Human-system interfaces for space cognitive awareness

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ABSTRACT

Space situational awareness is a human activity. We have advanced sensors and automation capabilities but these continue to be tools for humans to use. The reality is, however, that humans cannot take full advantage of the power of these tools due to time constraints, cognitive limitations, poor tool integration, poor human-system interfaces, and other reasons. Some excellent tools may never be used in operations and, even if they were, they may not be well suited to provide a cohesive and comprehensive picture. Recognizing this, the Air Force Research Laboratory (AFRL) is applying cognitive science principles to increase the knowledge derived from existing tools and creating new capabilities to help space analysts and decision makers. At the center of this research is Sensemaking Support Environment technology. The concept is to create cognitive-friendly computer environments that connect critical and creative thinking for holistic decision making. AFRL is also investigating new visualization technologies for multi-sensor exploitation and space weather, human-to-human collaboration technologies, and other technology that will be discussed in this paper.

1. OVERVIEW

Satellites are critical assets to our national security thus making them potential targets for adversaries. However it is difficult for space analysts to recognize threatening situations with the current suite of tools available to them. To help address this shortcoming, the Air Force Research Laboratory (AFRL) is conducting research into how to improve knowledge tools from the standpoint of the sensor systems, information systems, and the human. This paper will focus on the human performance research from a cognitive science standpoint. The goal is to make effective use of available information to make timelier, better informed decisions.

Based on interviews of space professionals, there are several issues that need to be addressed to improve information utilization. [14] These issues range from improved sensor visualization to better human-to-human collaboration. However we feel that the major issue that needs to be addressed is work flow. More specifically, the issue is how the tools used by space analysts affect the decision process. If the analyst spends too much time on overhead tasks such as tool navigation, fewer cognitive resources will be spent on the actual decision. [6] While conducting cognitive task analyses of Air Force space operations one message came through repeatedly: “We do not want more tools!” [14]

An approach advocated by the AFRL Human Effectiveness Directorate is to develop a unified work environment that harnesses the power of these specialized tools while staying within cognitive limitations. The concept may seem simple, but developing such a system requires a formal scientific methodology and iterative usability testing. The result of the research is that separate computer applications are unified into a cognitive work environment that flows naturally with human decision-making processes. Such an environment, referred to as a work-centered support system (WCSS), has been shown to reduce time required to make decisions and a reduction in erroneous conclusions. [13] We hypothesize that these results can be attributed to a reduction in work complexity. Specifically, we notice an improved information transfer and a reduction in the demands on the analyst’s limited cognitive resources. Current research is looking to expand on the WCSS concept to create Sensemaking Support Environment technologies which are elaborated in a following section.

This paper outlines the space situational awareness research being conducted in AFRL Human Effectiveness Directorate and explains how each technology is envisioned to fit into a Sensemaking Support Environment. We will provide a possible approach to human-system interface design that integrates seemingly dissimilar information

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14. ABSTRACT
Space situational awareness is a human activity. We have advanced sensors and automation capabilities but these continue to be tools for humans to use. The reality is, however, that humans cannot take full advantage of the power of these tools due to time constraints, cognitive limitations, poor tool integration, poor human-system interfaces, and other reasons. Some excellent tools may never be used in operations and, even if they were, they may not be well suited to provide a cohesive and comprehensive picture. Recognizing this, the Air Force Research Laboratory (AFRL) is applying cognitive science principles to increase the knowledge derived from existing tools and creating new capabilities to help space analysts and decision makers. At the center of this research is Sensemaking Support Environment technology. The concept is to create cognitive-friendly computer environments that connect critical and creative thinking for holistic decision making. AFRL is also investigating new visualization technologies for multi-sensor exploitation and space weather, human-to-human collaboration technologies, and other technology that will be discussed in this paper.

15. SUBJECT TERMS

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sources and services such as intelligence, space weather, fused sensor data, telemetry link protection, and conjunction analysis. We aim for the unified human-system interfaces developed by this research to be part of a larger AFRL Focused Long Term Challenge demonstration in the 2015-2017 timeframe. This demonstration will include new AFRL satellite, sensor, and information technologies in addition to legacy systems. Without integration from the user standpoint, the operational viability of these technologies could be significantly diminished.

2. HUMAN IN THE SSA LOOP

Humans play many key roles in the Space Situational Awareness (SSA) process – arguably the most important roles. Some humans are specialized in sensor data analysis. Others may specialize in space weather. Still others may focus on a certain form of intelligence. Many of them do not wear a single hat but rather do different jobs based on organizational needs.

These analysts use data and information to make judgments about the situation. Alone, this information may have little value but, once combined with other information sources, the value can increase considerably. Ultimately information needs to be conveyed to the decision maker or commander in a format they can quickly understand and act upon.

Space operations differ from air operations in significant ways. Even though we are all Air Force, there are noticeable cultural differences between operators, analysts, and decision makers in the air and space domains. The difference may be likened to differences noticed between the Army and the Air Force upon the standup of the Air Force in 1947. Although we have yet to quantify or fully explain them, nonetheless these differences exist. Perhaps the differences are a result in the differences in technology, persistent operations, use of “untouchable” assets, and time spent collecting and analyzing data vs. time spent taking action. In addition, space COAs rarely involve direct life and death decisions.

Human-system interface technology. As we begin to better understand the operational space domain, we can start to develop and apply specific human-system interface concepts. One such concept is new display technologies. Research in display technology, particularly visual and audio, has been shown to have significant payoff in human effectiveness but it is not limited to new hardware. Much research needs to be conducted to understand how humans acquire information with modern technology.

Determining the optimal use of computer displays has become a critical research area for commercial and military operations. What may seem like a simple issue of putting the most important information on the screen is, in fact, a major oversimplification of a fairly complex problem. It misses an opportunity to improve information flow to the most critical system – the human. For example, three-dimensional (3D) or spatial displays provide an opportunity to increase situation awareness within human sensory constraints. Users may not realize that they are maintaining mental models for many aspects of their work. But these mental models – be they spatial or conceptual – can tax a user’s cognition, taking away from the creative work that humans do best. [3] Effective use of 3D models, intelligent agents, and other human-centric technologies can relieve some of these burdens.

Audio displays can augment a user’s ability to assimilate information more quickly and effectively compared to visual displays alone. [1] If implemented optimally, the interplay between visual and audio displays can reinforce a user’s understanding. Audio can be used to gain attention without the need to be in the line-of-sight. However if implemented incorrectly, audio can be a distraction for the user and those in close proximity. Audio isolation technologies exist, such as focused sound domes or active earplugs, which allow a user to receive information relevant to them without isolating them from their ambient environment. [12]

Audio can also be a power medium for user input. In previous research, a speech interface was developed by the Human Effectiveness Directorate to control Analytic Graphics, Inc. Satellite Tool Kit® (STK) and intelligent agents for specific SSA tasks. The interface allowed the user to invoke multiple STK commands, intelligent agent actions, or operating system calls with a single intuitive verbal phrase. For example, if the user said, "Set satellite 6451 in view 1 vector axes on," the following STK command line would be invoked: *VO */Satellite/6451 VectorAxes Modify "LVLH" Axes Object Show ON*. In laboratory studies where subjects were expected to determine whether an anomaly was the result of an intentional act or some other phenomenon, a dramatic improvement in speed and accuracy were recorded. [8]

Space operations, as with most other enterprises, benefit from many individuals working together to create a single "awareness." These individuals may be spread across many globally-distributed organizations. In our studies of SSA organizations, we have found that, in many cases, analysts call people they know rather than people that may have the knowledge they seek. Collaboration technologies will be discussed in a later section.

3. ANALYZING THE ANALYST

Humans, as knowledge creators, are able to apply their wisdom to creative solutions to problems. But as information processors, humans are relatively slow and inconsistent compared to computers. Cognitive scientists study the strengths and limitations of the brain and develop methods to augment the strengths while addressing the limitations.

In developing human-system interfaces, cognitive scientists realize that the design must consider many factors such as input channels, cognitive processing and synthesis, temporal considerations, work inconsistencies, and the decision making process. Individual analysts must not work in isolation so collaboration technologies are also critical.

A cognitive scientist needs to ask many questions of end users and subject matter experts to develop novel and perhaps revolutionary human-system interface concepts. The goal is to determine what the real objective of the work is, how it is done today, and how can it be improved. The problem is complicated by the fact that situations change over time. What indeed may be important at one moment may not be the next. Thus cognitive scientists should not be fixed to a single human-system interface concept. Multiple concepts should be created and tested both in laboratory and operational environments.

In past research efforts, the Human Effectiveness Directorate has performed an in-depth analysis of Satellite Operations Squadrons (SOPS) [11] and initial studies of the Joint Space Operations Center (JSpOC) [6]. Currently an effort is underway to conduct a more complete cognitive task analysis of the JSpOC. Two or more site visits to the JSpOC will be conducted for this effort. The first visit will involve observing JSpOC operations with a focus on elements including:

- Analyze task and activity triggers.
- Determine whether tasks are stand-alone or sequential; if tasks are sequential, any branching will be noted, along with the rationale for the selection of one branch over any other(s).
- Analyze activities in terms of their cognitive structure. Input to a task, operations on the input and work products will be described.
- Analyze rhythm of work including temporal characteristics of the operational structure.
- Note workarounds due to deficiencies in existing tools, unnecessary mental models, and other constraints such as limited work space or screen size (the latter may be inferred by excessive scrolling).

Follow-up visits will expand on the findings from the first visit with more focused observations and interviews. The results of this effort will provide a foundation for the directorate's continued research in SSA. We hope to also perform task analyses of other key SSA organizations such as the United States Strategic Command (STRATCOM) and the National Air and Space Intelligence Center (NASIC). [17]

4. SENSEMAKING SUPPORT TECHNOLOGY

Sensemaking is the ability to make sense of an ambiguous situation. More exactly, sensemaking is the process of creating situational awareness and understanding in high complexity or high uncertainty environments in order to make decisions. It is a "motivated, continuous effort to understand connections (which can be among people, places, and events) in order to anticipate their trajectories and act effectively." [10] With this in mind, a Sensemaking Support Environment is a flexible analytic work environment that includes work aids to assist the analyst in the 'dynamics of thinking' during the analysis and synthesis of assessment product formation. The concept is to create layers of sensemaking support on top of specialized tools and models (Fig. 1). As stated by Dr. Robert Eggleston of the Human Effectiveness Directorate, a goal of sensemaking support is to connect critical and creative thinking for holistic decision making. [2]

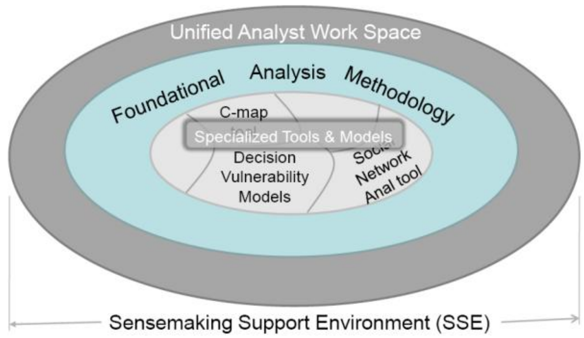

Fig. 1: Layered view of a Sensemaking Support Environment

At the root of Sensemaking Support Environment is the Work-Centered Support System (WCSS) technology which has provided the basis for much of our SSA research to date. WCSS does not use the traditional computer application paradigm. Instead, a seamless interface and automation facilities are provided that directly support the work. By representing the cognitive aspects of the work on the display, the interface acts to amplify and facilitate user decision-making, problem solving, collaboration and overall task performance while rendering the underlying computational paradigm transparent. Further, machine automation augments the work-centered presentation to provide context to alerts to aid in situation awareness and rapid problem resolution. The context appropriate visualizations allow the team to focus on the direct work of problem solving, decision making and collaboration to achieve mission success. Less effort is expended on overhead work such as application navigation, locating, retrieving, mentally fusing and distributing information, while remaining synchronized with other team members in a dynamic and changing operational environment. [13]

Work-centered support systems. A WCSS is a human supervised, automated, command and control user interface client that provides a cognitively tailored, real-time situational awareness workspace. A focus of the WCSS research is to provide radically advanced user-interfaces by understanding and supporting the cognitive aspects of the work and to design displays that facilitate mentally demanding tasks.

Typically, a traditional human-computer interface provides access, or is interfaced to, only one system at a time. For example, portal technology improves the user interface by providing access to a variety of systems within a single interface, yet users must log into and out of multiple systems to find the data they need to make decisions or perform a task. WCSS overcome this problem by integrating all information into a single display or spreadsheet. However, due to the complexity of command and control environments, the displays often contain enormous amounts of information which require excessive physical manipulation. They also require the operator to mentally fuse the data to obtain situation awareness. In time-critical situations, the operator simply does not have the time to assimilate the data to perform their job. This can result in a state of information overload in which relevant information ends up not being used in the decision process.

The WCSS technology may provide the ability to make the huge amounts of SSA information more manageable. Since SSA information comes from so many heterogeneous, geographically distributed sources, the challenge for implementing an effective WCSS is steep. However if we are not able to create timely, actionable knowledge from existing sources, there may be no need to add more sensors or intelligence sources. [7]

STEED. The Satellite Threat Evaluation Environment for Defensive Counterspace (STEED, Fig. 2), originally developed on a Small Business Innovative Research (SBIR) effort by The Design Knowledge Company, was the first WCSS developed for SSA. STEED incorporates some key data sources, including Satellite as a Sensor (SAS) fused data (developed by AFRL/VS contractors), space weather, proximity, radio frequency interference, intelligence, and threat data. [11]

The system, built on the Eclipse Rich Client Platform, provides a flexible and robust environment that is based on open-source tools, cross-platform technology and a flexible interface features to support legacy tools. STEED incorporates collaboration tools, decision support aiding based on an innovative data visualization technique, work management support that includes an innovative navigation/control graphical user interface widget, and product development support.

STEED was delivered to the Space and Missile Systems Center, Space Superiority Systems Wing (SMC/SY) in December 2007 as part of the JSpOC Situation Assessment & Response System (JSARS). JSARS was an AFRL rapid response effort to address the need for better knowledge tools in the JSpOC.

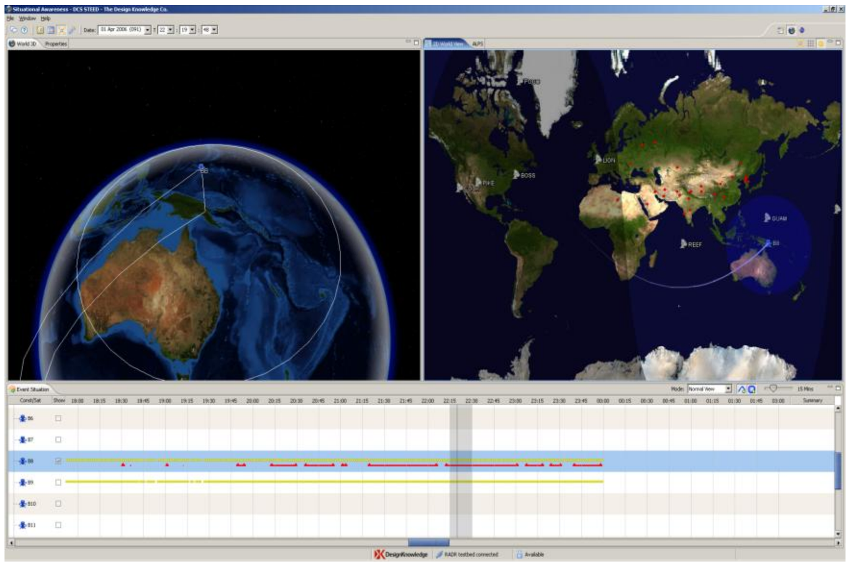

Fig. 2: STEED operator console station used for track management

5. VISUALIZATION TECHNOLOGY

Visualization can be a powerful tool to convey information quickly and effectively. Although it sounds trite, a picture can indeed be “worth a thousand words” and animations can be worth many pictures. Visualization for SSA is not limited to computer-aided design (CAD) models of satellites circling the earth. Visualization of data can be a powerful tool to detect trends that may have otherwise gone unnoticed. The ability to add motion to three-dimensional (3D) visualizations adds to the analysis process. For example, a cloud of dots in 3D can be meaningless until they are rotated revealing a pattern that was previously undetected.

Current research at the AFRL Human Effectiveness Directorate includes quantifying the benefits of 3D visualizations for certain SSA tasks. This effort is researching human factors design and evaluation procedures for 3D visualizations and operator interaction. It also is developing a set of human factors metrics for the evaluation of 3D display hardware and guidelines for 3D displays and operator interaction techniques for Space Command, Control, Intelligence, Surveillance and Reconnaissance (C2ISR) applications.

Another effort that involves visualization is a 2008 Small Business Innovative Research (SBIR) effort that focuses on space weather. A major part of this effort will be to investigate optimal visualization concepts and methods to display space weather for various analysts. The human-system interfaces for someone who specializes in space weather differs considerably from someone who simply needs to know how the space environment will affect their satellite. Therefore we will conduct task analyses of various space weather users and analysts across the nation to determine how space weather should fit into the work flow.

Sensor data, especially fused sensor data, is another key area for visualization research. In previous research we have quantified the benefits of color, motion, flashing, and other visualization effects, so we hope to apply some of these concepts, plus some newer novel concepts, to the area of sensor fusion. This work will be conducted in cooperation with the AFRL Sensors and Information Directorates.

Penn State University Applied Research Laboratory has developed immersive displays that allow analysts to interact with 3-D visualizations to see SSA data trends. [15] Features of the immersive environment include human-centered fusion, multi-sensory synthetic environments, presentation of uncertainty, and collaborative decision-making. The human-centered fusion allows effective, human-in-the-loop approaches to data fusion and multi-source information aggregation, integration, and presentation. The multi-sensory synthetic environments increases the human-computer interface bandwidth by bridging the gap between computing resources and humans by exploiting advanced sensory stimulation techniques that employ multiple human senses (primarily visual and audio) and cognitive processes. The presentation of uncertainty provides techniques that focus on new methods for characterizing ambiguous information, improving its contribution to decision-making. When sharing an immersive environment, the collaborative decision-making provides techniques to improve team-oriented analysis and decision-making processes. (Fig. 3)

Fig. 3: Examining space debris data in a Cave immersive environment

6. COLLABORATION TECHNOLOGY

No single system or person has complete situational awareness of space. One can only hope to understand the situation well enough for their area of responsibility. To achieve a more comprehensive space picture, communication can be critical between many different people distributed around the world. This concept of collaboration, information sharing, and integration among agencies and departments is highlighted in guidelines of the U.S. National Space Policy. [18]

The Human Effectiveness Directorate is applying new research methodologies to this problem. There are three challenges in this research. The first involves finding the people with the knowledge. This can be thought of as human knowledge mining. [9] The second involves facilitating human-to-human collaboration which can involve groups of people collaborating with individuals or other groups. Finally we aim to ensure the collaboration is optimized with minimal disruption to workflow.

<u>Human knowledge mining</u>. A goal of this research is to determine how to link those with the knowledge with those who need the knowledge. We envision the need for a human knowledge index that allows people who need knowledge to find:

1. Witnesses – such as a satellite operator that first recorded an anomaly.
2. Analysts – such as an engineer who came up with possible causes of an anomaly.
3. Experts – such as an expert in sensor vulnerabilities.

<u>Methods to collaborate</u>. Once a person is located who has relevant knowledge, a method to collaborate needs to be established. Many are not comfortable collaborating with someone who they have never met. Furthermore with verbal communication, significant time can be spent off task. So we aim to quantify the benefits of non-verbal collaboration. Some direct communication options could be video, speech-to-text, text-to-speech, shared virtual

spaces, chat, e-mail, and messaging. In addition, indirect collaboration techniques may be explored where two people may not realize they are collaborating. In any case, the method may differ depending on the task complexity, urgency, and number of people involved.

Workflow integration. Most people realize that human-to-human collaboration can impact workflow. Humans have a tendency to get sidetracked or engage in non-related discussions. In keeping with the work-centered support concept [4], the collaboration capability needs to conform to or enhance workflow. Our customers have been clear that they don't want more tools, so this needs to be as unobtrusive as possible. Typically, this has required integration into a work environment rather than a separate computer application. There are also issues with information security that will need to be considered.

There are significant challenges to this research. The first challenge will be to understand the cognitive dynamics of the enterprise. For example, what knowledge is needed or exists at the Joint Space Operations Center (JSpOC), space operations squadrons (SOPS), intelligence agencies, U.S. Strategic Command (STRATCOM), and industry? Furthermore, how do the organizational dynamics change as critical events unfold? To contain the problem, it may be necessary to focus on a few organizations such as the JSpOC, intelligence agencies, and SOPS. The second challenge will be to break down the bureaucratic barriers that exist between agencies. Each agency has its own organizational structure and protocols. A collaborative system must be versatile enough to allow for effective inter-agency collaboration while still maintaining the standard practices of each.

7. SUMMARY

The human factor in space situational awareness is often overlooked. However, the human can be the "long pole in the tent" in this process. But today, the manual method is necessary for sorting through and making sense of data that comes from heterogeneous sources. Some argue that we never will or even ought to take the human out of the loop [16]. The science and technology from the Air Force Research Laboratory, Human Effectiveness Directorate is addressing the cognitive strengths and limitations of space analysts and decision makers. A major focus of the research is to create a work-centered support system that allows analysts to make use of the great tools already at their disposal. Advanced visualization and collaboration technologies are also a critical part of that solution.

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