Advanced Visual Integration Methods for Enhanced Decision Making and Supervisory Control of Semi-Autonomous Sensor Platforms

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1. Executive Summary

This paper proposes novel information presentation techniques that will allow heterogeneous teams of autonomous systems, Intelligence, Surveillance, and Control (ISR) operators, and Command and Control (C2) decision makers to develop shared understanding through the contextual representation of their interrelated roles within a mission framework. In spite of significant advances in complexity, capability and autonomy of command and sensing systems, human supervisory control will remain a critical element of mission operation for the foreseeable future. Supervisors must observe and diagnose systems behavior on multiple levels, make informed trade-offs between goals, capabilities, risk, and urgency, and finally, consult and collaborate with other potentially remote team members in a many-to-many command setting. Current mission effectiveness is limited by the ability to integrate, present and interact with these complex, real-time data. Recent advances in ecological interface design, visual information integration and decision theories can provide new insights into how to design interfaces that will overcome these challenges facing human supervisors. To this end, we propose a novel approach to visual integration based on 2.5D/3D hybrid scene representation that leverages high-definition stereoptic touch-screen displays and direct tactile interaction with analytic and semantic visualizations and control algorithms. Our approach will aid the decision-maker in grasping potentially cluttered situational cues by reinforcing contextual attentiveness in the search for anomalies and opportunities. In this project we plan to create a research prototype with the goal of exploring and evaluating alternative control paradigms based on these design principles. To chart progress, we will work in collaboration with SPAWAR personnel to conduct dual evaluations: *system feasibility analysis* will subjectively determine functional deficiencies; *component efficiency analysis* will objectively measure the contribution of individual visual elements to task performance improvements.

2. Introduction

Autonomy implies a built-in ability to form and execute decisions without direct and immediate

external control. Semi-autonomous, unmanned surveillance assets, both mobile and fixed, are increasing in prevalence, capability, and sensor richness. These resources can generate large quantities of data, essential to sensitive and time-critical decision-making operations. Being able to consume, interpret, and make sense of these large data sets is an ever increasing challenge for military commanders and decision makers. The need for autonomous consumption of data from surveillance platforms is evident, particularly in settings where communication may be constrained, network bandwidth can be limited, and control signals may be significantly delayed due to physical distance and feedback data processing.

While automation of routine tasks has been used successfully to minimize or eliminate human error, current autonomous systems are poorly suited to evaluating, setting, and managing goals, and their performance is especially brittle in unfamiliar and novel situations. Thus, the role of human supervision remains essential in the face of potential automation failure [3,6]. Moreover, the demand for increased scale of operations with larger numbers of coordinated platforms, for increased mission size and capability as well as improved reliability and precision of *situational awareness*, presents novel challenges for mission supervisors and the design of their decision support systems.

The exploratory nature of surveillance missions and their correlation to mission monitoring and planning tasks implies a potentially enormous load on real-time operational performance in terms of maintaining sensor requirements, adaptation to new environmental conditions, and even changing mission parameters. Surveillance platforms may have unique combinations and arrangements of sensor payloads. The various types of sensors, not all of which are image based, include flash-LIDAR, LADAR, millimeter wave, electro-optical, IR, sonar, etc. Each sensor type has its own constraints with respect to optimal performance, such as platform placement, and bounds on distance, direction, and elevation. Supervisory and operational inputs will include platform and sensor capabilities and status, mission objectives and hazards, as well as weather reports and forecasting.

3. Visualization for supervisory control and decision support

In a mixed-initiative or exploratory mission, it is expected that complex trade-offs must be made within this sensor and environment constraint space. For example, to read the name of a ship, a surveillance craft may need to utilize a narrow-field camera at a low altitude, which could temporarily compromise quality of feed from a wide-field camera currently in use, and perhaps risk detection. The urgency of exact identification must be weighed against other simultaneous objectives. This decision space grows exponentially more complex as the number and complexity of platforms, sensors, and goals expands. Collections managers, sensor operators, pilots, and meteorologists all contribute to navigating this dynamic decision space. Each must understand the goals of the mission, the constraints of the environment, and how their role fits within this mission context. Furthermore, fewer operators will be asked to control greater numbers of more heterogeneous systems concurrently.

Increased low-level autonomous platform behavior promises to relieve operators of fine-grained attentional tasks, enabling them to focus on mission goals, planning and comparing alternative mission strategies en-route, and handling unexpected or erroneous events and circumstances. It is expected that for the next 10-20 years a hybrid solution will prevail, with the human serving as a supervisory controller to review autonomous actions and recommendations. Thus, in spite of advances in autonomous control, many tasks will still require collaborative analysis across the operational team and iterative control, where the supervisor reviews data products and redirects the automation.

Surveillance platforms issue multiple parallel and heterogeneous data sources, to varying degrees of reliability, certainty, and abstraction, in a real-time operational setting. These data need to be cognitively grasped by the supervisor, more or less simultaneously, and shared among collaborating and likely distributed team members for effective and timely command and control decision-making. *Visual Data Fusion* methods have been shown to significantly improve the ability to clarify situational fuzziness using various methods, from orthorectification to those involving computational analysis and automated reasoning. The principles of data fusion stem from an understanding that multiple overlapping and disjoint sources of information allow for situational perception that is not possible from individual sensors alone [17]. Interactive *Visual Data Mining* techniques, such as graphical *brushing* and *linking* between sub-displays, provide more in-depth insight than if considering component visualizations independently [8].

A range of fundamental questions have yet to be answered with regard to how to define a uniform data model that bridges the structure of the data with its usage model, as well as with forecasting and prediction models [19]. As well, we will need to define a flexible and extensible interface that is also sufficiently clear and simple enough to minimize system operation training, and to support efficient and timely planning performance and decision support. New dynamic and interactive visualization methods for managing sensor constraints and high-level mission parameters are needed to meet the challenges of scalable mission complexity as well as improved operator efficiency. In this proposal, we seek to develop more advanced, real-time and predictive dynamic visualization tools in support of these unique decision spaces.

4. Areas for specific advancement

We have identified numerous clearly defined areas in mission management that would benefit from new developments in data and systems-status visualization techniques and manipulation abilities. New visual operating environments are essential to improving the performance and efficiency of individual operators and their functional abilities, on the scale of overall mission and team efficiency, or multi-team missions, and ultimately within the larger theater.

- **Sensor collections and trade-off management.** Platform assets need to be planned and managed. The task of supporting needs, goals, and processes associated with obtaining high quality sensor data is referred to as *collections management*. This involves resolving a trade-off space, a decision-making problem which could benefit from supportive semantic visualization methods. A supervisor should be able to use this visual representation as an aid to predicting outcomes of trade-off decisions within the sensor constraint and overall mission space.
- **Sensor data processing and review.** Dynamic visualization methods are needed to provide a mission supervisor with a higher level understanding of sensor data, in order to review autonomous action recommendations. The supervisor may iterate using further analysis in order to approve an action. Improved visualization techniques will increase human supervisory capability and/or reliability, and allow fewer people to manage more complex platforms.
- **Action recommendation analysis.** Hybrid human-automation teams require close iteration to review and analyze automated decision recommendations. To ensure that hybrid systems are robust, a supervisor needs to visualize the algorithms, rules, and heuristics involved in the automated decision-making process. A visualization that can portray the dependencies of the platforms, sensors, and tasks involved should improve efficiency of operator training and decision-making performance.
- **Monitoring adaptive workflows.** Visual tools are commonly used for goal and task planning (Gantt and Critical Path charts, etc). Decision-makers need improved analysis

tools to help validate plan trajectories and intentions. Due to trade-offs and changing conditions, a planner needs to dynamically switch between visualizations for validation and for monitoring. The development of an integrated visualization methodology that supports continuous adaptive workflow monitoring is needed to acquire goals in a rapidly changing environment.

- **Many-to-many systems supervision.** The hybrid supervisor model needs to scale to larger numbers of systems and more complex platforms. This will require the ability to break from the one-to-one man/system control model, to enable a more flexible many-to-many supervisory model. This implies a decoupling of the visualization interface from a fixed system configuration, and will facilitate shared understanding during operations, and cross-training to improve team performance.
- **Enhanced decision and solution support.** Hybrid human-automation systems require human interpretation and intervention at non-procedural decision points. In order to improve decision-making agency and efficiency, algorithms may be used to generate near-optimal solutions for rapid review. Novel visualization methods need to be developed to rapidly compare differences in decision and solution space.

5. Issues in designing supervised autonomy

The objective of many function automation systems is to eliminate or minimize human error, through reducing the operator's cognitive task load while sustaining situational awareness. In contrast, the role of human supervision remains essential due to the possibility of automation failure. This dual relationship serves as the basis for collaborative human-machine interface design studies. Problematically, it has been observed that increases in automation do not automatically lead to better performance, since the operator has been further removed from the underlying functions, potentially reducing system transparency [6,18]. Additionally, the system must not only support the collaboration between human operators and automation, but in a many-to-many paradigm must also support collaborations between multiple human supervisors.

Ongoing research in visual system portrayal and computerized graphical interfaces indicates the need to address flexibility in the form of multiple, layered, contiguous abstractions so that an supervisor can dig into details, or step back for a better overall picture, providing access to essential information at each level without causing perceptual or cognitive overload. The field of *Hierarchical Task Analysis* as applied to systems operation attempts to provide a framework for addressing just this problem [16].

Empirical analysis of previous efforts in designing for unmanned platform operation [18] have highlighted the need for standard design guidelines and *critical design principles*, addressing integration of multiple data sources (data and visual fusion), realistic pictorial representations (perceptual correspondence), predictive and comparative aids, as well as discriminability of visual cues (uniquely identifiable symbology). Our approach to design will address these fundamental human factors issues, so as to maintain appropriate attentional levels corresponding to different levels of urgency, by making effective use of peripheral visual and multisensory cues [6].

6. High-level informatic fusion and situation monitoring

Visual tools for complex systems operation are essential for conveying the status and interaction of technology components, at many possible levels of representation. The study of perceptual data fusion in the role of decision-making has been explored recently as an area ripe with Grand Challenges [2]. In the past decade, study panels have convened to clarify goals, priorities, and principles to guide development and evaluation of visual fusion solutions. These include, for example, optimized data reduction in order to retain essential information suited to

the level of task abstraction, minimizing both irrelevant visual artifacts and non-negligible data loss [24]. Data reduction is essential from the perspective of not only human operators who can become overwhelmed, distracted, and misled, but also computationally intensive algorithms used in situational analysis for autonomous systems, which may run in exponential time, or are otherwise NP-hard, such as data clustering and network link analysis [11]. Our interface must present this reduced data carefully in order to retain its meaning unambiguously for the supervisor.

The task of integrating visual data from disparate sources into a coherent, interactive display has been termed *Visual Data Fusion* [19]. The rationale behind Information Fusion (IF) is to address the problem of system operational appraisal in the presence of uncertainty by explicitly identifying uncertainty as a feature of the problem space [4]. The goal of an IF application is to support the detection, identification, and prediction of the observable phenomena. While the IF model does not prescribe a specific design or assembly for a given scenario, it offers a structured approach to understanding the underlying ontological modeling problem that the interface is expected to resolve. Recently, the Information Fusion research community has been identifying useful distinctions between low-level and high-level visual information fusion techniques (LLIF, HLIF) in the design of systems that support situation assessment and planning. There is also considerable interest in the ability to dynamically portray and compare hypothetical plans, in order to enhance confidence in solution space exploration.

Of critical interest in the modeling of autonomous systems is the support of situational awareness, which can be realized by cognitive integration (via visual fusion and interaction) in the mind of the supervisor, or in terms of *machine fusion*, represented and implemented algorithmically. At the broader ontological level of Information Fusion analysis, these are considered one and the same type of problem [5,9]. In a mixed, semi-autonomous, supervised system, we can expect that the boundaries between component classes will necessarily be made flexible, as interface models are tweaked, and new technological modules, techniques, and systems concepts become available.

7. Applying systems design concepts in a nested systems space

We will apply the above Information Fusion concepts to advance available methods and tools to support supervisors and operators in a time-critical decision-making context. This effort requires the application of systems and design concepts at several conceptual levels. Ultimately, we are faced with the design and evaluation of an interface for designing and evaluating decisions, with the added challenge of managing team-based decision-making in a time-critical setting. To address this added temporal performance challenge we will examine the application of *cognitive systems engineering* (CSE) toward understanding and modeling complex task environments. The study of CSE looks at how humans cope with complexity, how work is accomplished by the use of artifacts, and how human-machine systems and *sociotechnical* systems can be described as joint cognitive systems.

In order to conceptualize and design for extremely large and deep systems made up of layered and parallel subsystems, particularly those which incorporate human expertise as essential components, we need to explicitly address the need for conceptual reduction. This requires identifying the hierarchical nature of system component relations which will aid in the manipulation of higher level abstractions, and delineating the subsystems that are more or less internally independent of the framework in which they operate. Conceptual commonalities can be found in the various systemic approaches to overall hierarchical systems design and modular

analysis.

In order to clarify this potentially confusing nesting of multi-level integrated systems components, we propose the following taxonomy of interleaved, but conceptually distinct subsystems:

- **Mission model**: The sum of sensors and their performance constraints, data feeds and post-processing, operator roles, mission goals, engagement rules, and their interactions and dependencies, must be modeled and understood.
- **Perception model**: The individual supervisor must be provided sufficient and comprehensible information to make effective high-level decisions at unexpected points, while maintaining low-level attention to routine procedures, without extraneous information.
- **Interface model**: The sum of display devices and elements, symbol legends, and interaction options for both passive and active manipulations of the view, and the system, respectively.

In order to develop effective command and control tools, the mission model must be gathered from domain experts, and the perception model must be gathered from direct consultation with experienced operators. Based on these inputs, we can begin to address the construction of representational elements and interaction models for evaluation, testing, and design iteration.

8. Applying cognitive systems engineering to interface development

In the field of cognitive systems engineering, the theory of *sociotechnical systems* describes a level of systems analysis that takes into account human operators as integrated entities: part of the larger system design [13]. Rather than simply a 'user', an operator is considered in terms of his or her functional, semantic properties, such as skill-set, knowledge of operational rules, and analytic reasoning ability. In cognitive systems engineering, the challenge of implementing system improvements is described as a joint optimization problem, often requiring the close coordination of technical changes with changes in social organizational and communication patterns. Joint optimization problems entail optimization of multiple competing problems that are expected to compromise to arrive at equilibrium optima.

We observe that the differing requirements and limitations of various platform sensors being considered, and the exploratory mission goals, also constitute a complex run-time joint optimization problem. This problem must be resolved en-route, through rapid interactive analysis of the impact of new data and conditions on existing plans and goals. Its resolution presents special challenges for the design of visual tools that can facilitate time-critical trade-off negotiation, as well as the review of automated solution suggestions.

To address these specific operations improvements, we will turn to the principles of *Ecological Interface Design*. EID describes a theoretical framework for the design and development of interfaces for complex sociotechnical systems [23]. The aim of this framework is to support high-level system supervisory roles, and crucially, to facilitate operator adaptation to situational changes and novel events. EID builds on the skills/rules/knowledge (SRK) human cognitive performance taxonomy for evaluating appropriate mappings of task to attention, and a systems abstraction hierarchy, the Hierarchical Knowledge Representation (HKR), which was derived to facilitate decision-making, and complex systems management and diagnosis [16].

While EID does not prescribe a specific design solution, it provides a set of analytic criteria that can be used to evaluate and diagnose issues while exploring a problem space. The intrinsically

iterative nature of both the problem analysis and design evaluation phases of such development has been mapped out as a Visual Design Methodology (VDM) [21], which makes these design iterations explicit. We observe that this method implements a joint optimization model geared toward a specific interface solution. As such, it may serve as an effective guide to the development of mission-critical run-time optimization solutions, and novel interfaces that facilitate real-time plan review and execution.

9. Managing perceptual complexity with stereopsis

To support the challenge of making a good decision in a timely manner, assuming that the relevant and appropriate information to support that decision is available, we must address efficient data presentation. This means that complexity inherent in the data collection is sufficiently reduced and disambiguated such that perception, and hence cognition, is not so overwhelmed as to impede decision-making. This is, in essence, the visual data mining problem. The field of *Visual Analytics* uses parallel, interlinked visual representations to support comparative analysis for exploring hypotheses. Our approach will involve two coordinated, high-definition stereo-enabled displays, one with a tactical 2.5D overview containing depth-encoded analytic data, the other providing a 3D perspective rendering capable of portraying synthetic cockpit, bird's eye, and aerial views, augmented with live video feeds.

Due to the large number of complex data sources and analysis methods that may be involved in supervising autonomous mobile behavior, we anticipate the need for even more aggressive methods to enhance perceptual comprehension. Drawing from recent studies of applied stereoptic visualization methods [1,15], we believe that full support of stereo-enabled depth perception is essential for managing the perceptual complexity involved in our visual fusion approach. Stereoptic perception (stereopsis) requires each eye to be presented with a slightly different perspective of the 3D scene, which results in mentally fused optical parallax. In a dynamic display context where exact layouts of scene objects, labels, and other visual indicators cannot be explicitly manipulated, overlap is expected, so crucial details and associations can be obscured unless other methods are applied to alleviate them. This has shown to be similarly true in complex graph layouts, where sheer clutter can confound the perception of element relations. Transparency of overlying layers can be useful, but by itself can cause meaningless visual artifacts, and is often not sufficient for discerning spatial relations of overlapping elements.

Empirical research has shown that stereo cues operate in parallel: they do not interfere with the cognitive performance of other search cues [14], and up to five transparent surfaces can be discerned concurrently [20]. This feature of stereopsis has been exploited in the form of *stereoscopic highlighting*, which has been shown to be effective in complex graph visualizations, for discerning sub-groups and their relations amidst cluttered contextual data [1]. Due to the complexity and variety of sensor sources and mission parameters that we will attempt to visually fuse, we anticipate that exploiting stereopsis for visual clarity will be essential to maintaining cognitive clarity for situational review.

10. Exploring enhanced geovisualization techniques in 2.5D

The bulk of data sources aboard autonomous platforms can be correlated with respect to the geospatial reference frame. As such, when considered within the context of a mission, the integration of multiple command and sensor sources for situational analysis constitutes an *egocentric geovisualization* task. This phrase implies a view of the world, or localized situation, which emphasizes an individual perspective, details relevant to that perspective, and

requirements for sustaining that perspective. Emerging from the field of interactive cartography, geovisualization is strictly defined around the tradition of 2-dimensional, map-based spatial reasoning (top-down planar view), but has been extended to address non-geographic information, including domain knowledge visualization [7,10].

Geovisualization research focuses on developing tools to support real-world knowledge construction and decision-making, and typically employs *2.5D visualization* coupled with direct, touch-based interaction in the 2D cartographic space [12]. The ad hoc term *2.5D* refers to graphical techniques that coordinate intrinsically planar data features while leveraging the 3rd spatial dimension (display depth) in a restrained manner. Widely used to build early video games, 2.5D rendering presents a simplified world view, without spatially confounding features such as camera-view perspective and global rotations. Geographic directions, relations, and distances are thus preserved to assist in spatial reasoning, while retaining the option of utilizing the 3rd dimension to encode other pertinent features and parameters.

We observe that while researchers continue to learn how to rectify interaction within strictly 2D multi-point touchscreen technology against fully 3D stereo scene rendering [22], the geovisualization concept maps quite readily and intuitively due to its emphasis on the planar field. While the top-down cartographic approach is well suited to grasping the geographic aspects of the operator's situational overview, there remain numerous aspects of platform piloting that are better managed from the perspective of the craft itself. For this reason, we maintain that *at least* two distinct, yet symbolically and logically linked displays will be required for this class of application.
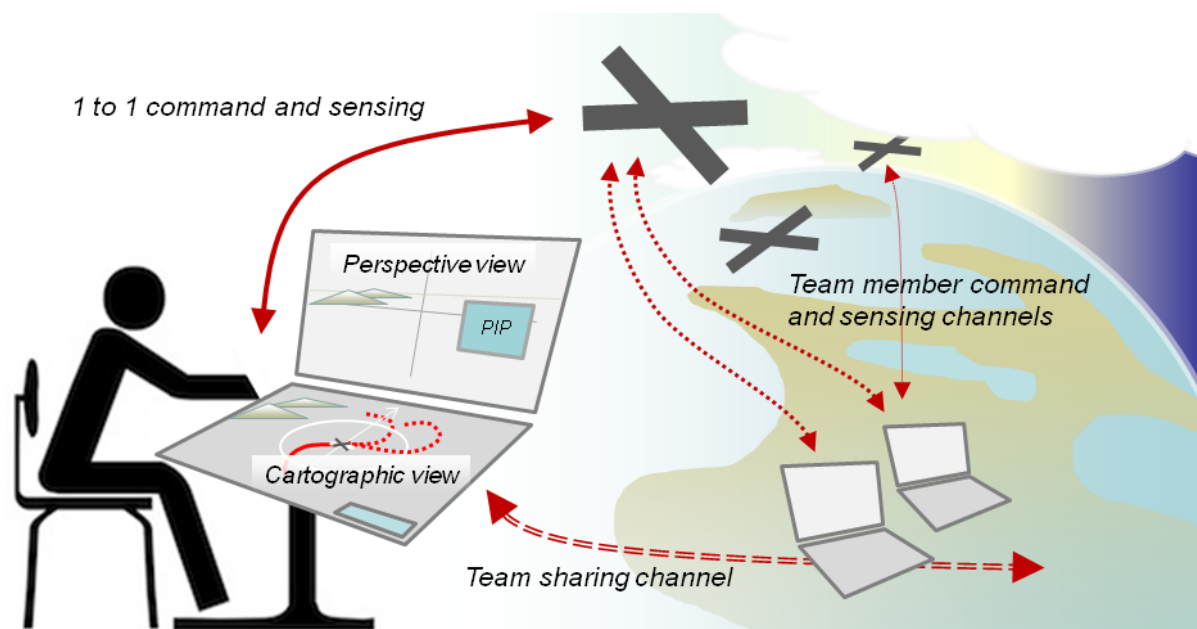

Figure 1. Depicting a general purpose command and control graphical console coordinating with a heterogeneous team for many-to-many supervision within a dynamic network.

11.   Experimenting with hybrid stereo first-person augmented rendering

Our secondary display will augment the 2.5D tactical overview with first-person perspective rendering, satisfying perceptual correspondence for point-of-view (POV) sensor data (e.g., platform cameras) as a critical principle in design for human factors. By linking the displays, we

mean that objects of interest that appear within each view are represented in the same or corresponding manner (discriminability), and that interaction (i.e., selection) in one view entails identical interaction in the other (prediction and comparison).

Previous studies investigating the efficacy of different POV display methods for unmanned vehicle control have demonstrated the usefulness of specific novel augmentation techniques. Sparse, transparent overlay grids aid in perception of changes in orientation more sensitively than raw camera information. Similarly, picture-in-picture (PIP) presentation, in which a video feed is inserted into a larger, synthetic view can increase the effective field-of-view (FOV), and enable accurate spatial association between multiple disjoint views, or even overlapping views of different data types [6].

We intend to extend these types of augmentation by exploring a hybrid 2.5D/3D scene representational model for our supplementary POV display. While it is often assumed that first-person POV displays will employ 3D stereo parallax for full 3D geometric scene comprehension, the relevance of this convention may not be entirely appropriate, and can lead to perceptual artifacts and distortion, not to mention operator dizziness, if not handled precisely. Accurate, calibrated *virtual reality* systems require low-latency head/eye tracking for these problems to be minimized.

In contrast, we anticipate that a novel trade-off between 2.5D and 3D perspective rendering, with respect to stereo cues, will offer a unique opportunity to experiment with depth-enhanced POV situational overlays. In other words, the perspective view can be shown monoscopically (or compressed in depth), with out-of-the-plane analytic elements inserted into the scene using stereopsis in a manner similar to our proposed 2.5D geographic overview. Very little research has been done to advance understanding of how to exploit stereo effects in a hybrid manner such as we propose here.

12.   Building a platform for evaluating prototypes

To support complex, scalable decision-making teamwork, we will develop advanced command and control tools that emphasize graphically integrated representation of platform status, sensor requirements, and mission parameters. By comparing different arrangements of symbolic and interactive elements, we will be able to empirically ascertain which features help to enhance situational clarity, and enhance the ability to communicate novel situations with team members. To accomplish this end, we will create a flexible prototype console development platform that will enable experimentation with rendering and interaction techniques for visual analysis of complex trade-off spaces.

Our approach to visualization will meet the requirements for retaining conceptual clarity, situational awareness, and the concept of a *mental map*, to minimize head-down time and attention shifts. We anticipate that the coming wave of innovation in advanced collaborative console design will involve exploring and realizing the difficult intersection between newly evolving high-definition (HD) autostereo and touchscreen display technologies. We will be building on recent research in effective use of these new display platforms, such as stereo-highlighting, as well as on new ideas for efficient perception of merged, or *fused*, data sources and disparate data types.

We believe that improving situational awareness in a more complex systems arrangement can be addressed by providing an integrated multi-view, multi-touch interaction tool, which is capable of systems representation at multiple levels of functional abstraction. Our portrayal of systems components and their relations will be designed hierarchically and contiguously, to enable zooming in and out of different levels of command and control abstractions. By

emphasizing the primacy of touchscreen interaction, we expect our approach to further reinforce an operator's situational attention to the elements of the scene, defined as *presence*, rather than the nuances of the physical interface.

Even without advanced knowledge of required layout and representation models, we anticipate that a common denominator in the physical apparatus will involve linked stereoscopic touchscreen displays, to support rich, comparative visual analysis. Our experimental platform will allow us to develop prototypes for sustained situational awareness and efficient interactive control. We recognize from numerous studies in the literature that empirical analysis is required to tease out critical yet subtle human factors issues.

To evaluate the efficacy of our approach, we will work closely with team members in SPAWAR Human Factors and Human Centered Design group to leverage domain experts and develop a standardized set of mission goals to evaluate our approach via two separate measures. *System feasibility analysis* will help us to determine whether the interface supports the tasks that are required, using subjective evaluations to identify deficiencies in the feature set. Previous research has followed this approach, through a series of phased demonstrations that increase in complexity and difficulty [18]. *Component efficiency analysis* will make objective evaluations of task performance with different combinations of interface components, such as overlays, multiple views, and stereoptic effects. This approach has been applied to evaluation of stereoscopic labeling for air traffic control [15].

13.   Schedule and milestones

Year 1:
- **Quarter 1**
  - Initiate construction of mission and perception models with domain experts.
  - Define an initial interface model to facilitate design discussions and iterations.
  - Create sketches of various layout and prospective display features.
- **Quarter 2**
  - Build initial illustrative navigation simulator with dual monoscopic views.
  - Add simulated sensor feeds based on high level sensor descriptions.
  - Gather and formalize descriptions for low level sensor data.
- **Quarter 3**
  - Conduct informal feasibility evaluations of interface control concepts.
  - Formalize mapping of interactions between mission, perception, and interface models.
  - Survey and evaluate hardware/software configurations for touch/stereo displays.
- **Quarter 4**
  - Develop representative display and interaction models for exploration of basic sensor parameters.
  - Create initial graphic symbology for command and control representation.
  - Finalize hardware recommendations.

Year 2:
- Refine integrated task model to address realistic operations scenarios.
- Develop variety of realistic application graphics to convey sensor constraints and mission features for comparative analysis.
- Assemble working hardware platform and software for touch interaction and stereo scene features.

Year 3:
- Extend task model to incorporate multiple operators and distributed control.

- Conduct in-depth, *in-situ* review and evaluation of touch-based interaction, and analyze perceptual issues.
- Formalize evaluations, publish discoveries and recommendations for further application design and research.

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