Sensor-Based Robots: Algorithms and Architectures

Edited by C. S. George Lee

NATO ASI Series

Series F: Computer and Systems Sciences, Vol. 66

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Springer-Verlag Berlin Heidelberg New York
London Paris Tokyo Hong Kong Barcelona
Published in cooperation with NATO Scientific Affairs Division

Proceedings of the NATO Advanced Research Workshop on Sensor-Based Robots: Algorithms and Architectures, held in Château de Bonas, France, October 12–14, 1988.

ISBN 3-540-52298-0 Springer-Verlag Berlin Heidelberg New York
ISBN 0-387-52298-0 Springer-Verlag New York Berlin Heidelberg

Printed in Germany

Printing: Druckhaus Beltz, Hemsbach; Binding: J. Schäffer GmbH & Co. KG, Grünstadt
45/3140-543210 – Printed on acid-free-paper

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Series F: Computer and Systems Sciences, Vol. 66

Preface

Most industrial robots today have little or no sensory capability. Feedback is limited to information about joint positions, combined with a few interlock and timing signals. These robots can function only in an environment where the objects to be manipulated are precisely located in the proper position for the robot to grasp (i.e., in a structured environment). For many present industrial applications, this level of performance has been adequate. With the increasing demand for high performance sensor-based robot manipulators in assembly tasks, meeting this demand and challenge can only be achieved through the consideration of: 1) efficient acquisition and processing of internal/external sensory information, 2) utilization and integration of sensory information from various sensors (tactile, force, and vision) to acquire knowledge in a changing environment, 3) exploitation of inherent robotic parallel algorithms and efficient VLSI architectures for robotic computations, and finally 4) system integration into a working and functioning robotic system. This is the intent of the Workshop on *Sensor-Based Robots: Algorithms and Architectures* — to study the fundamental research issues and problems associated with sensor-based robot manipulators and to propose approaches and solutions from various viewpoints in improving present day robot manipulators in the areas of sensor fusion and integration, sensory information processing, and parallel algorithms and architectures for robotic computations.

This Workshop was held on October 12-14, 1988, at Chateau de Bonas, Bonas, France, and was held in conjunction with another NATO Advanced Research Workshop on *Knowledge-Based Robot Control*, organized by Professor George N. Saridis of Rensselaer Polytechnic Institute and Professor Harry E. Stephanou of George Mason University, which was held at the same location on October 10-12, 1988. Both Workshops addressed a common theme on October 12 — Sensor Fusion. The purpose of holding these two Workshops back to back was to reinforce each Workshop's findings and to integrate the results since they are closely interrelated.

A total of 30 participants attended the Workshop with 14 speakers, 12 participants, and 4 committee members. Each day of the Workshop was devoted primarily to a brief presentation of research results followed by a discussion in each of the three major areas in sensor-based robots: *sensor fusion and integration, vision algorithms and architectures,* and *neural networks, parallel algorithms and control architectures*. This book includes all the twelve papers that were presented at the Workshop.

A total of five papers were presented at the Workshop addressing problems in sensor fusion and integration, such as sensing with uncertainty, sensor modeling, description, representation, and integration of sensory information in multisensor environment. Only three papers were included in this book and the other two papers were included in the NATO ARW book, *Knowledge-Based Robot Control*, edited by Professors G. N. Saridis and H. E. Stephanou. The first paper, "An Integrated Sensor System for Robots," by Rembold and Levi, describes an experimental autonomous mobile system with sensors, called KAMRO (KArlsruhe Mobile RObot), for manufacturing applications. The paper details the architecture and functions of the sensor system of KAMRO. The second paper, "Robot Tactile Perception," by Buttazzo, Bicchi, and Dario, describes an active or exploratory sensing strategy for a tactile sensor in a 4 DOF "hand." The paper describes an approach for decomposing complex tactile operations into elementary sensory-motor actions, each of which extracts a specific feature from the explored object. The third paper, "Uncertainty in Robot Sensing," by Grant, describes approaches and possible solutions for dealing with the inherent uncertainty that is associated with the modeling, planning and motion of manipulators and workpieces.

For the vision algorithms and architectures session, algorithms and architectures of model-based and/or knowledge-based vision systems were addressed to add intelligence to robotic systems. A total of four papers were presented in this area. The paper, "Robotic Vision Knowledge System," by Wong, describes the use of local features and geometric constraints for constructing knowledge-based vision system for object recognition. The paper, "Algorithm for Visible Surface Pattern Generation — a Tool for 3D Object Recognition," by Majumdar, Rembold, and Levi, describes the use of a CAD model for modeling and the manipulation of 3D objects which can be transformed and used for vision recognition. The paper, "Knowledge-Based Robot Workstation: Supervisor Design," by Kelley, describes a knowledge-based system for planning and scheduling tasks to be executed on various robotic workstations. The paper, "Robot/Vision System Calibrations in Automated Assembly," by King, Puskorius, Yuan, Meier, Jeyabalan, and Feldkamp, describes a fully-implemented vision-guided robotic system. The robot (Merlin robot) is equipped with a pair of CCD cameras for automated assembly tasks.

For the neural networks, parallel algorithms and control architectures session, a total of five papers were presented. The paper, "A Unified Modeling of Neural Networks Architectures," by Kung and Hwang, proposes a unified modeling formulation for a variety of artificial neural networks (ANNs), which leads to a basic structure for a universal simulation tool and neurocomputer architecture. The paper, "Practical Neural Computing for Robots: Prospects for Real-Time Operation," by Aleksander, describes the use of a neural machine called WISARD for pattern classification and its extension to experiential knowledge-based tasks. The paper, "Self-Organizing Neuromorphic Architecture for Manipulator Inverse Kinematics," by Barhen and Gulati, proposes a novel neural learning formalism, based on "terminal attractors" for solving a large class of inverse problems, including the inverse kinematics of redundant robots. The paper, "Robotics Vector Processor Architecture for Real-Time Control," by Orin, Sadayappan, Ling, and Olson, describes a restructurable VLSI robotic vector processor (RVP) architecture, which exploits the parallelism in the low-level matrix-vector operations in robot arm kinematics and dynamics computation. Interconnection of multiple RVPs can be used to match the computational requirements of specific robot control strategies. The paper, "On the Parallel Algorithms for Robotic Computations," by Lee, describes the inherent parallelism in robotic computation which was exploited to develop efficient parallel algorithms to be computed on SIMD machines for controlling robots. Finally, a report on the group discussion entitled "Neural Networks in Robotics" was written by Torras.

The presentations and discussions at this Workshop only present a small sample of solutions for an important research area of algorithms and architectures for sensor-based robots. I expect the research in this area to continue to grow, and more NATO Advanced Research Workshops about this area may be appropriately scheduled in the near future.

Finally, I would like to take this opportunity to thank Dr. Norm Caplan of the National Science Foundation (USA) for his continued encouragement throughout the process of organizing and realizing this Workshop. I also would like to thank the Organizing Committee, Professor R. L. Kashyap of Purdue University, USA, Professor F. Nicolo of University of Rome, Italy, Professor U. Rembold of Universität Karlsruhe, FRG, and Professor H. E. Stephanou of George Mason University, USA, for their hard work for putting the program together. Special thanks are also due to Ms. Dee Dee Dexter for her clerical work associated with the Workshop and for putting all the manuscripts together. Last but not the least is Professor G. N. Saridis who deserves special thanks for his advice on organizing the Workshop, without whose continued push for perfection, the Workshop would not have been a success.

C. S. George Lee

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Part I

Sensor Fusion and Integration

An Integrated Sensor System for Robots

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Summary

In this paper the architecture and functions of the sensor system of an autonomous mobile system are described. The sensor system supports the operation of the planning, execution and supervision modules necessary to operate the robot. Since there is a multitude of concepts of vehicles available the sensor system will be explained with the help of an autonomous mobile assembly robot which is being developed at the University of Karlsruhe. The vehicle contains a navigator, a docking module and an assembly planner. The driving is done with the help of cameras and sonic sensors in connection with a road map under the direction of the navigator. The docking maneuver is controlled by sensors and the docking supervisor. The assembly of the two robot arms is prepared by the planner and controlled by a hierarchy of sensors. The robot actions are planned and controlled by several expert systems.

1 Introduction

For several years, various autonomous mobile robots are being developed in Europe, Japan and the United States. Typical areas of application are mining, material movement, work in atomic reactors, inspection of under-water pipelines, work in outer space, leading blind people, transportation of patients in a hospital, etc. The first results of these research endeavors

NATO ASI Series, Vol. F 66
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indicate that many basic problems still have to be solved until a real autonomous mobile vehicle can be created; e.g. the development of an integrated sensor system for the robot is a very complex effort. To recognize stationary and moving objects from a driving vehicle is several orders of magnitude more complex than the identification of workpieces by a stationary camera system. In most cases the autonomous system needs various sensors. For processing of multi-sensor signals, science has not found no good solution to date. An additional problem imposes the presentation and processing of the knowledge needed for operating the sensor system. Unexpected obstacles have to be recognized by the sensor and interpreted. If necessary, an alternate coarse of action has to be planned.

Seldom, an autonomous system is used for driving missions only. In general, it has retrieve parts from a storage, to bring them to a work table and to assemble them to a product, Fig. 2. All work has to be done autonomously, according to a defined manufacturing plan which is given to the system. In this article, the sensor module for an autonomous mobile system is being described, whereby the functions are explained with the help of the Karlsruhe Autonomous Mobile Assembly Robot (KAMRO).

2 *Autonomous Mobile Systems for Manufacturing*

There are various applications for autonomous systems in manufacturing. Most of the early projects concerned with this subject, involved the conception and implementation of vehicles for the movement of materials and workpieces. Hitherto, the efforts only succeeded in developing semi-automatic vehicles which can follow a path laid out by a guide system, such as an induction loop or a painted stripe on the floor. This type of guidance needs a simple sensoric and control strategy to steer the vehicle. The developments allowed to significantly increase the flexibility of manufacturing systems, whereby various manufacturing orders may be processed by a different combination of machine tools. Thus, it is possible to conceive simple programmable manufacturing facilities. However, the motion of the vehicle is confined by the guide system.

With autonomous mobile robots it is possible to develop manufacturing plants of great flexibility. Any combination of machine tools may be selected according to a virtual manufacturing concept. E.g. an autonomous assembly system equipped with robot arms is capable of working at various assembly stations. For welding or riveting tasks, the robot can move along a large object, such as the hull of a ship and perform the desired operations. An increase in flexibility can only be obtained by the use of knowledge based planning, execution and supervision modules which are sensor supported. In addition, omnidirectional drive systems have to be conceived, capable of giving the vehicle a three-dimensional flexibility, including turning on a spot.

3 *Components of an Autonomous Mobile System*

An autonomous system must be capable of planning and executing a task according to a given assignment. When a plan is available, its execution can start. A complex sensor system must be activated which leads and supervises the travel of the vehicle. Furthermore, it is necessary to recognize and solve conflicts with the help of a knowledge processing module. The basic components of an autonomous intelligent robot are shown in Fig. 3. To conceive and build these components, expertise of many disciplines such as physics, electronics, computer science, mechanical engineering, etc. is required. It is very important to design good interfaces between the functional components of the system.

The most difficult task is building the software. This is a universal problem with automation efforts involving computers. Designing software for autonomous vehicles is, however, complicated by the fact that very little is known about their basic concepts. An autonomous vehicle must have the following capabilities:

- autonomous planning and preparation of actions according to a given task
- independent execution and supervision of the actions
- understanding of the environment and interpretation of the results from sensor information
- independent reaction to unforeseen events
- passive and active learning capabilities

Figure 4 shows the planning and control system of the autonomous vehicle. It consists of several hardware and software modules which are interconnected to a functional unit.

The planner obtains information to assemble a product. In order to execute the assignment knowledge about the product is obtained from a CAD database. Furthermore, the robot has to know its environment, operating parameters and sensor hypotheses. This knowledge is obtained from a world model. The information about its work scenario must be current and dynamically updated by the sensor system. The planning is a very difficult and time consuming process and is done off-line with a powerful scientific computer. Since the planner needs live sensor data a link to the computers executing the plan must be provided.

The execution of the plan is done by a distributed vehicle computer. There are several CPUs operating in parallel to expedite the processing of the work assignment. The vehicle computers interprete stepwise the instructions and execute them. In addition, expert knowledge is given to the vehicle computer to process sensor information and to solve conflicts which may arise during the navigation, docking or assembly. Since the size of the vehicle computer is restricted, it only can solve simple problems. In serious situations the main computer will be notified and it in turn tries to find a solution. It will also prepare and issue a situation report for the operator.

The supervisor observes the operation of the vehicle and reports any problems. There are two types of disturbance which may occur, they are of parametric and structured nature. Parametric problems stem from wrong sensor parameters. If properly recognized they can be corrected locally. Structured problems stem from unforeseen changes in the robot world where the location of parts may have changed. In this case the operation has to be replanned off-line by the planner. To perform its task, the supervisor constantly reads and evaluates sensor data. Since conclusions may have to be drawn from measurements of various sensors the evaluation of the sensor data may be very involved.

The control module operates the feedback loops of the robot system, it compares the set points with the controlled variables and tries to correct deviation. Any problems are reported back to the executive and planner and are used for corrective actions if necessary.

In the further discussion of this paper only the sensor system will considered.

4 *The Sensor System*

A sensor system of the Karlsruhe autonomous mobile robot consists of various sensors which are interconnected by a hierarchical control concept. The sensors furnish the planning and supervision modules with information about the status of the robot world. For each of the three major tasks of the vehicle, the navigation, docking and assembly an own sensor system is provided.

The sensoric has the following assignments:

- locating workpieces in storage
- supervising the vehicle navigation
- controlling the docking maneuver
- identifying the workpieces and their location and orientation on the assembly table
- supervising the assembly

- inspecting the completed assembly

For the navigation of the autonomous vehicle, a multisensor system is necessary. A distinction is made between vehicle based internal and external sensors and world based sensors. Internal sensors are incremental decoders in the drive wheels, a compass, inclinometer, etc. External sensors are TV cameras, range finders, approach and contact sensors, etc. World based sensor systems use sonic, infrared, laser or radiotelemetris principles. For the navigation various approches may be used:

- deadreckoning
- navigation under the direction of a compass
- the use of world based sensor systems
- driving under the guidance of floor markers and vehicle based external sensors
- navigation by vehicle based external sensors, such as a camera or a laser range finder
- the use of a combination of navigation principles

A vehicle driving in an obstacle free environment may use any of the first four principles. In case obstacles are entering or leaving the vehicle´s path or when it is possible that the robot may veer off the course, vehicle based external sensors must be used. For example, the vehicle must constantly monitor the path with a camera system. Most advanced autonomous vehicles use a combination of several approaches systems to react to unforeseeable events. Recognition is done by extracting specific features from the picture of the scenario and comparing these with a sensor hypotheses obtained from a world model. For scenes with many and complex objects the support of an expert system is needed for the sensor evaluation.

The docking maneuver will be supported by optical, magnetical or mechanical proximity sensors. Thereby, for coarse positioning a vision system may be used and for fine positioning mechanical feelers.