Enabling Robust C2 Systems through Evolvable Human-In-The-Loop Data Fusion

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Data Fusion is...

- Data fusion systems combine, correlate, and aggregate heterogeneous and distributed sources of information with the goal of providing needed information (Waltz & Llinas, 1990)

- For detection, tracking, classification, and identification
  - Across 10 seismic sensors, there’s enough evidence to detect a passing vehicle
  - At time t and t+1, point \((x_1, y_1, z_1)\) is the same entity as point \((x_2, y_2, z_2)\), form a vector - this entity is traveling at 40mph NE

- How?
  - Computational methods galore!
Data Fusion and Ontologies

- Computational methods typically require fixed descriptions of the world – “ontologies”
  - A definition of a specification

- Examples:
  - Weather = rain, sleet, hail, snow, cloudy, clear

- Ontologies are used as data structures within fusion systems and to guide inferences
  - If sensor X reports “wet” then report “rain”

- Fusion ontologies are typically designed from sensor capabilities
  - And often early in system design
    ... leading to problems in adapting to change
Goals

- The research is being performed as part of an Army program focused on developing next-generation fusion methods that:
  - Enable data fusions systems that will be knowledge-intensive
  - Respond to a changing battlefield environment:
    - New threat doctrine
    - Varying tactics, techniques, and procedures (TTPs)
    - Equipment or weapon changes by the threat
    - Man-made and natural terrain features)

- A key goal of the program is to develop practical, operational systems

- This includes *evolvable support* (Roth et al., 2006) for data fusion systems

- How do we design and build an evolvable data fusion system?
  - With a human in-the-loop?
  - To evaluate different course of action (COAs)?
Approach: Cognitive Systems Engineering

- Performed initial Cognitive Task Analysis
  - Interviews with 3 primary Army Intelligence SMEs
  - Visits to military installations - 40+ active-duty soldiers interviewed
  - Rough estimate of interviewee-hours: >750

- Identify functions performed by the analyst and the data fusion system
  - E.g., monitoring, diagnosing/assessing, deciding, planning, communicating
  - Understand the “as is” or current process vs. prescribed/doctrinal process
  - Understand the goals and constraints in the environment

- Identify sources of information and meta-information for each function
  - E.g., pedigree, confidence, rigor

- Define the complexities of the problem domain from an operator’s perspective
  - E.g., time pressure, lack of information, information overload, uncertainty

- Study existing data fusion processes and how they currently account for evolution

  *Provides the basis for understanding how operators need to interact with and reason about the data fusion process to perform optimally*
Cognitive Analysis and Initial Development: Human-in-the-Loop Data Fusion

- Examined over 200 objective questions that soldiers may need to address with the fusion system
  - E.g., What is the most effective COA when facing a unit employing SA-6 surface-to-air capabilities?

- Interviews revealed categories of factors most important to answering these questions

- Developed an interrogative interface that targets these factors
  - What is your primary objective?
  - Characterize the terrain where your objective is located?

- Developed an initial set of answers to questions

- Related answers to ontology employed in the fusion algorithm

- The user *guides* the data fusion with these answers!
Initial Prototype: Support for Human-in-the-Loop Data Fusion

- **Operational Goals**
  - Mission: Evacuation operation

- **Operational Situations**
  - Requires support from air assets

- **Courses of Action**
  - Use defensive IR-guided weapons

- **Dimensions of Performance**
  - Weather, terrain, adversary assets

- **COA Performance Impact Analysis Algorithm**
  - *Will the employment of IR-guided systems be effective?*
Assume we are interfacing with Bayesian reasoning algorithm to direct a fusion system’s prioritization of targets, then...

Dimensions of Performance
- Weather
  - States: Sunny, Cloudy
  - Evidence: 57.00, 26.00
- Adversary Equipment
  - States: Armored, Wheeled, Tracked
  - Evidence: 0.00, 100.00, 0.00

Ontology describing adversary equipment

COAs
- Weapon Sensors
  - States: IR Seeking, EO Seeking, Heat Seeking
  - Evidence: 30.00, 81.00, 43.00
- Weapon Impact
  - States: Positive, Negative
  - Beliefs: 60.47, 39.43

Operational Goals
- Mission
  - States: Disable, Destroy
  - Evidence: 0.00, 100.00

Operational Situation
- Range
  - States: 100M, 1000M, 10000M
  - Evidence: 60.00, 23.00, 4.00
Adapting to Change

- Did evaluations at ~6-month intervals over 2 years
  - Terminology, TTPs changing fast!
  - **Need evolvable system!**

- But how?
  - Revisited Cognitive Task Analysis
    - *To understand the vulnerabilities to change*

- Defined questions to reveal transient aspects of domain, e.g.,
  - “What will the new doctrine do to how you define X?”
  - “When you were first trained, how did you assess the impact of factor Y?”
  - ...

- *Iterated* on evolvable parts of system
  - Across domain experts’ and users’: Areas of expertise, areas of experience, years of experience
  - Repeated interviews
  - Repeated tests and refined system designs
  - Developed corpus of examples (!)
Revisiting our Cognitive Task Analysis and Design: Terminology Issues

- What is transient?
  - Terminology – and association with doctrine, adversary tactics
  - But not underlying meaning and implications

- Performed iterative analysis to develop abstract representation
  - Resistant to terminology change

- E.g., “Pickup truck”, “A Technical”, “VBIED”
  ... “a singular instance of a small, vehicle-based threat”

- Example abstractions
  - Count: singular, multiple
  - Area: point, line, defined/undefined area, abstract
  ... remember, these map to data fusion methods
Revisiting our Cognitive Task Analysis and Design: Terminology Issues

- In our data fusion system, support definition of new or missing terms

- Users can:
  - Drill down to find explanation of specific terms in abstraction
  - Using an existing term as a basis – define by analogy
  - Define the term against the abstraction
  - Create categories of terms with properties and inheritance

- E.g.,
  New term: “Foo”
  A type of “a singular instance of a small, vehicle-based threat”
  But, using large vehicles...
Revisiting our Cognitive Task Analysis and Design: Uncertainty in Terminology

- Found that abstraction is inherently higher-level and vague
  - Need well framed terms and/or explanations
  - Need ability to say “I don’t know” in the face of an unanticipated case not well supported by abstraction

- This uncertainty needs to be okay in underlying system!

- Users can:
  - Simply express “unknown” as response
    - Underlying formalism must still respond given known definitions
  - Annotate their definition
    - “Not sure if this fits this category or not”
Revisiting our Cognitive Task Analysis and Design: Ownership and Authority

- Who owns the evolvability?

- In our case, experts expressed desire for:
  - Maintain individual adaptability
  - Authority for incorporating terms into shared, group-level system
  - Authority at a specific echelon level (e.g., Bn)
  - In other words, facilitate existing organizational methods for collaboration

- Design implication: Create both individual and shared corpus of terminology and definitions

- Future work:
  - Observe individual and group ontologies, use as data for refining abstraction
Conclusions: Developing an Evolvable Systems

- Cannot take off-the-shelf CTA approach for evolvable systems
  - Ability to evolve appears proportional to on-going analysis effort!
  - Iteration really, really needs to happen
  - Domain experts’ length and variation of experience is critical
  - Focus on transient elements of the domain
  - Higher effort in interview question design and analysis of example
    - What parts of your answer were different two years ago?

- System engineering for evolvability requires more design savvy and ingenuity... and, potentially, cost
  - Fortunately, engineers are encultured to think about extensibility
    Though typically w.r.t to systems, not users
  - And lifecycle cost assessment is harder to do

- Evolvable systems can provide feedback to design processes
Questions?

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