Principles of Autonomy and Decision Making

Brian Williams and Nicholas Roy
16.410/16.413
September 8th, 2004
Today’s Assignment

• Read Chapters 1 and 2 of AIMA
  – “Artificial Intelligence: A Modern Approach” by Stuart Russell and Peter Norvig
  – 2nd Edition (not 1st Edition!!)
  – AIMA is available at the Coop
Outline

• Objectives
• Agents and Their Building Blocks
• Agent Paradigms
• Principles for Building Agents:
  – Modeling Formalisms
  – Algorithmic Principles
• Building an Agent: Fall 03 Projects
Course Objective 1: Principles of Agents

16.410/13: To learn the modeling and algorithmic building blocks for creating reasoning and learning agents:

- To formulate reasoning problems.
- To describe, analyze and demonstrate reasoning algorithms.
- To model and encode knowledge used by reasoning algorithms.
Course Objective 2: Building Agents

16.413: To appreciate the challenges of building a state of the art autonomous explorer:

Fall 03, goals were:

• To model and encode knowledge needed to solve a state of the art challenge.
• To work through the process of autonomy systems integration.
• To assess the promise, frustrations and challenges of using (b)leading art technologies.

Fall 04, stay tuned.
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1. Mission-Oriented Agents

``Our vision in NASA is to open the Space Frontier . . . We must establish a virtual presence, in space, on planets, in aircraft and spacecraft.”

- Daniel S. Goldin, NASA Administrator, May 29, 1996
Inner and Outer Planets Missions

MESSENGER mission to Mercury
Venus Sample Return
Comet Nucleus Sample Return

Europa Lander
Titan Explorer
Europa Orbiter
Neptune Orbiter
Pluto/Kuiper Express

Primitive Bodies Missions

MESSENGER mission to Mercury

Courtesy of JPL
2003 Twin Mars Exploration Rovers

- Will learn about the climate on Mars and scout for regions where mineralogical evidence of water has been found.
- The rover twins will determine the geologic record of the landing site, what the planet’s conditions were like when the Martian rocks and soils were formed, and help us learn about ancient water reservoirs.

First microscopic view of Mars

Rover 1:  
Launch: May 30, 2003  
Landing: January 4, 2004

Rover 2:  
Launch: June 27, 2003  
Landing: January 25, 2004
Mission Objective: Learn about ancient water and climate on Mars.

- For each rover, analyze a total of 6-12 targets
  - Targets = natural rocks, abraded rocks, and soil
- Drive 200-1000 meters per rover
- Take 1-3 panoramas both with Pancam and mini-TES
- Take 5-15 daytime and 1-3 nighttime sky observations with mini-TES
One day in the life of a Mars rover

rover operation (7 hr)

- tactical sci assess & obs planning (5 hr)
- tactical end-of-sol eng assess (5 hr)

SOWG mtg (2 hr)

- activity integration & validation (3.5 hr)
- sequence development (5.5 hr)

sequence integration & validation (4 hr)
Agent Building Blocks

- Activity Planning
- Execution/Monitoring
Agents As Engineers

• 7 year cruise
• ~ 150 - 300 ground operators
• ~ 1 billion $
• 7 years to build

Affordable Missions

• 150 million $
• 2 year build
• 0 ground ops
Four launches in 7 months

Mars Climate Orbiter: 12/11/98


Stardust: 2/7/99

QuickSCAT: 6/19/98

courtesy of J
Mars Polar Lander

Spacecraft require a good physical commonsense...

Launch: 1/3/99
courtesy of JPL
Traditional spacecraft commanding

**GS, SITURN, 490UA, BOTH, 96-355/03:42:00.000**;

CMD, 7GYON, 490UA412A4A, BOTH, 96-355/03:47:00:000, ON;
CMD, 7MODE, 490UA412A4B, BOTH, 96-355/03:47:02:000, INT;
CMD, 6SVPM, 490UA412A6A, BOTH, 96-355/03:48:30:000, 2;
CMD, 7ALRT, 490UA412A4C, BOTH, 96-355/03:47:02:000, INT;
CMD, 6ASSAN, 490UA412A6B, BOTH, 96-355/03:48:30:000, 2;
CMD, 7SAFE, 490UA412A4D, BOTH, 96-355/03:52:00:000, UNSTOW;
CMD, 7VECT, 490UA412A4E, BOTH, 96-355/03:56:10:000, 0, 191.5, 6.5,
CMD, 7STAR, 490UA412A4F, BOTH, 96-355/03:56:12.000, SYS1, NPERR;
CMD, 7TURN, 490UA412A4F, BOTH, 96-355/03:56:14.000, MVR;
MISC, NOTE, 490UA412A99A, , 96-355/04:00:00:000, START OF TURN;
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CMD, 7STAR, 490UA412A406A4C, BOTH, 96-355/04:00:06.000,
CMD, 7STAR, 490UA412A406A4D, BOTH, 96-355/04:00:08.000,
CMD, 7STAR, 490UA412A406A4E, BOTH, 96-355/04:00:10.000,
CMD, 7STAR, 490UA412A406A4F, BOTH, 96-355/04:00:12.000,

What's a better paradigm?
Houston, we have a problem ...

- Quintuple fault occurs (three shorts, tank-line and pressure jacket burst, panel flies off)
  - Diagnosis.
- Mattingly works in ground simulator to identify new sequence handling severe power limitations.
  - Planning & Resource Allocation
- Mattingly identifies novel reconfiguration, exploiting LEM batteries for power.
  - Reconfiguration and Repair
- Swaggert & Lovell work on Apollo 13 emergency rig lithium hydroxide unit.
  - Execution
Remote Agent on Deep Space 1

Started: January 1996
Launch: Fall 1998
Remote Agent

- Goal-directed
- First time correct
  - projective
  - reactive
- Commonsense models
- Heavily deductive

Goals

Scripts

Mission Description

Executives

Diagnosis & Repair

Planner/Scheduler

Mission-level actions & resources

component models
Remote Agent Experiment
See rax.arc.nasa.gov

May 17-18th experiment
• Generate plan for course correction and thrust
• Diagnose camera as stuck on
  – Power constraints violated, abort current plan and replan
• Perform optical navigation
• Perform ion propulsion thrust

May 21th experiment.
• Diagnose faulty device and
  – Repair by issuing reset.
• Diagnose switch sensor failure.
  – Determine harmless, and continue plan.
• Diagnose thruster stuck closed and
  – Repair by switching to alternate method of thrusting.
• Back to back planning
Course Objective 2

Plan

Monitor & Diagnosis

Execute
Agent Building Blocks

- Activity Planning
- Execution/Monitoring
- Diagnosis
- Repair
- Scheduling
- Resource Allocation
2. Mobile Agents

Day 1
Long-Distance Traverse (<20-50 meters)

Day 2
Initial Position; Followed by “Close Approach”
During the Day
Autonomous On-Board Navigation Changes, as needed
Day 2 Traverse Estimated Error Circle

Day 3
Science Prep (if Required)

Day 4
During the Day
Science Activities

Target
Multi-Vehicle Path Planning
Of 100 rock samples, Nomad correctly classified 3 as meteorites and incorrectly classified a 4th.

Images courtesy of D. Apostolous, CMU
Groundhog

Movie courtesy of S. Thrun, Stanford University
The Minerva Experience
Agent Building Blocks

- Activity Planning
- Execution/Monitoring
- Diagnosis
- Repair
- Scheduling
- Resource Allocation

- Path Planning
- Localization
- Map Building
3. Agile Agents
Agent Building Blocks

- Activity Planning
- Execution/Monitoring
- Diagnosis
- Repair
- Scheduling
- Resource Allocation

- Path Planning
- Localization
- Map Building
- Trajectory Design
- Policy Construction
3. Human-Robot Interaction

Nursebot Pearl

Assisting Nursing Home Residents

Longwood, Oakdale, May 2001
CMU/Pitt/Mich Nursebot Project
Agent Building Blocks

- Activity Planning
- Execution/Monitoring
- Diagnosis
- Repair
- Scheduling
- Resource Allocation
- Path Planning
- Localization
- Map Building
- Trajectory Design
- Policy Construction
- Plan Adaptation
- Dialogue Management
- People Tracking
NASA Exploration Initiative

• NASA has developed a bold vision focused on robotic and combined human-robotic exploration
  – Response to critical need to augment human presence in space missions with automated, closely cooperating robotic devices
  – Significant cost reduction and safety improvement
Challenge

• Autonomous humanoid robots
  – Can execute tasks intended for humans

• Human-robot interaction
  – Understand human tasks
Example: orbit assembly and repair

- Robonaut – Humanoid robot for EVA assistance
Example: surface exploration

- ERA – EVA robotic assistant follows astronaut and helps with sample collection, instrument placement
Example Mission Scenario: Task Execution

- Robot walks to its sample area
- Begins collecting samples
- Walks back to astronaut
  - Stumbles over unseen rock along the way, but recovers using appropriate limb motions
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Agent Paradigms
Model-based Agents

- State
- How the world evolves
- What my actions do
- What the world is like now
- What action I should do now
- Effectors

World Model
Reflexive Agents

Agent

Sensors

What the world is like now

Condition–action rules

What action I should do now

Effectors

Environment
Goal-Oriented Agents

- State
- How the world evolves
- What my actions do

Sensors
- What the world is like now
- What it will be like if I do action A

Agent
- Goals
- What action I should do now

Environment
- Effectors
Utility-Based Agents
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Building Blocks for Agent Paradigms

- Extensive Reasoning
- Extensive Optimization
- Extensive Learning
Models Underlying The Building Blocks

Building Blocks:

- Activity Planning
- Execution/Monitoring
- Diagnosis
- Repair
- Scheduling
- Resource Allocation
- Global Path Planning
- Task Assignment
- Trajectory Design
- Policy Construction

Models:

Consistency-based:

- State Spaces
- Rules, First Order Logic
- Strips Operators
- Constraint Networks
- Propositional Logic

Probabilistic & Utility-based:

- Weighted Graphs
- Linear Programs
- Mixed Integer Programs
- Markov Decision Processes
- Graphical Models
Sondik, 1971

Probability and Decision Theory

States

Rewards

Actions

Beliefs

Observations

Observable

Hidden

$S_1$ -> $S_2$
Probability Models

- **Bayes Rule**

\[
p(x \mid z) = \frac{p(z \mid x)p(x)}{p(z)}
\]

- **Graphical Models**
Algorithm Instances
Of Building Blocks

- Activity Planning
  - Graphplan, SatPlan, Partial Order Planning
- Execution/Monitoring
- Diagnosis
  - Constraint Suspension
- Repair
  - Rule-based
- Scheduling
  - CSP-based
- Resource Allocation
  - LP-based

- Global Path Planning
  - Roadmap
- Task Assignment
- Trajectory Design
  - MILP
- Policy Construction
  - MDP
  - Reinforcement Learning
Modeling Cooperative Path Planning as a Mixed Integer Program
Cooperative Path Planning: MILP Encoding: Fuel Equation

\[ \min = J_T = \min_{w_i, v_i} \sum_{i=1}^{N-1} q'w_i + \sum_{i=1}^{N-1} r'v_i + p'w_N \]

- total fuel calculated over all time instants \( i \)
- past-horizon terminal cost term
- slack control vector \( w_i, v_i \)
- weighting vectors
- slack state vector
Cooperative Path Planning: 
MILP Encoding: Constraints

- $s_{ij} \leq w_{ij}$, etc.  
  State Space Constraints
- $s_{i+1} = A_s i + B u_i$  
  State Evolution Equation
- $x_i \leq x_{\text{min}} + M t_{i1}$
- $-x_i \leq -x_{\text{max}} + M t_{i2}$
- $y_i \leq y_{\text{min}} + M t_{i3}$
- $-y_i \leq -y_{\text{max}} + M t_{i4}$  
  Obstacle Avoidance (for all time $i$)
- $\sum t_{ik} \leq 3$  
  (t introduce IP element)
- Similar equation for Collision Avoidance (for all pairs of vehicles)
Uninformed Search:
- Depth First, Breadth First
- Iterative Deepening
- Backtrack Search
- Backtrack w Forward checking
- Conflict-directed Search

Informed Search:
- Single Source Shortest Path
- Best First Search (A*, Hill Climbing, …)
- Simplex
- Branch and Bound
Algorithm Principles
Underlying Building Blocks

**Deduction:**
- Unification
- Unit Clause Resolution
- Arc Consistency
- Gaussian Elimination

**Relaxation:**
- Value Iteration
- Reinforcement Learning

**Divide and Conquer:**
- Branching
- Sub-goaling
- Variable Splitting
- Dynamic Programming
- Uninformed & Informed

**Abstraction:**
- Conflicts
- Bounding
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16.413 Project: Example of a Model-based Agent:

- Goal-directed
- First time correct
  - projective
  - reactive
- Commonsense models
- Heavily deductive
16.410/3 Student Teams

- Ground Science Planning for Rovers
  - Jessica Marquez and Julie Arnold
- Onboard Planning and Execution on Rovers
  - Stephen Licht, Andrew Vaughn, Steve Paschall
- Model Based Diagnosis and Execution on Rovers
  - Lars Blackmore, Steve Block, Thomas Leauté, Emily Fox
- Model Based Execution on SPHERES I
  - Mehdi Alighanbari, Tsoline Mikaelian, Martin Ouimet, Mike Voightmann
- Model Based Execution on SPHERES II
  - Robert Effinger, Jacomo Corbo, Jonathon Histon, Sameera Ponda
Rover Testbed Setup

- Sensors give information on motion and environment.
- Onboard PC allows for real-time computation and command processing.

Figures from Seung Chung’s Project Description handout
Simple Slipping Scenario

- Initialize in all-stop state
- Command ‘go’ : successful driving
- Command ‘stop’ : successful stopping
- Command ‘go’ : slips
- Command ‘stop’ : successful stopping
- Command ‘go’ : successful driving
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