Planning, Execution & Learning: Execution Architectures

Reid Simmons

Manuela Veloso

Capabilities

- *Support Goal Achievement*
  - Complex tasks involving multiple steps
  - Conditional execution depending on environment
- *Support Acting in a Dynamic Environment*
  - Monitor for (relevant) changes
    - Contingencies / failures
    - Unexpected opportunities

What is a Robot Architecture?

- Conceptual Framework for Designing Robot Systems
- Implementation "Glue" for Integrating and Coordinating Robot Systems
- Important Constraints on Architecture Design
  - Situated / embedded / interacting
  - High perceptual bandwidth
  - Dynamic / unpredictable environment
  - Uncertainty in sensing and action

Architectural Design Principles

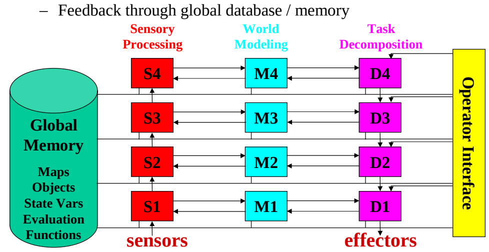
- *Modularity*
  - Reduces complexity
  - Algorithms and representations tuned to particular roles
- *Concurrency*
  - Monitor environment while carrying out plans
  - Concurrent planning and execution
- *Hierarchy*
  - Layers of increasingly complex behaviors
  - Promotes reactivity
  - *Disagreements on how to create hierarchy*

Approaches to Hierarchy

- Temporal
- Behavioral
- Functional

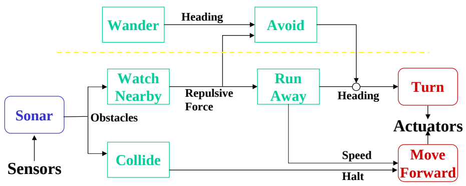
Temporal Architectures

- RCS (Albus)
  - Layers operate at different temporal scales (order of magnitude)
  - Fixed, rigid communication patterns
  - Feedback through global database / memory



Behavioral Architectures

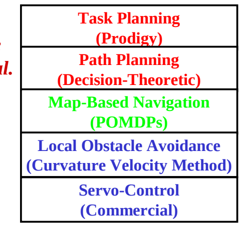
- Subsumption (Brooks, 1986)
  - Collection of concurrent FSAs
    - Direct, fixed connections between sensors and effectors
  - Minimal internal state
    - "World is its own best model"
  - Higher layers subsume output of lower layers



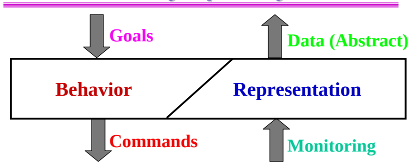
Functional Architectures

- Upper layers utilize functionality of lower layers to implement more complex tasks
- Upper layers typically operate at lower ***temporal*** and ***spatial*** resolutions

Xavier Architecture (Simmons et.al. 1995)

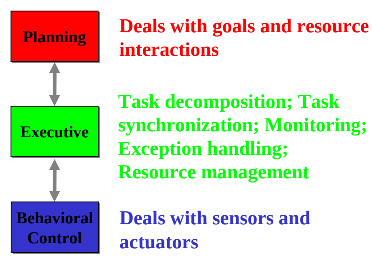


Anatomy of a Layer



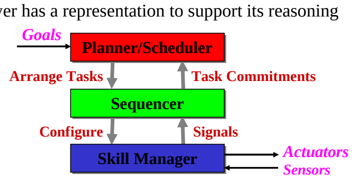
- Each Layer Provides "Guidance" to Next Lower Level
- Each Layer has Relative Autonomy to Achieve Tasks Robustly, in Face of Uncertainty
- Each Layer Abstracts Data for Higher Levels
  - Each layer must monitor progress of lower level

Three-Tiered Architectures



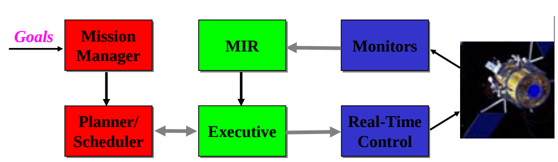
3T (Bonasso & Kortenkamp, 1996)

- Explicit Separation of Planning, Sequencing, and Control
  - Upper layers provide ***control flow*** for lower layers
  - Lower layers provide ***status*** (state change) and ***synchronization*** (success/failure) for upper layers
- Heterogeneous Architecture
  - Each layer utilizes algorithms tuned for its particular role
  - Each layer has a representation to support its reasoning



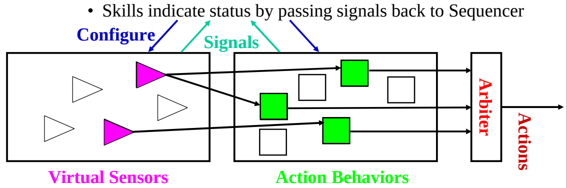
Remote Agent (NASA, 1999)

- First Truly Autonomous System in Space
  - Controlled DS1 spacecraft for several days in 1999
  - Closed-loop, goal-based commanding
  - Model-based programming
  - Real-time inference
  - Integrated declarative/procedural paradigms



Managing Sets of Behaviors

- 3T "Skill Manager"
  - ***Skills*** are concurrent behaviors, including perceptual behaviors
  - Dynamic creation of real-time feedback loops
    - Higher tier ("Sequencer") connects sensing and action modules and ***enables*** subsets of skills
    - Skills indicate status by passing signals back to Sequencer



Sequencer / Executive

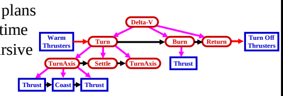
- Forms a Bridge Between Planning and Behaviors
  - Discrete vs. continuous control
  - Symbolic vs. numeric representations
  - Real-time considerations
- Basic Roles
  - Decompose task into subtasks and dispatch tasks
  - Monitor execution for contingencies and opportunities
  - Reschedule tasks (or schedule new tasks) upon failure
- Differences Between Approaches
  - Methods for distributing functionality
  - Representation of domain and control knowledge
  - RAP (Firby); TCA/TDL (Simmons); ESL (Gat); PRS (Georgeoff)

TDL *(Simmons & Apfelbaum, 1998)*

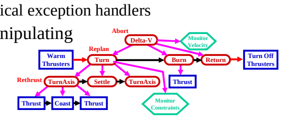
- High-Level Language Tailored to Task-Level Control
  - Extension of C++ with explicit syntax for task-level control constructs
  - Syntax for task decomposition, sequencing, monitoring, error handling
  - Compiles into pure C++ with calls to task management library
- Requirements
  - ***Simple concepts*** should be expressible in ***simple terms***
  - Do not ***preclude*** expression of complex control constructs
  - ***Natural integration*** with existing code

Task Trees

- TDL Maintains and Coordinates ***Task Trees***
  - ***Execution trace*** of hierarchical plans
    - Created dynamically at run time
    - Can be conditional and recursive
  - Temporal constraints (partially) order task execution
  - Planning and sensing treated as schedulable activities; Concurrent planning, sensing, and execution



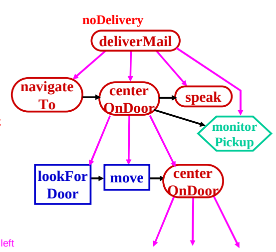
- Task Trees Augmented with ***Reactive*** Elements
  - Task-specific execution monitors
  - Context-dependent, hierarchical exception handlers
- Replan by Analyzing and Manipulating Task Trees
  - Terminate subtrees
  - Add new nodes and/or temporal constraints



TDL Example

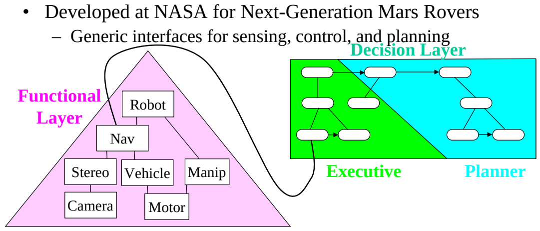
```
Goal deliverMail (int room)
    Exception Handler noDelivery
{
    double x, y;
    getRoomCoordinates(room, &x, &y);
    spawn navigateTo(x, y);
     spawn centerOnDoor(x, y)
       with sequential execution previous,
           terminate in 30.0;
     spawn speak("Xavier here with your mail")
       with sequential execution centerOnDoor,
           terminate at monitorPickup completed;
     spawn monitorPickup()
       with sequential execution centerOnDoor;
}

Goal centerOnDoor(double x, double y)
{
    int whichSide;
     spawn lookForDoor(&whichSide) with wait;
    if (whichSide != 0) {
      if (whichSide < 0) spawn move(-10); // move left
      else spawn move(10);  // move right
      spawn centerOnDoor(x, y)
        with disable execution until
           previous execution completed;
     }
}
```



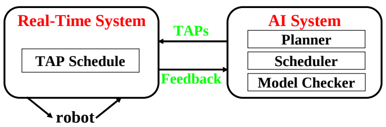
CLARAty *(Volpe & Nessnas, 2000)*

- Two-Tiered Architecture
  - Functional layer: Object oriented, reusable
  - Decision layer: Tightly integrates planner (ASPEN) and executive (TDL)
- Developed at NASA for Next-Generation Mars Rovers
  - Generic interfaces for sensing, control, and planning



CIRCA *(Musliner 1993)*

- Provide Both ***Bounded Rationality*** and ***Bounded Reactivity***
  - Distinguishes control-level and task-level goals
  - Guarantee achievement of control-level goals
    - AI system creates provably (probabilistically) feasible schedules that prevent failure
  - Trades off ***performance*** for ***reliability***
    - Reduce set of task-level goals
    - Change task parameters (e.g., move slower)



CIRCA Representations

- ***Test Action Pair*** (TAP)
  - Interface between real-time and AI system
  - Simple production rule with resource bounds

```
TAP stop-if-object-ahead
  TEST: [0.15] (< (sonar-forward) *safety-distance*)
  ACTION: [0.05] (progn (halt) (notify-AIS 'halted))
  RESOURCES: (sonar base-motors)
  MAX-PERIOD: 0.7
```

- Model of Dynamics
  - State diagram with event, action and temporal transitions
  - May be probabilistic