Workshop on Multisensor Integration in Manufacturing Automation

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Edited by

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Acknowledgments

Many people helped make the Workshop a success, but special thanks must be given to Howard Moraff for his support, and to Vicky Jackson for her efforts in making things run smoothly. Finally, thanks to Jake Aggarwal for helping to start the ball rolling.

1. Introduction

The coherent and efficient treatment of the information provided by multiple sensors, particularly when the sensors are of various kinds, has become an area of active research and interest over the last few years. With respect to manufacturing automation, the use of such systems is a necessity, but we are only beginning to understand and address the major issues in this domain. In addition to the specification and delineation of the role of such systems in the overall manufacturing process, there is also a need to better understand how such systems can be reconfigured, both for fault tolerance, majority sensor voting, and dynamic considerations.

Although multisensor integration is required in a wide range of applications, e.g., Automatic Target Recognition, Autonomous Vehicles, etc., the Workshop focused on multisensor integration systems in the context of manufacturing automation. It is clear that the need and availability of such systems is growing, as is the complexity in terms of the number and kinds of sensors within systems.

Many robotic sensor-based systems are currently being designed around several sensors and *ad hoc* techniques are being used to integrate them into a complete system. In the near future, such systems must operate in a reconfigurable environment; for example, there may be several cameras (perhaps of different types), active range finding systems, tactile pads, proximity sensors, and so on. In addition, a wide variety of sensing devices, including mechanical, electronic and chemical, are available for use in manufacturing sensing systems. Thus, the following issues need to be addressed with respect to multisensor systems:

1. their **role** in the manufacturing process and flexible automation,
2. their **organization** as required by the processes to be implemented,
3. their **properties** as seen from an integrated system viewpoint, and
4. their **management** in terms of the dynamics of manufacturing.

In addition, the emergence of significant multisensor systems provides a major motivation for the development of sensor specification and analysis methodologies. Designing and monitoring highly automated factories or complex chemical processes requires the integration and analysis of diverse types of sensor measurements.

A major lesson that has been learned by the members of the multisensor integration research community is that one way of obtaining 3D information is never enough. If one admits more than one source of information, then one must combine **redundant** and **complementary** information, which means that it is necessary to know the error from each source. Moreover, a distinction should be made between integration of information from <u>different</u> <u>modalities</u> (e.g., touch and vision) versus the integration of information from the same modality based on <u>different</u> <u>cues</u> (e.g., range from stereo and range from focus).

1.1. Scope and Purpose of the Workshop

In response to the needs outlined above, the Program for Automation and Systems Integration, part of the Division of Design and System Integration, sponsored a Workshop on Multisensor Integration in Manufacturing Automation held Feb. 4-7, 1987 at Snowbird, Utah. The major goals of the workshop were to:

1. Bring together the community of multisensor integration researchers and practitioners,

2. Provide an opportunity for industrial and academic counterparts to meet and mix, and

3. Identify promising research directions for NSF.

The two and half day meeting was organized with speakers and group meetings along the following lines:

- **morning sessions**: loosely packed paper/discussion sessions with each paper followed by discussion. Speakers were to present major advances, significant departures, summaries/surveys of emerging topic areas, or critiques of research activity in topic areas.
- **group sessions**: critical examination of individual research areas. Each group had a discussion leader and a reporter, with no more than eight in the group.
- **evening sessions**: evenings were used for informal and private preparation of conclusions and recommendations by individuals and groups.

The speakers were instructed to set the stage for discussion by giving tutorials, addressing new approaches or criticizing current approaches. The audience was to ask questions and challenge the speakers. The group discussions went through several stages, including brainstorming, then synthesis, and finally production of a list of research topics crucial to the understanding of multisensor integration.

Each participant was also requested to provide:

- **Academic Participant**
  - Brief Research Summary. A carefully worded one page summary of multisensor integration related research being conducted.
  - Ideal Research Statement. An outline of the research the participant would like to do if given free rein.
- **Industrial Participants**
  - Current Practice. A carefully worded summary of current engineering practice in multisensor integration.
  - Wish List. An outline of research results in multisensor integration which would be useful if given a genie.

In addition to the above information, each participant was asked to provide a list of essential readings (books, articles, etc.) on multisensor integration.

Prior to the Workshop, a set of issues concerning four major areas of concern in multisensor integration were circulated:

1. **Sensors/Signals**

- VLSI systems
- Characterization of significant information content of sensor
- Effect of nature of signal on feature extraction
- Relationship between significant information in one sensor vs. another
- Coöperative vs. independent information computation
- Symbolic vs. numeric descriptions
- Geometric registration
- Sophisticated sensors and data collection techniques
- Stereopsis and kineopsis
- Data reduction
- Noise
- Data integration
- Kalman filtering

- Control theory

2. **Systems**

- System requirements
- Important experiments which should be run
- How to evaluate software/hardware multisensor architectures
- Control
- Tradeoffs in specializing to important classes of large scale applications
- Application scale (Large scale: Factory; Medium scale: Workcell; Micro scale: Individual Unit)
- Role of multisensor systems in manufacturing
- Organization of multisensor systems in manufacturing
- Properties of multisensor systems in manufacturing
- Management of multisensor systems in manufacturing
- Realtime systems
- Models and specifications of multisensor systems

3. **Parallel, Distributed and Multi Systems**

- Combining distributed processes
- Interfacing
- Contention
- Compatibility
- Choice of sensors
- Dedicated, special purpose vs. general purpose systems
- Parallel algorithms
- Connectionism
- System resource allocation, scheduling
- Monitoring, debugging, tuning
- Reliability, redundancy
- Fault tolerance
- Load Balancing
- Complexity vs. number of processors, sensors
- Heterogeneous systems
- System abstraction
- Raw performance vs. desirable system attributes
- Mapping a problem to an architecture
- High-level models of multisensor systems (dataflow, Ada, object-based, etc.)
- Languages
- Numeric vs. symbolic

4. **CAD/CAM/AI**

- Organization of information and how to apply it to manufacturing
- What information is appropriate to sense in automated factory setting
- Knowledge integration
- Goal-directed sensing
- Numeric vs. symbolic
- Inference techniques
- Data structures, algorithms, system design
- Knowledge-based approach
- Intelligent control
- System specifications
- Computer aided design
- Computer aided manufacturing

- CAD-Based robotics

A group was formed to discuss that topic if a critical size of six people could be formed. Interestingly enough, the Signals/Sensors Group attracted enough participants so that it was split into two Groups, while the CAD/CAM/AI Group did not have enough members to constitute a Group. The final groups were as follows:

1. **Models**
2. **Sensors/Signals**
3. **Systems**
4. **Parallel, Distributed and Multi Systems**

Individuals had a "home" group, but could participate in other groups as well. The choice of groups represents a statement of the issues that the participants deemed important and timely. Each discussion group generated a summary of their deliberations, and those form the bulk of this report.

1.2. Multisensor Systems

Before going into the details of the group reports, it is useful to characterize the systems of interest. (This summary is based on a presentation by Bob Bolles.) First, the sensors of interest include:

- vision
- touch
- force
- torque
- ...
- kinesthetic
- inertial
- ...
- simulated.

This set of sensors dictates the research issues associated with their integration.

The point in using sensors is twofold: (1) to be able to perform more tasks, and (2) to perform tasks more reliably. Since these are two very useful goals, the question arises as to why aren't more multisensor systems available and in use. Is this due to sensor limitations? The answer is more likely to be found in the difficulty of adequately addressing systems issues:

- Interfacing
- Calibration
- Preprocessing,
- Information extraction,
- Etc.

Another answer is that the community is busy doing "research" and is not happy in the role of system builders.

On the other hand, there seems to be much potential in multisensor systems and at several levels. For example,

- **Task Level**
  - TV Acquires
  - Range verifies
  - Joints move
  - Touch grasps
- **Feature Level**
  - Recognition by combination of intensity, range and color features
- **Data Level**
  - Use range to correct intensity for texture analysis

The problems involved, though, are not just sensor data integration. There are also issues concerning data rates, hardware, and environmental conditions. It is also important to know the limits of one sensor. Finally, sensor characterization by manufacturers is a prerequisite for good research.

In order to share tools developed in the community (e.g., code, interfaces, ideas), a system characterization suitable for both human and machine consumption is required.

Control is another major issue which must be addressed for such systems. There are essentially three choices:

- Centralized - which leads to sequential procedure calls,
- Weakly centralized - which leads to a central control unit which initiates parallel processes, and
- Asynchronous - essentially autonomous modules reflecting an object-based organization.

Along with control, there is the issue of knowledge distribution in the system; multisensor systems may require some sort of core knowledge system or may be defined as interacting and distributed pieces of knowledge.

Research directions include sensor/technique/module characterization, both for people and for machines. Such characterizations should include analytic, statistical and experiential knowledge. Whatever control strategy is chosen, the possibility of debugging and performance measurement is essential. Finally, the calibration of such systems, whether self-defined or mutually defined between modules, is crucial to their usefulness.

2. Models

Group Participants

J.M. Brady (U. Oxford)
S.S. Chen (U. North Carolina)
H.F. Durrant-Whyte (U. Oxford)
O. Faugeras (INRIA)
P. Garrett (U. Cincinatti)
T. Henderson(U. Utah)
I. Horowitz (U.C. Davis)
A. Mitiche (INRS Telecom)

2.0.1. Sensor Models

To integrate multiple sensor observations effectively, we must be able to describe the information that can be provided by a sensor. We consider a sensor model as a description of the sensor's ability to observe and extract descriptions of the environment in terms of some prior world model. This model should provide an *a priori* description of capabilities through which observations can be aggregated, strategies developed, and coordination between sensor systems provided for. Therefore, models are needed for a number of components of the multisensor system.

- **Sensor**. A model specifies the sensor function, operation, and response performance.
- **Geometry**. Multisensor systems will deal mainly with the perception of space. The placement, shape, and spatial relationships of objects are of great importance in space perception. The relevant geometry needs to be identified and modeled.
- **Physics of the Environment**. Models of the physics of the sensed environment (e.g., irradiance) can provide useful relations in the sensor response.
- **Uncertainty**. The evaluation of uncertainty, and more importantly, the integration of uncertainty over the multisensor system, are crucial in the process of evaluation and validation of a system.
- **Sensor System**. A model describes the coordination and regulation of the various sensor activations.

Moreover, there are two important elements to a sensor model:

- The level of representation: should we model an irradiance equation, geometric information or provide a symbolic description?
- The capabilities that should be described: the ability to provide observations of geometric features in the environment, the ability of a sensor to change its location or operating state, and the dependence between observations made by different sensors.

This section describes some major issues in the development of sensor models and outlines important areas of research that need to be considered.

2.0.2. Building Sensor Models

The most important aspect of developing models of sensor capabilities is the level at which those abilities are described. Three main representations are:

- Models of sensor physics: irradiance equations, radiation detection, etc.
- Models of geometric feature extraction: descriptions of uncertain geometry, transforming information between coordinate systems, etc.
- Symbolic models of sensor capabilities: logical input-output descriptions of sensors, for

example.

In general, it is thought that all of these levels should be used, although initially work should concentrate on the first two of these, in an effort to provide *quantitative* descriptions of capabilities.

2.0.3. Control Strategies

A control strategy specifies the interface between the different models in the multisensor system and regulates their activation. The question must be addressed as to which properties of a control strategy are most appropriate for a given system. One has also to decide whether to commit each component of the system to the same set of properties, or to distribute properties as needed over the system components. Some of the control properties to consider are:

- Sequential / Parallel
- Probabilistic / Deterministic
- Coöperative / Competitive
- Feedback / Open Loop
- Modular / Hierarchical
- Goal-Directed / Data-Driven

An important advantage of using multiple sensor over single sensor systems is that coöperating observation sources provide more information than is available from a single source. The modeling of this coöperation and its use in developing sensor control strategies is very important. Elements of this problem are:

- Distributed control and system integration
- The exchange of information between sensor modules
- Resolving disagreements between systems
- The use of many sensors in a control loop
- The integration of complementary or competetive information.

Many of these considerations arise at all levels of model representation.

2.0.4. Integration of Constraints

The integration of constraints into the modeling and fusion process was considered to be an important part of sensor integration. In particular, the use of geometric constraints in linear filtering and symbolic constraints when reasoning about sensor capabilities. The integration of sensor information with constraints should be provided for at all levels of model representation. Space interpretation is based in part on the proper integration of constraints on object geometry provided by multiple observations, multiple viewpoints, motion, expectations, etc.

2.0.5. Levels of Representation

An important part of sensor modeling is the representation of the information supplied by the sensor. Indeed the representation of the environment can be considered as the dual of the sensor modeling problem. Three basic levels of representation were considered:

- Data level: reflectance properties, physical laws, etc.
- Feature level: surfaces, edges, etc. Of particular interest are mechanisms which allow many levels of geometric descriptions.

- Task level: planning and motion descriptions.

In a multisensor system, several different representations are likely to be used, each particularly suited to a given sensor. Compatibility between these representations is to be considered carefully in order to allow smooth fusion of multiple sensor information. The choice of a representation is tightly dependent on the level of sensor fusion (data level, feature level, and task level).

2.0.6. Representation of Uncertainty

A system theory is needed that can cope with uncertainty since uncertainty is intrinsic to the use of sensory information. In general, uncertainty should be treated explicitly and represented at all levels of modeling. The use of feedback theory which incorporates uncertainty has been suggested. Three problems raised are:

- What formal description of uncertainty should be used: feedback theory, probability, Dempster-Shafer, etc.
- Development of mechanisms to move uncertainty information between locations and representations.
- The validity of uncertainty models: e.g., the Gaussian noise model.

There seems to be general agreement on the use of probability models at the physics and geometry level. Other methods may be more appropriate at the symbolic level. Within probability, justification of existing methods for describing and manipulating uncertain geometric features was considered essential. There is some concern about the validity of Gaussian noise models (e.g., in laser range finding).

2.0.7. Algorithm Specification

A multisensor system is likely to require a large collection of algorithms which will often communicate through requests for information. As with any software package, it is necessary to follow strict specification guidelines to describe, for each algorithm, the input, output, side effects, complexity, stability, and relation to other algorithms. Specification is needed for algorithm development, testing and use. Appropriate specification can lead to the development of off-the-shelf algorithms.

2.0.8. State Models

In a multisensor system where several sensors are coöperating/competing toward a common goal, the proper functioning of the system is dependent on the ability to interrogate and determine the state of each sensor at any time. This is a necessary capability when resolving output from different sensors.

2.0.9. Benchmarks

A number of important benchmark problems were considered:

- The development of model standards, allowing the description of sensor capabilities supplied by a third party. This should include a description of features extracted, uncertainty estimates, dependence on other sensor information, error likelihoods, interface standards, etc.
- Task dependent evaluation criteria, providing a homogeneous framework for the comparison of different sensors and algorithms.
- Application of statistical testing and model-building techniques to describe sensor characteristics.
- The development of input-output descriptions for sensor data processing algorithms to provide modular systems.

Evaluation of system performance calls for benchmark experiments to be designed for use by the research community at large. There is currently a pressing need for the development of experimental models for (a) sensor evaluation (e.g., to be used to test or self-test), and (b) algorithm evaluation (e.g., what constitutes a good edge detector?).

3. Sensors and Signals

Group Participants

P. Allen (Columbia U.)
S. Hackwood (U.C. Santa Barbara)
J. Hollerbach (MIT)
R. Luo (NCSU)
I. McCammon (U. Utah)
G. Medioni (USC)
J. Schoenwald (Rockwell)
K. Wise (U. Michigan)

The workshop group on sensors and signals addressed a number of issues that were predicated on making sensors more available, reliable and usable. A key concern was that sensors are presently not well modeled, and obtaining reliable and accurate performance data for a sensor was seen as a particular problem. With respect to sensors being designed and produced, researchers would like to see a "spec sheet" for a sensor that would address the following sensor parameters:

- dynamic range
- localization
- hysteresis
- repeatability
- accuracy vs. precision
- bandwidth
- calibration needs
- error detection
- multi-dimensionality
- sensitivity

A specification sheet with respect to these parameters should be available for any new sensor being developed and released to the community.

A number of key sensors for robotics were discussed. They are:

- **tactile**: presently not reliable or robust. Spec sheet a must here.
- **range**: laser scanners are slow, expensive and inaccurate.
- **proximity**: both near and far proximity sensors were thought to be extremely noisy and unreliable, usually as a function of the sensed object's geometry
- **infra red**: an increasingly important sensing modality.

It should be noted that researchers felt present visible light imaging systems adequate and available. Concern was raised, however, that the TV industry was driving this technology and cannot be counted on to develop sensors for robotic applications. A particular interest was shown in foveated retina cameras for robotics.

A second area of concern was in the development of integrated arrays of detectors for process control. The areas to be looked at here are:

- chemical
- gas
- flow
- olfactory
- thermal

In the area of sensor design a number of proposals were put forth:

- A standard interface for sensors at the A/D level was proposed. This would make design of new sensors easier, and might lead to the development of sensor design tools, akin to VLSI circuit tools. Related to this is the building of modeling and simulation tools to configure and experiment with new sensor designs.
- self calibration & self test: Sensors should be designed with this capability
- automatic recovery routines for failing sensors are needed
- classification of low level sensor primitives should not be ignored. In many sensing modalities, the level above the raw signal needs to be classified and labeled (e.g., tactile primitives)
- cross disciplinary research: many of the sensors needed impinge on fields such as electrical engineering, materials science, biology, etc. It was felt that cross disciplinary research should be encouraged to develop better sensing devices.
- vertical cut in sensor design: this was suggested as an excellent way to promote good sensor design. By funding a complete sensor system, incorporating transduction, signal processing, primitive formation, and even higher level functions, good design would result. There is a tendency for devices to be built up to the initial digital interface level and stop. This sometimes encourages interesting phenomena to be exploited as a potential sensor but fails to follow through on the higher levels of interfacing.
- transduction, being the heart of sensing at its lowest levels, needs to be supported as a research topic.
- multiplexing schemes are important. Reducing wirecounts is still a critical task in sensors.
- low level signal processing algorithms are still needed.
- psychological packaging: building anthropomorphic sensors in line with observed behaviors of humans.

3.0.1. VLSI-based Sensor Technology

VLSI-based sensor technology was described in some detail by Ken Wise and represents a major area of importance to multisensor integration research. A summary of his presentation is given here. Integrated solid-state sensors are combinations of:

- custom thin films,
- precision microstructures,
- high-performance interface circuits, and
- microcomputer-based signal processing.

Current manufacturing automation systems have the following properties:

- dedicated automation for specific processes,
- largely open-loop,
- high-volume parts,
- very expensive, and
- sensor limited.

The goal is sensor-driven flexible automation. To achieve this presents several challenges. With respect to sensors, there are the problems of availability, reliability, system compatibility and cost. System issues include: reliability, adaptability, control architecture and information extraction.

In effect, manufacturing automation is an interdisciplinary challenge involving several topics:

- Process and equipment modeling,
- Improved sensors for equipment monitoring and product inspection,
- Improved equipment design (self-testing, modular, and upgradable),
- Measurement and inspection techniques,
- Expert system control structures, and
- Facility networking and simulation.

For a range on the cost per sensor in various applications, see Figure 1. For a summary of sensor systems (from current to fifth generation), see Figure 2.

As an example of future requirements, consider the typical automated VLSI wafer fabrication facility of the 1990's. There will be:

- Greater than 150 process stations,
- 50-100 Sensors per station,
- > 10,000 total sensors, and
- Facility cost of < $100M.

This requires distributed control of the sensing and a target individual sensor cost in the range of $100-$1000. Each such sensor will be characterized by:

- Standardized interface,
- Addressable, Bidirectional and bus compatible,
- self-testing and auto-ranging,
- Digitally compensated, 12-bit output accuracy,
- Operating temperature range: -40C to +175C, and
- Single 5V supply.

It should be possible to simultaneously measure gas pressure, flow rate, gas type, and temperature. Moreover, there will be internal storage of interface protocols, nonlinearity compensation, and slope/offset

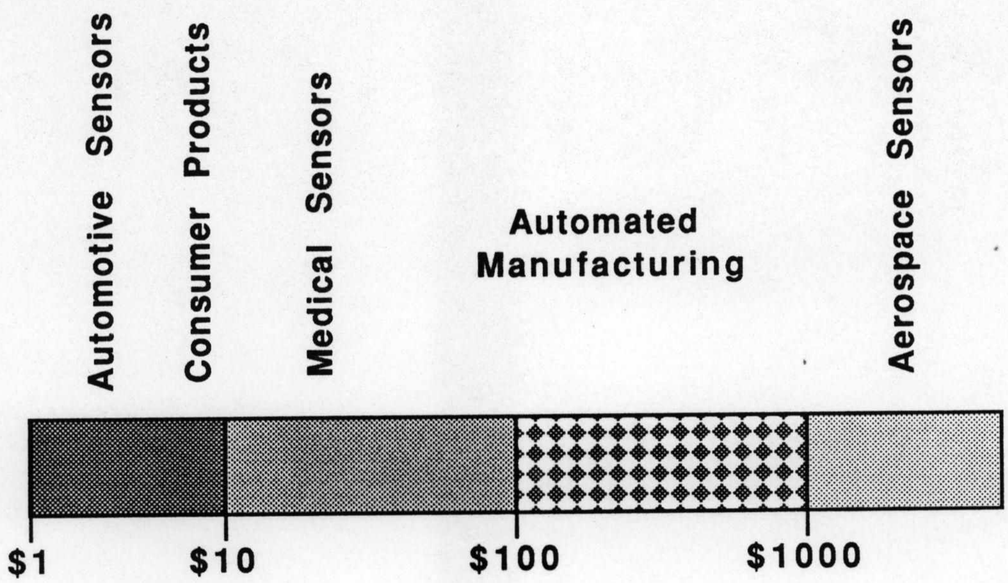

Figure 1. Typical Sensor Cost for Various Applications

compensation. Figure 3 shows a detailed fifth generation sensor. Research topics which must be addressed to achieve this goal include:

- Silicon micromachining,
- New sensing microstructures,
- Interface circuit techniques,
- PROM-based digital compensation,
- Sensor standardization, and
- Microcomputer-based signal processing.

Current research in the sensor area focuses on the development of new integrated solid-state sensors and their use in multisensor microcomputer-based instrumentation. Activities are divided into the subareas of silicon microstructures, transducer design and fabrication, custom interface circuits, and microcomputer-based signal processing. Work is centered primarily on devices for biomedical and automated manufacturing applications.

In the area of automated manufacturing, work focuses on three areas. Silicon thermal imaging arrays have been developed and are currently being applied to *in situ* VLSI process monitoring. Research is also underway to develop pressure- and temperature-based monolithic gas flowmeters and gas analyzers using thin dielectric diaphragms. This work has recently clarified the fundamental noise limits on ultrasensative pressure sensors. In a final area, work is proceeding to define appropriate interface standards for evolving integrated sensors which are self-testing, addressable, compatible with a digital

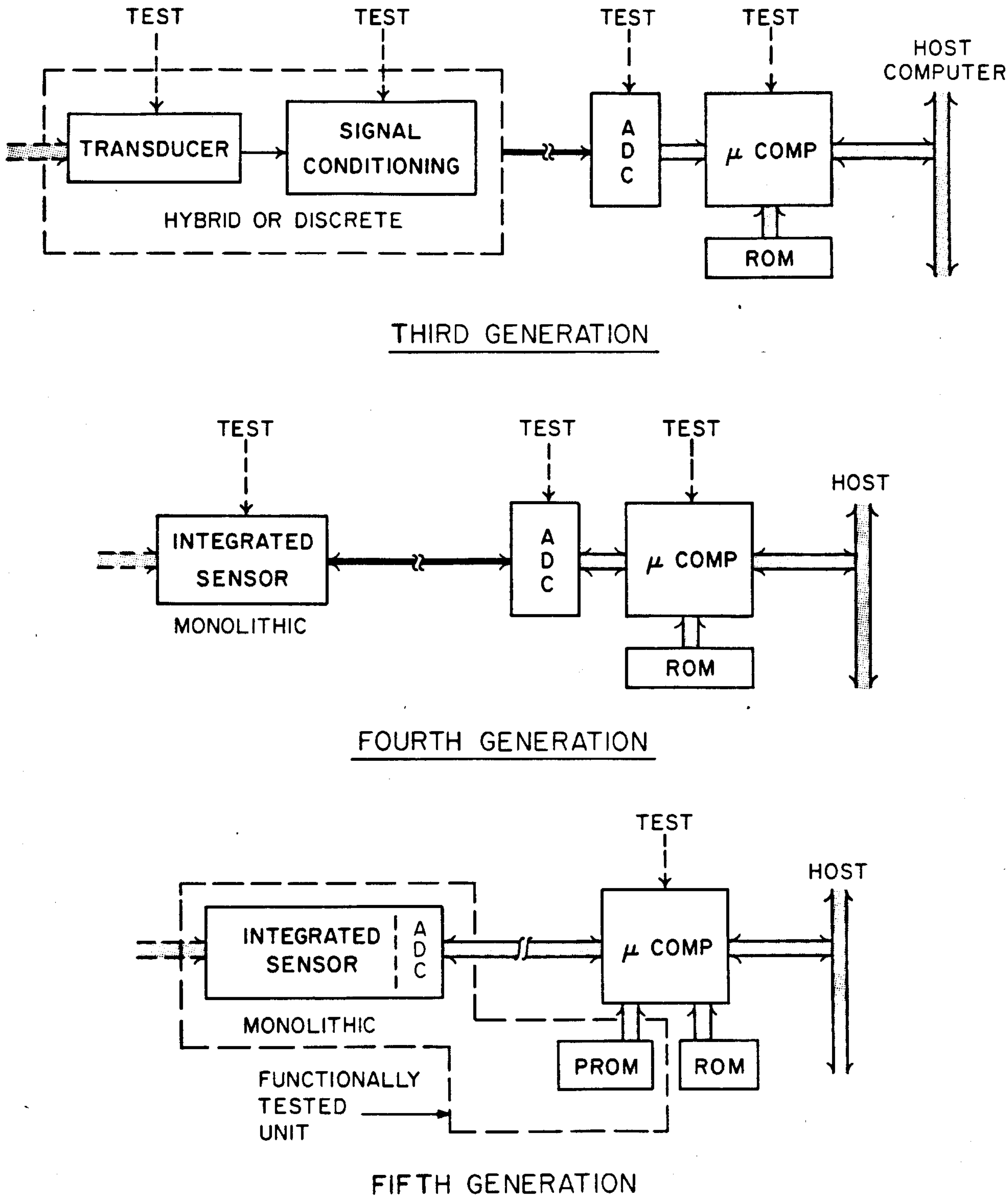

Figure 2. Sensing Systems for Automated Control

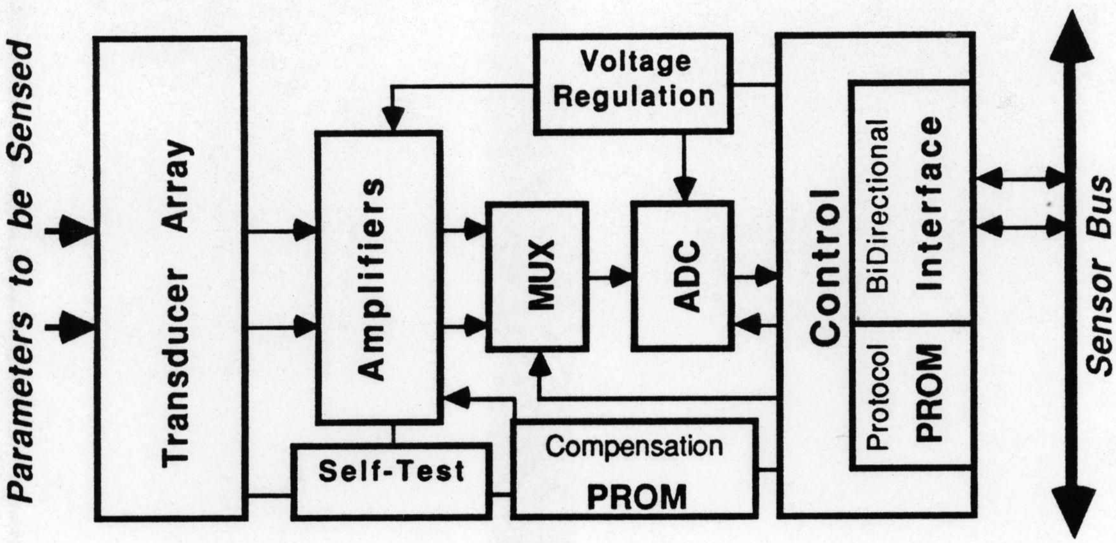

Figure 3. VLSI Fifth Generation Integrated Sensor

time-shared sensor bus, and digitally compensated. This work is helping to define the designs for next-generation sensors which will allow process equipment to be self-diagnosing and automatically upgradable.

Future research is expected to continue to concentrate primarily at the device and circuit levels, adding efforts in the development of process technology for additional thin films for transduction as well as additional activities in modeling, simulation, and system interface. In the first area, it is increasingly clear that the future development of new sensing structures will depend critically on the understanding of material properties well beyond the current art. This includes parameters such as stress in thin deposited films, surface interactions with gases and liquids, and the corresponding design of materials for optimization of the transduction process. For example, research on the use of GaAs-on-silicon to combine silicon micromachining and circuit capabilities with optical sources and detectors may allow the use of electroöptical sensing techniques for applications in gas analysis, chemical sensing, and measurement of mechanical parameters such as pressure and acceleration.

There has been very little work done in sensor modeling and simulation, and this is an important area for future research. Such work allows concepts of sensor operation to be tested and pinpoints areas where knowledge of important structural/material parameters may be missing. In some areas, modeling can serve as a guide to structural optimization. In pressure sensors, for example, a sensor compiler might be developed to translate performance parameters supplied by the user into specific device designs generated automatically.

Finally, much more needs to be done to clarify and standardize the sensor system interface and understand the trade-offs in partitioning system electronics. Such standards are critical to the successful utilization of multisensor data in next-generation instrumentation systems and to the ability to extract and appropriately utilize needed information from large data volumes.

4. Parallel and Multiprocessing

Group Participants

J. Aggarwal (U. Texas)
B. Fisher (HP Labs)
E. Kent (Philips)
M. Lavin (IBM)
R. Mann (Oak Ridge)
W. Snyder (NCSU)
J. Wood (U. Utah)

The first and most important observation is that there are many problems in Multisensor Integration where more MIPs won't help because we simply don't know how to solve the problem. Multisensor integration is new, and many (perhaps most) problems remain to be defined. We lack both a formalism in which to express problems and paradigms for conducting research in this area. Emphasis needs to be placed on the development of such formalisms.

In those cases where we do understand the problem, there is an opportunity to design special-purpose architectures, and ultimately chips, to do specific jobs.

The real-time context of robotics adds a particular dimension to efficiency of computation. Results must not merely be "timely," they must be timed to physical motion.

Although parallel architectures appear "natural" in the context of this problem domain, it appears unlikely that there is any generally applicable architecture that is efficient for all the types of problems encountered. This occurs because there is a large diversity of representations and algorithms, both numeric and symbolic. This diversity calls for a variety of architectures. Particularly relevant here is a well-defined diversity in memory architectures, including conventional memory, shared memory and associative memory. One possible exception to this statement is the class of architectures based on neural nets.

Relatively few members of the parallel computing community focus their design efforts on real-time applications as described above. Instead, they tend to design a "machine for all reasons." Our experience as robot system builders is "if I buy this, I can't do that."

To educate the machine designers in the needs of the robotics community, and to make the members of the robotics community cognizant of the capabilities of current machines, a program needs to be established to encourage interaction between the two groups. We encourage NSF to establish a program to support more interaction between the robotics and parallel architecture communities (see Section 7).

A successful autonomous system will require the ability to maintain and process several representations of knowledge simultaneously. As already noted, each representation may require a unique architecture, and therefore, before successful architecture work can continue, more extensive research in representations for knowledge is needed.

Lack of standardized interfaces, both hardware and software, is a key problem affecting our ability to make use of existing parallel processing systems.

5. Systems

Group Participants

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B. Bolles (SRI, Int.)
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S. Jacobsen (U. Utah)
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What is meant by a system? It is difficult to precisely define a system, but agreed that given a set of existing sensors the purpose of a system is to arrive at a desired goal. Five key components of a system are:

- the goal
- a model representation
- sensor representation
- a mapping between the sensor and model representations
- a strategy, e.g., goal-directed, coarse to fine.

5.0.1. Problems Needing Further Research

There are several areas requiring further research. Some of the key issues include:

- **Levels of Representation**. Often it is not possible to map directly from sensor input to the model representation or vice versa. There may therefore be a need to develop sensor and intermediate (between sensor and model) representations as well as mappings between the representations. It may even be necessary to have several different representations for the same data. Further, the detail contained in the representation is likely to vary depending on the quality of the sensory data; i.e., poor sensory information may or may not call for a more detailed model representation. However, as the quality of the sensory data improves, a less detailed model may be adequate.
- **Characterization of Modules**. Currently the reuse of modules between systems is severely hindered by a lack of understanding as to what the limitations of such modules are. One would like to know what the performance of a module is, over what range and with what uncertainty.
- **Strategy/Control**. It is uncertain whether a hierarchical control structure is appropriate in all circumstances. Goal strategies have been primarily serial in nature. However, a more opportunistic parallel approach would seem to be preferable.
- **Fault Tolerance, Self-Test, and Reliability**
- **Relation of Top Level System Performance to Sensor Performance**
- **Uncertainty**
- **How to deal with Contradictions?**

5.0.2. What's Needed to Make Progress?

- **Module Sharing between Systems**. It would be useful to develop systems from "plug compatible" modules; e.g., vision module, tactile module, etc., although we are currently far from this. Part of the problem is due to a lack of characterization of a module's capabilities. However, we are also hindered by a lack of any standard communication protocols, interfaces or data structures and the fact that many modules are very hardware dependent. Some hope is seen in a general trend toward commonality in the UNIX operating system and C or Lisp languages.
- **Explore the Idea of a Common Testbed**. There was almost unanimous consent on the frustration due to time wasted redeveloping controllers for commercial robots. A common testbed would have the advantages of a common open architecture facilitating the sharing of modules.

6. Industrial Needs

As part of the workshop, several industrial representatives were invited to participate. Of those, Jim Yates (Alcoa) provided the most extensive input. The strongest point made by industry representatives was that a workable technology transfer program must be created if the results of multisensor integration research is to be applied in industry. NSF can play a strong role in facilitating such ties between industry and the universities.

There is a great need on the factory floor for low cost sensors which linearize, condition, and preprocess input from all measured parameters. The integration of this information is crucial to system success. Particular needs include:

- better photoconductive sensors whose resistance decreases with increasing illumination, piezoresistive sensors whose resistance increases as a precise function of pressure and/or temperature, or temperature sensors whose resistance increases with temperature.
- packaging of these smart "sensors" that have both computational ability and decision making power built into them.
- indirect sensors that can measure gas, liquids, and liquid metals in a very hostile environment. They need to be low in cost and extremely small in size so they can fit on existing equipment and new material processing and handling systems.
- the integration of position and velocity sensing with limit switches and actuation.
- development of much more flexible and much higher resolution vision systems for identification of parts and guidance of material handling robots and tactile sensors on all the machine paths for not only workpiece dimensions, but all the adjustments of tool path problems.
- better, smaller and more reliable interferometers.
- devices which can monitor changes of position of objects by changes of interference patterns reflected from them. Most laser interferometers today are expensive, bulky and easily affected by the environment.
- much higher resolution optical encoders. The problem today is that the maximum allowable speeds of the measured object decreases as the resolution increases. This means that as the process speeds up, control of cutting speeds and movement speeds become unacceptable.
- better development and encapsulation of capacitive sensors. Problems exist due to susceptibility to error from stray capacitance, changes in electrode geometry, and the environment: dust and dirt on the electrodes.

- better noncontacting surface roughness sensors (scattered light, etc.), especially for quality control; i.e., scatter reflection, scatter distribution, faster decoders for control, 0.005-0.5 μ.
- noncontact 3-D sensors for automatic setup of workpieces and tools for monitoring cutters for wear and damage, for gauging holes, webs, fin sections, and other critical dimensions and in the inspection of finished parts. The existing probe systems are far too slow and the hysteresis and the stylist tips, deflection tips, are not as precise as needed.
- better linear-variable differential transformers (LVDTs). Today's devices are not as accurate as required over a large enough range.
- better strain measurement by incorporation of load cells into the sensor and better torque and vibration measurement.

The development of this kind of technology is extremely crucial in automatic drilling where the intent is to leave the machines unattended for hours. The sensors, besides having decision and diagnostic abilities, need to be able to measure drill thrust, torque, vibration, feed rate, rotational speed and depth.

Areas that require further work involving the introduction of artificial intelligence include:

- reasoning about shape from partial evidence,
- control programming paradigms for spatial reasoning,
- integration of tactile and force/torque sensing for assembly,
- reasoning architectures for spatial data,
- evidential reasoning for verifying vision,
- intelligent sensors that can recognize color, shape, size, orientation and mass estimates for inspecting, locating, tracking and inferential movement. It is important that they operate very fast because they must make measurements for ongoing processes.
- need better work environment vision matrix array for sensing one, two and three dimensions.
- need the ability to detect skewing on oil-covered, large, high-speed (one mile per minute) paths, and the ability to precisely detect the presence/absence of edging,
- need the ability to determine the thickness, or quality, of metal, by measuring fill levels and by using noncontact gauging of height, width, and depth in realtime. Size and speed are driving forces,
- need additional development in the fiber optic sensor area, with a much greater degree of insensitivity to EMI and RFI due to environment and the extraordinary broadband noise and destructive power surges in and around operating environments.

There is also a need for gas sensitive sensors. Several gas sensitive semiconductor resistor structures are commercially available. Most are used to measure partial pressures of oxygen trapped in porous structures. One goal is a small, low cost chemical sensor that is portable, rugged and inexpensive. A suitable variety of sensors fabricated on a single chip are required with a different response for different gases.

Another pressing problem is the coupling of vision, sonar ranging, and smell, i.e., chemical analysis of the environment, combined with the ability to map the environment to reach tens of goal positions.

Devices sensitive to magnetic fields are needed. Limitations with integrated Hall sensors include the fact that low sensitivity of silicon to magnetic fields has to be overcome by combining the sensor element with differential amplifiers on a single chip. A possible approach is the use of thin-film technology, and in particular, in the bolometer area for contactless temperature measurement which should in effect let the thin film measure radiation from each hot body.

Another goal is to extend or adapt Kalman filtering to the multisensor domain. The incorporation of hardware for better state space formulation, linear systems state targets and dynamic models would be useful. It is essential to make the adaptive design of higher-order dynamical systems specific rather than general using an *ad hoc* filtering technique. There is a need to understand divergence from tuning and filter tuning in theory. Methods are required for understanding computing process noise, covariant matrixes and spectral data relationships so that these can be incorporated into representational and feedback models. Also, the effects of biased and colored noise and continuous time problems need to be understood and incorporated into sensors.

A number of problems arise in signal acquisition, amplification and in impedance conversion due to the need to maintain the optimal operating temperature of the sensor. For example, infrared sensors may require cooling. The price of detector cooling equipment makes the use of such sensors impracticable. There is a need to encapsulate and integrate a number of devices capable of sensing and integrating thermal images, laser radiation sensors and multispectral data; both visible and infrared sensing are required on the factory floor. Increased sensitivity is required up in special ranges from about 1μ to about 25μ wavelength operating at a very rugged temperature range. Also desirable are quantum detectors for wavelengths greater than 3-5μ that do not have to be cooled.

In certain applications, there is a need for solid state X-ray and nuclear radiation sensors especially to allow acquiring information such as content, filling level, thickness and distances, and the chemical and structural composition of materials.

Other problems associated with chemical sensors such as gas FETs and ChemFETs include stability and lifetime (currently from hours to months).

Another interesting and difficult problem is the use of wireless links based on modulated infrared radiation, ultrasonic and electromagnetic waves. There are problems of transmission from sensor data on moving and rotating machine parts and from very remote measurement stations (autonomous vehicles and environmental control).

There is interest in the combination of thin-film polyvinylidene flouride with ceramic substrates to produce transducers for pulse echo ranging for detection of deformation of objects. The detection of slip by means of thermal sensing by incorporating thermistor functions held at constant temperature is a possibility. Finally, a thyristor incorporated in thin-film to detect heat incorporated with proximity sensing by use of reflective photosensing material combined with infrared might begin to approach human skin tactile sense.

Industry has many requirements for multisensor integration almost everywhere in the engineered material environment. Processes which must be controlled range from those characterized by differential equations to those which are understood only by accumulated experience. Multisensor integration also demands modularity of the components of such systems.

7. Conclusions and Recommendations

There was strong consensus that national funding agencies should solicit proposals for developing a national coordinated effort for sensor fabrication and evaluation. This is due to the fact that the most important problem is lack of available sensors for researchers to use. A number of ideas to help in this area were proposed.

- Create a center(s) for sensor fabrication and testing (in vitro & vivo).
- Provide support for replication of prototypes.
- Build a research robotic arm (and controller) for universities and research laboratories.
- Extend to sensors when designs and specifications stabilize (e.g., sensors for universities).

Another major problem in multisensor integration research is the requirement for a (potentially) large team of personnel due to the diverse activities involved in creating and maintaining such systems. It is crucial that funding be established either for the development of such facilities on a small-scale but widespread basis, or for the development of major centers with resources allocated for allowing visiting scientists to perform research (perhaps along the same lines as particle physics labs).

There is a need to develop a concensus of opinion within the research community as to the requirements for laboratory equipment for systems integration research. This might take the form of a procurement specification. Next, it must be determined how close such a specification is to existing technology. Is it possible to standardize on an existing commercial system?

NSF should provide funds for the purchase of such testbed equipment.

Additionally, defining performance benchmarks is premature since such benchmarks might distort the direction of research.

It is necessary to educate the machine designers, and in particular, parallel and multiprocessor designers, in the needs of the robotics community, and to make the members of the robotics community cognizant of the capabilities of current machines. To this end, it is recommeded that a program be established to encourage interaction between the two groups. We encourage NSF to establish a program to support:

1. A two-week visit by a graduate student in robotics to a site where a parallel machine is available. During this time the student will be trained on the machine. NSF would provide financial support for the student, and reasonable compensation for the host.
2. A second visit by the student, for a summer, during which the student would conduct some robotics research project on the parallel machine.

Finally, it was pointed out that there is a strong need for a geometric and probabilistic MACSYMA-like system (e.g., along the lines of work done by Mundy, Wu, et al.). Such a system would relieve individual investigators from re-solving many of the same problems.

I. Appendix A: Recommended Background Knowledge in Multisensor Research

The sensor area is very broad and can be approached from many directions. For work at the device level, a background in silicon integrated circuits and their technology is essential. For work on transducers, an understanding of materials processing is important as well as some familiarity with surface chemistry, heat flow, optics, or other disciplines depending on the particular type of device chosen. At the system end, expertise in signal processing techniques is important along with some background in the expert systems/AI approaches necessary to extract and utilize information from large multisensor data volumes. Because of the broad problems encountered in sensors, sensor research lends itself well to interdisciplinary research groups and is probably best pursued in such settings.

Broad areas of which some knowledge is required:

- Computer Vision
- Pattern Recognition
- Detection and Estimation Theory
- Intelligent Robotics
- Artificial Intelligence
- Knowledge Engineering
- Graph Theory
- Sensors and Control Engineering
- Probability and Statistics
- Computer Architecture
- Signal Processing
- Image Processing
- Adaptive Filtering
- VLSI
- Physics / Sensor Design
- Noise Analysis
- Software Systems, especially object-based languages

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