Deep Space One Remote Agent

Models of Spacecraft, Flight rules

Remote Agent
Estimated Spacecraft State and Plan Database

Remote Agent Reasoning Engines
- Planner/Scheduler
- Smart Executive
- State Estimator/Recovery Expert (Livingstone)

Ground Control

Goals, high or low-level commands

Observations and Command Responses

Spacecraft Flight Software and Hardware Systems

Low-level Commands

Winner of the NASA 1999 Software of the Year Award

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Deep Space One (DS1)

- Launched 10/98
- Remote Agent Experiment 5/99
- Other technologies flight-validated:
  - Ion Propulsion
  - SCARLET Solar Panels
  - Miniature Integrated Camera & Spectrometer
  - Autonomous Navigation
  - Beacon Monitor
- Current state:
  thrusting toward comet Borrelly for 9/2001 encounter
DS1 Remote Agent Architecture

Abstraction Level

- High-level declarative model
- Medium-level procedural model
- Low-level declarative model
- Low-level procedures

Plan Request
- Planner (PS)
- Executive (EXEC)
- MIR
- MI
- MR

High-level plan
- Remote Agent
- Planner Experts (e.g., navigation)

Plan Runner
- System Software (e.g., controllers)
- Observations
- Low-level commands
- State
- Recovery request
- Recovery command
Domain Requirements

- Achieve diverse goals on real spacecraft
- High Reliability
  - single point failures
  - multiple sequential failures
- Tight resource constraints
  - resource contention
  - conflicting goals
- Hard-time deadlines
- Limited Observability
- Concurrent Activity
Approach

- Constraint-based planning and scheduling
  - supports goal achievement, resource constraints, deadlines, concurrency
- Robust multi-threaded execution
  - supports reliability, concurrency, deadlines
- Model-based fault diagnosis and reconfiguration
  - supports limited observability, reliability, concurrency
- Real-time control and monitoring
Diversity of Goals

- **Final state goals**
  - “Turn off the camera once you are done using it”

- **Scheduled goals**
  - “Communicate to Earth at pre-specified times”

- **Periodic goals**
  - “Take asteroid pictures for navigation every 2 days for 2 hours”

- **Information-seeking goals**
  - “Ask the on-board navigation system for the thrusting profile”

- **Continuous accumulation goals**
  - “Accumulate thrust with a 90% duty cycle”

- **Default goals**
  - “When you have nothing else to do, point HGA to Earth”
Diversity of Constraints

- **State/action constraints**
  - “To take a picture, the camera must be on.”
- **Finite resources**
  - power
- **True parallelism**
  - the ACS loops must work in parallel with the IPS controller
- **Functional dependencies**
  - “The duration of a turn depends on its source and destination.”
- **Continuously varying parameters**
  - amount of accumulated thrust
- **Other software modules as specialized planners**
  - on-board navigator
Deep Space One Remote Agent

- Levels of autonomy supported on DS1 (listed from least to most autonomous mode):
  - single low-level command execution
  - time-stamped command sequence execution
  - single goal achievement with auto-recovery
  - model-based state estimation & error detection
  - scripted plan with dynamic task decomposition
  - on-board back-to-back plan generation, execution, & plan recovery
Personal Satellite Assistant (PSA)

Environment Monitoring

Oxygen: 15%
Nitrogen: 79%
Carbon Dioxide: 0.5%
Other: 0.1%
Temperature: 68F
Pressure: 14lbs
Humidity: 50%

Space Station Module

Drawing provided by Boris Rabin
Primary High-Level Control Modules (laptop server)

- Vocabulary / grammar
- Context / user profile
- Path Planning Expert
- State database (PSA & world)
- Planner
- Plan database
- Goal database

Connections:
- From/to PSA
- From PSA state database
- From PSA Executive
- From GUI / Joystick
- From Tele-operation Manager
- From Dialogue Manager
Primary Low-Level Control Modules
(on-board PSA)

- State database (PSA & world)
- Reactive Planner (repair / task decomposition)
- Plan database
- State Estimator
- Executive
- Smart Monitors
- Low-level Controllers
- PSA Hardware
  - Sensors (cameras, proximity, IMU, etc...)
  - Actuators

- Models

- To laptop state database
- From/to laptop plan database
- To laptop Planner

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PSA Human-Centered Autonomy Requirements

- Humans dynamically modify plans during generation and execution
  - direct control can always be taken by human
- Humans dynamically act as sensors and actuators
- Humans dynamically modify domain models
- Humans communicate with system using limited natural-language context-sensitive grammar
- Autonomous system state, goals, models, and plans visible to humans
- System interacts with humans in its environment
- Dynamically modify plans as new goals are added, models change, human roles change, or plans fail