Integrated Control for Mobile Manipulation for Intelligent Materials Handling

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***Abstract*— An integrated control system architecture for mobile manipulators is presented. This architecture incorporates a hybrid reactive/hierarchical structure and partitions the task into macro- and micro-manipulation components. Computer vision and other sensor modalities provide the input necessary to cope with materials handling tasks in a partially modeled and dynamic world.**

I. INTRODUCTION

A pressing need in the materials handling domain exists for an effective and efficient means for transferring material without requiring extensive restructuring of the environment. Current automatic guided vehicle (AGV) technology provides the transfer capability but is unable to cope effectively with changing job requirements or dynamic environments.

A. *Project Overview and motivation*

The fundamental research hypothesis we are addressing is that integrated planning and control regimes when supported by appropriate perceptual strategies and micromanipulation techniques can provide efficient and effective methods for a mobile manipulator to deal with complex material transport and manipulation problems. By mobile manipulator, we do *not* mean simply a mobile robot with an arm attached, but rather a fully integrated arm/vehicle system from a control viewpoint.

The technology we are developing potentially addresses a wide range of material handling problems. It also spans a wide range of robotic devices: from a small mobile manipulator capable of retrieving and delivering parts in a complex factory environment, to mid-range vehicles capable of performing at the task level of fork-lifts in warehousing operations, to large-scale robotic devices useful in tasks such as logging.

Our approach to this project presents a markedly different approach from the existing state-of-the-art. Summarizing these distinctions:

- The combination of both hierarchical planning and distributed reactive execution techniques for efficient navigation and manipulation, which are also separated along the dimension of ballistic control (for coarse trajectory planning) and micromanipulation (for fine control of parts during acquisition or mating operations) provides enhanced capabilities for a mobile manipulator functioning in a partially structured environment.
- The introduction of a significantly different approach to micromanipulation, integrating expert system-based strategies with low-level controllers. This method takes into account large-grain uncertainty and sensor feedback information to accomplish the micromanipulation task.
- Planning for nonholonomic systems in general and common steered vehicles in particular is incorporated into the hierarchical/reactive architecture for coordinated arm and vehicle motion.
- The use of multi-camera, dynamic scene analysis to enable a mobile manipulator to extract environmental and control information in a complex and dynamic environment.

B. *Related work*

Various research groups have developed autonomous mobile robots with arms. A sparse sampling of these groups includes Connell's subsumption-based robot [13] used to collect soda cans in the MIT AI Laboratory; the Hermies class of robots developed at Oak Ridge [27] for use in nuclear power plant environments; NASA Jet Propulsion Laboratory's work on mobile manipulators for planetary exploration [12]; and work at Karlsruhe [18] on a system that incorporates two arms to be used in assembly tasks in a manufacturing environment. What is characteristic of these robots and most others is their treatment of the arm and base as two distinct subsystems, by first having the robot move into position and then separately performing the manipulation task, and generally not as an integrated whole.

Georgopoulos and Grillner [16] argue that in biological systems, locomotion and reaching are closely connected and require visuomotor coordination. Bizzi, et al [1, 10] have studied limb movement extensively and describe the overall motion in the context of a vector field that is mapped within the spinal cord. The concept of ballistic and controlled motion originates from biological studies

[14, 24] and is closely aligned with the strategies of macro- and micromanipulation used within our approach. Additionally, psychological studies have also supported the coexistence of two distinct control systems for deliberative and automatic actions [22], a feature that is present in this project's architectural design through the use of both hierarchical and reactive control mechanisms [8].

II. AN INTEGRATED SENSOR-BASED HIERARCHICAL/REACTIVE PLANNING AND CONTROL ARCHITECTURE

Figure 1 illustrates the overall architectural philosophy that drives the research. The key aspects of this architecture are:

- Sensing/planning/control are integrated at all levels.
- The use of world representations is retained only at those levels where it is of greatest value (specifically at the hierarchical planning levels). This is consistent with the architectural developments we have achieved in our previous work on AuRA (the Autonomous Robot Architecture) [2, 5].
- A vertical split is introduced in the planning and control system, representing the different strategies used for ballistic motion versus controlled motion (micromanipulation). The transition from one control regime to the other occurs via perceptual triggers. This should not be viewed as a discontinuity but rather a smooth control flow which occurs when invoked by specific and timely perceptual cues, ensuring a clean transition.
- Nonholonomic steering constraints are implemented both in the planning subsystem and the reactive control subsystem to provide robust and generalizable motion planning and execution.
- Knowledge-based sensing is used to integrate the micromanipulation task with the entire kinematic structure of the mobile manipulator.
- Dynamic visual image analysis is used to provide information for both navigational and manipulation needs.

Elaborating upon these concepts which are discussed in detail in the sections that follow this one:

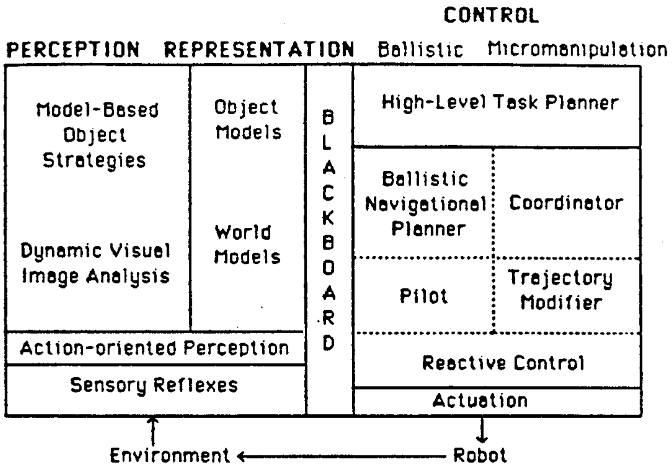


Fig. 1. System Architecture

1. Our previous work in integrated reactive control and hierarchical planning [2] provides a means for utilizing *a priori* knowledge of the world (and associated representations) to guide the instantiation of a real-time reactive control system. In particular, this aspect of the work concentrates on the ballistic motion of the mobile manipulator as it moves through the workspace on its way to achieving its material handling task (e.g., object acquisition and delivery). Appropriate sensor strategies, involving typically, ultrasound and vision, permit the vehicle to reconfigure itself based on local sensing. In this way it will be able to preshape itself to the intended configuration for material retrieval, and also to contort for passage through tight quarters based on local requirements in an unstructured environment as determined by sensing.
2. Algorithms and representations for dynamic image processing utilizing multiple cameras will enable the system to function in a dynamic and uncertain environment and to actively explore the environment to extract needed information for recognition and control. Some of this research involves adapting established dynamic image processing algorithms to take advantage of the constraints made possible by mobile manipulation. It also involves new ways of organizing sensing. Object models are being developed based upon the similarities between inference techniques used in dynamic scene analysis and the constraints and relationships used to describe object models for model based recognition. This enables activities such as recognition, pose determination and tracking.
3. An intelligent expert system based trajectory modifier has been introduced to the micromanipulation phase to insure that command trajectories are downlinked to low-level controllers to assure a stable and robust task execution by accounting for reaction forces. The trajectory modifier module is a dynamic fuzzy logic-based expert system which receives force/torque and tactile sensor inputs and, using a knowledge base which embodies geometrical data, quasi-static force information as well as heuristics from the work task domain, and provides command signals for control of the mobile manipulator.
4. The types of mobile manipulators which are of interest in this project typically incorporate nonholonomic components (such as the wheeled platform). The complexity and nonholonomic nature of of such mobile manipulators can make modeling and motion

planning difficult. Techniques to simplify modeling the kinematics and dynamics of these mobile manipulators in an integrated fashion are being developed.

5. The representations that we use to support this knowledge-based control and sensing regime include free-space models of the materials handling environment [6], explicit models of spatial and orientational uncertainty of the robot relative to the environment [4], models of visual landmarks, target material, and other perceptual cues. These serve to localize the robot as well as provide the stimulus for reactive control, and to provide models for objects to support their acquisition using visual recognition. The role of representational knowledge is primarily to serve during the planning phases of the mobile manipulation, determining the set of behaviors and perceptual strategies that are necessary to complete the given materials handling manipulation task.
6. An important facet of this research lies in the massive reduction in computational load afforded by the distributed mechanisms of schema-based reactive control [9], enabling real-time operation of an integrated mobile manipulator in a dynamic environment.

For the final implementation, a blackboard architecture is being developed as the medium for exchanging information between the individual processes. A blackboard architecture utilizes a centralized global data structure to serve as the primary repository for data. This data includes time-stamped sensor reports, intermediate sensor interpretation results, important inter-process messages, and other related information. Each individual processing agent corresponds to an asynchronous knowledge source, capable of reading and/or writing at will to the blackboard. Partitioning or layering structures are also feasible within a blackboard and facilitate rapid access of information by permitting clustering of relevant data items. We have previously included blackboards for inter-process communication within the design of the Autonomous Robot Architecture at Georgia Tech [5].

The advantages of blackboard architectures [21] are manifold: modular development and design of the knowledge sources; free communication between individual processes; easy addition and deletion of new knowledge sources; facilitation of real-time responsiveness; and utilization on parallel and/or distributed processing hardware. The integration and development of a complex system of peer processes is more easily managed by clear interface specifications to the blackboard [23].

A. *Supporting Knowledge Representations*

Representational knowledge plays a crucial role in our system. It provides:

- A basis for deriving the appropriate reactive control configuration for a given environment and task.
- A means for localizing the mobile manipulator relative to a known world model.
- Landmark and target object recognition capabilities for perceptual processing.
- A means for providing visual cues for reflexive action during plan execution.

1) Representation for Navigation: Previous work in mobile robot navigation [7] has provided us with general purpose world modeling techniques. These include the ability to model free navigational space, obstacles, and landmarks for the guidance of an intelligent mobile robot.

A multi-level representation to support multi-sensor navigation (predominantly visual) has been developed and tested. A hybrid vertex-graph free-space representation based upon the decomposition of free space into convex regions capable of use in both indoor and limited outdoor navigation is utilized. This "meadow map" is produced via the recursive decomposition of the initial bounding area of traversability and its associated modeled obstacles. This work has already been tested in the context of a Flexible Manufacturing System [6]. Knowledge supporting visual perception can also be embedded in the meadow map, facilitating the actual path traversal by the vehicle. The navigational planner utilizes the data available in the above representational scheme. An A^* search algorithm incorporates appropriate cost functions for multi-terrain navigation.

Representation for visual navigation is another important area of our research. Our reactive approach is predicated on action-oriented perception; utilizing only those sensors and sensor strategies which are pertinent to the successful achievement of our current goals [3]. Our previous robotic architectural research has been developed to support visual navigation experiments [5]. Employing both high-level semantic knowledge and control structures consisting of low-level motor schemas, action-oriented perception and schema-based navigation are being extended to mobile manipulators. Specific perceptual strategies are associated with appropriate motor behaviors to guide the vehicle along its way.

Landmark models are readily embedded within the meadow map. The actual representational form used for the landmarks will depend on the landmark itself and its relationship to the mobile manipulator's goals. Research in the storage of multiple views of landmarks that remain invariant over significant viewpoint ranges strongly influences the representation chosen for this particular task.

2) Representation of Uncertainty: Our strategy for representing position and orientation uncertainty [4] is accomplished through the use of a spatial uncertainty map. This map reflects the plausible limits of the mobile manipulator's position within the world itself, beginning with an initial amount of uncertainty in the starting position. Each translational or rotational movement of the vehicle is accompanied by a probable difference between the actual amount of distance traveled (and rotation accomplished) from the amounts commanded the mobile manipulator. This uncertainty depends on several factors, not least of which is the type of surface being traversed. A spatial uncertainty map, representing both the center of probability of the vehicle's position as well as the probable limits of the vehicle's position, is maintained and updated on every completed move.

The chief significance of this approach lies in the ability to use this data to reduce the processing requirements for sensor interpretation. The mobile manipulator's position is known sufficiently well to enable us to restrict the possible interpretations of sensor data or to window the visual images fed to the perception subsystem, thus decreasing the computational burden. If no plausible interpretation is found within these limits, special procedures can be invoked calling for additional sensor data to re-establish the vehicle's bearings.

B. *Hardware Integration*

The mobile manipulator is being constructed from a Denning MRV-2 mobile robot and a CRS A251 industrial robot arm. Figure 2 shows a photo of the arm installed on the base. The computational effort is divided into two major groups. The first group's effort revolves around a SUN sparcstation which handles most of the processing responsibilities including macromanipulation and data integration. The second group uses a 486 based personal computer which handles only the micromanipulation aspect.

The SUN processing system has a direct link to the Denning Mobile Robot, the CRS robotic arm, and the video camera(s). Software written for macromanipulation runs on the SUN. Feedback such as position, velocity, and ultrasonic information is received along the same link. The communications link is a standard RS-232 port or a RF modem. The RF modem has the benefit of a wireless connection. The video camera, mounted on the robot, interfaces to the SUN via a VHF transmitter and receiver. The receiver sends the images broadcast from the robot to the SUN's videopix digitizer. All image processing is performed on the Sparcstation.

The CRS A251 industrial robotic arm has five degrees of freedom along with an additional degree of freedom in the gripper. The arm also communicates via a serial link and can therefore be controlled by both the SUN and PC. A Zebra MW-1 Force/Torque sensor mounts between the end of the arm and the gripper. It has the cability to detect forces and torques along three axes.

The 486 personal computer (PC) processing system is used only for the micromanipulation task. The PC communicates to the base and arm via a serial link to the Sparcstation. The link handles all commands to the mobile manipulator and receives all requested feedback. The PC also communicates directly to the Zebra Force/Torque Sensor mounted on the arm.

III. MACRO (BALLISTIC) MOTION

In this section, we examine some of the issues involved in planning and executing large-scale (or *macro*) motions of a mobile manipulator.

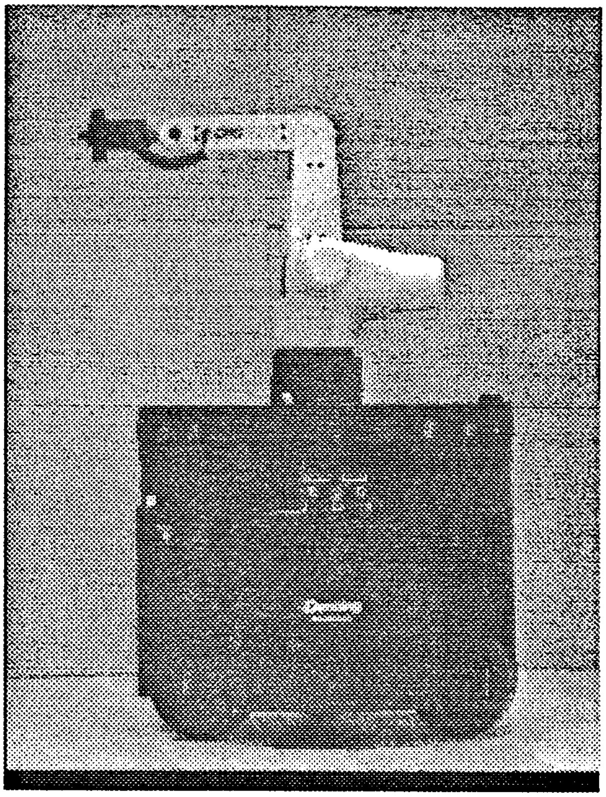


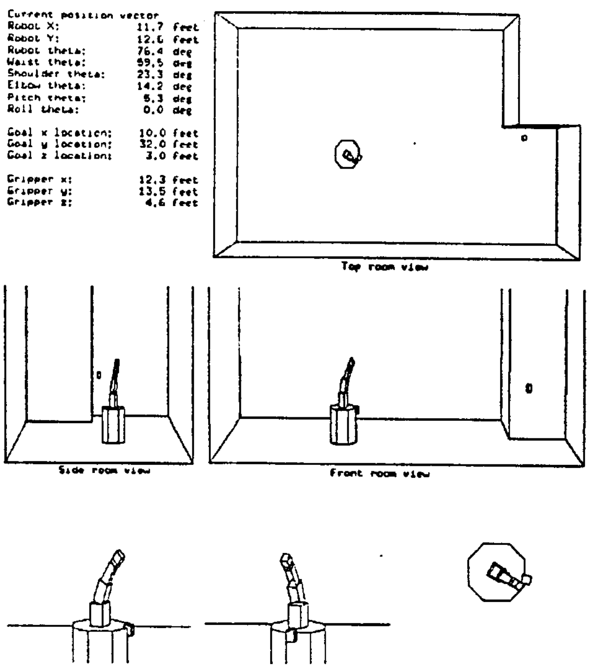
Fig. 2. Integrated Mobile Manipulator

A. *Simulating Macro Motion*

Developing control software for a mobile manipulator requires a simulation environment as a safe place to try out new ideas and untested algorithms. A simulation has been developed to provide a direct replacement for the hardware to allow simple off-line testing. A graphical display package has been developed to display vehicle telemetry using the SRGP and SPHIGS packages, developed in [15]. Figure 3 shows an example of the display running in black and white mode. Vehicle telemetry is displayed in the upper left. A three view representation of the mobile manipulator moving within the laboratory is shown in the three upper windows. A three view egocentric display of the vehicle is shown below.

B. *Nonholonomic Issues*

Most mobile platforms are wheeled vehicles which are essentially nonholonomic in nature. *Nonholonomic* usually means that there are fewer degrees of freedom locally than there are globally. For instance, a wheeled vehicle can only move in the direction the wheels are pointing even though it can get anywhere in the workspace by judicious maneuvers. If an approach is used where the wheels are turned before forward motion is started, some types of wheeled vehicles, such as a Denning MRV-2, can be treated as if they



Current position vector
Robot X: 11.7 feet
Robot Y: 12.6 feet
Robot theta: 76.4 deg
Waist theta: 59.5 deg
Shoulder theta: 23.3 deg
Elbow theta: 14.2 deg
Pitch theta: 5.3 deg
Roll theta: 0.0 deg

Goal x location: 10.0 feet
Goal y location: 32.0 feet
Goal z location: 3.0 feet

Gripper x: 12.3 feet
Gripper y: 13.5 feet
Gripper z: 4.6 feet

Fig. 3. Simulation Environment Display

were holonomic. However, one of the goals of this project is to integrate the motion of the arm and mobile platform to give smooth, rapid, coordinated motions. When continuous motion is desired, even a Denning MRV-2 is nonholonomic. So the nonholonomic nature of the mobile base cannot be avoided.

One of the implications of the nonholonomic nature of wheeled mobile manipulators is that global motions are not always successful if executed using only local information. That is why motion planning is an important part of this project. Research is underway on how to combine motions based on tailored preplanned trajectories (based on global information) with motions based on local information using a reactive control paradigm.

C. *Modeling a mobile manipulator*

As mentioned earlier, modeling a mobile manipulator can be difficult. Deriving the kinematic relationships and dynamical equations of motion necessary to understand, simulate, and control such a system can involve lengthy derivations which are tedious and error prone. We have developed a symbolic derivation package to assist in these derivations. It is a Mathematica [29] package called `motion.m`. The input to this package is a brief and simple description of the mechanism. It can process this mechanism description to provide symbolic forms of most desirable kinematic and dynamic quantities for the end effector, any joint, or the entire system. For instance, it is easy to construct the position and velocity information for a joint. It can also construct system-wide quantities such as Jacobians or equations of motion. These results can be used directly for analysis or can be processed further to generate program code for simulation or control. A more detailed description of this package can be found in [11].

A unique feature of this package is that wheels are treated simply as another type of joint. A number of joint types are implemented including revolute and prismatic joints as well as others suitable to model wheeled platforms such as a Denning MRV-2 or a car. This approach allows construction of kinematic and dynamic models which are automatically integrated.

D. *Reactive motion control for ballistic motions*

In this project, large-scale motions of mobile manipulators are executed using reactive control concepts. Basically, this involves using behavioral schemas to direct the motion of the base and the arm in a coordinated way. For instance, a **move-to-goal** motion schema generates artificial (or pseudo) forces which "pull" the end effector towards the goal. For each obstacle, an **avoid-obstacle** motion schema generates pseudo-forces and pseudo-torques which "repel" the arm and vehicle. All these artificial forces and torques provide inputs to the **move-robot** schema. In the **move-robot** schema, all these forces and torques are combined to produce the total artificial force and torque acting on the vehicle and each joint of the arm. Then the torques each joint (or wheel) motor has to exert to generate these artificial forces and torques is computed using appropriate Jacobians. Once each joint pseudo-torque is known, an artificial joint damping model is applied to compute the corresponding desired joint speeds. Finally, these desired joint speeds are used to drive the simulation or hardware. For more details see [11].

This approach is unique in several ways. It is one of the few applications of reactive control concepts for controlling a mobile manipulator which includes a complex arm in an integrated way. It is also one of the first applications of Jacobians for converting the pseudo-forces and pseudo-torques acting on each joint into the corresponding joint drive torques.

IV. MICROMANIPULATION

It is essential to introduce intelligence to obtain a more effective controller which can operate reliably and efficiently in unstructured environments. There are several characteristics in self-organizing control. First, it requires only a minimum knowledge about its environment. Hence there exists more flexibilities in modeling the system. Second, it has self-adaptive learning functions. As the result, it can choose the most optimal control action. A fuzzy self-organizing entropy measure is being used as methodology for a rigid part mating problem. A fuzzy logic theory is implemented as the self-organizer of the intelligent mobile system for the micro-tasking problem (part mating task). The entropy metric is employed to measure the uncertainty

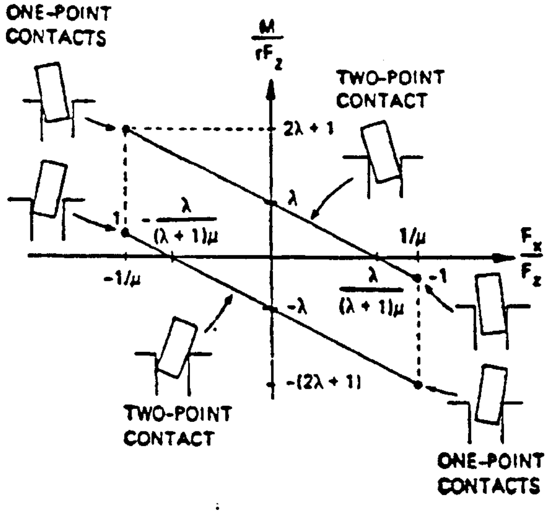


Fig. 4. Jamming Figure

of the hierarchical system. The top level determines the best appropriate plan which has the highest probability from the plans and then the selected plan is fed to the lower level of the hierarchical system to execute the specified mating task.

A. The rigid part mating problem

It is necessary to consider the forces and the moments applied on the peg in addition to the geometric compatibilities in order to determine whether the part mating is a success or not. Jamming is a situation in which the peg can't move in the hole due to the wrong ratio of the forces and moments on the peg [28]. A similar situation, wedging, occurs if two point contact occurs too early. The cause of wedging is due to the geometrical state rather than incorrectly proportioned forces. Here we consider only the jamming situation. The equilibrium equations for one point contact are $\frac{f_x}{f_z} = \pm\frac{1}{\mu}$, $\frac{m_y}{rf_z} = \pm 1$ or $\pm(2\lambda + 1)$ which yield the line equations $\frac{m_y}{rf_z} = -\mu(1+\lambda)\frac{f_x}{f_z} \pm \lambda$. The two point contact occurs along a line between the points (μ,-1) and (-μ,1), where f_z,f_x,and m_y are the applied axial force, lateral force, and moment respectively, μ is the kinetic friction coefficient, r and l are radius and depth of peg respectively, and $\lambda = \frac{l}{2r\mu}$. To avoid jamming, the forces and moments applied to the peg should be inside of the parallelogram in Fig. 4. The measured data (f_x, f_z, m_y, l) with force/torque and tactile sensor are provide feedback to the top level of hierarchical system where appropriate control action is determined.

B. The fuzzy self-organizer

The trend of recent research in mobile robotic systems focusses not only on the precise control of robotic system but also on combining intelligence which operates efficiently in fully or partially unknown and unstructured environment. Under such circumstances, a certain degree of planning and decision-making is needed to cope with complex tasks. To deal with a quasi-static part mating problem, the fuzzy logic based self-organizing control methodology is applied [26].

During the reasoning phase of the self-organizer, the input command is recognized. Each input command is associated with particular basic element events which compose a plan for a specific task. By approximate reasoning, the meaningful relations between them are assigned. The appropriate ordering of each basic element's events and the removal of meaningless plans are achieved in the planning step. Finally, through decision-making, a plan which is the most suitable for a specific task is chosen. Entropy is introduced to describe the uncertainty of the system. Fuzzy theory is used to represent a type of the system. Its uncertainty means its fuzziness. This fuzziness will be measured by a fuzzy entropy. The fuzziness of a fuzzy set $F = (x, \mu_F(x))$ can be measured by the fuzzy entropy $H_F = C\sum_{i=1}^{n} S(\mu_F(x_i))$, where $\mu_F(x)$ is the membership function of F for the fuzzy element x. $C(> 0)$ is a constant. n is the number of fuzzy elements and S(m)=-mln(1-m)ln(1-m) is known as Shannon's function. It is defined $J_x = \frac{f_x}{f_z}$ and $J_y = \frac{m_y}{rf_z} + \frac{f_x}{f_z}\mu(1+\lambda)$ from the jamming diagram. From the measured sensory information, the following fuzzy rulebase for the geometrical correction of the angle (θ) and the lateral movement (x) of the peg with respect to the hole can be derived to avoid the jamming situation.

$$\begin{array}{l}
(J_x = PL) \wedge (J_y = PL) \Rightarrow (\theta = NS) \wedge (x = NL) \\
(J_x = PL) \wedge (J_y = SZ) \Rightarrow (\theta = SZ) \wedge (x = NS) \\
(J_x = PL) \wedge (J_y = NL) \Rightarrow (\theta = PS) \wedge (x = NL) \\
(J_x = SZ) \wedge (J_y = PL) \Rightarrow (\theta = NS) \wedge (x = SZ) \\
(J_x = SZ) \wedge (J_y = SZ) \Rightarrow (\theta = SZ) \wedge (x = SZ) \\
(J_x = SZ) \wedge (J_y = NL) \Rightarrow (\theta = PS) \wedge (x = SZ) \\
(J_x = NL) \wedge (J_y = PL) \Rightarrow (\theta = NS) \wedge (x = PL) \\
(J_x = NL) \wedge (J_y = SZ) \Rightarrow (\theta = SZ) \wedge (x = PS) \\
(J_x = NL) \wedge (J_y = NL) \Rightarrow (\theta = PS) \wedge (x = PL)
\end{array}$$

where $\Rightarrow$ means $if - then$ production rule and $\wedge$ represents the conjunction *and*. The values for J_x, J_y, θ, and x are the linguistic quantities PL(positive large), PS(positive small), SZ(small near zero), NS(negative small), and NL(negative large). Based on the above rulebase, the corresponding self-organizing algorithm is activated.

V. VISION IN SUPPORT OF MOBILE MANIPULATION

The visual processing in support of mobile manipulation is currently organized into three areas: navigation, tracking and obstacle detection, and model-based object recognition. Navigation is concerned with how the robot can use landmarks to get bearings and orient itself with respect to a workspace; tracking and obstacle detection is concerned with obtaining the layout of environmental surfaces and tracking independently moving objects; object recognition involves recognizing an object in the workspace.

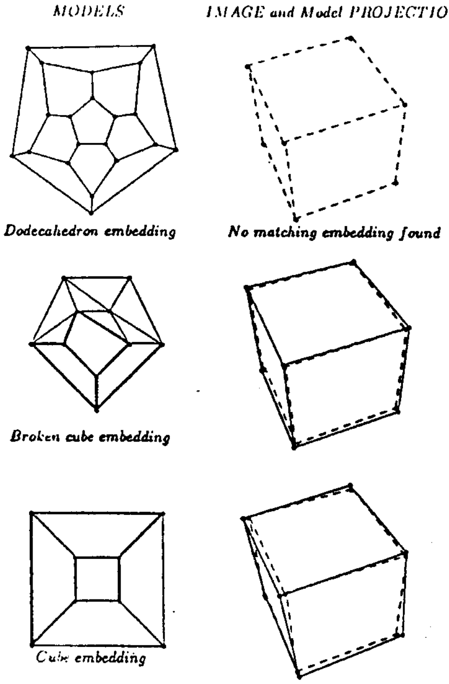


Fig. 5. Model-based Recognition Process

The work in navigation is based on extending the theory of qualitative navigation found in [19] with specializations for indoor robots. Among these are the use of a compass, new navigation algorithms with no reliance on determining the range to landmarks, and the ability to deal with simple and non-distinct landmarks. We have developed a set of navigation algorithms to operate under these assumptions which have been tested in simulation. Future work will involve implementing these algorithms to work with the newly obtained panoramic viewer [20].

Our current work with motion processing is based on exploiting two types of constrained motion which are common in the world of indoor robotics. The first of these is local translational motion. This means that the motion of an object over short periods of time can be approximated as translational. This tends to be true of a large number of moving objects, such as cars, due to their limited turning radii. The second involves motion constrained to a plane, such as a mobile robot constrained to move along a floor or objects constrained to move along a table top or conveyor belt. The translational algorithm is based on the strong geometric constraints on image motion in the case of translation (radial motion of image features from a focus of expansion, determined by the intersection of the direction of translation with the imaging surface). It is possible to determine the direction of translation to within a few degrees in small image areas, using only a few features and then improve the estimated motion by using trajectory fitting and Kalman filtering techniques. The geometry of planar motion constrains flow vectors to directly determine the direction of motion of the corresponding environmental points. This allows us to associate with each image point a 3-dimensional trajectory over time. These trajectories are grouped with those from other points using a rigidity constraint to determine independently moving objects and surface layout. Future work will involve extending the model matching to work with image sequences by taking advantage of the strong similarity between the inference techniques used in dynamic scene analysis and the constraints and relationships used to describe object models for model based recognition. We also will begin to work with images obtained from a gripper-mounted camera.

An example of the current model based recognition process is shown in Figure 5. One column shows the models of different polyhedral objects represented as planar graphs with explicit position and orientation information associated with the nodes and arcs. The other column shows the models being matched to a perspective image (this is duplicated for each model as it is matched to the image). The first stage of processing involves a planar graph matching procedure based upon [17] to determine potential correspondences between model features and image junctions and edges. To deal with the potential combinatoric complexity of subgraph matching, a convex cycle in the extracted image features is used to identify a subgraph from the plane graph of the model. The geometric interior or exterior of this cycle must correspond to the image graph (if there is a match). Candidate isomorphisms are then evaluated by using the size and relative position information from the model along to back project model features for potential correspondences relative to image features. The validity of the match is then verified by a chamfering process (a set of techniques for forming an image of distances to nearest features which is used for robust matching).

VI. SUMMARY AND FUTURE WORK

A novel approach to the mobile manipulation problem for dynamic and uncertain environments has been presented. It incorporates methods of both reactive and hierarchical control, principles of macro- and micro-manipulation and is potentially extensible to a wide range of holonomic and nonholonomic vehicles. Motion processing and model-based computer vision techniques have been developed to support this effort.

Future work involves the continued deployment of these algorithms to our hardware robotic platform and testing in realistic problem scenarios such as part acquisition and simple assembly. The combination of nonholonomic motion planning and reactive collision avoidance in tight surroundings is under study for warehouse applications. Other potential applications involve nuclear waste management through our group's involvement with Westinghouse Savannah River Laboratories.

Acknowledgments

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