Lecture 25

Hybrid Deliberative/Reactive Architectures

Lecture Objectives

- To understand the limitations of purely reactive and purely deliberative methods when each is considered in isolation.
- To study biological models of hybrid reactive/deliberative systems.
- To recognize the issues in establishing interfaces between reactive control and deliberative planners and to express several models for these interfaces.
- To study several representative hybrid architectures, especially AuRA, Atlantis, Planner-Reactor, and PRS.
1. Why Hybridize?

2. Biological Evidence in Support of Hybrid Systems

3. Traditional Deliberative Planners

4. Deliberation: To Plan or Not to Plan

5. Layering

6. Representative Hybrid Architectures

7. Lecture Summary
1. Why Hybridize?

- The central issues:
  - How to develop a unifying architectural methodology ensuring a system capable of robust robotic plan execution with a high-level understanding of the nature of the world and a model of user intent.

- Reactive systems produce robust performance effectively under the strong assumptions such as
  - The environment lacks temporal consistency and stability.
  - The robot’s immediate sensing is adequate for the task at hand.
  - It is difficult to localize a robot relative to a world model.
  - Symbolic representation of world knowledge is of little or no value.
1. Why Hybridize?

- Deliberative systems permit following representational knowledge to be used for planning purposes in advance of execution:
  - Behavioral and perceptual strategies can be represented as modules and configured to match various missions and environments.
  - A priori knowledge can be used to configure or reconfigure these behaviors efficiently.
  - Dynamically acquired world models can be used to prevent certain pitfalls to which non-representational methods are subject.
1. Why Hybridize?

- Hybrid deliberative/reactive robotic architectures
  - Capable of incorporating both deliberative and behavior-based execution.
  - Combining aspects of traditional AI symbolic methods and their use of abstract representational knowledge,
  - Maintaining the goal of providing the responsiveness, robustness and flexibility of purely reactive systems.
  - Permit reconfiguration of reactive control systems based on available world knowledge.
  - Dynamic control system reconfiguration based on deliberation (reasoning over world models) is an important addition to the overall competence of general purpose robots.
2. Biological Evidence in Support of Hybrid Systems

- As many psychologists moved from behaviorism (Watson’25, Skinner ’74) to cognitive psychology (Neisser ’76) as an acceptable description of human information processing, research in the use of hybrid systems expanded to include these concepts.

- Two distinct models of behavior: Willed and Automatic (Shiffrin and Schneider’77):
  - Modeled the coexistence of two distinct systems concerned with controlling human behavior (Norman and Shallice’86).
    - One system models ‘automatic’ behavior which executes automatic actions without awareness, starts without attention, and consists of multiple independent parallel activity threads (schema).
    - The second system controls ‘willed’ behavior and provides an interface between deliberate conscious control and the automatic system.
2. Biological Evidence in Support of Hybrid Systems

- Norman-Shallice model:
  - Model for integrated automatic and willed behaviors
  - Automatic schemas (behavioral tasks) are modulated by attention arising from deliberate control.
  - The vertical threads provide the schema selection mechanism.
  - The model lacks a mechanism by which the deliberative process is conducted.
  - Neuropsychological experiments are consistent with this model.
3. Traditional Deliberative Planners

- Deliberative planning: hierarchical planning
  - A structured and identifiable subdivision of functionality relegated to distinct program modules
  - Rely heavily on the world models, can integrate world knowledge, and have a broader perspective and scope.
4. Deliberation: To Plan or Not to Plan

- The hierarchical approach is best suited for integrating world knowledge and user intent to arrive at a plan prior to its execution.
  - Deliberative planning w/o considering difficulties in plan execution (dynamic and unmodeled world changes) can lead to restricted usage.
  - Reactive systems deal with the immediacy of sensory data but is less effective in integrating world knowledge.
4. Deliberation: To Plan or Not to Plan

- Deliberative/Reactive
  - Planner/Reactor, Lyons ’92
  - Cognitive/Subcognitive systems, Malcolm and Smithers’90
    - Cognitive component: high-level functions (planning)
    - Subcognitive portion: controls the robot’s sensors and actuators

- Interface design
  - What is the appropriate boundary for the subdivision of functionality?
  - How is coordination effectively carried out?
4. Deliberation: To Plan or Not to Plan

- Lyons methods
  (A) Hierarchical integration of planning and reaction
  (B) Planning to guide reaction: projecting the outcome of continuously formulated plans and reconfiguring the reactive system
  (C) Coupled planning-reacting: each guiding the other
5. Layering

- Multi-layered hybrid architecture (Hexmoor and Kortenkamp’95):
  - A top-layer planning
  - The interface or middle layer
    - Key function: linking rapid reaction and long-range planning
  - A lower-level reactive system

- Questions:
  - How to effectively partition deliberative and reactive functions.
  - Where and how to implement coordination of the deliberation and reactivity.
6. Representative Hybrid Architectures

- Four principal interface strategies:
  - Selection (Planning is viewed as configuration): AuRA
    - The planning component determines the behavioral composition and parameters used during execution. The planner may reconfigure them as necessary because of failures in the system.
  - Advising (Planning: advice giving): Atlantis
    - Plans offer courses of actions, but the reactive agent determines whether each is advisable.
6. Representative Hybrid Architectures

- Adaptation (Planning: adaptation): Planner-Reactor
  - The planner alters the ongoing reactive component in light of changing conditions within the world and task requirements.

- Postponing (Planning: a least commitment process): Procedural Reasoning System
  - The planner defers making decisions on actions until as late as possible.
  - This enables recent sensor data, by postponing reactive actions until absolutely necessary, to provide a more effective course of action.
6.1 AuRA

- **Autonomous Robot Architecture**
  - The robot navigational system that integrates a deliberative hierarchical planner, based on AI, and a reactive controller, based on schema theory
Planning components:

- A mission planner
  - Establishing high-level goals for the robot and the constraints within which it must operate.
  - An interface to a human commander.
- A spatial reasoner (navigator)
  - Constructs a sequence of navigational path legs.
- A plan sequencer
  - Translates each path leg into a set of motor behaviors for execution.
**Schema controller:**

- For controlling and monitoring the behavioral process at run time
  - Motor and perceptual schemas
- A homeostatic control system is interwoven with the schemas
  - Internal sensors (fuel level, temperature transducers) provide information which alters the behaviors’ and internal parameters’ relative strengths to maintain balance and system equilibrium.
If a component fails, only the component one level higher is invoked to solve the problem as follows:

- If the reactive execution fails, the plan sequencer attempts to reroute the robot.
- If unsatisfactory, the spatial reasoner is reinvoked to and attempts to generate a new global route that bypasses the affected region.
- If this still fails, the mission planner informs of the difficulty and asks for reformation or abandonment of the mission.

Modularity, flexibility, and generalizability to a wide range of problems.

AuRA: deliberative planning, reactive control, homeostasis, action-oriented perception, and machine learning
6.2 Atlantis

- A three-level hybrid system at JPL, Gat’91
- Design proceeds from the bottom up:
  - Reactive-controller level: low-level primitive activities are first constructed.
  - Sequencing level: suitable sequences of the primitive behaviors
  - Deliberator: planning and world modeling to assist in the decisions the sequencer makes
6.2 Atlantis

- A deliberator:
  - Deliberation occurs at the sequencing layer’s request.
  - The planner’s output is viewed only as advice to the sequencer layer.

- A sequencer:
  - Initiation and termination of low-level activities to the reactive controller.
  - Addresses reactive-system failures (status) to the deliberator.
  - Conditional sequencing occurs upon the completion of various subtasks or the detection of failure.
    (Cognizant failure: The robot’s ability to recognize on its own when it has not completed or cannot complete its task.)

- A reactive controller:
  - Managing primitive activities
For integrating planning and reactivity with anytime planning

The planner:

- An execution monitor that adapts the underlying behavior control system in light of the changing environment and the agent’s underlying goals, as a mechanism to continuously modifies an executing reactive control system

RS (Robot Schema) model:

- To model and implement the reactor component
6.3 Planner-Reactor Architecture

- Anytime planners:
  - At any point a plan is available for execution, and the quality of the available plan increases over time.

Lyons and Hendricks (92, 95)
6.4 The Procedural Reasoning System

- A least-commitment strategy (Georgeff and Lansky ’87) defers making a decision until it is absolutely necessary to do so.
  - The information necessary to make a correct decision is assumed to become available late in the process, thus reducing the need for backtracking.
6.4 The Procedural Reasoning System

- **Reactivity:**
  - Postponement of the elaboration of plans until it is necessary.

- **Plans:**
  - The primary mode of expressing action, but continuously determined in reaction to the current situation.
  - Previously formulated plans undergoing execution can be interrupted and abandoned at any time.
  - Representing the robot’s desired behaviors instead of the traditional planner’s output of goal states to be achieved.
Representations of the robot’s beliefs, desires, and intentions are all used to formulate a plan.

The interpreter drives system execution, carrying out the most current suitable plan.

As new beliefs, desires, and intentions arise, the plan may change, with the interpreter handling the plan switching.

- A symbolic plan always drives the system, so it is not reactive in the normal sense of tight sensorimotor pair execution, but it is reactive in the sense that perceived changing environmental conditions permit the robotic agent to alter its plans on the fly.
6.5 Other Hybrid Architectures

- **SSS (Connel ’92)**
  - Servo, subsumption and symbolic
  - The symbolic level handles where-to-go-next decisions (strategic) and the subsumption level, where-to-go-now choices (tactical)
  - A coarse geometric map of the world is present at the strategic level.

- **Multi-valued logic (Saffiotti et al. ’95)**
  - For behaviors (motor schema) as the reactive component coupled with the gradient field.
  - Provides the ability to have a variable planner-controller interface that is strongly context dependent.

- **SOMASS (Malcolm and Smithers ’90)**
  - An assembly system with the cognitive (deliberative) and subcognitive (reactive) components.
6.5 Other Hybrid Architectures

- **Agent Architecture (Hayes-Roth et al. ’93)**
  - Plans: descriptions of intended courses of behavior
  - The physical level for perception and action, and cognitive level for higher level reasoning needs such as problem-solving and planning.
  - Reactive and deliberative behaviors can coexist within each level.

- **Teho-Agent (Mitchell ’90)**
  - “React when it can, plans when it must.”
  - Focuses on learning how to become more reactive, more correct in its actions, and more perceptive about the world’s features.
  - Planner is invoked only when there is no rules to determine a suitable course of action.

- **Generic Robot Architecture (Noreils and Chatila ’95)**
  - Planning, control system, and functional levels
6.5 Other Hybrid Architectures

- **Dynamical Systems Approach (Schoner and Dose, ’92)**
  - Significantly influenced by biological systems research.
  - The deliberative planner operates within the reactive controller’s representational space, dealing with the controller’s mathematics and dynamics.

- **Supervenience Architecture (Spector, ’92)**
  - A multilevel implementation of the architecture referred to as the abstraction-partitioned evaluator (APE) has been implemented.
  - Multilevels ranging from perceptual/manual to spatial, temporal, causal, and finally conventional (highest level), connected in a strict hierarchy.
  - Leans towards a more traditional hierarchical design.

- **Telereactive Agent Architecture (Benson and Nilsson, ’95)**

- **Reactive Deliberation (Sahota, ’93)**

- **Integrated Path Planning and Dynamic Steering Control (Krogh and Thorpe, ’86)**
Both deliberative planning systems and reactive control systems have limitations when considered in isolation.

The interface between deliberation and reactivity serves as the focus of research.

Hybrid models include hierarchical integration, planning to guide reaction, and coupled planning and reaction.

Representative hybrid architectures

- AuRA: selection,
- Atlantis: advising
- Planner-Reactor: adaptation,
- PRS: postponement