criteria including: performance, computational complexity (both space and time), possibility for concurrency, modularization, and the use of multi-sensor systems for greater fault tolerance and reliability. Some examples from the domain of remote sensing are given.

[56] **Henderson**, T., and Bhanu, C. H. B. The specification of distributed sensing and control. *Journal of Robotic Systems* 2, 4(1985), 387-396.

Logical Sensor Specification (LSS) has been introduced as a convenient means for specifying multi-sensor systems and their implementations. In this paper the handling of control issues has been demonstrated. In particular, the LSS is extended to include a control mechanism which permits control information to flow from more centralized processing to more peripheral processes, and be generated locally in the logical sensor by mens of micro expert system specific to the interface represented by the given logical sensor. Examples are given including a proposed scheme for controlling the Utah/MIT dextrous hand.

[57] **Henderson**, T., and Fai, W. S. MKS: a multi-sensor kernel system. *IEEE Transactions on Systems, Man, and Cybernetics* SMC-14, 5 (September/October 1984), 784-791.

The Multisensor kernel system (MKS) is presented as a means for multisensor integration and data acquisition. This system has been developed in the context of a robot work station equipped with various types of sensors utilizing three-dimensional laser range finder data and two-dimensional camera data. Specific goals that have been achieved include, developing a suitable low-level representation of raw data and/or features extracted from the raw data of the various sensors, providing a method for efficient reconfiguration of the sensor system in terms of logical sensors which map onto physical sensors and computation and providing a basis for high-level object modeling techniques.

[58] **Henderson**, T., and Fai, W. S. Pattern recognition in a multi-sensor environment. Computer Science UUCS 83-001, University of Utah, July 1983.

Current pattern recognition systems tend to operate on a single sensor, e.g., a camera. However, the need is now evident for pattern recognition systems which can operate in multi-sensor environments. For example, a robotics workstation may use range finders, cameras, tactile pads, etc. The Multisensor Kernel System (MKS) provides an efficient and coherent approach to the specification, recovery, and analysis of patterns in the data sensed by such a diverse set of sensors. It is how shown how such a system can be used to support both feature-based object models as well as structural models. The problem solved is the localization of a three-dimensional object in 3-space. Moreover, MKS allows rapid reconfiguration of the available sensors and the high-level models.

[59] **Henderson**, T., and Hansen, C. A kernel for multi-sensor robotic systems. In *Proceedings of the CAD/CAM, Robotics and Automation Institute and Conference* (February 1985), pp. 217-222.

Multi-processor and multi-sensor systems are being proposed to solve a wide range of problems. In particular, distributed sensing systems and general robot workstations require real-time processing of information from visual, auditory, tactile and other types of sensors. This paper proposes the *spatial proximity graph* as a low-level representation of sensory data from diverse sources and uses this as the basis for high-level organization and control over the acquisition of data. The notion of logical (or abstract) sensor allows for flexible hardware/software mix in terms of a multi-sensor system and permits a simple method of reconfiguration whenever logical or physical sensors are added to or removed from the system.

[60] **Henderson**, T., and Hansen, C. Multisensor knowledge systems. Tech. Rep. UUCS-TR-114, The University of Utah, Department of Computer Science, September 1986.

This paper describes an approach which facilitates and makes explicit the organization of the knowledge necessary to map multisensor system requirements onto an appropriate assembly of algorithms, processors, sensors, and actuators. The Multisensor Kernel System and Logical Sensor Specifications have been introduced before as a means for high-level specification of multisensor systems. The main goals of such a characterization are: to develop a coherent treatment of multisensor information, to allow system reconfiguration for both fault tolerance and dynamic response to environmental conditions, and to permit the explicit description of control. In this paper it is shown how Logical Sensors can be incorporated into an object-based approach to the organization of multisensor systems. In particular, a multisensor knowledge base, a sensor specification scheme, and a multisensor simulation environment are discussed. An example application of the system to CAD-based 2-D vision is also given.

[61] **Henderson**, T., Hansen, C., and Bhanu, B. The synthesis of logical sensor specifications. In *Proceedings of the SPIE Conf. on Intelligent Robots* (Boston, MA, September 1985).

A coherent automated manufacturing system needs to include CAD/CAM, computer vision, and object manipulation. Currently, most systems which support CAD/CAM do not provide for vision or manipulation and similarly, vision and manipulation systems incorporate no explicit relation to CAD/CAM models. CAD/CAM systems have emerged which allow the designer to conceive and model an object and automatically manufacture the object to the prescribed specifications. If recognition or manipulation is to be performed, existing vision systems rely on models generated in an ad hoc manner for the vision or recognition process. Although both Vision and CAD/CAM systems rely on models of the objects involved, different modeling schemes are used in each case. A more unified system will allow vision models to be generated from the CAD database. The model generation should be guided by the class of objects being constructed, the constraints of the vision algorithms used and the constraints imposed by the robotic workcell environment (fixtures, sensors, manipulators and effectors). This paper proposes a framework in which objects are designed using an existing CAGD system and logical sensor specifications are automatically synthesized and used for visual recognition and manipulation.

[62] **Henderson**, T., Hansen, C., and Fai, W. S. Organizing spatial data for robotic systems. *Computers in Industry* 6, 5 (October 1985), 331-344.

Successful robotics systems require the organization and analysis of a tremendous amount of sensor data. Such multi-dimensional vectors must be organized such that spatial searching is efficient and so that the spatial proximity is easily determined. In this paper spatial proximity graph is defined as a low-level organizational structure, and it hs shown how it can be built efficiently. Some examples are also given.

[63] **Henderson**, T., Hansen, C., Shilcrat, E., and Fai, W. S. Logical sensor specification. In *Proceedings of the SPIE Conference on Intelligent Robots* (November 1983), pp. 578-583.

Multi-sensor systems require a coherent and efficient treatment of the information provided by the various sensors. A framework is proposed in which the sensors can be abstractly defined in terms of computational processes operating on the output from other sensors. Various properties of such an organization are investigated.

[64] **Henderson**, T., and Shilcrat, E. Logical sensor systems. *Journal of Robotic Systems* 1, 2 (1984), 169-193.

Multisensor systems require a coherent and efficient treatment of the information provided by the various sensors. In this paper a framework, Logical Sensor Specification, is proposed in which the sensors can be defined abstractly in terms of computational processes operating on the output from other sensors. Various properties of such an organization are investigated, and a particular implementation is described.

[65] **Henderson**, T., Shilcrat, E., and Hansen, C. A fault tolerant sensor scheme. Computer Science UUCS 83-003, University of Utah, November 1983.

Multi-sensor systems pose the problem of how to coherently and efficiently treat the data provided by the various sensors. However, the availability of greater numbers of sensors also broadens the ability to build fault tolerant sensor systems. A framework in which sensors can be abstractly defined in terms of computational processes operating on the output from other sensors is defined. Such processes are called logical sensors. Logical sensors make sensor configuration and integration easier and facilitate reconfiguration of sensor systems so that fault tolerance can be both expressed and achieved.

[66] **Henderson**, T., Shilcrat, E., and Hansen, C. A fault tolerant sensor scheme. In *Proceedings of the International Conference on Pattern Recognition* (August 1984), pp. 663-665.

A framework is defined in which sensors can be abstractly defined in terms of computational processes operating on the output from other sensors. Such processes are called logical sensors. Logical sensors make sensor configuration and integration easier and facilitate reconfiguration of sensor systems so that fault tolerance can be both expressed and achieved.

[67] **Henderson**, T. C., Bhanu, B., and Hansen, C. Distributed control in the multisensor kernel system. In *Proceedings SPIE Conference on Intelligent Robots* (Cambridge, Massachusettes, November 1984), pp. 253-255.

The Multi-sensor Kernel System (MKS) has been introduced as a convenient mechanism for specifying multi-sensor systems and their implementations. In this paper, how control issues can be handled in the context of MKS is demonstrated. In particular, the Logical Sensor Specification is extended to include a control mechanism which permits control information to (1) flow from more centralized processing to more peripheral processes, and (2) be generated locally in the logical sensor by means of a micro-expert system specific to the interface represented by the given logical sensor. Examples are given including a scheme for controlling the Utah/MIT dextrous hand.

[68] **Henderson**, T. C., and Fai, W. S. A multi-sensor integration and data acquisition system. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition* (June 1983), IEEE, pp. 274-280.

The Multi-sensor Kernel System (MKS) is proposed as a means for multi-sensor integration and data acquisition. This system is being developed in the context of a robot workstation equipped with various types of sensors, including tactile sensors mounted on a dextrous hand and cameras. Specific goals are to: develop a suitable low-level representation of raw data and/or features extracted from the raw data of the various sensors, provide a method for efficient reconfiguration of the sensor system in terms of "logical" sensors which map onto physical sensors and computation, and provide a basis for 3-D object modeling techniques which allow the derivation of constraints useful in controlling and directing the acquisition of data for object recognition.

[69] **Horowitz**, I. Uncertain MIMO systems with internal variable feedback. *Int. Journal of Control* 36 (1982), 989-1009.

There is a linear time invariant multiple-input-multiple-output (MIMO) plant with internal variables and outputs available for feedback. It is shown how the MIMO uncertainty problem can be replaced by a number of single-input-single-output (SISO) multiple loop uncertainly problems. A suitable fixed point theorem guarantees that the solution of the SISO problems solves the original MIMO problem. Extensions to disturbance attenuation under uncertainty and to uncertain time-varying and non-linear MIMO plants are also discussed.

[70] **Horowitz**, I., Neumann, L., and Yaniv, O. Quantitative synthesis of uncertain cascade multiple-input multiple-output feedback systems. *Int. Journal of Control* 42 (1985), 273-303.

This paper deals with an *nxn* multiple-input multiple-output (MIMO) linear time invariant plant of *m* cascaded sections, each an *nxn* matrix of transfer functions. The basic problem is how to divide the feedback burden among the *m* available loop matrices. A technique is presented in this paper based on two synthesis techniques previously devised for two associated problems. It has the following features: conversion of the *nxn* MIMO cascaded m-section problem into *n* cascaded m-section SISO synthesis problems, bandwidth propagation wherein the loop matrices take turns dominating the design over specific frequency ranges, and design perspective wherein one can a priori make good estimates of the optimum division of the overall feedback burden between the loop matrices. It is shown that proper use of internal MIMO plant variables may enormously reduce the effect of sensor noise at the plant input.

[71] **Horowitz**, I., and Sidi, M. Synthesis of cascaded multiple-loop feedback systems with large plant parameter ignorance. *Automatica* 9 (1973), 589-600.

In a cascaded plant with *n* sensing points, *n* independent feedback loops are available to achieve quantitative sensitivity specifications. The optimum design is defined as that which achieves this with minimum net effect, of the *n* sensors noise resources, at the plant input. The paper presents a synthesis theory, where one works backwards step by step from the system output, designing each loop function as if the remaining loops are perfect. The design procedure is highly transparent with strong universalistic features, permitting the use of universal design curves.

[72] **Horowitz**, I., and Wang, B. Quantitative synthesis of uncertain cascade feedback systems with plant modification. *Int. Journal of Control* 30 (1979), 837-862.

In this first quantitative work of its kind, the feedback in a control system, consisting of n cascaded sections, each of whose outputs can be sensed for feedback purposes, is proceeded directly to the internal plant variables, constituting a 'plant modification'. This permits greater reduction in the 'cost of feedback', in terms of feedback loop bandwidths and effect of sensor noise, at the cost of increase in plant internal signal levels. The maximum permitted increase in signal level is part of the design specifications. A step by step design procedure is presented for satisfying this requirement. This permits the designer to achieve desired trade-off between increased plant signal level and cost of feedback.

[73] **Horowitz**, I., and Wang, T. Quantitative synthesis of multiple-loop feedback systems with large uncertainty. Int. Journal of System Science 10 (1979), 1235-1268.

This work extends single input-output linear time invariant minimum phase 'quantitative feedback synthesis' to two new complex plant structures with internal sensing points. One is the triangle structure. The second consists of parallel branches, each with cascaded sections. Due to uncertainty, the plant parameters are elements of the given sets. Numerous design examples with very large uncertainty illustrate the design procedures and the advantages of multiple-loop design.

[74] **Horowitz**, I., and Yaniv, O. Quantitative cascaded MIMO synthesis by the improved method. *Int. Journal of Control* 42 (1985), 305-331.

This paper deals with an nxn multiple-input multiple-output (MIMO) linear time invariant plant of m cascaded sections, each an nxn matrix of transfer functions. The basic problem is how to divide the feedback burden among the m available loop matrices. This paper presents a synthesis procedure which is easier to implement, in some respects, and is much more economical in loop gains and bandwidths than the other methods. However, the relations and trade-offs between mn individual loop transmissions are more subtle and complex.

[75] **Howard**, I. *Human Visual Orientation.* John Wiley, New York, 1982.

The book is about how human beings visually perceive the directions and orientations of objects based on psychophysical and behavioral evidence. The perception of depth or distance is not discussed. The perception of movement is discussed only with respect to its effect on judgements about direction and orientation.

[76] **Hu**, G., and Stockman, G. 3-D scene analysis via fuson of light striped image and intensity image. In *Proceedings of the 1987 Workshop on Spatial Reasoning and Multi-Sensor Fusion* (St. Charles, Illinois, October 1987), pp. 138-147.

A fusion scheme that uses both 3-D data and intensity information and generates a 2 1/2D sketch-like representation is presented. 3-D surface data are collected from light striping and used for determining locations and rough shapes of objects. An intensity image of the same scene provides gradient (edges), contours, and shading information. The information obtained from the two sources complements each other to produce a more reliable scene representation. To study the integration to the two channels of information and the relations between patches and contours, a set of inference rules and production system control is currently used.

[77] **Huntsberger**,T. L., and Jayaramamurthy, S. N. A framework for multi-sensor fusion in the presence of uncertainty. In *Proceedings of the 1987 Workshop on Spatial Reasoning and Multi-Sensor Fusion* (St. Charles, Illinois, October 1987), pp. 345-350.

In this paper a multiple valued logic based framework for image understanding, which contains a method for representation and combination of evidence from various sensor inputs, is presented. This framework, called **FLASH** (Fuzzy Logic Analysis System in Hardware) is shown to be suitable for the fusion of information from multiple sensors such as laser range finding, MMW radar, FLIR, and multispectral images.

[78] **Hutchinson**, S. A., et al. Planning sensing strategies in a robot work cell with multi-sensor capabilities. In *Proc. IEEE International Conference on Robotics and Automation* (Philadelphia, April 1988), pp. 1068-1075.

In this paper an approach to planning sensing strategies in a robot work cell with multi-sensor capabilities is presented. The system first forms an initial set of object hypotheses by using one of the sensors. Subsequently, the system reasons over different possibilities for selecting the next sensing operation, this being done in a manner so as to maximally disambiguate the initial set of hypotheses. The next sensing operation is characterized by both the choice of the sensor and the viewpoint to be used. Aspect graph representation of objects plays a central role in selection of the viewpoint, these representations being derived by a solid modeling program.

[79] **Jain**, R., and Grosky, W. I. Hyper-pyramids for integration of spatial information. In *Proceedings of the 1987 Workshop on Spatial Reasoning and Multi-Sensor Fusion* (St. Charles, Illinois, October 1987), pp. 72-81.

An intelligent autonomous system working in an unstructured, changing environment requires a world model to direct all its actions. This model is used in integration of information acquired using disparate sensors. The representations used for this model should work with both spatial and symbolic information. In this paper a hierarchical representation using relinkable hyperpyramids for world modeling is presented. This structure will be combined with a graph-based representation of objects to integrate and assimilate information about objects in the environment for navigation for a mobile robot.

[80] **Kak** A., et. al., A knowledge-based robotic assembly cell. *IEEE Expert* Spring (1986), 63-83.

The paper discusses the ongoing development of an integrated knowledge-based robotic assembly cell that uses sensory feedback for true flexibility. Major progress in vision and motion planning modules has been reported. Sensory feedback gives this integrated cell enchanced flexibility and lessens the need for high-priced parts feeders and precision fixturing.

[81] **Kent**, E., and Albus, J. Servoed world models as interfaces between robot control systems and sensory data. *Robtica* 2 (1984).

[82] **Ko**, W., Bao, M., and Hong, Y. A high-sensitivity integrated-circuit capacitive pressure transducer. *IEEE Transactions on Electron Devices* (January 1982), 48-56.

A high-sensitivity capacitive pressure transducer with active processing circuit on the chip has been demonstrated and evaluated. The configuration is optimized by computer-aided design to achieve highest sensitivity for a given maximum dimension.

[83] **Ko**, W. H., Hynecek, J., and Boettcher, S. F. Development of a miniature pressure transducer for biomedical applications. *IEEE Transactions on Electron Devices* (December 1979), 1896-1905.

The main design parameters of miniature absolute pressure transducers needed for biomedical applications are: sensitivity, size, hysteresis, temperature coefficient, long-term stability and bio-compartibility. The results of a development program on implantable and indwelling pressure transducers are reported with emphasis on the study of long-term stability and reproducibility associated with reduced size.

[84] **Krotkov**, E., and Kories, R. Adaptive control of cooperating sensors: focus and stereoranging with an agile camera system. In *Proc. IEEE International Conference on Robotics and Automation* (Philadelphia, April 1988), pp. 548-553.

This paper presents a cooperative computer vision procedure in which focus ranging and stereo ranging operate together, verifying the results of each other in computing the position (but not the shape) of arbitrary objects in a stationary, unknown environment. The procedure increases the reliability of the position measurements by enforcing measurement consistency via mutual constraint, and increases their accuracy by combining them with a maximum likelihood estimator into an estimate of lower variance than any of the measurements alone.

[85] **Kuijpers**, E. Multi-sensor systems seen from different points of view. Tech. Rep. FVI 86-02, University of Amsterdam, January 1986.

Examples of problems and solutions for multi-sensor systems are given to show different aspects of multi-sensor systems that need further theoretical and experimental research are presented. The examples are grouped in modeling for sensors, reasoning with sensors, classification and interaction between sensors, learning, and testing for sensors and architectures for sensors.

[86] **Lee**, I., and Goldwasser, S. A distributed testbed for active sensory processing. In *Proc. IEEE International Conference on Robotics and Automation* (St. Louis, March 1985), pp. 925-930.

A distributed testbed designed to support the development of a multi-sensory (vision and tactile) system for investigations in active perception of three dimensional objects is presented. The nucleus of the testbed is a network of heterogeneous computers designed to support low-level knowledge-based systems. The programming environment of the testbed facilitates the construction and execution of a distributed multi-sensory system from sequential programs written in different programming languages.

[87] **Lee**, K., and Wise, K. SENSIM : A simulation program for solid-state pressure sensors. *IEEE Transactions on Electron Devices* (January 1982), 34-41.

A simulation program is described which is capable of calculating the output response of silicon piezorestive or capacitive pressure sensors as a function of pressure and temperature. Both analytical and finite difference solutions are available, depending on the structure of the sensor.

[88] **Lee**, Y., and Wise, K. A batch-fabricated silicon capacitive pressure transducer with low temperature sensitivity. *IEEE Transactions on Electron Devices* (January 1982), 42-47.

A batch-fabricated solid-state capacitive pressure transducer's design is presented. It is developed with silicon integrated circuit technology and exhibits a dynamic range of 350mmHg and a pressure sensitivity of about 1100 ppm/mmHg.

[89] **Lesser**, V., and Corkhill, D. Functionally accurate, cooperative distributed systems. *IEEE Transactions on Systems, Man, and Cybernetics* SMC-11, 1 (January 1981), 81-96.

A new approach to structuring distributed processing systems, called functionally accurate, cooperative (FA/C), is proposed. The approach differs from the conventional ones in the emphasis on handling distribution-caused uncertainty and errors as an integral part of the network problem-solving process. The nodes cooperatively problem-solve by exchanging partial tentative results within the context of common goals. The approach is suitable for applications in which data necessary to achieve a solution can not be partitioned in such a way that a node can complete a task without seeing the intermediate state of task processing other nodes.

[90] **Luo**, R., and Henderson, T. C. A servo-controlled gripper with sensors and its logical specification. *Journal of Robotic Systems* 3, 4 (1986), 409-420.

The logical specification of a microprocessor-based air-servo-controlled robot hand is presented, as well as its actual implementation. This hand can accommodate a wide variety of workpieces and allows for flexible assembly through the use of an automatic quick-change fingertip. A PUMA 560 is used to test the success of the entire process.

[91] **Luo**, R., and Tsai, W. Object recognition using tactile image array sensors. In *Proceedings of the IEEE Conference on Robotics and Automation* (San Francisco, CA, April 1986), pp. 1248-1253.

The objective of this paper is to develop an object recognition system through the combination of 2-D tactile image array and visual sensors. A video camera is used to acquire a top view image of an object and two tactile sensing arrays are mounted on a gripper are used to detect the tactile information about the lateral surfaces of the object. 3-D reference object models are established as a decision tree, and recognition of unknown objects is accomplished through measuring and comparing input object features hierarchically with those of the reference objects associated with the decision tree. The clustering process and the recognition procedures are described. The recognition scheme is implemented and the resulting decision tree is also presented.

[92] **Luo**, R. C., and Lin, M. Mutli-sensor integrated intelligent robot for automated assembly. In *Proceedings of the 1987 Workshop on Spatial Reasoning and Multi-Sensor Fusion* (St. Charles, Illinois, October 1987), pp. 351-360.

The objective of this paper is to develop an intelligent robot system through the integration of multiple sensors into robot tasks. The investigation is based on a Unimation PUMA 560 robot employing various sensors. These include overhead vision, eye-in-hand vision, proximity, tactile array, position, force/torque, cross-fire, overload, and slip sensing devices. The efficient fusion of data from different sources will enable the machine to respond promptly in dealing with the real world. A general paradigm of a sensor data fusion system has been developed. This system allows the robot to handle uncertainty in sensory data as well as to verify and recover sensor errors.

[93] **Luo**, R. C., and Lin, M. Robot multi-sensor fusion and integration : optimum estimation of fused sensor data. In *Proc. IEEE International Conference on Robotics and Automation* (Philadelphia, April 1988), pp. 1076-1081.

The objective of this paper is to address the problem of robot multi-sensor fusion and integration with special emphasis on optimal estimation of fused sensor data. The investigation is based on a Unimation PUMA 560 robot and various external sensors. These include overhead vision, eye-in-hand vision, proximity, tactile array, position, force/torque, cross-fire, overload, and slip sensing devices. The efficient fusion of data from different sources will enable the machine to respond promptly in dealing with the real world. Towards this goal a general paradigm of a sensor data fusion system has been developed, and some simulation results as well as results from actual implementation of certain concepts of sensor data fusion have been demonstrated.

[94] **Luo**, R. C., Lin, M., and Scherp, R. S. The issues and approaches of a robot multi-sensor integration. In *Proceedings 1987 IEEE International Conference on Robotics and Automation* (Raleigh, North Carolina, March-April 1987), pp. 1090-1096.

The objective of this paper is to develop an intelligent robot system through the integration of multiple sensors into robot tasks. The investigation is based on a Unimation PUMA 560 robot employing various external sensors. These sensors include overhead vision, eye-in-hand vision, proximity, tactile array, position, force/torque, cross-fire, overhead and slip. The efficient machine representation of acquired sensory knowledge will enable robots to deal with the real world. The general paradigm of a sensor data system has been developed. This system allows the robot to handle uncertainty in sensory data as well as verify and recover sensor errors.

[95] **Lyons**, D., and Arbib, M. A task-level model of distributed computation for sensory-based control of complex robot systems. COINS-TR-85-30, University of Massachusetts, 1985.

[96] **Ma**, Y., and Krishnamurti, R. REPLICA - A reconfigurable partitionable highly parallel computer architecture for active multisensory perception of 3-dimensional objects. In *Proc. IEEE International Conference on Robotics and Automation* (Atlanta, March 1984), pp. 176-184.

REPLICA is a special-purpose computer architecture for active multi-sensory perception of 3-D objects. Active multi-sensory perception of 3-D objects mean the ability to manipulate and probe objects as well as to see, hear, and touch them, where the objects may be static, changing, or in motion. In this paper the architecture of the system is presented as well as a set of interconnection networks.

[97] **Magee**, M., and Aggarwal, J. Using multisensory images to derive the structure of three-dimensional objects - a review. *Computer Vision, Graphics, and Image Processing* 32, 2 (1985), 145.

This paper presents a brief synopsis of efforts using only intensity images and a more extensive review of research that incorporates range imagery. The strengths and the weaknesses of both intensity and range domains are discussed with an eye toward combining them into a system that uses the advantages of each domain to offset the disadvantages of the other.

[98] **Magee**, M., Boyter, B. A., Chien, C., and Aggarwal, J. Experiments in intensity guided range sensing recognition of three-dimensional objects. IEEE Transactions on Pattern Analysis and Machine Intelligence PAMI-7, 6 (November 1985), 629-637.

This paper presents a method of combining the two sensory sources, intensity and range, such that the time required for range sensing is considerably reduced. The approach is to extract potential points of interest from the intensity image and then selectively sense range at these feature points. After the range information is known at these points, a graph structure representing the object in the scene is constructed. This structure is compared to the stored graph models using an algorithm for partial matching. The results of applying the method to both synthetic data and real intensity/range images are presented.

[99] **Matthies**, L., and Elfes, A. Integration of sonar and stereo data using grid-based representation. In *Proc. IEEE International Conference on Robotics and Automation* (Philadelphia, April 1988), pp. 727-734.

This paper proposes the use of a cellular representation called the *Occupancy Grid* as a solution to the problem of integrating noisy data from multiple sensors and multiple robot positions into a common description environment. The Occupancy Grids are used to combine range information from sonar and one-dimensional stereo into a two-dimensional map of the vicinity of the robot. It is simple to manipulate, treats different sensors uniformly, and models uncertainty in the sensor data and in the robot position.

[100] **Melsa**, J., and Cohn, D. *Decision and Estimation Theory.* McGraw Hill, New York, 1978.

The book provides a unified presentation of the basic tools of decision and estimation theory. The book deals with the problem of making decisions about both discrete and continuous messages, which are treated in parallel fashion. Estimation with gaussian noise is discussed. Sequential estimators, and nonlinear estimators are presented. The state estimation problem and Kalman filter are introduced.

[101] **Minsky**, M. A framework for representing knowledge. In *The Psychology of Computer Vision* (New York, 1975), pp. 211-277.

This paper Introduces a coherent theory of knowledge representation. The essence of the theory is that when one encounters a new situation one selects from memory a substantial structure called a *frame*. This is a remembered framework to be adapted to fit by changing details as necessary. Many examples from several fields, e.g., scene analysis, language understanding, learning, control, spatial imagery, etc., are considered.

[102] **Minsky**, M. *Robotics.* Double-Day, Garden City, NY, 1985.

Different aspects of artificial intelligence including computer vision, incorporating common sense in AI and robotics systems, autonomous systems, etc., are discussed.

[103] **Mitiche**, A., and Aggarwal, J. An overview of multisensor systems. *SPIE Optical Computing* 2 (1986), 96-98.

Multiple sensing is the ability to sense the environment with the concurrent use of several sensors. There are currently a number of different sensors routinely used in image processing applications, and the trend is toward the development of more sophisticated and less expensive sensors. This trend is complemented by the development of parallel and multiprocessor architectures for processing the large amount of data collected by these sensors. This paper discusses the advantages of multiple sensor integration/fusion with different sensors through image processing and identifies a number of associated problems. It reviews preliminary work on the solution of these problems and indicates the direction of future research.

[104] **Moerdler**, M. L., and Kender, J. An approach to the fusion of multiple shape from texture algorithms. In *Proceedings of the 1987 Workshop on Spatial Reasoning and Multi-Sensor Fusion*

(St. Charles, Illinois, October 1987), pp. 272-281.

This paper describes an approach that intelligently integrates several conflicting and/or corroborating shape-from-texture methods in a single system that derives the orientation of surfaces and aids in their separation and segmentation. The system uses a new data structure, and *augmented texels*, each of which combines multiple constraints on orientation in a compact notation for a single surface patch. The augmented texels initially store weighted orientation constraints that are generated by the system's several independent shape-from-texture components. This knowledge fusion approach is illustrated by a system that integrates information from two shape-from-texture methods. The system is demonstrated on camera images of artificial and natural textures including images containing more than ine surface.

[105] **Nandhakumar**, N., and Agarwal, J. K. Thermal and visual information fusion for outdoor scene perception. In *Proc. IEEE International Conference on Robotics and Automation* (Philadelphia, April 1988), pp. 1306-1308.

This paper presents a new technique for automated image analysis. Information from thermal and visual imagery is fused for classifying objects in outdoor scenes. Pixel level information fusion yield a feature based one the lumped thermal capacitance of the objects. Region level fusion employing a decision tree classifier categorizes imaged objects as being either vegetation, building, pavement, or a vehicle.

[106] **Nii**, H., and Feigenbaum, E. Rule-based understanding of signals. In *Pattern Directed Inference Systems* (New York, 1978), Academic Press.

[107] **Nilsson**, N. *Principles of Artificial Intelligence.* McGraw-Hill, New York, 1971.

Fundamental AI ideas underlying many applications are presented in this book. The important role played by generalized production systems and predicate calculus is stressed. Among the topics covered are various search procedures, production systems, predicate calculus, theorem proving, rule based deduction systems, planning, and knowledge representation. One of the earliest books on the field.

[108] **Nishizawa**, J., Tamamuchi, T., and Ohmi, T. Static induction transistor image sensors. *IEEE Transactions on Electron Devices* (December 1979), 1970-1977.

New image sensors, based on the operational principle of static induction transistor (SIT) are described. Two operational modes of SIT image sensors are also described.

[109] **Norton**, H. *Sensor and Analyzer Handbook.* Prentice-Hall, Englewood Cliffs, 1982.

[110] **Overton**, K. *The Acquisition, Processing, and Use of Tactile Sensor Data in Robot Control.*

PhD thesis, University of Massachusetts, Amherst, Massachusetts, May 1984.

Robots are machines capable of interacting with their environments in intelligent manners. In order for such capabilities to exist, these machines must be able to act relative to their environments, sense quantities about both themselves and their environments, and make decisions guided by the sensor input. This dissertation is directed toward developing a sense of touch for robot systems. Robot senses are discussed and a classification scheme developed with particular attention paid to the definition of tactile sensors. Current tactile sensors in use in laboratories are presented along with the design of the sensor developed in this work. Issues surrounding the response characteristics of the sensor and static and dynamic tactile image processing are presented and several experiments discussed. An approach to the utilization of sensory information in high-level control is also presented.

[111] **Overton**, K. Range vision, force, and tactile sensory integration: issues and an approach. In *Proceedings of the IEEE Conference on Robotics and Automation* (San Francisco, California, April 1986), p. 1463.

[112] **Petersen**, K. Silicon as a mechanical material. *Proceedings of the IEEE 70* (May 1982), 420-457.

This review describes the advantages of employing silicon as a mechanical material, the relevant mechanical characteristics of silicon, and the processing techniques which are specific to micromechanical structures. The potentials of the new technology are illustrated by numerous detailed examples from literature.

[113] **Reuber**, M., and Regan, K. Design and integration of a 3-D force sensor. In *Proceedings 1987 IEEE International Conference on Robotics and Automation* (Raleigh, North Carolina, March-April 1987), pp. 1941-1946.

A force sensor is described which measures three-dimensional forces (three forces and three moments), excludes the unwanted inertial effects of a robot's hand mass, and has outout that can be coupled to reduce the processing of forced data. A simple second-order mass-spring model of sensor performance is introduced and used to evaluate the effect of sensor location on performance. Ways to improve the integration of the sensor into a robot control system are discussed, including measuring forces as close to the point of load applications as possible, processing force data at the sensor, and shifting force control from the robot to a microprocessor and dedicated actuators.

[114] **Richardson**, J., Marshand, K., and Martin, J. Techniques of multisensor signal processing and their application to the combination of vision and acoustical data. In *Proceedings of the 4th International Conference on Robot Vision and Sensory Controls* (London, GB, October 1984).

[115] **Rosenbloom**, P., et al. R1-SOAR: An experiment in knowledge intensive programming.

IEEE Transactions on Pattern Analysis and Machine Intelligence PAMI-7, 5 (September 1985), 561-569.

This paper presents an experiment in knowledge-intensive programming within a general problem-solving production-system architecture called *Soar.* In *Soar*, knowledge is encoded within a set of problem spaces, which yield a system capable of reasoning from the first principles. Expertise consists of additional rules that guide complex problem-space searches and substitute for expensive problem-space-operators. The resulting system uses both knowledge and search when relevant. The approach is demonstrated on the computer-system configuration task, the task performed by the expert system *R1.*

[116] **Ruokangas**, C., et al. Integration of multiple sensors to provide flexible control strategies. In *Proceedings of the IEEE Conference on Robotics and Automation* (San Francisco, CA, April 1986), pp. 1947-1953.

The design and operation of an experimental robot workstation that adaptively responds to a disordered or changing environment are presented. The adaptive control is provided by the use of several sensor subsystems in a distributed architecture workcell. Included in the workstation are a commercial 6-axis robot, a microprocessor-based vision subsystem, an acoustic-ranging sensor subsystem, and a force-torque sensing subsystem; each subsystem is microprocessor based and supervisory control is provided by a workcell host computer. Five demonstrations of adaptive control are described, including real-time path modification by single sensors and integrated use of multiple sensors.

[117] **Sanderson**, A., and Perry, G. Sensor-based robotic assembly systems: research and applications in electronic manufacturing. *Proceedings of the IEEE* 71, 7 (July 1983), 856-871.

This paper presents an overview of research in the Flexible Assembly Laboratory at CMU and describes results in force, tactile, and visual sensing, sensor-based control, gripper design, and the configuration of a testbed multirobot integrated system for experiments in assembly of electronic components, using vision for the acquisition and orientation of parts and tactile sensing for assistance in insertion tasks.

[118] **Schmidt**, S. *Measuring Uncertainty.* Addison-Wesley, Reading, Ma, 1969.

This is an introductory textbook on bayesian statistics. Basic concepts are shown using Bayes' theorem are covered. Not much discussion on the analysis of variance is presented.

[119] **Schwan**, K., Bihari, T., Weide, B., and Taulbee, G. GEM: operating system primitives for robots and real-time control systems. In *Proceedings of the IEEE Conference on Robotics and Automation* (St. Louis, March 1985), pp. 807-813.

The Generalized Executive for real-time Multiprocessor applications (GEM) is an operating system that addresses several problems arising due to the unique requirements of operating software, including: GEM supports two different sizes of tasks and task scheduling, called processes and micro-processes, and offers a variety of real-time scheduling calls, and GEM supports multiple models of communication.

[120] **Sebeok**, T. Sight, *Sound and Sense.* Indiana University Press, Bloomington, IN, 1978.

This book discusses the origin and methodology of semiotics: a science that studies all possible variety of signs, the rules governing their generation and production, transmission, and exchange, reception and interpretation. Several applications of the theory including prophylactic implications of learning, translation, etc. are also presented.

[121] **Shaw**, S. W., and deFueiredo, R. J. P., and Krishen, K. Fusion of radar and optical sensors for space robotic vision. In *Proc. IEEE International Conference on Robotics and Automation* (Philadelphia, April 1988), pp. 1842-1846.

Robots operating in space need complete three dimensional description of both the workspace and the objects in it. By integrating the information coming from individual sensors a more confident, complete, or robust interpretation may be derived. Optical sensors may be augmented with microwave scattering data in the form of polarized radar cross-sections for better surface reconstruction. The radar scattering information must be converted into spatial form and then combined with other sensory data. This may be guided by the optical image.

[122] **Shekhar**, S., Khatib, O., and Shimojo, M. Sensor fusion and object localization. In *Proceedings of the IEEE Conference on Robotics and Automation* (San Francisco, CA, April 1986), pp. 1623-1628.

In this paper, the issues of locating objects through multiple sensory information is presented. Sensor measurements are subject to limitations of sensor precision and accuracy. The concept of *good measurement* is used in selecting and weighing partial estimates of the position and orientation. The problem of finding the best estimate of the position and orientation is formulated as a linear system of these multiple estimates. The best estimate is then obtained by solving this system in a weighed least square sense. This method has been implemented for a manipulator end-effector instrumented with centroid and matrix tactile sensors.

[123] **Shen**, S. A geometric approach to multisensor fusion and spatial reasoning. In *Proceedings of the 1987 Workshop on Spatial Reasoning and Multi-Sensor Fusion* (St. Charles, Illinois, October 1987), pp. 201-210.

In this paper a geometric approach to multisensor fusion and spatial reasoning is presented. There are three parts of this paper. The first part is concerned with a spherical sensory model. It provides an efficient and unified representation scheme for multisensor fusion, navigation, motor control, and spatial reasoning. The second part deals with some efficient algorithms for navigation using the spherical data structure locally at each point of a path. This illustrates how to combine this spherical sensory model with navigation and motor control which is special topic of the field of spatial reasoning. The third part is concerned with spatial reasoning. It is explained why the spherical data structure - spherical octree, is an efficient representation scheme in spatial reasoning.

[124] **Shilcrat**, E. *Logical Sensor Systems.* Master's thesis, University of Utah, Salt Lake City, Utah, June 1984.

The thesis defines a framework, Logical Sensor Specification, in which sensors can be abstractly defined in terms of computational processes operating on the output from other sensors. It is shown how the use of abstraction and functional language features in the Logical Sensor Specification System leads to a natural and simple solution to the problem of sensor configuration and integration, while facilitating reconfiguration of sensor systems so that the fault tolerance can be both expressed and achieved.

[125] **Shilcrat**, E., Panangaden, P., and Henderson, T. Implementing multisensor systems in a functional language. Tech. Rep. UUCS-84-001, The University of Utah, February 1984.

This paper discusses a methodology for configuring systems of sensors using a functional language. To date no such general methodology exists, and existing multi-sensor systems have been hand-crafted around a particular application. The main point is that the use of abstraction and of functional language features leads to a natural and simple approach to this problem. This work exploits features of a particular functional programming environment, Function Equation Language (FEL) running on the REDIFLOW simulator, to develop a simple fault-tolerance scheme that avoids complicated issues of state restoration and switching protocols, and to develop implementations of multi-sensor systems that are very close to the abstract system specification and are hence manifestly correct.

[126] **Shin**, K., and Epstein, M. Communication primitives for a distributed multi-robot system. In *Proc. IEEE International Conference on Robotics and Automation* (St. Louis, March 1985), pp. 910-917.

An *integrated multi-robot system* (IMRS) consists of two or more robots, machinery and sensors and is capable of executing almost all industrial processes with efficiency, flexibility and reliability. In order to support a distributed, modular architecture of an IMRS, in this paper low-level communication and synchronization primitives for the IMRS are proposed. This is done by comparing and analyzing the primitives developed/proposed for general concurrent programming, and carefully examining the generic structure and interactions of IMRS processes.

[127] **Siegel**, D., et. al., Computational architecture for the UTAH/MIT hand. In *Proceedings of the IEEE Conference on Robotics and Automation* (St. Louis, March 1985), pp. 918-924.

This paper presents the computational architecture for the Utah-MIT hand, and discusses design issues encountered in its hardware and software development. The large number of linkages, actuators, and sensors offers a potentially severe computational burden for control. A multiprocessor hardware configuration has been developed to distribute this computation. In the interests of efficiency, minimal operating systems were devised for each processor which nevertheless were made sufficiently general for general for task scheduling, intertask communication, and debugging. This computational architecture is a general system which is potentially useful for other robotics applications.

[128] **Stroustrup**,B. *C++*. Addison Wesley Press, New York, 1986.

The book describes the details of the C++ language. C++ is a general purpose programming language which is a superset of the C programming language. The key concept in C++ is *class*, which is a user defined type. Classes provide data hiding, guaranteed initialization of data, implicit type conversion for user-defined types, dynamic typing, user-controlled memory management, and mechanism for overloading operators. It also provides much better facilities for type-checking and expressing modularity than C does.

[129] **Tanigawa** H., et. al., MOS integrated silicon pressure sensor. *IEEE Transactions on Electron Devices* (July 1985), 1191-1195.

An MOS integrated silicon-diaphragm pressure sensor's design is presented. It was fabricated using the standard IC process. It contains two piezoresistors in a half-bridge circuit, and a new simple signal-conditioning circuit with a single NMOS operational amplifier.

[130] **Taylor**, R., Korein, J., G. Maier, and Durfee, L. A general purpose control architecture for programmable automation research. In *Proceedings of 3rd Robotics Research Symposium* (Gouvieaux, France, October 1985).

This paper proposes a general-purpose, highly configurable controller for a wide variety of sensor-based programmable automation equipment. This system will provide a flexible programming and computational environment to support a wide range of research spanning the development of new functional technology, manipulator motion control methods, explicit programming, model based program generation, and integrated manufacturing experiments. The system consists of an interactive *Programming System* connected through shared memory to a multiple-processor *Real Time System* that performs time-critical operations.

[131] **Wang**, Y. F., and Aggarwal, J. K. On modeling 3-D objects using multiple sensory data. In Proceedings 1987 IEEE International Conference on Robotics and Automation (Raleigh, North Carolina, March-April 1987), pp. 1098-1103.

In this paper a new algorithm for modeling objects using information gathered from both active and passive sensing mechanisms is introduced. Construction of the structural description of a 3-D object is composed of two stages: the visible surface orientation and partial structure are first inferred from a set of single views, and the partial surface structures inferred from different viewpoints are integrated to complete the 3-D structural description of the object. In the first stage, an active stripe coding technique is used which projects spatially modulated patterns to encode the object surfaces for analysis. In the second stage an iterate construction/refinement scheme is used which exploits both active and passive sensing.

[132] **Wise**, K. The role of thin films in integrated solid-state sensors. *J. Vac. Sci. Tech.* A-4, 3 (May/June 1986), 617-622.

This paper reviews recent developments in integrated solid-state sensors, with emphasis on the important roles played by thin films in these device structures. Most such sensors employ transducers and custom interface circuits on a common substrate, with fabrication based on the processes associated with integrated circuits. Specific examples are used to illustrate the important electrical, mechanical, thermal, optical, and chemical properties of thin films in integrated sensors.

[133] **Wise**, K. Intelligent Sensors for Semiconductor Process Automation. In *Proceedings of IEEE IECON'86*, (September 1986).

This paper discusses recent progress in the development of integrated solid state sensors for automated process control in the semiconductor industry. The possible evolution of sensors towards self-testing, addressable structures which offer high-level bus-compatible digital outputs is discussed. Issues associated with PROM-based compensation and standardization are described along with the need for generic control architectures. Several examples of emerging sensors using suspended dielectric films are given, including devices for one-contact thermal imaging, pressure measurement in reduced pressure ambients, and gas flow.