Autonomy Architecture for a Raven Class Telescope with Space Situational Awareness Applications

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Space Situational Awareness

- SSA is [Joint Publication 3-14]
  - SSA involves **characterizing, as completely as necessary**, Resident Space Objects (RSOs)
- Needs are articulated by
  - National Space Policy (2010)
  - DoD National Security Space Policy (2011)
- Helps to ensure [Joint Publication 3-14]
  - Space flight safety
  - Protecting economic interests
  - Protecting space capabilities
  - Protecting military operations and national interests
  - Implementing international treaties and agreements
Why SSA is Hard

- Data deprived [Sabol et al. 2002 & Nielsen et al. 2012]
- SSN sensors not centrally controlled [Nielsen et al. 2012]
- Increased # of data product customers [Nielsen et al. 2012]
- Air Force analyst staffing issues [Weeden 2012]
Need for Autonomy in SSA

Dull, repetitive tasks:
- Modern systems make hundreds of observations nightly [Sabol et al. 2002]
- Developing observation schedule complex

Fast timescales:
- Objects cross telescope field of view in seconds [Shell 2010]
- Dynamic local environment motivates near real time local schedule repair (e.g., weather)
Overview

• Motivation
• **Telescopes**
• Autonomy
• Proposed Architecture
• Example
Raven-class Telescope Overview

• Started as AFRL R&D effort
• Combination of COTS hardware and software
• Many Ravens currently in operation
• 1 Raven at Maui Space Surveillance Site contributes to SSN (Sabol et al. 2002)
Other Autonomous Telescopes

LANL RAPTOR [Ver Strand et al. 2008]

NASA MCAT [Mulrooney et al. 2010]
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Two common cognition models

- **Observe, Orient, Decide, Act** (OODA) loops developed by Col. John Boyd [Boyd 1976]
- NASA Goddard developed **Plan, Perceive, Act** (PPA) loop [Truszkowski et al. 2009]
Control Loop as a Cognition Model

Orient
Reference Generation

Decide
Controller

Act
Actuator Processing

Observe
Filter / Estimator
Sensor Processing

Real World
## Autonomy Architectures

<table>
<thead>
<tr>
<th>Intelligent Machine Design Levels</th>
<th>Autonomy Architectures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflection</td>
<td>Planning</td>
</tr>
<tr>
<td>Routine</td>
<td>Executive</td>
</tr>
<tr>
<td>Reaction</td>
<td>Functional</td>
</tr>
</tbody>
</table>

**Reflective** Agents have the ability to learn  
**Routine** Agents have the ability to evaluate & plan  
**Reactive** Agents interface with hardware (e.g., control loops)
Machine Learning Background

Categorized by type of feedback available [Russell and Norvig 2009]:

• Supervised
  – Learns function to map input-output pairs

• Reinforcement
  – Agent rewarded or punished for actions taken

• Unsupervised
  – No explicit feedback provided
Constraint Satisfaction Problems

Cast dynamic scheduling problem as CSP [Russell and Norvig 2009]:

- Solved using general purpose heuristics
- Partial sets that violate constraints removed
- Utility function used to select best alternative

Used extensively in space applications:

- Hubble [Johnston 1990]
  - Identify opportunistic science
- Chandra [Brissenden 2001]
  - Prioritize data downlinks
- Spitzer [Tyler et al. 2008]
- EO-1 [Sherwood et al. 2007]
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Distributed Sensor Networks

Centralized superior when minimizing overall catalog covariance [Hobson et al., 2011]

Current Space Surveillance Network [Hill et al., 2010]

- Uses knowledge of covariance
- Limited sensor knowledge

Decentralized superior to current SSN [Jayaweera et al., 2011]

- Limited covariance knowledge
- Excellent sensor knowledge

Centralized

Distributed

Robustness & Complexity
Proposed Autonomy Architecture

Increasing Machine Intelligence

Reflection
Routine
Reaction

Commanded Objectives

Space Object Catalog

Other networked sensors

Central Planning Agent

Raven Class Telescope

Agent

Agent

Agent

Agent

Agent

Agent
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Space Object Detection

• To detect a Space Object, need an SNR $\sim 6$

\[
SNR = \frac{E_{SO} \cdot \tau_{atm} \cdot \tau_{opt} \cdot A \cdot QE \cdot t_{int}}{\sqrt{L_b \cdot \tau_{opt} \cdot A \cdot QE \cdot t_{int} \cdot \mu^2 + e_n^2}}
\]

• Biggest factor without a model: Atmospheric Transmittance!

• **Goal**: Autonomously estimate transmittance for local azimuth and elevation over short time periods to enable local schedule repair / improvement
AllSky340
640x480 KAI-340 CCD
F/1.4 Fujinon fisheye lens

SQM-LU-DL
HWHM: 10deg
$\tau_{atm}(\alpha, \delta, t)$

High Transmittance (SNR)

Low Transmittance (SNR)
Learning with Response Surface Methodology

Challenges:
• Lack of first-principles model for local micro-climate
• Computational effort

Approach:
• Physics-based response surface equations [Kirby 2001]
• Catalog star observations selected intelligently using DoE [Box and Draper 1987]
Example Autonomy Architecture

- Reflection
- Routine
- Reaction

Increasing Machine Intelligence

Commanded Plan

Central Planning Agent

Space Object Catalog

Other networked sensors

Raven Class Telescope

RSM Agent

CSP Agent

Functional Agent
Raven Example Continued

Autonomous DoE to observe impactful catalog stars

Empirical Function Fit (RSM)

Empirical Probability of Detection

Can then use $p_{\text{detect}}$ as an input to a CSP scheduler
THANK YOU