Planning to Behave: A Hybrid Deliberative/Reactive Robot Control Architecture for Mobile Manipulation

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Abstract

Hybrid architectures provide an effective means for integrating world knowledge with reactive control. This paper describes the motivation behind the architectural decision to hybridize, and presents a case study in mobile manipulation in the context of the Autonomous Robot Architecture (AuRA).

INTRODUCTION

Hybrid deliberative/reactive architectures emerged as a result of the recognition that there is an appropriate use of symbolic knowledge in the formulation of robot behaviors [2]. Such systems take advantage of *a priori* knowledge of the world to formulate correct behavioral sets that can be used during run-time. Representations are used during plan formulation but not during plan execution. This creates greater flexibility for a reactive robot by allowing a high-level deliberative planner to configure the robot's behaviors in accordance with the task at hand, known or anticipated environmental conditions, and available robotic resources.

This paper first surveys and reviews the developments that lead to the emergence of hybrid deliberative/reactive architectures. The Autonomous Robot Architecture (AuRA) serves as a specific example of this paradigm. A case study involving the extension of this work into the task of mobile manipulation is presented, describing the principles and methodologies involved in the development of a hybrid architecture.

BACKGROUND

Hybrid deliberative/reactive architectures, of course, only emerged after developments in the individual approaches from which they are composed. This section describes early work and hallmarks of both purely hierarchical and reactive systems and the subsequent emergence of hybrid designs.

Precursors to Hybrid Systems

Hierarchical Planners

The many examples of hierarchical control systems share a structured and clearly identifiable subdivision of functionality. This functionality is relegated to distinct program modules which communicate with each other in a predictable and predetermined manner. Numerous examples illustrate this technique (e.g., [4,20,22,26]).

A typical subdivision of functionality is dependent on both planning scope and temporal constraints. At the highest level of a hierarchical planner, the most global and least specific plan is formulated. The time requirements for the production of this plan are the least stringent. As one proceeds down the planning hierarchy, the scope becomes narrower, focusing on smaller regions of the world while requiring more rapid solutions. At the lowest levels, rapid real-time response is required, but the planner is only concerned with its immediate surroundings and has lost sight of the "big picture". Meystel [22] has developed a theory for hierarchical planning which emphasizes the significance of scope and invokes the concept of nested controllers.

Reactive Control

Reactive robotic control systems afford the opportunity for real-time response in dynamic and unstructured environments. There exist a diversity of these systems (e.g., [1,11,16,25]) many of which share a common aversion to the use of representational knowledge.

Brooks' subsumption architecture is perhaps the best known representative of the reactive school. His approach advocates the "horizontal decomposition" of planning into a collection of concurrent layered behaviors, each connected to its own sensory inputs. Although this method has provided successful demonstrations of autonomous behavior, it is lacking in its ability to incorporate world knowledge and alterations in user intent based upon changes in environmental circumstances and internal conditions. Even though early models of the subsumption architecture [11] did provide for the integration of world models, it is our position that a better approach involves a synthesis of hierarchical planning and reactive control.

Many other navigational systems using reactive control have been developed. These include Payton's reflexive behaviors [25], Kadonoff's arbitration strategies [19], Arkin's motor schemas [1], and many others [15,30]. Although each of these methods differ significantly in the way the primitive behaviors are integrated, controlled, and selected, they share in common a decomposition of motor action into a collection of primitives which can be closely tied to incoming sensory information.

Hybrid Architectures

The approach used in our laboratory, embodied in the Autonomous Robot Architecture (AuRA [2,3]), has from its onset been concerned with the integration of hierarchical and reactive planning mechanisms and is among the first of such hybrid designs. Several other methods have since emerged. Some of these methods push planning into a more reactive form (e.g., [23]), while others make reactive control more representational (e.g., [21]). A more common method involves the treatment of the planning problem as two separate systems which interface with each other [16,18,31,29]. AuRA's approach fits into this category. There is psychological and neurophysiological evidence for the co-existence of two distinct planning systems in humans [24] which lends support to this approach as a potentially effective methodology for robotic systems.

To set the stage for the description of the mobile manipulation system, a brief overview of AuRA is presented below.

AuRA

Within the framework of AuRA, techniques have been developed for navigational path planning in the presence of *a priori* world models, spatial uncertainty management, reactive and homeostatic control, and the integration of vision in the context of action-oriented and expectation-based perception. Navigational experiments using mobile robots have been conducted in several locales, including the interior of buildings, outdoor campus settings, and manufacturing environments. Previously this work has concentrated on navigational tasks - more recently it has been extended to include mobile manipulation.

AuRA exploits several forms of knowledge representation [2]: *a priori* world maps and landmark models, dynamically acquired spatial occupancy maps in a local context, and collections of intelligent motor behaviors and perceptual strategies (schemas) which are selected, parameterized, and instantiated in a manner consistent with available knowledge. Much of this work has been and continues to be influenced by psychological and neuroscientific studies [8,9]. Although complete integration of the hierarchical planner at the highest cognitive levels is ongoing research, the mechanisms for behavior selection and modulation are in place. The mission planner is concerned with the high-level broad-brush concerns of the robot's mission. It has the grandest scope and the least temporal constraints. The subordinate navigator chooses a point-to-point path consisting of a series of piecewise linear segments produced through an *a priori* map of the robot's world and that is consistent with the mission planner's specifications. The pilot then focuses further on an individual segment of the navigator's path, selecting and parameterizing the appropriate motor schemas (behaviors) and perceptual strategies necessary for successful completion of the path leg.

When plan formulation is completed by the selection of motor and perceptual schemas, plan execution is turned over to the concurrently active schemas. The configuration and activity levels for each of these individual reactive schemas changes dynamically as the robot proceeds through its world. There is no reliance on representational knowledge at this level. If goal attainment is not realizable at the reactive execution level, the hierarchical planner is reinvoked to compute an alternate strategy based upon available world models (first referring to a dynamically acquired model and if that fails then the *a priori* one). A diversity of methods have been developed for adapting behavioral strategy at the purely reactive level [13,10,27] to minimize the reliance on deliberative reasoning.

A CASE STUDY IN MOBILE MANIPULATION

Mobile manipulation affords an extension of many of our already developed techniques successfully used for navigation. This article addresses one part of a larger project [6], the macro-motion phase of mobile manipulation, where the robot is delivered into the predefined acquisition region of the object being manipulated. We are not treating the aspects of the manipulation itself here (micromotion phase).

Deliberative Aspects for Mobile Manipulation

In order to facilitate reactive motion of the mobile manipulator in a dynamic world, it is useful to exploit world knowledge whenever it is available. Information provided to the behavioral planner includes: spatial models of the environment, express representations of spatial uncertainty, perceptual characteristics and location of landmarks, available motor behaviors and perceptual strategies, and the resources and limits of the robotic system itself.

Knowledge Representations

World knowledge is provided through the use of the *meadow map* strategy we have previously developed [4]. This decomposition of free space into a collection of connected convex regions (cf. [14,17]) provides a basis for both conducting path planning as well as embedding other information such as landmark location.

The available motor behaviors and perceptual strategies are represented as schemas and are discussed in more detail below. Landmarks contain information regarding the spatial location and the means by which they may be recognized. Holonomic constraints can also be represented at this level indicating fundamental limitations on either the kinematics or dynamics of the robot.

Path planning

Planning for mobile manipulation is conducted in a manner similar to the navigational method [4]. The fundamental difference lies in how the end-effector position is computed. The path planner previously generated a list of via-points for the pilot. These points were two dimensional, targeted for a ground vehicle, and planned relative to the center of the robot's footprint using A^* search techniques.

With the mobile manipulator, planning is relative to the end-effector, since that is what must interact with the world. Intuitively, the base is just pulled along as the end-effector moves towards the goal. With the via-points now being generated for the end-effector, they must be three dimensional. It has not been necessary to extend the representation to three dimensions although such a representation is available [28]. Instead, suitable performance has been obtained by a linear interpolation between the end-effector's initial height and the height of the final goal position.

Reactive Aspects for Mobile Manipulation

Reactive behaviors enable the mobile manipulator to function in dynamic and partially modeled environments. Motor schemas provide the basis for reaction. This approach [1] uses an analog of the potential field methodology to provide instantaneous response to unplanned events during the execution of the robot's plan.

Motor Behaviors

The reactive behaviors that have been reformulated for specific use in the mobile manipulation project are:

- **move-to-goal**: generates a constant magnitude three dimensional attractive force on the end-effector, pulling it towards the goal position. This differs from the previous method in that the force is exerted upon the endpoint of the kinematic chain, not the base.
- **avoid-static-obstacle**: generates forces and torques on the vehicle, repulsing it from obstacles. First, a cylindrical field is constructed around each link in the robot (the robot base is considered one link). If an obstacle is detected to lie within the field, a torque is generated on the link, pushing it away. Second, a spherical field is constructed around each joint. Obstacles within this field generate repulsive forces acting on the joint.
- **move-ahead**: Draws the end-effector in a particular compass direction.
- **docking**: generates forces and torques on the mobile manipulator forcing the end-effector to approach in a particular oriented region [5] for tasks such as pin insertion.

The motor schemas use a vehicle (arm and base combined) Jacobian matrix with the forces and torques computed by the individual motor behaviors determining the overall resultant torque acting on each joint [12]. Individual damping functions control each joint's freedom to move. The damping model is used to convert joint torques into joint velocities, which are then sent to the robot for execution.

Perceptual Support

Several different sensors are being used for this system. We are currently relying on ultrasound and shaft encoders. At this time computer vision algorithms are being developed for use in this project as well [6].

PLANNING TO BEHAVE: SYSTEM INTEGRATION

Results show that the mobile manipulator is able to function efficiently in widely varying environments due to behavioral planning. Without this advantage, the system must be reconfigured by hand when changing environments, or very general parameters must be used with an accompanying reduction in performance.

Once the navigator has planned a route through the modeled environment, the pilot process must execute it. It does this by instantiating appropriate motor schemas with suitable perceptual schemas, each configured to function in the anticipated environment. The pilot then monitors the progress of the motor schemas in reaching the desired goal. In the case of failure, the pilot must replan to accommodate the changed conditions. In the case of success, the next leg of the route can be executed.

When instantiating a particular behavioral configuration, the pilot must take into account expected environmental conditions, internal resources, mission planner intentions, the set of behaviors available (schemas) and their constraints. Plans are currently represented using a finite state acceptor (FSA) model (e.g., [7]). The input to the behavioral planner includes world knowledge, mission intentions, the available behavioral and perceptual repertoire, and internal resources. The resulting output is an FSA that captures the relationships between the schemas themselves as well as parameters that are optimized for performance of the task in this environment. In this example using the mobile manipulator, the **move-to-goal** and **avoid-static-obstacle** schemas constitute the basic elements of the FSA.

The mobile manipulator used for this research appears in Figure 1. Figure 2 shows a simulated path the navigator has planned through the meadow map. The initial position of the robot is on the left and the goal is on the right. The robot is shown in equal time steps as it moves to the goal.

CONCLUSIONS AND SUMMARY

This paper describes the advantages of hybrid reactive/deliberative architectures. In particular, an application of a behavioral planning system to the task of mobile manipulation is described. Knowledge representations, planners and reactive execution mechanisms which support this methodology have been presented. Results on actual robotic hardware are being tested.

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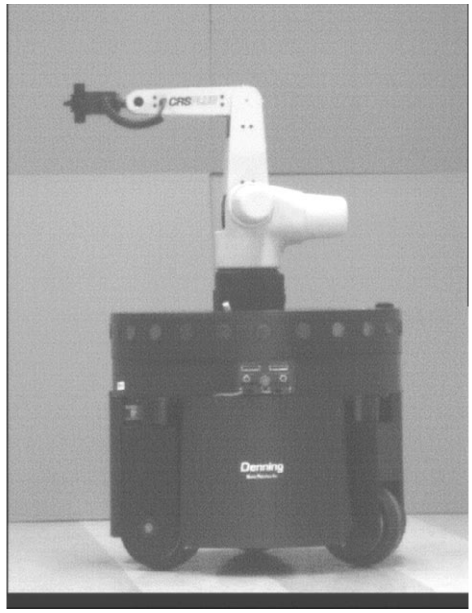

Figure 1: Mobile manipulator

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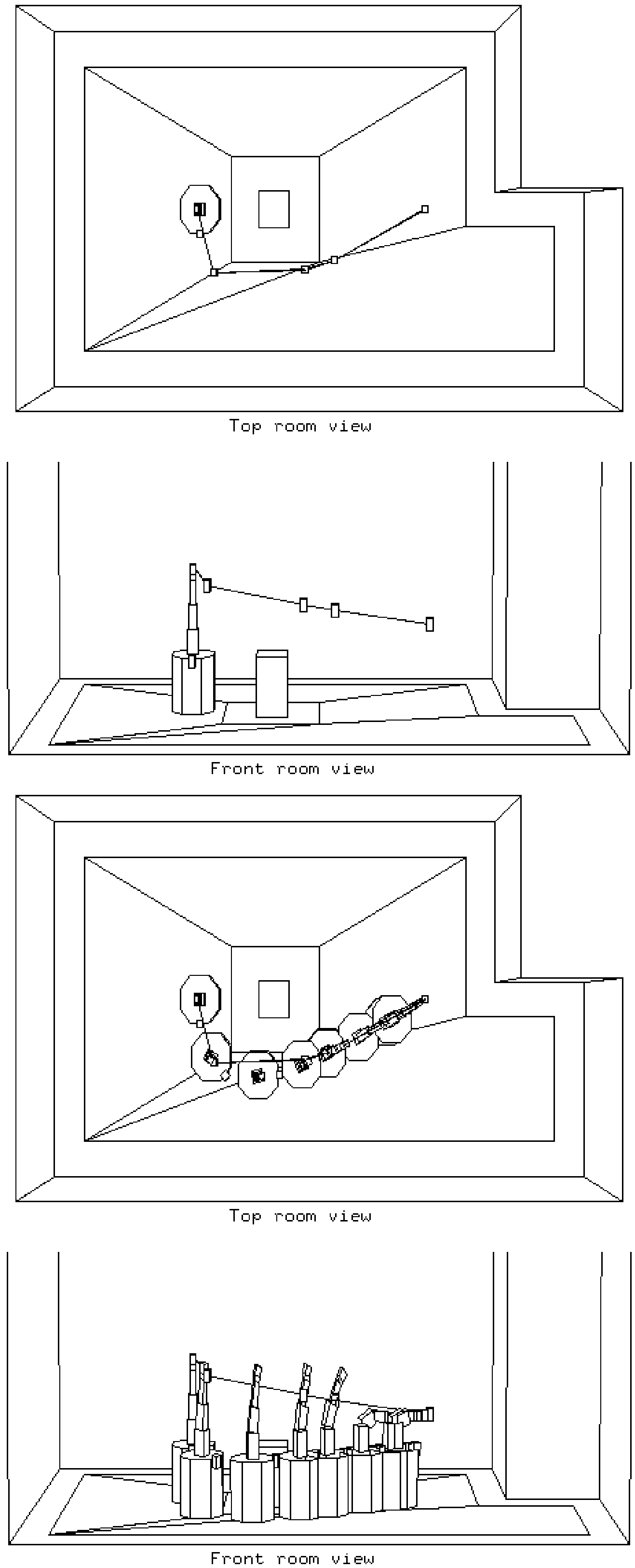

Figure 2: Simulation of macro-manipulation phase. The path that the navigator has planned through the modeled obstacles is shown with the accompanying via-points. The actual path the robot took is shown by overlaying snapshots of the vehicle position at equal time increments

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