

**Intelligent Mobile Robots in the Workplace:
Leaving the Guide Behind**

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Technical Report: GIT-ICS-88/08

This paper also appears in the
*Proceedings of the First International Conference on
Industrial Applications of Artificial Intelligence and Expert Systems*
Tullahoma, Tenn., June 2-3, 1988.

Abstract

Flexible manufacturing systems (FMS) that incorporate transport robots are currently dominated by the use of automatic guided vehicles. These AGVs generally require significant restructuring of the workplace in order for them to be useful. The concept of flexibility in manufacturing is somewhat compromised by this strategy.

Our previous work in mobile robots, resulting in the Autonomous Robot Architecture (AuRA), is applied to the manufacturing domain. This approach, contrary to the AGV methodology, embeds significant amounts of knowledge (both environmental and behavioral) to ultimately give a mobile robot far greater latitude in interacting with its environment.

This paper presents the motivation and subsequent simulation studies that demonstrate the feasibility of migrating schema-based navigation into an FMS. In particular, the creation of a docking motor schema to accomplish interaction with the workplace is detailed.

This research is supported in part by the Computer Integrated Manufacturing Systems (CIMS) Program and the Material Handling Research Center at the Georgia Institute of Technology.

Intelligent Mobile Robots in the Workplace: Leaving the Guide Behind

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1. Introduction

Manufacturing applications for autonomous mobile robots constitute an area that has received little attention when compared to research performed in the context of outdoor navigation (e.g. autonomous land vehicle) or hazardous environments (e.g. nuclear power plants). The preponderance of the current research in mobility surrounding flexible manufacturing systems (FMS) involves the use of automatic guided vehicles (AGVs). These vehicles simplify the problem of navigation by restricting their paths to predetermined routes, typically demarcated by striping the floor in some manner or by using buried cables. A major issue is just how "flexible" such systems are.

Our previous research in the development of the Autonomous Robot Architecture (AuRA) has provided a framework that is readily adaptable to manufacturing environments. Our goal is to eliminate or minimize the restructuring of the workplace to satisfy the navigational needs of a mobile robot. This approach necessitates the representation of significant amounts of *a priori* knowledge of the manufacturing environment, the use of a diversity of sensors and sensor strategies, and the selection and specification of relevant motor behaviors for this particular domain.

This paper first reviews the current approaches towards achieving mobility in the workplace, describing the role of AGVs and some of the preliminary work of other groups in autonomous vehicles. Section 3 presents an overview of the Autonomous

Robot Architecture (AuRA), a general-purpose system designed for experimentation in the domain of intelligent mobility. The means by which navigation is accomplished within this framework is specifically addressed. Section 4 describes the changes made to AuRA to adapt it to function in a flexible manufacturing environment, discussing the types of knowledge that need to be incorporated and the new motor behaviors required for this domain. Simulations of both navigational planning and reactive/reflexive motor schema-based navigation in an FMS environment are presented in Section 5. A summary and description of future work conclude this paper.

2. Mobility in the workplace

Many papers exist describing the role and history of AGVs in flexible manufacturing systems (e.g. [11,22,25]). It is evident that intelligent sensing has not played a major role in most of this research. The work area of an FMS frequently undergoes significant change in adapting it to meet the perceptual needs of an AGV rather than improving the vehicle's intelligence. This typically involves the laying of cables [27], the painting of stripes, using magnetic markers [23], the placement of retro-reflective landmarks [10] or infrared beacons [13]. In other cases, almost complete reliance on highly accurate dead reckoning systems is required [17]. World modeling is generally kept to a minimum as travel is usually severely restricted within the workspace.

The problem of docking has also been studied. Docking strategies, using lasers for space applications [14] or visual techniques in FMS environments (e.g. [21]) have been developed. Many groups are addressing this problem, far too many to cite them all. The reader is referred to [24] for a review of the progress in this area.

Autonomous mobile robots are also being investigated for use in FMS by other research groups. Giralt and Chatila [16] at LAAS in France are migrating the techniques developed on Hilare for use in manufacturing environments. Work at the University

of Karlsruhe [26] is also concerned with this problem.

Our previous research in the general issues of intelligent navigation [6] is now being migrated to manufacturing environments. We propose that this is a more coherent approach to the problem of mobility in flexible manufacturing systems. Instead of attempting to solve, in an *ad hoc* manner, the needs of one narrow problem domain, we choose to address the more general issue of intelligent navigation in man-made environments, then migrating what we have learned in this broader case to a specific instance (e.g. FMS). Granted, this will not lead to short-term solutions and immediate applications. Nonetheless, it is our premise that for significant long-term progress to be made in mobility for manufacturing environs (or anywhere else for that matter), a deep understanding of and consideration for the issues and difficulties of perception and motor action is necessary.

3. AuRA

The Autonomous Robot Architecture [5,6] was initially developed as a framework for studies in the intelligent connection of perception to action in the context of mobile robotics. Domain-independent general purpose navigation was a primary focus of this research. Many of the strategies developed within AuRA can be exploited effectively when a limited domain of interaction is present, as is found in a flexible manufacturing environment. The ability to incorporate *a priori* knowledge in a world that is relatively closed facilitates the navigational process. Nevertheless, new behaviors must be created to allow the robot to interact productively in such an environment. The remainder of this section describes the general AuRA architecture and how navigation is conducted within its framework. The balance of the paper then describes its application specifically to a manufacturing setting. It should be stated that the AuRA architecture is in an evolving state; not all of the components are fully integrated at this time.

3.1 Architecture overview

The AuRA architecture (Fig. 1) consists of 5 principal components: the perception, cartographic, planning, motor, and homeostatic control systems. An overview of their roles is presented below. The reader is referred to [6] for more detailed information.

The role of the perception subsystem is to acquire sensory information (currently monocular monochromatic vision, ultrasonic, and shaft encoder data), perform preliminary filtering on the raw data, and structure the information in a form that is useful to the planning and cartographic subsystems. Visual strategies [8] currently provide data relevant to vehicle localization and path following (using line-finding and region segmentation algorithms), while both ultrasonic data and vision yield information suitable for obstacle avoidance applications. The shaft encoders provide information pertinent to the management of spatial and orientation uncertainty [9].

The cartographic subsystem subsumes several responsibilities. It is the principal repository of *a priori* knowledge for guiding both mid-level navigational planning techniques and expectation-based perceptual processing. In addition to this static long-term memory representation, it is also responsible for building a dynamic world model based on sensor observations (short-term memory). This is used when schema-based navigational techniques fail. Finally, spatial uncertainty management is maintained within the confines of the cartographic subsystem [9].

The motor subsystem is delegated the responsibility for issuance of specific motor commands to the mobile robot (in our case, George, a Denning research vehicle - Fig. 2). Communication issues, status monitoring, and low-level motor control fall within the confines of this subsystem. A design goal of AuRA is to assure vehicle independence as much as possible. As a result, vehicle dependency is largely isolated within the motor subsystem component of the overall AuRA architecture.

Homeostatic control is concerned with the issues of robot survivability in danger-

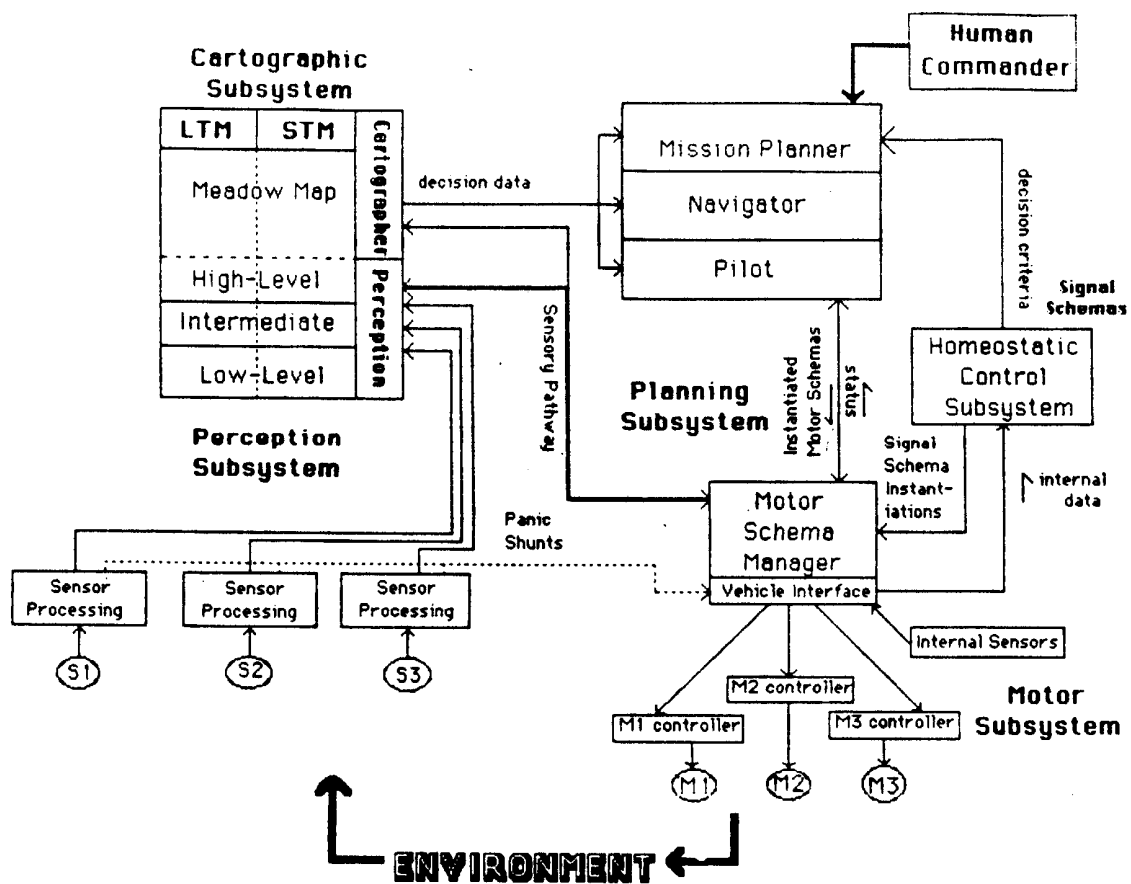


Figure 1. Autonomous Robot Architecture

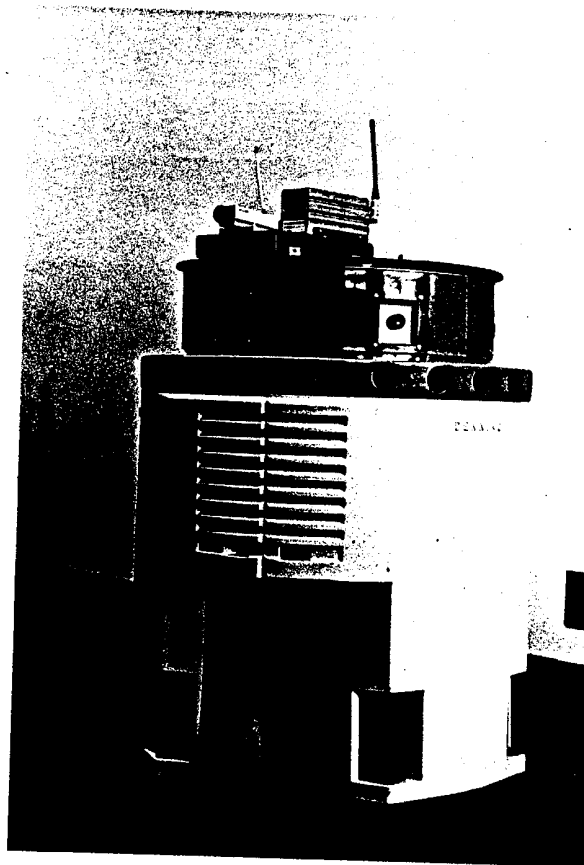


Figure 2. George.

ous environments. The manufacturing setting is considerably safer than many other potential applications of the AuRA architecture, such as space exploration vehicles, rescue operations, and undersea environments. Thus, homeostatic control issues are not a concern of this paper.

The planning subsystem incorporates both a hierarchical planner (mission planner, navigator, and pilot) and a distributed control plan executor (the motor schema manager). The way in which these components are structured is described in the following subsection.

3.2 Navigation

AuRA's planning subsystem is depicted in Figure 3. The hierarchical planning component consists of a mission planner, navigator, and pilot. The mission planner's role is to determine mission objectives, set behavioral and planning parameters for other components of the planning subsystem, and interface with the human commander, or a central computer in a CIMS (computer integrated manufacturing systems) environment.

The navigator is delegated the task of computing an initial path based on *a priori* world knowledge [3]. A series of path legs is produced which then serves as the input to the pilot. The pilot analyzes an individual leg in light of information embedded within long-term memory. The output of this analysis is a collection of parameterized motor behaviors and associated perceptual strategies (schemas - see [4]) which are used within the confines of the motor schema manager to produce intelligent goal-driven, action-oriented behavior. A methodology based on the potential fields approach [19,20] is used to provide the robot with specific motor commands at any point in time that reflect, in a reactive/reflexive manner, the perceptual uncertainty in the environment. This schema-based approach to navigation has a strong correlate with neuroscientific and psychological behavioral studies [7].

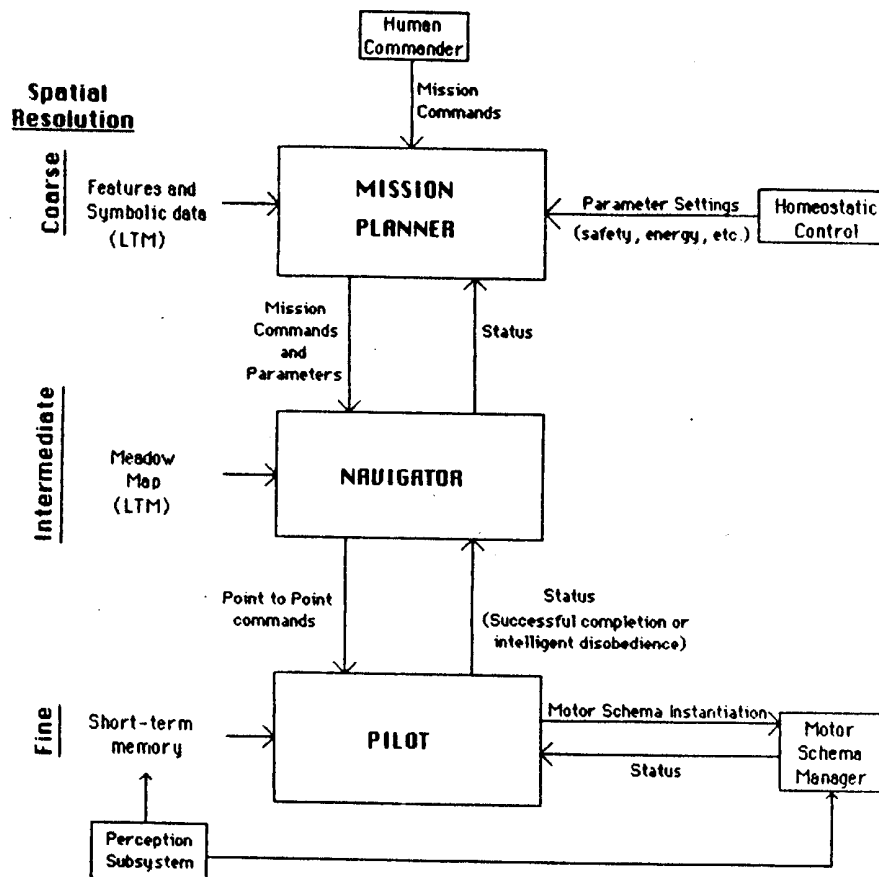


Figure 3. AuRA's planning subsystem.

4. AuRA in Manufacturing

The issue now confronting us is how to utilize the concepts developed within AuRA in the context of a manufacturing environment. By so doing, we anticipate considerably greater flexibility and extensibility than the previous efforts involving automatic guided vehicles afforded. That is not to say that our approach will supplant this technology immediately, as it does not purport to be cost-effective at this point in time. Nonetheless, as hardware costs drop, these methods are envisioned to become more and more economically competitive.

The motivation for our approach is first described. A discussion of the environmental knowledge available in a flexible manufacturing setting that can be used to provide information stored within AuRA's long-term memory to guide both navigational planning and perceptual processing is then presented. This is followed by a study of the behaviors germane to manufacturing tasks, including strategies such as docking which have been created specifically for these FMS applications.

4.1 Motivation

The essence of our approach involves the specification of appropriate motor behaviors and associated perceptual strategies to fit the particular needs of a manufacturing task. The integration of *a priori* knowledge to assist in perception is another fundamental tool. Manufacturing environments allow us to make reasonable predictions, regarding perceptual events, that might not be plausible in more unconstrained situations (e.g. outdoors).

Intelligent docking is the particular focus of our research at this time. Motor control in this case can be viewed as the application of two distinct strategies, ballistic motion and guarded motion [2]. Ballistic motion, for our purposes, is characterized by a feedforward control mechanism. This control regime brings the vehicle rapidly

into the approach zone of the workstation with minimal sensory feedback. Upon entry of the approach zone, guarded motion takes over, characterized by feedback control, higher sensory sampling rates, and slower motion. Previous work at the Cranfield Institute of Technology [1] has also considered coarse and fine navigation strategies in the context of AGVs.

One of the most critical control issues concerns the transition point from ballistic to guarded motion. Whether both control paradigms should be active concurrently with one inhibiting the other, or whether a direct transition from ballistic to guarded motion should occur based on specific perceptual trigger events, is unresolved. Our initial work (see Section 5.2) takes the latter tack.

Different perceptual strategies are in play for each of the control paradigms. In our first pass of research, ballistic motion relies predominantly on shaft encoder data (dead reckoning) to bring the vehicle approximately to a known position relative to its docking goal. Certainly other sensors are actively involved during this motion to cope with dynamic obstacle avoidance and vehicle localization. The action-oriented component of the ballistic motion for docking will ultimately be tied more closely to the spatial uncertainty map [9] of the AuRA architecture moving further from reliance on dead-reckoning methods.

Our first approach to the guarded motion component of docking encompasses both vision and ultrasonic data. Our monocular video camera will provide the vehicle with orientation data, targeting on known features of the workstation. Two perceptual algorithms, the fast-line finder and the fast region segmenter [8] are being applied to this problem. Ultrasonic data, coupled with vision, provide the depth information for final positioning. Although vision can yield depth information, based on *a priori* knowledge of workstation features and camera geometry, initially we will use a combination of sensors to achieve our goal.

Perception also decomposes into two subtasks: recognition and tracking. Worksta-

tion recognition is undoubtedly the more difficult aspect of the problem. If workstations *au naturel* prove difficult to distinguish, we may add an artificial landmark to facilitate this process. It is intended, however, that this landmark be for use by passive sensing, akin to the work done by Fukui [15], Courtney et al [12], and Kabuka et al [18]. Once the initial landmark has been discovered, the task of tracking is greatly simplified by updating the initial expectations of the feature(s) characteristics to match more closely the data perceived by our sensors (transferring belief from what is expected to what is perceived), and by using information regarding the robot's commanded motion between frames to provide tighter constraints on where the feature(s) may occur within the new incoming images.

4.2 Environmental knowledge

We have modeled Georgia Tech's Materials Handling Research Center Laboratory (Figures 4 & 5) using the techniques available within the AuRA architecture. A meadow map (connectivity graph of free space regions [3] - see also Sec. 5.1) is produced which allows for the production of paths, using an A* search algorithm, guaranteed to be free of collisions with all modeled obstacles. This path, in conjunction with additional information available from long-term memory, is then used to select appropriate perceptual strategies and motor behaviors (schemas) to enable the robot to recognize its goal, avoid obstacles (both moving and stationary), and accomplish its current task.

4.3 Manufacturing motor behaviors

Schema-based navigation allows our robot (George) to function in a dynamically changing world. Using an analog of the potential field approach, the robot reacts to its current sensor data in an intelligent manner. The individual primitive motor behaviors developed in AuRA for both indoor and outdoor navigation [4] have been migrated

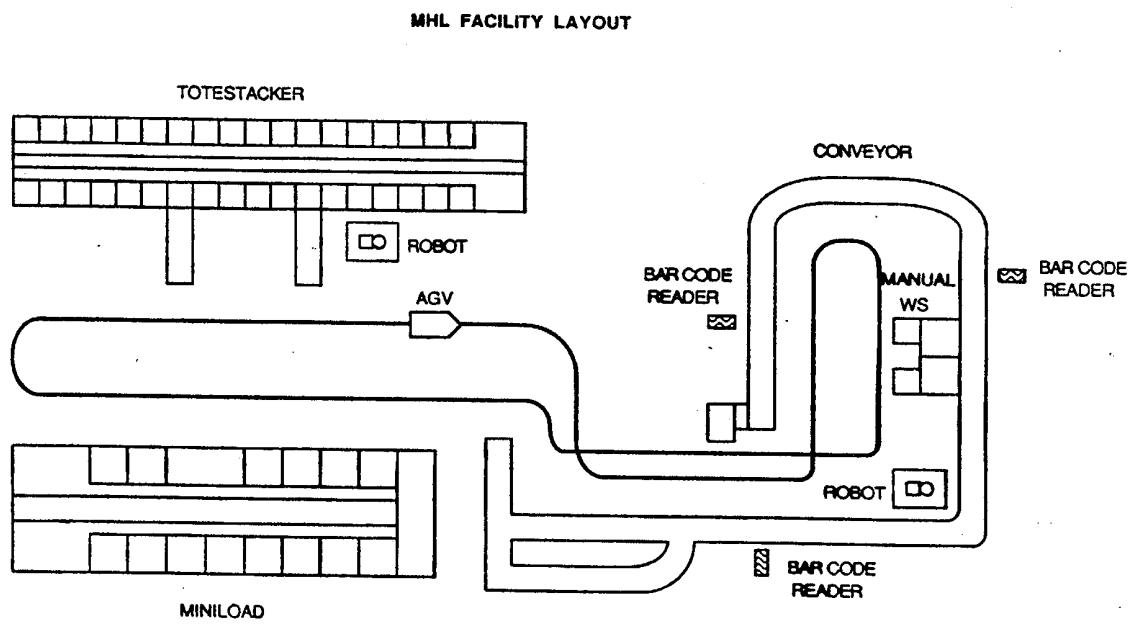


Figure 4. Schematic diagram of Materials Handling Research Center Laboratory
(not to scale).

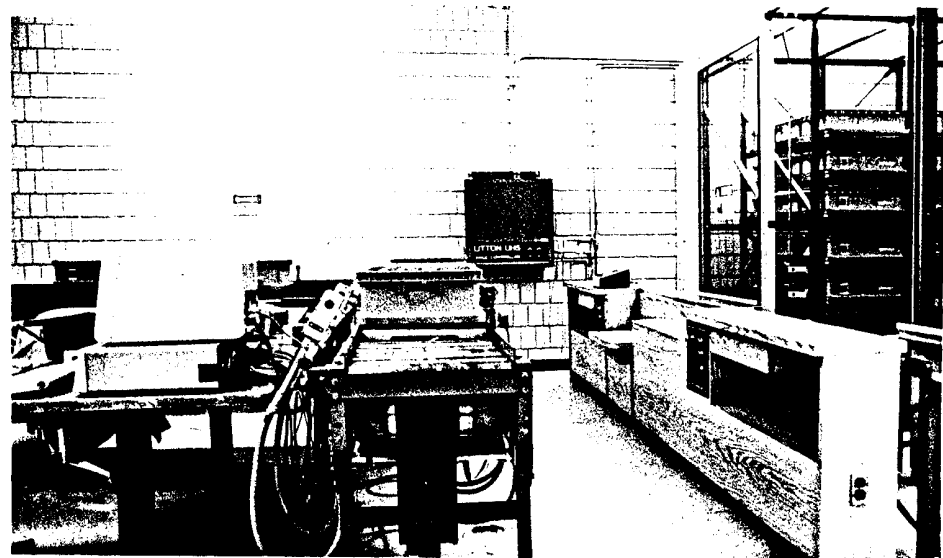
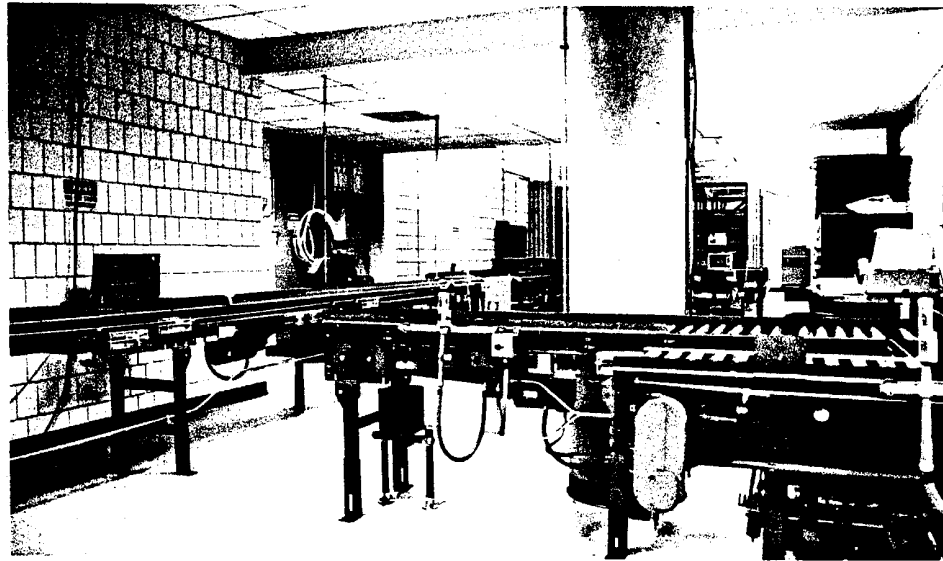


Figure 5. Two views of the Materials Handling Research Center.

to the manufacturing environment. These include the **move-ahead**, **avoid-static-obstacle**, **move-to-goal**, and **stay-on-path** schemas (Fig. 6).

One new motor behavior developed for this work is a **docking** schema which incorporates both ballistic and fine motor control strategies (Fig. 7). An approach zone, incorporating the preferred orientation of the vehicle relative to the docking site, is an integral component of this field. This particular motor schema, when coupled with an appropriate perceptual schema (both computer vision and ultrasonic strategies are available), can be used to guide the vehicle into the desired position for interaction with the other manufacturing equipment typically found in an FMS. AuRA has previously employed computer vision algorithms including fast line-finding and fast region-segmentation for general navigational purposes. Their application within a manufacturing environment is being developed.

5. Simulations

This section describes the simulation work performed using the AuRA framework for testing the concepts described above. Our next step is to realize these successful simulation studies by implementing them on our mobile robot George.

5.1 Navigational planning

Figure 8 is an illustration of the meadow map produced from data obtained from the Materials Handling Research Center Laboratory at Georgia Tech. The algorithms developed within AuRA for map-building and path planning [3] have proved effective in both modeling the FMS environment and producing paths that are appropriate for navigation of the vehicle from one workstation to another. It is important to note that the paths produced (Fig. 9) are guaranteed to be free of collisions with all modeled obstacles. Nevertheless, due to inaccuracies in the robot's internal model

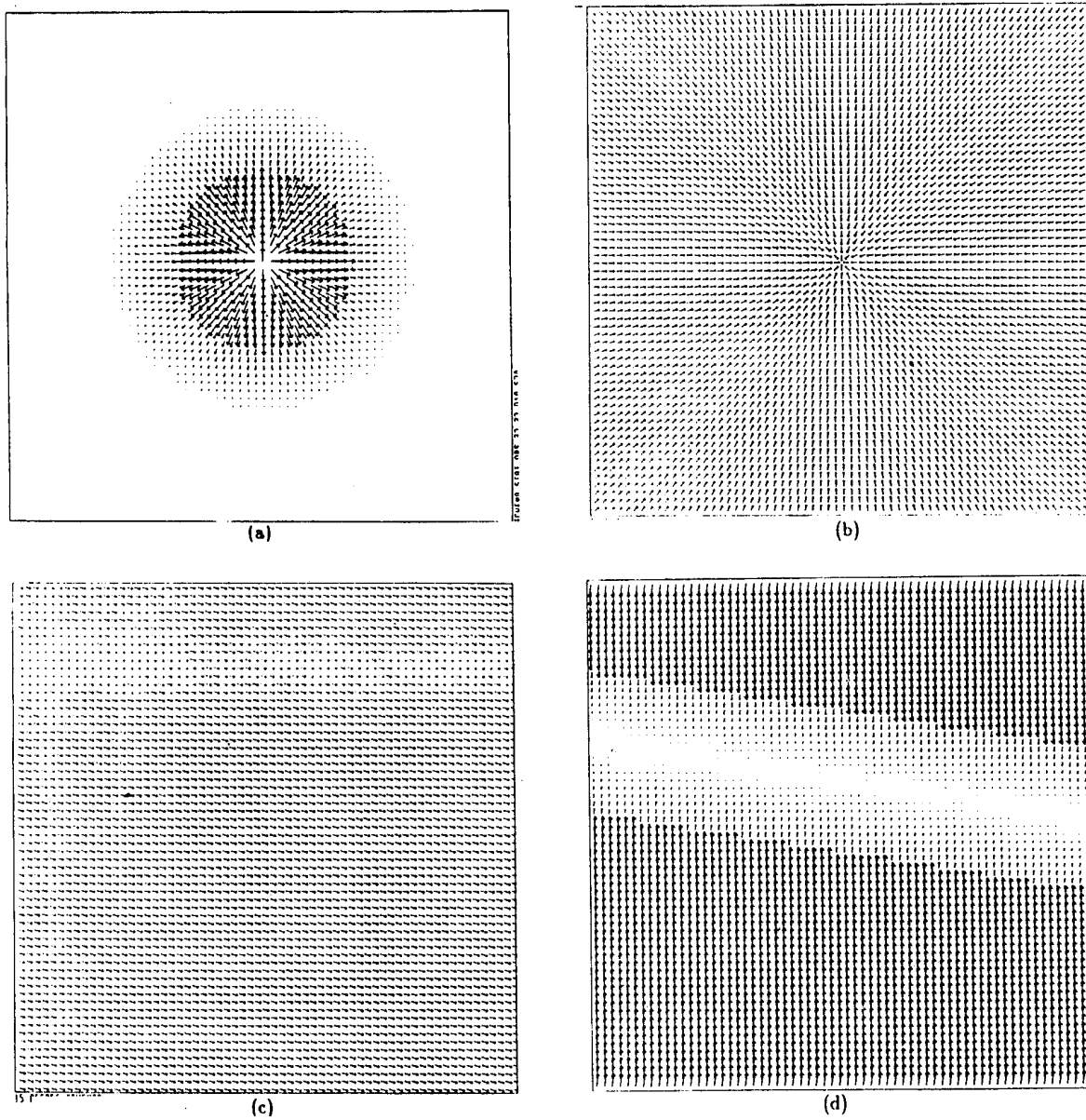


Figure 6. Several primitive motor schema vector fields.

- a) **Avoid-static-obstacle**
- b) **Move-to-goal**
- c) **Move-ahead**
- d) **Stay-on-path**

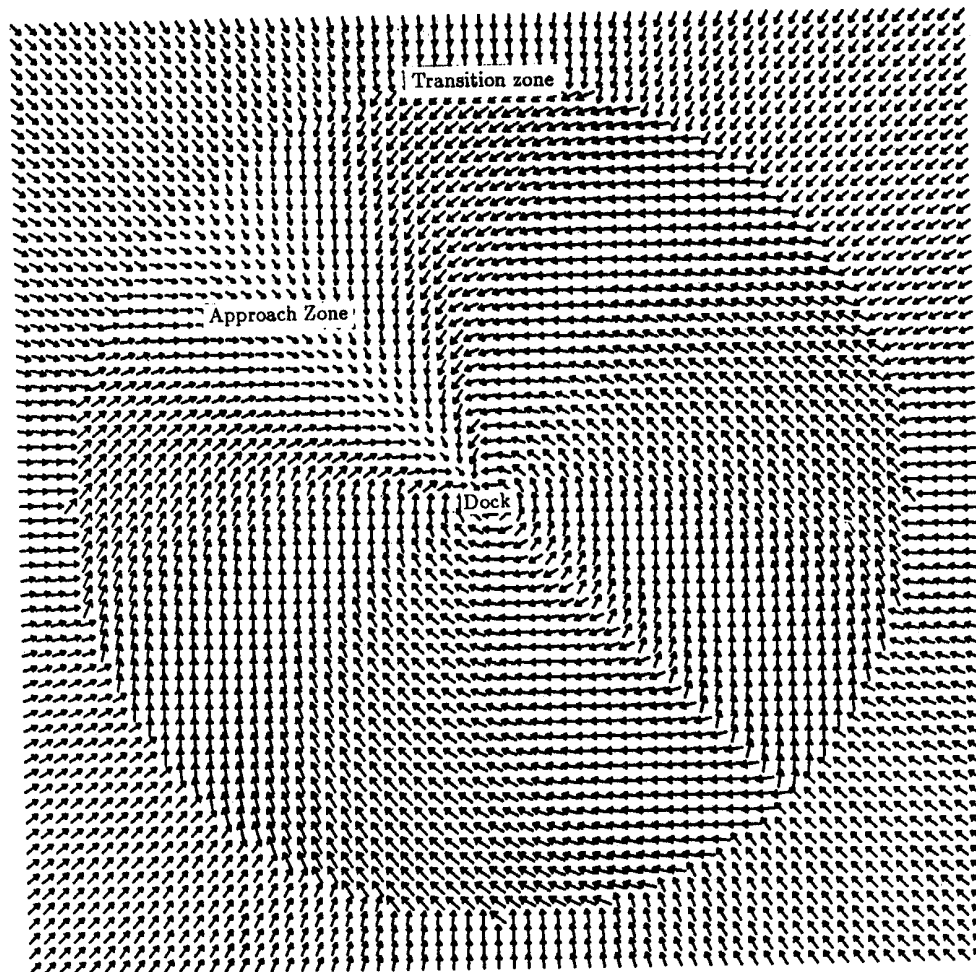


Figure 7. Docking motor schema.

of its position relative to the world and errors in carrying out the motor commands due to wheel slippage and other related problems, actual path execution is handled via schema-based control. The presence of unmodeled obstacles (including moving ones) is always allowed and will of necessity force deviations from the navigator's prescribed path.

5.2 Docking

The motor schema for docking behavior, shown previously in Figure 7 and discussed in Section 4.3, is used for docking simulations. General navigation simulations (i.e. not in an FMS environment) illustrating schema-based control are shown in [5] and actual mobile robot experiments are presented in [6].

Figure 10 shows the robot's behavior as it approaches an unblocked docking zone. Note the transition as the vehicle changes from ballistic to guarded motion as it enters within the sphere of influence of the docking goal. The simulation's perceptual trigger is simply the distance relative to the goal. In upcoming robot experiments, we anticipate using vision to initiate this control transition. The spiraling in of the vehicle towards the approach zone is also apparent. When the docking is completed, the vehicle has assumed both the correct position and orientation.

The second set of simulations (Fig. 11) show the robot's path through an obstacle-strewn environment to the docking site. Note how it successfully navigates around all perceived (and unmodeled) obstacles as it wends its way to the docking position. This simulation incorporates uncertainty measures in perception that affect the strength of the repulsive field around the obstacles. (Actual obstacle avoidance results have previously been successfully demonstrated using our mobile robot [6]). These obstacles do not produce motor action until the robot is within a certain distance of them (i.e. the robot's perceptual limits). The schemas are also deinstantiated as the robot passes beyond their perceptual range. In rare instances, higher level reasoning will need to

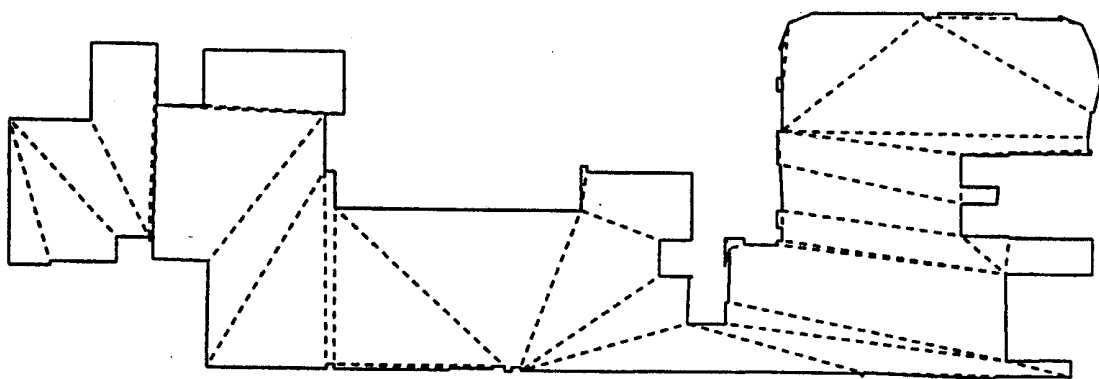


Figure 8. Meadow map representing the Materials Handling Research Center.

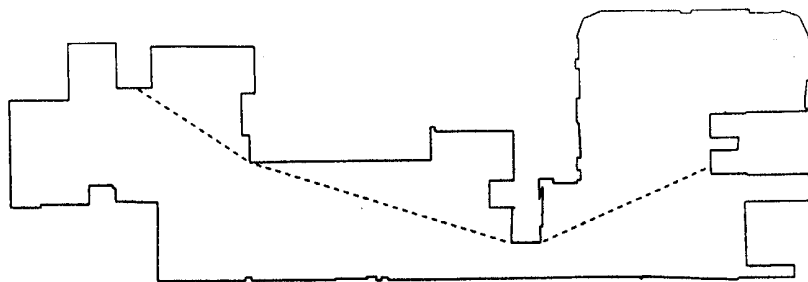
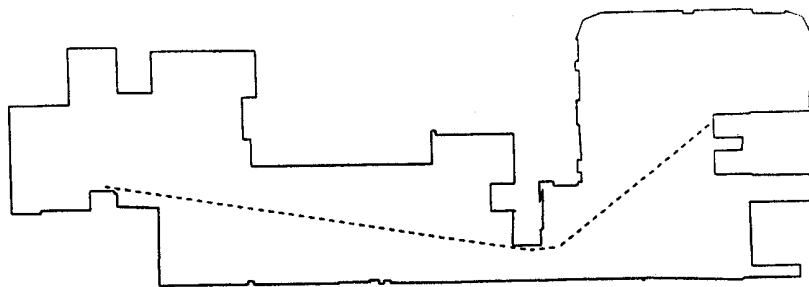
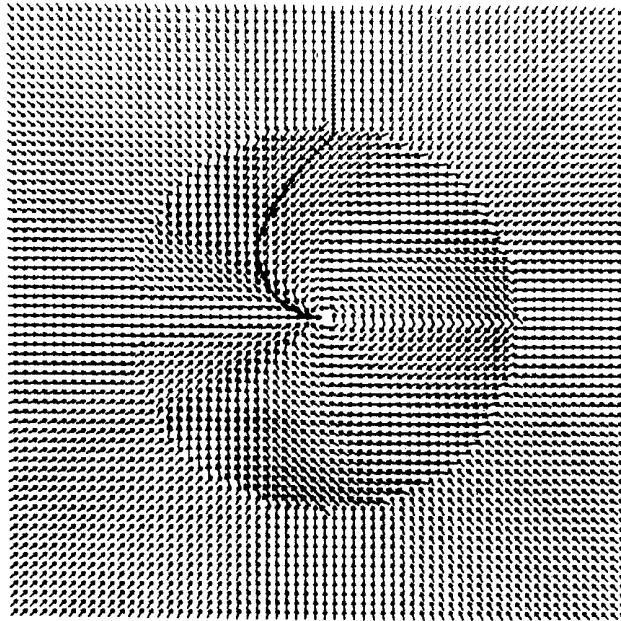
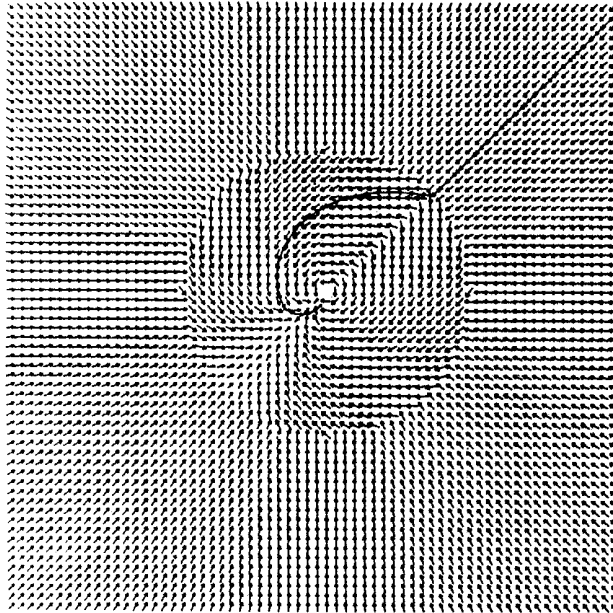


Figure 9. Two example paths, produced by the navigator, connecting workstations in the MHRC.



(a)



(b)

Figure 10. Docking in an uncluttered environment.

- a) Approach from the side results in a spiraling into approach zone before final orientation.
- b) Worst case approach (from rear).

be brought to bear to insure path completion due to the inherent pitfalls associated with the potential field methodology [6].

The third simulation (Fig. 12) shows the approach of the robot to a workstation slightly behind the docking position. In this run, the robot settles into a point short of the goal. At this point, a change in the nature of the avoid-obstacle schema will occur, resulting in a drop-off in the repulsion of the workstation itself, allowing the vehicle to approach more closely than would normally be allowed.

6. Summary

Existing approaches used by AGVs in flexible manufacturing systems place severe restrictions on the ability of the vehicle to interact with the workplace. In many instances, it cannot leave a pre-defined track nor cope with any unexpected obstacles in its way (other than wait for them to be removed). Furthermore, significant restructuring of the workplace is often required for AGVs to be useful.

The approach used in the Autonomous Robot Architecture enables a mobile robot to take advantage of *a priori* knowledge of its environment to produce a path that is free of collisions with all modeled obstacles and is not dependent on any fixed track or network. This path is then passed to the motor schema manager (via the pilot) for actual path execution. The presence of unmodeled obstacles poses little difficulty for this behavior-oriented approach to navigation.

Perceptual strategies using vision and ultrasonic sensing are advocated as methods to supplant the heavy reliance on dead-reckoning found in AGVs. By utilizing information regarding characteristics of the workplace, little or no restructuring of the robot's world is needed for it to accomplish its tasks.

Future work will involve exploitation of the fast line finder and fast region segmentation algorithms, already used successfully for hallway and outdoor navigation

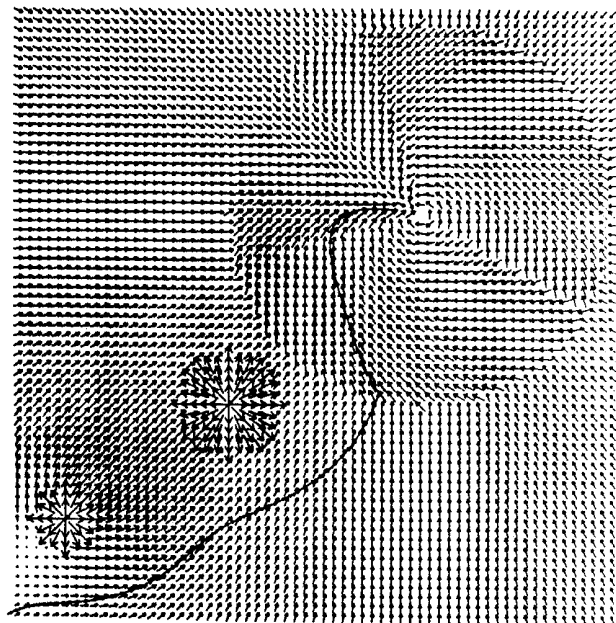
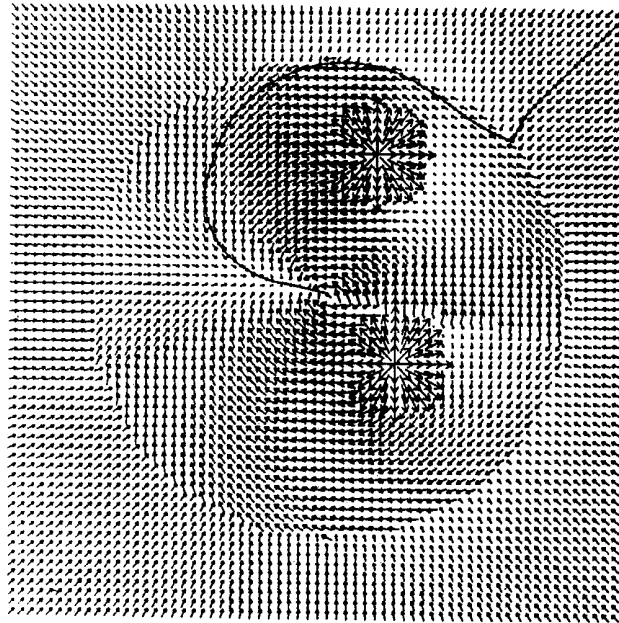


Figure 11. Docking in a cluttered environment.

Two example runs showing how the robot navigates around unmodeled obstacles on its way to the docking site.

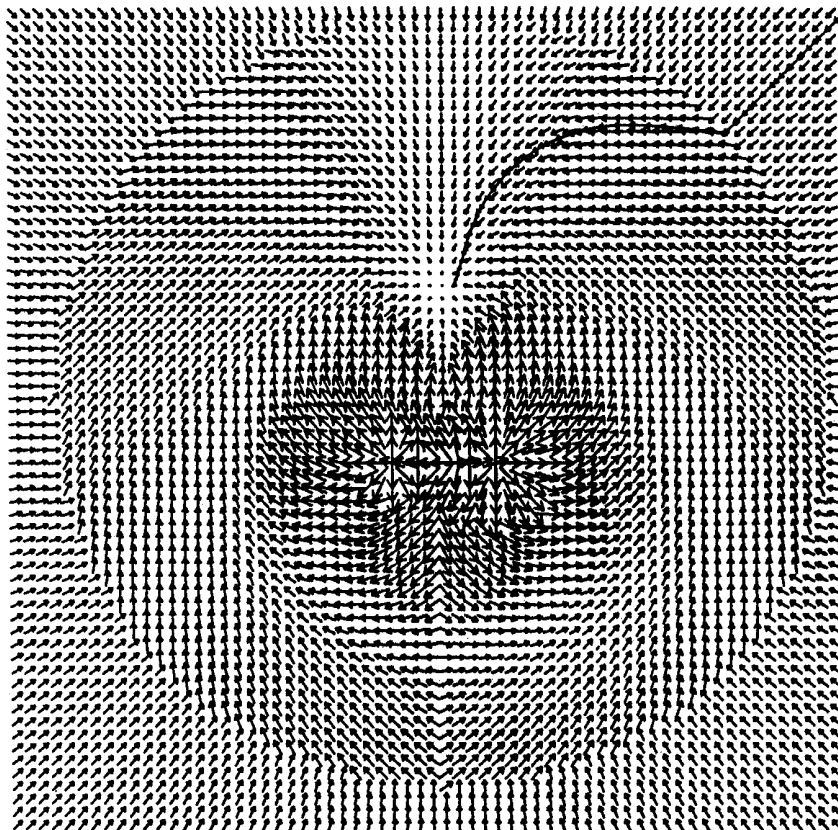


Figure 12. Docking approach to a workstation.

Note how the robot stops before final docking position is achieved. It is at this point that the repulsive force on the workstation would be lowered, allowing the final approach to be completed.

[8], for recognition, tracking, and control triggering in the FMS environment. In the near future we will implement the schema-based docking operator on our mobile robot George and test this approach in a cluttered workplace.

Acknowledgments

This research is supported in part through the Computer Integrated Manufacturing Systems Program and the Material Handling Research Center at Georgia Tech. The author would also like to thank Robin Murphy for her work on implementing the docking schema simulations.

REFERENCES

- [1] Allen, D., "Craft - A small, prototype AGV for Parts Transfer between Machine Tools", *Proc. 3rd Int. Conf. on Automated Guided Vehicle Systems*, Stockholm, pp. 112-121, Oct. 1985.
- [2] Arbib, M., "Perceptual Structures and Distributed Motor Control", *Handbook of Physiology - The Nervous System II*, ed. Brooks, pp. 1449-1465, 1981.
- [3] Arkin, R., "Path Planning for a Vision-based Mobile Robot", *Mobile Robots, SPIE Proc. Vol. 727*, 1986. Also *COINS Technical Report 86-48*, Dept. of Computer and Information Science, Univ. of Mass., 1986.
- [4] Arkin R., "Motor Schema Based Navigation for a Mobile Robot: An Approach to Programming by Behavior", *Proc. IEEE International Conference on Robotics and Automation*, Raleigh, N.C., 1987.
- [5] Arkin, R., Riseman, E. and Hanson, A., "AuRA: An Architecture for Vision-based robot Navigation", *Proceedings of the DARPA Image Understanding Workshop*, pp. 417-431, Los Angeles, Feb. 1987.

- [6] Arkin, Ronald C., "Towards Cosmopolitan Robots: Intelligent Navigation in Extended Man-made Environments", *Ph.D. Dissertation, COINS TR-87-80*, University of Massachusetts, Amherst, Sept. 1987.
- [7] Arkin, R.C., "Neuroscience in motion: The Application of Schema Theory to Mobile Robotics", to appear in *Sensorimotor Coordination in Amphibians: Experiments, Comparisons, Models and Robots*, ed. P. Ewert and M. Arbib, Plenum Publishing Co., 1988.
- [8] Arkin, Ronald C., Riseman, E. and Hanson, A., "Visual Strategies for Mobile Robot Navigation", *Proceedings of IEEE Computer Society Workshop on Computer Vision*, Miami Beach, Fla, pp. 176-181, Dec. 1987.
- [9] Arkin, Ronald C., "Spatial Uncertainty Management for a Mobile Robot and its Role in Expectation-Based Perception", *in preparation*, to appear in *Proc. Symposium on Robot Control '88*, Karlsruhe, Oct. 1988.
- [10] Banta, L., Dickerson, S., Bohlander, R. and Holcombe, W., "A Reduced-order, Extended Kalman Filter for AGV Navigation". *Proc. Winter ASME Meeting*, 1987.
- [11] Boegli, P., "A Comparative Evaluation of AGV Navigation Techniques", *Proc. 3rd Int. Conf. on Automated Guided Vehicle Systems*, Stockholm, pp. 169-180, Oct. 1985.
- [12] Courtney, J., Magee, M. and Aggarwal, J., "Robot Guidance using Computer Vision", *Pattern Recognition*, Vol. 17, no. 6, pp. 585-592, 1984.
- [13] "Denning Research Vehicle (DRV-1) Software Documentation", Denning Mobile Robotics, Inc., Woburn, Ma., 1985.
- [14] Erwin, H., "Laser Docking System", *Proc. 7th Annual Rocky Mountain Guidance and Control Conference*, Keystone, Col., Feb. 1984.
- [15] Fukui, I., "TV Image Processing to Determine the Position of a Robot Vehicle", *Pattern Recognition*, Vol. 14, Nos. 1-6, pp. 101-109, 1981.

- [16] Giralt, G. and Chatila, R., "Task Programming and Motion Control for Autonomous Mobile Robots in Manufacturing", *Proc IEEE Int. Conf. on Robotics and Automation*, Raleigh, N.C., April, 1987.
- [17] Hongo, T., Arakawa, H., Sugimoto, G., Tange, K. and Yamamoto, Y., "An Automatic Guidance System of a Self-Controlled Vehicle", *IEEE Transactions on Industrial Electronics*, Vol. IE-34, No. 1, pp. 5-10, Feb. 1987.
- [18] Kabuka, M. and Arenas, A., "Position Verification of a Mobile Robot using Standard Pattern", *IEEE Journal of Robotics and Automation*, Vol. RA-3, No. 6, pp. 505-516, Dec. 1987.
- [19] Khatib, O., "Real-time Obstacle Avoidance for Manipulators and Mobile Robots", *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 500-505, St. Louis, 1985.
- [20] Krogh, B. and Thorpe, C., "Integrated Path Planning and Dynamic Steering Control for Autonomous Vehicles", *IEEE Conf. on Robotics and Auto.*, pp. 1664-1669, 1986.
- [21] Mandel, K. and Duffie, N., "On-line Compensation of Mobile Robot Docking Errors", *IEEE Journal of Robotics and Automation*, Vol. RA-3, No. 6, pp. 591-598, Dec. 1987.
- [22] McEllin, P., "AGV design for FMS", *Proc. 3rd Int. Conf. on Automated Guided Vehicle Systems*, Stockholm, pp. 346-355, Oct. 1985.
- [23] Miura, T., Kondo, Y. and Yamauchi, F., "Automated guided vehicle using magnetic marker", *Proc. 3rd Int. Conf. on Automated Guided Vehicle Systems*, Stockholm, pp. 181-188, Oct. 1985.
- [24] Murphy, R., "Intelligent Docking in an FMS/MH Environment", *Technical Report* (in preparation), School of Information and Computer Science, Georgia Institute of Technology, 1988.
- [25] Premi, S. and Besant, C., "A Review of Vehicle Guidance Techniques that can be used by Mobile Robots or AGVs", *Proc. 2nd Int. Conf. on Automated Guided Vehicle Systems*, Stuttgart, pp. 195-209, June 1983.

- [26] Rembold, U. and Dillman, R., "Annual Report 86", Institute for Informatics III, Research Group: Process Control Computer Technology and Robotics, Univ. of Karlsruhe, FRG, 1986.
- [27] Warnecke, H. and Schuler, J., "Mobile Robot Applications", in *Handbook of Industrial Robotics*, ed. S. Nof, Wiley & Sons, pp. 1002-1010, 1985.

