SSA Decision Support System Development and Evaluation using Cognitive Systems Engineering

A. D. Jaunzemis(1), D. Minotra(1), K. M. Feigh(1), M. J. Holzinger(1), M. W. Chan(2)

(1)Georgia Institute of Technology, (2)Lockheed Martin Space

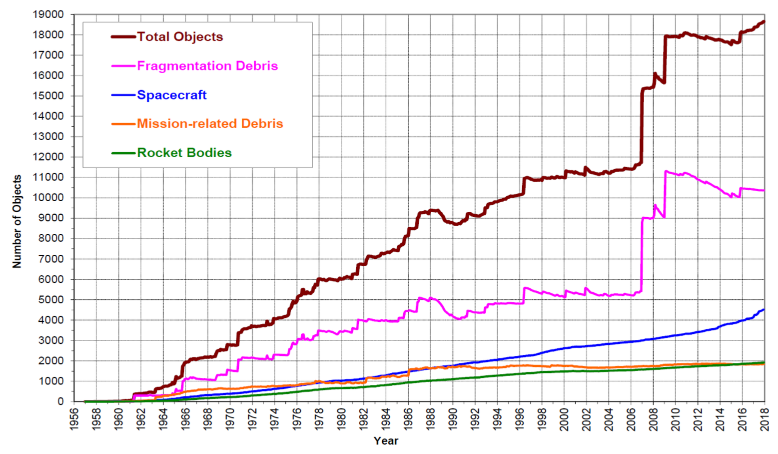
INTRODUCTION & MOTIVATION

Growing orbit population
    Congested and contested

Limited number of sensors

Out-dated tasking techniques
    Human-intensive

Varied hypotheses of interest
    E.g. collision, mode of operation, maneuver status, anomaly resolution



Credit: NASA Orbital Debris Program Office, Orbital Debris Quarterly News, Feb 2018

Sensor tasking goal: gather evidence to answer specific SSA questions
    Hypothesis resolution

Cognitive Systems Engineering (CSE):
Provides designer with realistic model of how human functions cognitively

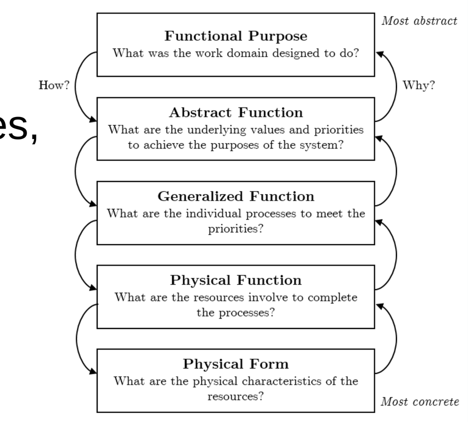
Dimensions of Complexity in SSA:
Large problem space, Dynamic, High-risk, Social, Distributed, Uncertainty, Disturbances, Automation

COGNITIVE WORK ANALYSIS APPLIED TO SSA

Work Domain Analysis (WDA)

Purpose: analyze operator goals, work domain affordances and constraints

Abstraction hierarchy: linkages between purposes, priorities, functions, and resources of domain
    Structural means-ends relationships
    Varying levels of detail



Two hierarchies: SSA work domain (below)
    SSA environment (see paper)

Functional Purpose	Space Asset Safety	National Security						
Abstract Function	Orbital Dynamics	Sensor Phenomenology	Space Object Asset Priority	Hypotheses and Priorities	Workflow Efficiency			
Generalized Function	Event Detection	Conjunction Risk Assessment	*Information Fusion*	*Sensor Allocation*	Catalog Maintenance	Accuracy Degradation	Uncorrelated Track Processing	Information and Alert Dissemination
Physical Function	Computational Resources	Sensor Network Resources	Signal Transmission and Processing Capability	Personnel Capability	Complete Space Object Catalog	Individual Ephemerides	Public Space Object Catalog	
Physical Form	Number, Type, and Location of Tracked Objects	Number, Type, and Location of High-Priority Assets	Number, Type, and Location of Sensors	Signal Characteristics (uncertainty, ambiguity)				

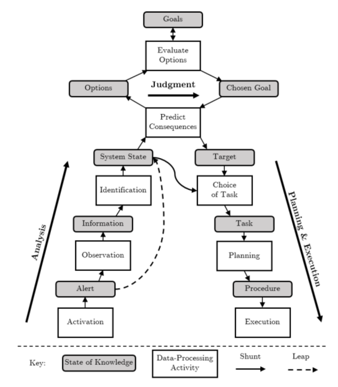
WDA Insights

1) Data aggregation should account for the fusion of disparate sensor resources and various signal characteristics, including considerations of uncertainty, ambiguity, and unobservability
2) Sensor allocation approaches should be able to directly address varied decision-maker objectives or hypotheses
3) Fused data should be reflected through updated hypothesis knowledge

Control Task Analysis (ConTA)

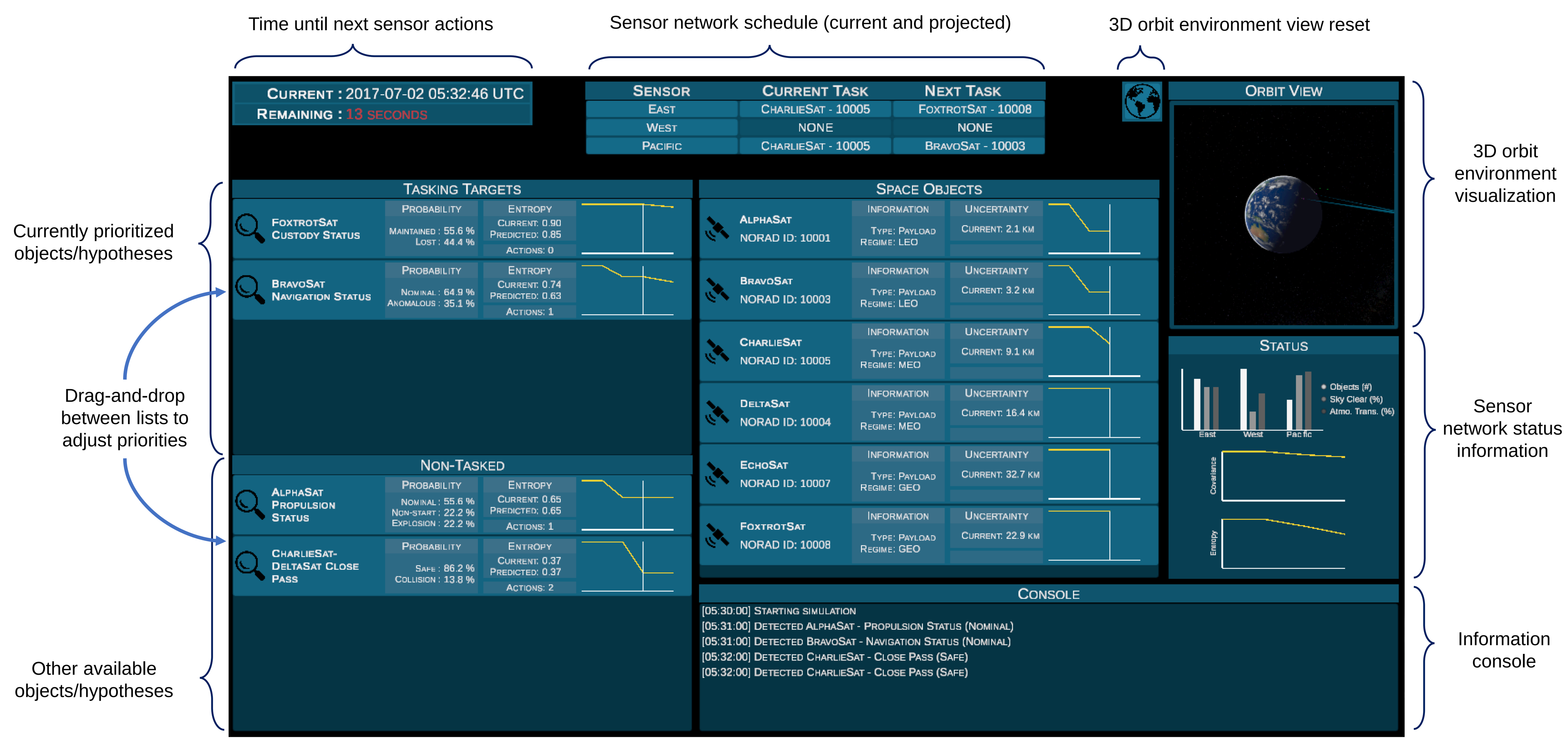
Purpose: model task-required cognitive processes

Decision ladder: maps information processing and states of knowledge
    Encourages flexibility/expertise
    Cognitive work & information relationship requirements



CWR-3: Translate observational data into evidence
CWR-6: Track hypothesis resolution, compare to thresholds
CWR-9: Capability to adjust hypothesis priorities
CWR-10: Assess expected hypothesis resolution
CWR-13: Generate actions/requests to reach target hypothesis resolution

PROTOTYPE DECISION SUPPORT SYSTEM DEVELOPMENT



CWRs Addressed

- Processes observation data into evidence, applied toward hypothesis resolution and state uncertainty reduction (CWR-3)
- Informs operator of current (CWR-6) and predicted (CWR-10) hypothesis resolution and state uncertainty
- Allows operator to re-order object/hypothesis priorities (CWR-9), automatically re-schedules planned observations (CWR-13)

HUMAN-IN-THE-LOOP DATA COLLECTION

Sensor Network Scheduling Approaches

Purpose: Translate operator-assigned priorities into sensor network actions
    Schedules observations to gather evidence to help answer decision-making questions
    Evaluated two different scheduling objective functions:

Covariance-Based
Reduce uncertainty in space object state
Position & velocity covariance

$$\mathcal{A}^* = \arg\min_{\mathcal{A}\in\mathbb{A}} \sum_{j=1}^{N} w_j \frac{\mathrm{Tr}\mathbf{P}_j^+}{a_j}$$

Operator assigns priorities to space objects

Hypothesis-Based
Reduce uncertainty in hypothesis resolution
Entropy (conflict and non-specificity)

$$\mathcal{A}^* = \arg\min_{\mathcal{A}\in\mathbb{A}} \sum_{i=1}^{H} w_i \tilde{H}_{JS}^+(m_i)$$

Operator assigns priorities to hypotheses

Experimental Design

Scenarios: 7 minutes long, 1-minute action intervals
    3 electro-optical sensors (i.e. telescopes)
    6-7 space objects distributed in LEO, MEO, and GEO
    5-6 hypotheses (see table to right for types)
    Perform each scenario once with each scheduler

Hypothesis	Propositions
Close Pass	Safe, Collision
Propulsion Status	Nominal, Non-Start, Explosion
Navigation Status	Nominal, Anomalous
Custody Status	Maintained, Lost

Dependent Variables:
    Performance: Measure average hypothesis entropy at scenario end
    Situation Awareness: Task-relevant questionnaire in middle and at end of scenario
        Operator indicates answer (score = # correct) and confidence in correctness of response

Analysis: Two-factor repeated measures analysis of variances (ANOVA)

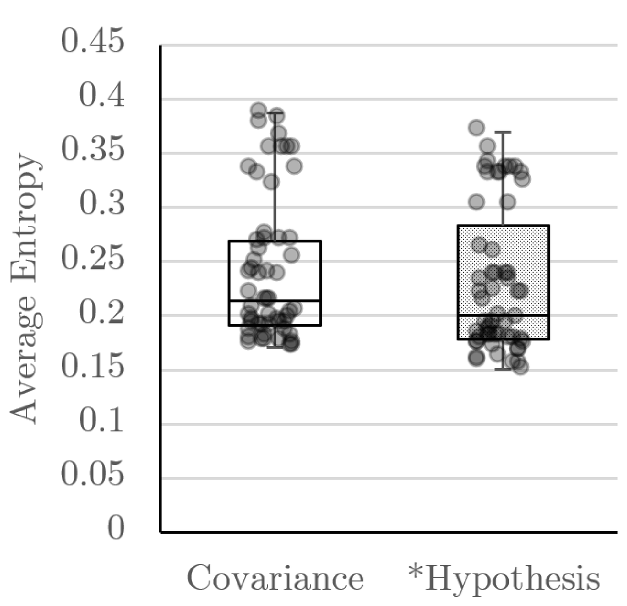
HUMAN-IN-THE-LOOP TEST RESULTS

Performance

**Avg. Entropy: $F_{1,4}$ = 5.97, p = 0.016*

Objective measurement of effectiveness in assigned task of hypothesis resolution
    Low entropy means low conflict and ambiguity from gathered evidence

Result: Statistically significant improvement in entropy using hypothesis-based approach
- Improved resolution quality
- Consistent across all scenarios (low interaction)



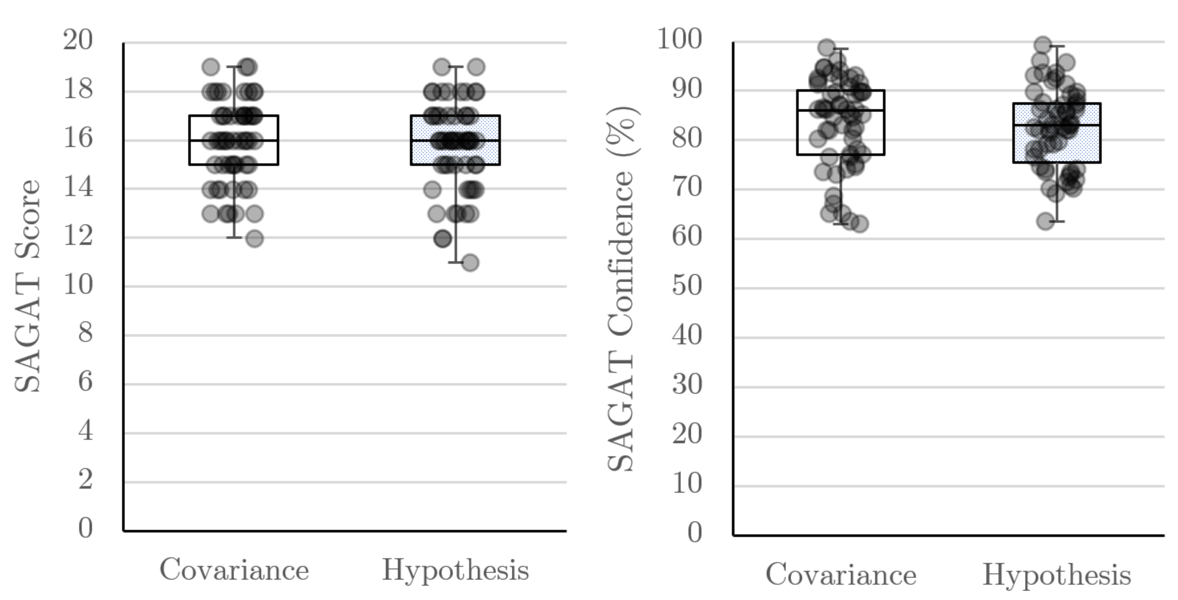
Situation Awareness (SAGAT)

Score: $F_{1,4}$ = 0.42, p = 0.520 | Confidence: $F_{1,4}$ = 0.47, p = 0.494

Situation awareness global assessment technique (SAGAT)

Ex: Level 1 SA (perception)
    Which sensor has the worst observation conditions?
Ex: Level 2 SA (comprehension)
    Which hypothesis has the strongest evidence?

Result: No statistically significant differences between schedulers
- Similar score and confidence



CONCLUSIONS

Cognitive Work Analysis:
    Affordances/constraints of SSA work domain & environment
    Decision support system design insights and requirements
        Information fusion & sensor allocation

Prototype Decision Support System Development & Evaluation:
    Addressed design requirements derived from CWA
    Performance: improved with hypothesis-based approach
    Situation awareness & confidence: similar for both schedulers

Full study includes cognitive support objectives & workload
    Journal of Cognitive Engineering and Decision Making

Future work:
    Improved scenario realism, increased complexity
    Address additional cognitive work requirements