Increased Space Situational Awareness through Augmented Reality Enhanced Common Operating Pictures

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ABSTRACT

Support for space situational awareness (SSA) is required to enable military commanders and space operations center operators to maintain an advantage over our adversaries in the space enterprise. Well-designed visualization and human-computer interaction (HCI) technologies can be employed to allow them to perceive, reason about, explore, and act on timely intelligence, but current tools are lacking. A new generation of display modalities such as large-screen shared displays, touch-tables, and augmented reality (AR) can be used to power innovative visualization and data interaction capabilities, but these technologies must be implemented carefully in the context of potential operating environments. To apply novel display modalities and truly support operator needs in the context of space operations, Charles River Analytics is designing, developing, and validating a system for Space Operations Visualization Leveraging Augmented Reality (SOLAR). This paper provides an overview of our current prototype SOLAR application capabilities, with a focus on novel applications of augmented reality to promote SSA and shared awareness in a collaborative and dynamic mission-centric, high tempo, operations environment. We highlight unique integration points with traditional mission-centered displays where augmented reality is anticipated to add unique benefits, particularly for joint operations and situations where multiple operators must contribute different expertise, serve in different supporting roles, and make recommendations and/or decisions based on different levels of strategic and/or tactical understanding (e.g., due to differing information authorizations). The current SOLAR prototype has gone through four rounds of iteration with space operators. Consequently, we provide a summary of initial results acquired from actual space operators with respect to the demonstrated value SOLAR integrated augmented reality capabilities offer. Finally, we present conclusions focused on envisioned next steps based on the most recent feedback from operators to continue to advance the SOLAR prototype to a true value-add capability to improve SSA and enhance Space BMC2 execution.

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1. INTRODUCTION

Space operations rely on commanders' and operators' ability to effectively reason about the complex and uncertain relationships among space and terrestrial assets owned by various state and non-state actors. Friendly space assets support nearly all components of modern civilian life (e.g., communications, navigation) and military (e.g., early warning, munitions guidance, unit guidance, and surveillance) operations. As a result, sustaining the effectiveness of friendly space assets is critical.

To illustrate the complexity of modern space operations in an example, consider a situation where intelligence indicates activity near a key military base of an adversary, and allied operators have degraded and intermittent connectivity with a U.S.-owned satellite in Low Earth Orbit (LEO) that has high-resolution imaging and radio frequency sensors. This LEO asset is in a polar orbit and has the target site in its Field of Regard (FOR) twice a day, once in light and once in dark, and always with only a partial view. The adversary may be able to deny access when the target site is in the LEO asset's FOR by moving key activities indoors temporarily, or disrupting communication between the satellite and a ground station. There is currently no capability that unifies a representation of what is known about this situation, what is inferred, how stale those inferences are, and the probabilities and uncertainties associated with each inference. In addition to those space situation awareness (SSA) oriented difficulties, operators and commanders must reason about COAs that could be enacted proactively or in response to adversary COAs. Operators and commanders have a broad array of COAs available to them, ranging from diplomatic relations (e.g., strategic communications with owners of assets that may interfere with friendly space assets or ground stations) to actions in cyberspace or kinetic actions involving space and terrestrial assets. However, given the significant lead

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times and cost in restoring, repairing, or replacing space assets, proactive COAs are often required, and this initially broad array of available mitigation strategies disappears quickly.

Examples like this highlight the increasing need for Space Battle Management Command and Control (SBMC2) enabled by timely and accurate SSA, which is dependent on operators understanding the spatiotemporal and conceptual relationships among high-dimensional data (e.g., space weather, incomplete data about friendly assets and potential threats), in addition to other contextual details (e.g., socio-political relations and climate). SSA is a key requirement for planning, evaluating, and identifying COAs that allow operators and commanders to maintain an advantage in space operations.

Well-designed visualization and human-computer interaction (HCI) technologies allow users to perceive, reason about, explore, and act on timely intelligence. However, most developed techniques have been data-driven, rather than operator need-driven, focusing on the data processing and inference with little consideration given to how raw and processed data and results are presented to an operator to enable specific workflows and decisions (e.g., via graphical user interfaces (GUIs). If a capability could be developed that focuses on integrating the specific and timely information requirements of the operator into a more effective operating picture that provides actionable intelligence aligned with operators' true working needs, space operators could be more responsive to time-sensitive threats, could perform more detailed and insightful analyses of situations, and leadership could issue more successful and less resource-intensive COAs to meet mission goals. New innovative HCI approaches are required that go beyond desktop conventions and provide efficient mechanisms for perceiving and understanding decision- and task- critical planning information that are responsive to operators' needs (e.g., to visualize spatiotemporal data in support of COA evaluation, and to visualize meta-data associated with the terrestrial and space assets involved).

Given the diversity of data (and agencies and systems that generate them), the context-dependent nature of relevant data, and the tight coupling of intelligence to the design of effective COAs within the space enterprise, a holistic approach is required to characterize space operations workflows and identify opportunities for innovative HCI approaches that both provide actionable information to the user and minimize the cognitive workload required to understand, integrate, and appropriately act on that information. Any novel approach to visualization and HCI in this domain should take advantage of emerging developments in the state of the art in display technology and naturalistic interaction methods, to support individual and collaborative (both co-located and distributed, and synchronized and asynchronous) work. Modern advances include touch-tables, which foster collaboration through shared and concurrently interactable views, and augmented reality (AR) displays, which facilitate a more effective and efficient naturalistic means of perceiving (e.g., improved spatial cognition facilitated by volumetric AR displays) and interacting with (e.g., through gesture, voice, controller, and other adaptive HCI methods) data. Dome or cave-based displays have become more readily available, and can be used to provide a sense of immersive presence to one or more observers. While these devices offer many potential benefits, they must be carefully adapted to their intended work environment, but often degrade or prohibit traditional and established workflows that may not adapt to integrate with such novel technologies. For example, touch-tables and dome displays require users to be in their physical proximity and are typically prohibit concurrent interactions with a traditional workstation. Given the emerging threat environment in space operations, the diversity in skills and experience of operators, and the diversity of operational situations, operators must be able to construct, view, and share tailored Operational Pictures (Common, COPs; or User-Defined, UDOPs) based on dynamic data relevant to the specific situation or threat at hand, in support of SSA and SBMC2.

To overcome these challenges, we are leading the design and evaluation of a prototype system for Space Operations Visualization Leveraging Augmented Reality (SOLAR). SOLAR applies multimodal visualization and naturalistic interaction methods, including augmented reality (AR) and large shared displays, informed by a targeted work domain analysis (WDA) using Cognitive Systems Engineering (CSE) methods [1]–[4] and designed using a combination of both user-centered design (UCD; [5], [6]) and ecological interface design (EID; [7], [8]) to unite the science of cognition with practical applications for fostering the understanding necessary for space object measurement, identification, characterization, and COA generation and evaluation that go well beyond traffic control. This paper provides an overview of the envisioned SOLAR capabilities suite, along with an update on progress to date, as informed by a series of evaluation events conducted with representative space operations subject matter experts (SMEs), which were executed as part of the DARPA and USAF funded Hallmark program (www.darpa.mil/program/hallmark).

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2. APPROACH

Experience with the introduction of new technology has shown that increased computerization does not guarantee improved human-computer system performance [9], [10]. Poor use of technology can result in systems that are difficult to learn or use, create additional workload for system users, or in the extreme, result in systems that are more likely to lead to catastrophic errors (e.g., confusions that lead to pilot error and fatal aircraft accidents). Cognitive Systems Engineering (CSE) attempts to prevent these types of design failures in the design and development of complex systems by addressing design issues through careful analysis of the problem domain, the tasks to be performed by a human-computer system, and the limitations of both the human and the machine. The CSE approach is illustrated in a number of case studies in a wide range of domains, from process control, to military command and control [11]–[15], to computer network monitoring for defense against cyberwar [16]. While there are many different approaches to the analysis components of CSE (e.g., Cognitive Task Analysis [17], Cognitive Work Analysis [18], Work Centered Support Systems [19], Applied Cognitive Task Analysis [20]), they share a common overall view of system development. CSE consists of an analysis of the operator's capabilities and limitations, the problem domain, and the tasks they are trying to perform. It supports the development of system requirements that can be used to prototype computational support tools and user interfaces, and includes evaluations of the prototype system that help refine the system as part of an iterative development process. A broad overview of Cognitive Engineering methods and applications can be found in [21], [22], and a discussion of a practical application of these techniques through the development and evaluation of a complex system can be found in [13].

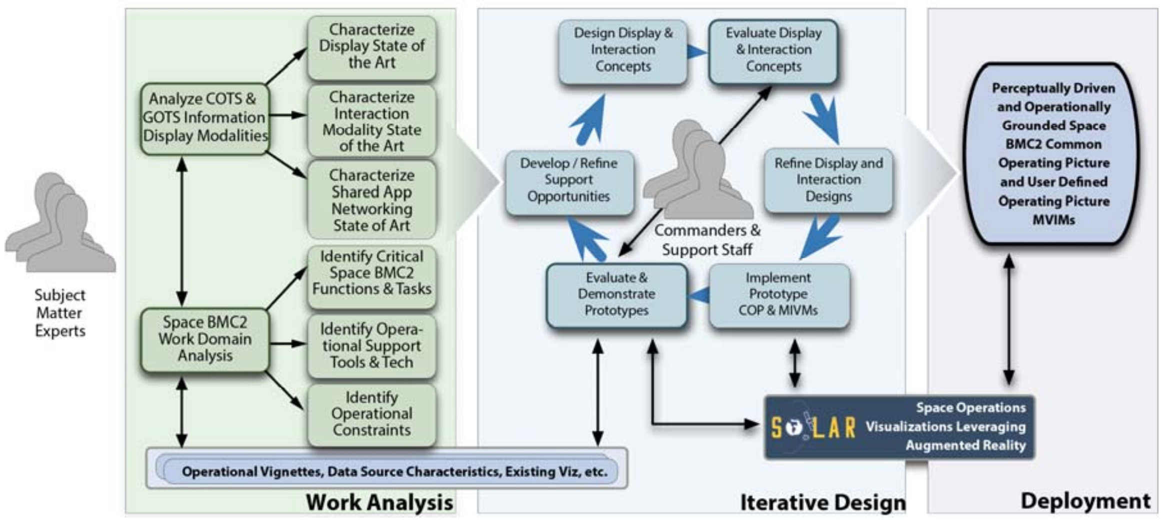

Fig. 1. Illustration of the iterative and user-centered approach to SOLAR design, development, and evaluation

Our approach to design SOLAR therefore began with a targeted work domain analysis (WDA; given an aggressive timeline to establish a baseline prototype), based on the application of CSE methods. This process is illustrated in Fig. 1. The goal of this WDA was characterize the critical requirements, user limitations, work environment, and other contextual factors that influence the potential success of a technology-mediated decision support system (DSS) intended to aid operators in their goal of establishing and applying SSA towards COA generation and evaluation to support space BMC2 missions. To accelerate this analysis, we built upon past work conducted by the USAF Research Lab (e.g., [23], [24]), which investigated cross-domain visualization and distributed collaboration on Air, Space, and Cyber user-defined operating pictures (UDOPs), and in particular a CTA focused on joint space operations [25]. Working with space operations SMEs, we extended this foundation to generate a series of artifacts used to inform design requirements for the SOLAR effort. For example, 385+ operational questions and issues that impact space operations decision-making processes, along with relevant information to address those questions and potential sources for that information, were generated as part of an exhaustive exercise working with space operator SMEs. Table 1 provides an example of these questions and associated information. To complement information-centric requirements that were established, a list of 50+ exemplar COAs were established within a number of categories based on the intent of a given COA (e.g., detect and assess threats, assess own spacecraft status, maneuver, report threat) to inform the types of interactions and COA planning workflows that would ideally be supported (see Table 2). Finally, to inform the identification of AR-based capabilities that could address information and/or interaction design requirements resulting from the targeted WDA,

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we worked with a Command SME to establish high-level impact opportunities with potential for AR-driven capabilities and information displays to provide benefits to SBMC2 operators. As AR capabilities were conceptualized, they were evaluated against these impact opportunities (see Table 3) to determine if the use of AR was justified (i.e., does the design of an AR capability add benefit beyond what an analogous capability on a traditional 2D workstation display could provide?).

Table 1. Examples of questions and information that impact space operations decision-making processes

Questions:	Info-->	Age of Satellite	Satellite Remaining On-Board Fuel	Space Environmental Situation	Previous Satellite State	Satellite Prior On-Board Indicators	Satellite Vulnerability	Current Space Situation & Conflict Level	Space Surveillance Network Current Tracks	Space Surveillance Network Predicted Future Tracks	Was Satellite Over Suspected ASAT site When It Failed?	INTEL Community Detections	INTEL Indicators of Prior Attack Preparations	Spurious Signals Detected	Debris Cloud Present	Debris Cloud Future Tracks
Q.1	Is cause of problem due to component failure?	X														
Q.2	Is cause of problem due to natural environmental effects?															
Q.2.1	Solar Storm?			X		X										
Q.2.2	Cosmic Rays?			X		X										
Q.2.3	Meteor strike?			X		X										
Q.2.4	Space debris hit?					X			X							
Q.3	Is cause of problem due to human-induced failure?				X	X	X	X								
Q.3.1	Unintentional error?				X	X	X	X								
Q.3.2	Intentional attack?				X	X	X	X	X		X	X	X			
Q.3.2.1	Kinetic Kill Vehicle (KKV)?					X	X		X		X	X	X	X	X	
Q.3.2.2	Cyber/jamming?					X	X		X		X	X	X			
Q.3.2.3	Rendezvous & Proximity Operations (RPO)?					X	X		X		X	X	X			
Q.3.2.4	Directed Energy (DE) - Lasers or High Powered Microwaves (HPM)?					X	X		X		X	X	X			
Q.4	What are the impacts of this problem?				X	X	X									
Q.4.1	Impacts to satellite mission?		X		X	X	X									
Q.4.1.1	Impacts critical Civil and Military missions?		X					X		X						X
Q.4.1.2	Impacts Commercial missions?		X		X	X	X			X						X
Q.4.2	Impacts to other satellite missions?		X							X						X
Q.4.2.1	Impacts to friendly country satellite missions that may be hit by failed satellite?		X							X		X	X			X
Q.4.2.2	Impacts to adversary country satellite missions that may be hit by failed satellite?		X							X		X	X			X
Q.5	When will the mission degradations be alleviated?			X	X	X	X									
Q.5.1	When will satellite be fixed?			X	X	X	X									
Q.5.2	When will alternative means to support satellite mission be implemented?			X	X	X	X									
Q.5.2.1	Spare satellites brought online?			X	X	X	X	X								
Q.5.2.2	Terrestrial alternatives implemented?			X	X	X	X	X								

Table 2. Sample tactical COAs associated with detection and assessment of a spacecraft threat

	Tactical COA Characteristics								
Space COA's	Probability of Effectiveness	Probability of Conflict Escalation	Cost to Satellite	Active	Passive	LREZ - Green (ASAT More Than 20 Min. Away)	CAEZ - Yellow (ASAT 20 Min. Away)	CAEZ - Red (ASAT 5 Min. Away)	Comments
Detect & Assess Threat									
Task On-Board Sensors	80%	5%	Medium		X	X	X	X	Task On-Board Sensors to develop better information
Collect INTEL on Threat Object	60%	5%	Low		X	X	X	X	Collect INTEL data from approaching threat satellite
Continuously Point Towards Threat Object (Maintain Relative Range & Attitude)	80%	5%	Medium		X		X	X	
Conduct Local Area Search for Threat Objects & Track When Found	70%	5%	Low		X		X	X	
Request Neighborhood (Local SDR) Federated Asset Imagery of Own & Threat Spacecraft	70%	10%	Low		X		X	X	
Accept a Sensor Tasking Request from Another Federated Asset	90%	10%	Medium		X		X	X	
Task Ground Based Spectral Signature Assets to Assess Spacecraft Changes	100%	10%	Low		X		X	X	
Task Onboard Cameras to Determine If Anything Has Changed	80%	5%	Medium		X		X	X	
Blow Pyros & Automatically Deploy Pop-Off Self-Inspector	90%	10%	High		X		X	X	
Downlink to Ground Threat Space Object Characterization Data	100%	5%	Low		X	X	X	X	

Table 3. Impact opportunities with potential for AR-driven SBMC2 benefits

Opportunity	AR Potential for SBMC2 Benefits
Compressed Cycles	Benefits realized from AR technologies that will support time reduction of both planning and operational execution cycles.
Ability to Discern	Benefits realized from AR technologies that will provide Commanders and staff with enhanced abilities to discern the many nuances of spatial and temporal relationships that govern the space enterprise.
Ability to Resolve	Benefits realized from AR technologies that will provide Commanders and their staff with enhanced abilities to disambiguate complex or conflicting information.
Ability to Direct	Benefits realized from AR technologies that will provide Commanders and their staff with enhanced abilities to provide precise and timely operational directions.
Highly Accurate Spatiotemporal Representations	Benefits realized from AR technologies that will support a fused representation of complex temporal and spatial information (e.g., High-Resolution Common Operating Picture).
Operational Information Integration	Benefits realized from AR technologies that will support rapid understanding of complex data sets, beyond simply spatiotemporal data (e.g., probabilistic threat assessments, RF signatures, patterns of life) from a myriad of relevant sources (including both raw data and processed data from third-party tools).

The outcome of our targeted WDA was then complemented and cross-validated using a set of 200+ user stories that were generated under the DARPA Hallmark program and focused on the needs of SBMC2 operator needs. These user stories were grouped into functional topic areas (e.g., threat assessment) and operational capability categories (i.e., a technological capability grouping; e.g., data gathering, prediction, warning) in an attempt to highlight technology gaps, which combined with our question/information gaps list, resulted in an initial list of priority information areas to attempt to address, given the envisioned capabilities a decision support system like SOLAR could offer.

Leveraging the guiding artifacts that the WDA yielded, categories of information that SOLAR planned to support were established (e.g., spatiotemporal asset relationships, COA concepts and plans, asset detail and status information, operations floor priorities and operator status / taskings). For each of these categories, notional assignments of information being appropriate vs. inappropriate for AR visualization were assigned to inform initial design efforts. Our design efforts then consisted of a rapid prototyping approach that centered on gathering feedback from representative end-users using increasing fidelity prototypes to inform agile design and development sprints (e.g., the DARPA Hallmark program executed a simulated operations floor event, incorporating the SOLAR prototype software, every three months under the program's Phase I effort). A discussion of the design and iteration of the traditional visualizations, which were developed as a flexible web-application, are out of scope for this paper. For the AR content, we developed a series of prototypes that were intended to focus on targeted AR capabilities to explore limitations of current generation AR hardware platforms, the effectiveness of different interaction mechanisms with AR content, and the effectiveness of different information visualization / presentation strategies in AR. For example, Fig. 2, Fig. 3, and Fig. 4 show a simple AR prototype visualization along with captions describing specific issues that were uncovered during use to inform SOLAR AR design guidance.

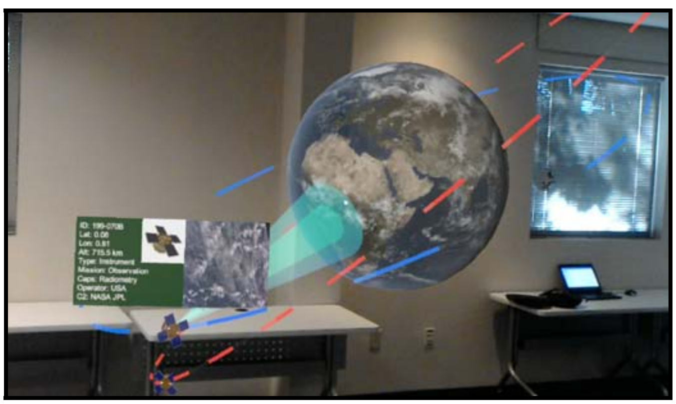

Fig. 2. AR scene illustrating issues of digital occlusion (i.e., a satellite is not viewable as it is located behind the earth) and 2D text readability requirements (i.e., the 2D text panel must continuously adapt its orientation to remain perpendicular to the user's gaze)

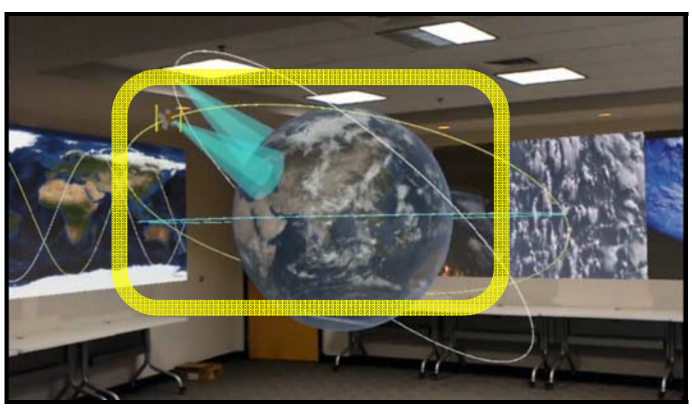

Fig. 3. AR scene illustrating the unconstrained AR space and the ability for the user to place different 2D AR content displays throughout their real-world location, and illustrating (via the yellow box) the approximated FOV using the HoloLens (versus the fully rendered scene shown in the image)

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Fig. 4. AR scene illustrating readability issues of rendering dense 2D text in AR from a third-party source (in this case a website) with the Microsoft HoloLens

3. RESULTS

The iterative design and feedback cycles presented in the prior section were repeated both opportunistically (e.g., as access to SMEs became available through events such as the National Space Symposium) and periodically scheduled events (e.g., the Hallmark program events, regular design reviews with our team's consulting SMEs), ultimately resulting in a targeted set of capabilities that the SOLAR application has been designed to support. From a functional perspective, the resultant components of the SOLAR system are divided into four distinct parts:

(1) A **Backend Server and APIs** that facilitates communications between different components of the SOLAR system and third-party systems (discussion of which is outside the scope of this paper);

(2) A **Web-Application** that provides a traditional interface front end for interacting with SOLAR content that does not lend itself AR presentation and/or interactions;

(3) An **AR Client Application** that is installed on the AR HMD (currently the Microsoft HoloLens) to render AR information displays; and,

(4) An **AR Synchronization Application** that is used for presentation of layered virtual content that is synchronized with the web-application interface for multi-layer/-level security (MLS) content viewing in a joint / coalition operating environment.

Web-Application: The traditional web-based interface serves as the core SOLAR interface for users, enabling users to navigate to various SOLAR capabilities, and present SSA relevant information that is best suited to 2D presentation (e.g., tabular data and lists) and visualization (e.g., 2D map projections). For example, Fig. 5 presents a sample screenshot taken from a COA sandbox capability that is designed to support for forensic analysis of events of interest and generation of potential COAs to achieve desirable effects/outcomes.

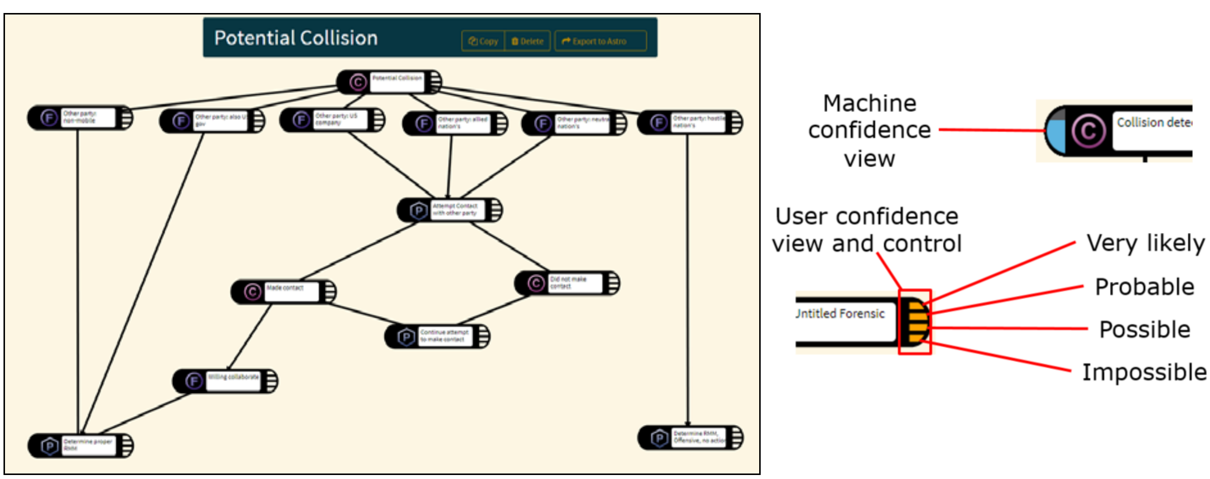

Fig. 5. Course of Action (COA) sandbox interface (left) used for conducting forensic exploration of events of interest and generation of potential COAs to achieve desirable effects / outcomes and node-integrated confidence details (right) that can be based on machine sources (e.g., fusion outputs) or operator input / expressed

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AR Client Application: The AR client application provides standalone AR volumetric displays (which are advanced versions of those presented in Fig. 2 and Fig. 3; see Fig. 6) designed to facilitate better understanding of spatiotemporal information (e.g., satellite orbital trajectory, sensor coverage zones, potential conjunction paths and timings, etc.) as part of an integrated common operating picture (COP), which can have multiple layers of information (e.g., different satellite constellations or watch lists, space weather, sensor coverage/blackout zones, terrestrial mission data, COA plans and projections) that are all synchronized to the same timescale and playback controls. These controls allow viewers to advance or rewind the current time in the COP visualization to review historic data or to project (where supporting data and algorithms permit) into the future to better anticipate upcoming events or planned COA outcomes. The intention of this AR COP is to enable operators to view mission-salient information as part of an integrated global visualization, better facilitating SSA by situating this data within the context where space operator workflows are conducted (i.e., as part of the larger multi-domain BMC2 effort).

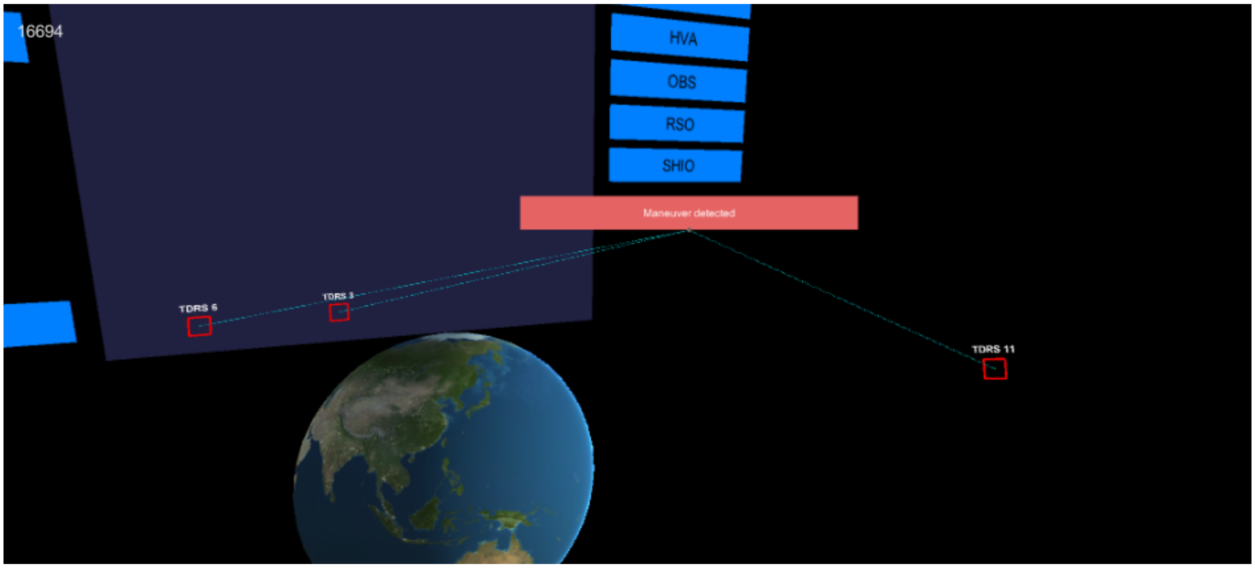

Fig. 6. AR Client Application showing a globe visualization along with the position of three satellites in orbit that have been highlighted based on a detected maneuver alert; the background shows a data panel and selection interface used to filter what assets are shown (using operator-defined watch lists) to reduce visual noise.

AR Synchronization Application: The AR synchronization application provides a concept to support multi -level/-layer security (MLS) through user access- and/or role- defined operating pictures (e.g., showing an individual operator data that s/he may have access to, which other co-located operators do not). SOLAR supports MLS AR overlays that can provide access-controlled information visualizations that are synchronized with the SOLAR web-application interface (presented on a traditional workstation monitor or a wall-mounted large-format display). This synchronization is design to enable AR content to be presented within the context of the web-application display content to augment what a user would normally have access to view on a public (within an ops floor environment that likely has other access controls) display. In addition, this synchronization allows the user to interact with the AR content using more familiar and intuitive control mechanisms, i.e., their normal keyboard and mouse setup. As the user navigates around the web-based interface, the view and content presented in AR is dynamically updated and aligned to integrate with the content being presented on the traditional display or wall-mounted display. For example, Fig. 7 shows an example AR synchronization display deployment with a rendered 3D Glove overlaid on the normal 2D globe that is presented as part of the Web-Application common operating picture (COP). The 2D glove is being shown on the TV on the wall, such that the AR synchronization display's 3D globe is aligned to replace and hide it from the user's perspective. As the user interfaces with the web-application (e.g., rotating the globe, changing zoom levels, updating filters to show different satellite and corresponding orbital trajectories), the AR content is also updated. The AR synchronization display then also includes additional pure AR panels around the TV to provide the user with a user-defined operating picture only they can see via the AR HMD. In this notional example, they are provided with details on the top based on their active satellite selection (no active selection is shown in the image), a chat window for private communications, and an alert window that can be used to show alerts for satellites or other assets that are restricted from being shown on the primary web application display (e.g., due to security levels or other access control restrictions).

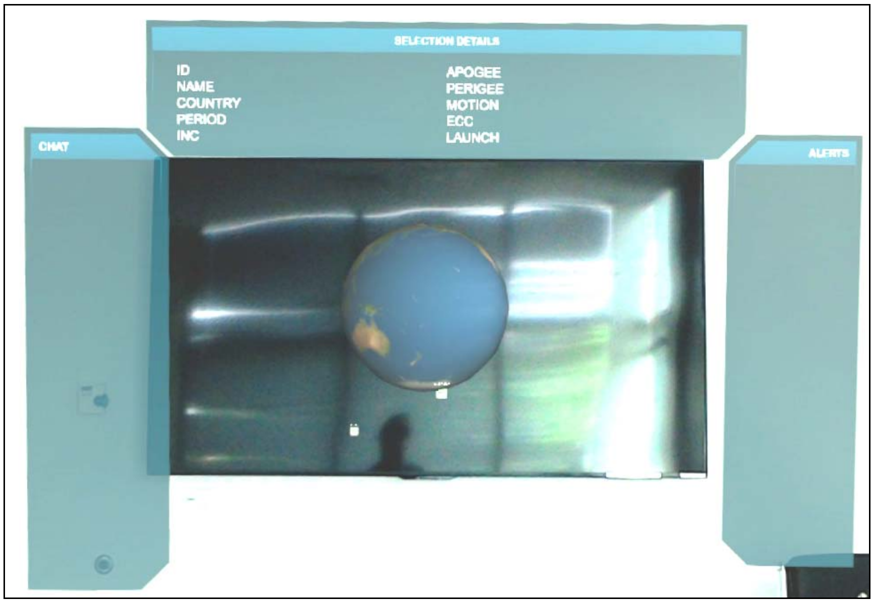

Fig. 7. Rendering of the AR synchronization display showing an AR globe, details window, alerts pane (used to show potential threats to operator assets of interest), and chat window overlaid on a physical television display showing the SOLAR web-application and the position of two satellite in orbit (lower part of the screen).

4. CONCLUSIONS AND NEXT STEPS

This paper describes a work in progress effort to explore the potential for augmented reality technologies to benefit SBMC2 operators by providing tangible impact across a number of identified dimensions related to SSA and COA generation and evaluation. Using a targeted work domain analysis to focus a series of rapid design, prototyping, and demonstration cycles, we identified a number of opportunities where AR technology can be applied to provide potential benefits beyond what traditional display technologies afford. As this is a work in progress, our next steps involve continuing iteration and development centered on feedback from representative end users. As we continue these iterative cycles, our plan is to focus on more advanced and higher fidelity AR prototype development, to enable demonstration and evaluations that more closely represent envisioned use cases.

5. REFERENCES

[1] E. Hollnagel and D. D. Woods, *Joint cognitive systems: Foundations of cognitive systems engineering*. CRC Press, 2005.

[2] W. C. Elm *et al.*, “Integrating cognitive systems engineering throughout the systems engineering process,” *Journal of Cognitive Engineering and Decision Making*, vol. 2, no. 3, pp. 249–273, 2008.

[3] C. Burns, G. Torenvliet, B. Chalmers, and S. Scott, “Work Domain Analysis for Establishing Collaborative Work Requirements,” *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 53, no. 4, pp. 314–318, Oct. 2009.

[4] J. D. Pfautz and S. L. Pfautz, *Methods for the analysis of social and organizational aspects of the work domain*. CRC Press Boca Raton, FL, 2009.

[5] D. A. Norman and S. W. Draper, *USER CENTERED SYSTEM DESIGN new perspectives on human-computer.*, 1st ed. S.l.: CRC PRESS, 1986.

[6] M. R. Endsley, *Designing for Situation Awareness: An Approach to User-Centered Design, Second Edition*. 2016.

[7] C. M. Burns and J. Hajdukiewicz, *Ecological Interface Design*, 1 edition. Boca Raton, FL: CRC Press, 2004.

[8] K. J. Vicente and J. Rasmussen, “Ecological interface design: theoretical foundations,” *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 22, no. 4, pp. 589–606, Jul. 1992.

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[9] E. M. Roth, J. T. Malin, and D. L. Schreckenghost, “Paradigms for Intelligent Interface Design,” in *Handbook of Human-Computer Interaction*, Elsevier, 1997, pp. 1177–1201.

[10] D. Woods and S. Dekker, “Anticipating the effects of technological change: A new era of dynamics for human factors,” *Theoretical Issues in Ergonomics Science*, vol. 1, no. 3, pp. 272–282, Jan. 2000.

[11] S. Potter, J. Gualtieri, and W. C. Elm, “Case studies: Applied cognitive work analysis in the design of innovative decision support,” in *Handbook for Cognitive Task Design*, E. Hollnagel, Ed. 2003, pp. 653–678.

[12] C. Talcott, S. Martinez, K. B. Bennett, C. Stansifer, and L. Shattuck, “An Empirical Evaluation of Interfaces for Army Tactical Operations,” *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 45, no. 18, pp. 1343–1347, Oct. 2001.

[13] J. Pfautz and E. Roth, “Using cognitive engineering for system design and evaluation: A visualization aid for stability and support operations,” *International Journal of Industrial Ergonomics*, vol. 36, no. 5, pp. 389–407, 2006.

[14] E. M. Roth, L. Lin, S. Kerch, S. Kenney, and N. Sugibayashi, “Designing a first-of-a kind group view display for team decision making: a case study,” in *Linking expertise and naturalistic decision making*, 2001, pp. 113–135.

[15] A. M. Bisantz, E. Roth, B. Brickman, L. L. Gosbee, L. Hettinger, and J. McKinney, “Integrating cognitive analyses in a large-scale system design process,” *International Journal of Human-Computer Studies*, vol. 58, no. 2, pp. 177–206, 2003.

[16] J. W. Gualtieri and W. C. Elm, “Power Tool for Countering Cyberwar: Visualizations for Information Assurance and Computer Network Defense,” *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 46, no. 3, pp. 463–467, Sep. 2002.

[17] Schraagen, J. M., *Cognitive Task Analysis*. CRC Press, 2000.

[18] K. J. Vicente, *Cognitive work analysis: toward safe, productive, and healthy computer-based work*. 2009.

[19] R. G. Eggleston, E. M. Roth, and R. Scott, “A Framework for Work-Centered Product Evaluation,” *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 47, no. 3, pp. 503–507, Oct. 2003.

[20] L. G. Militello and R. J. B. Hutton, “Applied cognitive task analysis (ACTA): a practitioner’s toolkit for understanding cognitive task demands,” *Ergonomics*, vol. 41, no. 11, pp. 1618–1641, Nov. 1998.

[21] J. M. Schraagen, S. F. Chipman, and V. L. Shalin, Eds., *Cognitive task analysis*. Mahwah, N.J: L. Erlbaum Associates, 2000.

[22] J. Rasmussen, M. Pejtersen, and L. Goodstein, “Cognitive Systems Engineering,” 1994.

[23] J. Moore and P. Havig, “Project UNITY: Cross Domain Visualization Collaboration,” Air Force Research Laboratory, Information Directorate Rome United States, AD1001978, 2015.

[24] J. Ianni, D. Aleva, and S. Ellis, “Overview of Human-Centric Space Situational Awareness (SSA) Science and Technology (S&T),” in *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference,* Wailea, Maui, Hawaii, 2012.

[25] D. Aleva and J. McCracken, “JSpOC Cognitive Task Analysis,” Defense Technical Information Center, ADA531755, 2009.

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