INL/CON-08-14732
PREPRINT

Human Factors Principles in Design of Computer-Mediated Visualization for Robot Missions

ISSNIP 2008/HRI

David I. Gertman
David J. Bruemmer

December 2008

Human Factors Principles in Design of Computer-Mediated Visualization for Robot Missions

#David I Gertman [1], David J Bruemmer [2]

[1]*Human Factors and Advanced I &C Department,* [2]*Robot and Intelligent Systems Department*
Idaho National Laboratory (INL)
Idaho Falls USA

[1]David.Gertman@inl.gov, [2]David.Bruemmer@inl.gov

Abstract— **With increased use of robots as a resource in missions supporting countermine, improvised explosive devices (IEDs), and chemical, biological, radiological nuclear and conventional explosives (CBRNE), fully understanding the best means by which to complement the human operator's underlying perceptual and cognitive processes could not be more important. Consistent with control and display integration practices in many other high technology computer-supported applications, current robotic design practices rely highly upon static guidelines and design heuristics that reflect the expertise and experience of the individual designer. In order to use what we know about human factors (HF) to drive human robot interaction (HRI) design, this paper reviews underlying human perception and cognition principles and shows how they were applied to a threat detection domain.**

I. Introduction

The presentation of highly complex sensor-based data vital to robot missions is best served by designing visual representations and interactions that highlight salient aspects of the data, provide situation awareness, and support cognitive and analytic reasoning processes. The goal is to transform highly complex, multifaceted data into simple, abstracted information that is visually structured to support situation awareness and decision making. Displays supporting countermine, improvised explosive device (IED), chemical, biological, radiological, and nuclear (CBRN) and emergency response missions should allow for user-directed interrogation of the environment and robot status, and should employ real world representations that benefit from our understanding of perception and human information processing.

Guidelines for computer-mediated visualization should encompass what we know about: graphic design, processes underlying visualizing quantitative information, the unique aspects of the task and task conditions and cognition and perception principles. Further, the user should be able to request additional information or have the same information presented in a different fashion, i.e., be able to change the perspective or detail.

To date, much HRI research has focused upon improving human-robot dialog as a means to overcome communication challenges. HRI has also leveraged heavily on roboticists' efforts to develop robot physical and cognitive behaviors. In terms of the latter, there has been much effort focused upon face and gesture reading by robots and the development of companion robots. For the past 4 years, the European Union (EU) has funded the *Cogniron Project* whose objectives include developing a cognitive companion robot with mobility, task skills, and the ability to engage in social interactions with humans for long periods of time on a daily basis [1]. For a survey of the videos highlighting interaction, issues and progress in recent developments of companion bots see Bartneck and Kanda 2007 [2].

Whether the robot is intended for the home environment or assisted living as in the case above or for other applications, HRI research has been defined by the domains to which it has been applied including countermines, bomb detection and disposal, search and rescue, aerospace, and medical. With a few notable exceptions, HRI has not diligently sought human factors principles for visualization. The first exception is the SRI DaVinci system surgical robot being used at University of California San Diego (UCSD) medical center that provides physicians situation awareness via highly dexterous manipulation capability coupled with 10x magnification, and 3D visualization. Further examples of research examining 3D visualization and operator situation awareness in support of robot interaction can be found in Bruemmer et al 2006 [3] and 2008 [4].

Often, robotics research less emphasis upon the representation provided to the operator than on the robot's performance. Operators find themselves adapting to the interface. Clearly, if robot technology is difficult for the end-user to intuitively grasp, the utility of potentially valuable technology will be limited. The more autonomous or intelligent robots become, the more necessary it is for the interface to provide the human with a window into the intentions and internal state of the robot. To further this endeavor, the following paper argues for a greater emphasis on human factors in HRI research and highlights key yet overlooked areas of human factors that may facilitate effective HRI.

II. HF Considerations for Interactive Control

Human factors (HF) focuses on the role of sensation, attention, perception, cognition, effort, utility (value), and physiological and psychological influencing factors on cognition and the human-system interaction—issues that are rarely the focus of HRI research. By looking at these issues, extracting human factors principles, and applying them to further HRI, we have the opportunity to complement gains in technology with gains in human-system performance and user acceptance. The sections that follow highlight some of the more notable human factors issues relevant to robot visualization and control.

A. Response consistency in terms of task demand.

Operator control actions should be consistent with task demands including mapping operator response modality to task requirements. Is a task inherently graphical, auditory or haptic in nature? Forcing tasks with a strong auditory or haptic component into a purely graphic format may fall short in terms of supporting operator performance. For example, performing highly dexterous robot manipulation associated with IED disposal or triage surgery under battle conditions should employ fine motor haptic input with enhanced visualization stereoscopic input. This mimics the haptic modality in the real world. Support for this approach is evidenced by the success in the US with robot assisted prostate surgery. Unlike most mobile robots currently in use, the control modality used by the operator should be appropriate to and complement the task at hand.

B. Use of different modalities.

Many tasks people perform are limited to one modality. Tasks that are multimodal in nature—that is, use different sensory modes—may allow operators to concentrate on more than one task at a time. This is because spatial and verbal information is stored separately in human memory. From a neural perspective there are distinct physical locations such as Broca's area for auditory processing and separate locations within the visual cortex area of the brain for visual processing. Vibration is another modality that can be employed to cue behavior. Recently, there is evidence that naturally occurring gestural interaction can be harnessed to directly manipulate robot navigation. For example, field studies conducted by the Idaho National Laboratory (INL) for Maneuver Support Center (MANSCEN) at Fort Leonard Wood, MO, in 2007 demonstrate that inertial sensing available in the Wii game controller allows natural gestures by military personnel to support robot path planning [4].

C. Stimulus-response considerations.

One of the most obvious dimensions for conceptualizing human computer interaction is in terms of time. Time to perceive, referred to in the behavioral sciences literature as the "perceptual fusion time constant" is 100 msec, while minimum human motor response time takes longer and is on the order of 250 msec. As a general rule, 10 seconds is an agreed upon time for complex search tasks [5-6]. In order to conform to this rule, interface design should simplify representation and tasking.

Proctor and Vu (2005) [5] review models and processes underlying identification, action selection and action execution. Identification is aided by feature extraction performed on a lower physiological level. Response selection occurs on a higher level. Reaction time also occurs as a function of the number of possible alternative responses to the same stimuli. Therefore, one-to-one mapping of stimulus to response has an obvious advantage in terms of reaction time and reduced error. Increases in alternatives result in corresponding increases in reaction times. This phenomenon is known as the Hick-Hyman law presented in Proctor and Vu [5] where:

$$RT = a + b\log_2 N$$

RT denotes reaction time, *a* is a base response time for subject response to a stimulus, *b* is the increase in time associated with increases in *N*, the number of alternatives. Other factors influencing performance include distance traversed to take the response execution/control action (Fitts Law), stimulus-response capability, stimulus quality, and mental rotation. For robots, the input device (e.g., track ball, touch screen, joystick, keyboard, or Wii controller) also can also profoundly effect action execution. As part of effective design for operational environments, stimulus-response alternatives need to be examined and tested prior to implementation.

III. Data Presentation

> *"If the doors of perception were cleansed every thing would appear to man as it is, infinite." Poet William Blake- [7]*

Currently, computer-mediated visualization is as much art as science. Although guidelines for graphical user interface (GUI) design are widely available [8-10], designers typically use their own design heuristics to develop representations for the robot and operator view of the world [11]. In the best case, end-users participate in the process to help with the construction and selection of candidate representations. This is consistent with Nielsen's [12] widely cited arguments for usability. However, involvement does not always guarantee success. End-user participation in conjunction with effective guidelines and the addition of rigorous experimentation is to be preferred. In terms of guidelines, Norman [in 13] presents three principles to support the development process – *appropriateness*, *naturalness* (of the information presented), and *matching* (tuning the interface to the task to be performed). Other researchers such as Tversky, Zacks [14] and Tversky [15] have proposed *congruence* (correspondence with the structure and content of the desired mental representation) as a construct for design and operation. The issue is determining what constitutes a proper and appropriate mental representation.

A. Provide abstraction to support cognition.

Abstraction is crucial to effective HRI system performance. Abstraction, in this case, refers to reducing unnecessary details, moving away from raw data towards higher level, semantic representations – preferably ones that coincide with human mental models. In the literature on human perception, there is a large body of evidence promoting processes that reduce the number of stimuli. Sensory information is taken in, parsed, and filtered into meaningful perceptual units. In biological systems, these processes are genetically hard wired and largely invariant across individuals. The HRI researcher is faced with coalescing complex information into a usable form, determining what elements or characteristics of data should be represented and which should be discarded. The key challenge is how to layer perceptual processes within the robot intelligence architecture that transform raw sensor data into semantic representations.

Abstraction is also required for aspects of control. Perceptual abstractions become the inputs for control. Whereas perception abstracts sensory data, control abstraction is the layering of actions. Metaphors are useful in establishing the salience of abstractions. By metaphor we mean an attempt to frame the process of data abstraction and the fundamental modes of communication towards a well understood interaction model or method. One example is a countermine robot that mimics the behavior and interaction techniques involved in handling a bomb sniffing canine. Another example is a robot control interface for search and rescue that mimics a well-known video game. Across all examples of control abstraction the same need exists to layer behaviors from simple stimulus response pairings to high level cognitive capabilities.

B. Promote Task Based Perception in a 3D World.

Task-based perception has been used as a basis for 3D displays. In his review of 3D spaces, Ware [16] notes that humans get shape, in part, from shading. They also depend upon stereoscopic vision and contributions from structure-from-motion. In fact, our most important depth cues may come from stereoscopic and structure-from-motion cues. Depending upon the task, one cue may be more effective than the other. Both Durgin et al. and Tittle et al. reveal the advantages of each [16]. For example, in stereoscopic displays, we have increased sensitivity to curvatures in a horizontal as opposed to vertical plane. Additionally, as one would expect, there is interaction between structure-from-motion and stereoscopic depth. The two in combination are often more effective than either alone. Motion and depth can be used to cue operator response and contribute to situation awareness.

C. Supply Navigation Metaphors.

From the same OCUs, fundamentally different navigation metaphors can be used to facilitate data identification and initiate operator control of robot actions. When controlling the robot's search, navigation or path planning activities, the operator can use a target to indicate an end destination, waypoints to indicate a path, a carrot to lead the robot from a short distance ahead, an eyeball, to tell the robot where to look or a nose to tell it where to sniff for chemicals. The robot can be navigated through sensor readings mapped to the geographical environment. In computer science applications, navigation metaphors have been used to promote understanding for instances in which there have been no travels in a geographic sense. Navigating through landscapes – both of information and real terrain -- is a key element of situation awareness. For a review of situation awareness, see Endsley and Garland [17] or Wickens [18]. Control and display are inextricably bound. The metaphor provides the substrate for understanding. The immediate advantage is that when the right metaphor is used, and the operator is cued properly, the operator can predict system behavior for a wide spectrum of operator input actions.

D. Link Metaphors to Affordances.

Each metaphor comes with certain affordances. Affordance theory, by Gibson [19] states that in order to operate upon the environment we have been genetically predisposed to *perceive* possibilities for action—objects *afford* actions and interactions. It follows then that when we select metaphors for display and control, we do so in such a way that users have the right affordances available to them.[17] Metaphors for 3D display used in recent HRI research have included the God's eye view and first-person shooter.. Metaphors for 3D navigation, search, and path planning include target drop, terrain fly-through or fly-over and walking. [3-4].

Gibson believes we are hard-wired to directly see the action possibilities associated with different real world environments. In contrast, computer renditions of the environment are abstractions and representations that may be associated with a different set of affordances. One can not assume a one-to-one mapping of affordances between the computer renditions of the environment with the environment itself. Even if video streaming is provided, there are still issues associated with field of view, color, update rate, compression, data uncertainty, and parallax that differ from what the operator sees in the real world. Also, there are no clear cut guidelines for designers as to when exaggeration of some feature present in the computer rendition of the environment will lead to a corresponding change in affordances. Conducting a human factors test and evaluation of alternate display and control metaphors may be helpful.

E. Design computer-generated maps to be compatible with human cognitive maps.

While using a computer-generated map, humans maintain a cognitive logical and spatial model with categorical and spatial coordinates. This mental model includes magnitude relationships in terms of distance between objects. In conjunction with cognitive logical and spatial models, there exist cognitive models for interaction. (Ware [17]). These models for interaction take the form of metaphors that can make the operator's prediction of system behavior easy to understand. Some researchers have considered providing navigation through landscapes as a useful metaphor for user navigation through data.

Seigel and White [in 5] put forth the notion of the user's internal cognitive spatial map. Within the map users are able to estimate fairly reliably the distances between points for which they have had no direct travel. Data from their studies suggest these maps are easily formed when an overview of the environment is provided. Whether designing for 2D or 3D display environments, displays that provide an overview support cognitive spatial map development. To promote

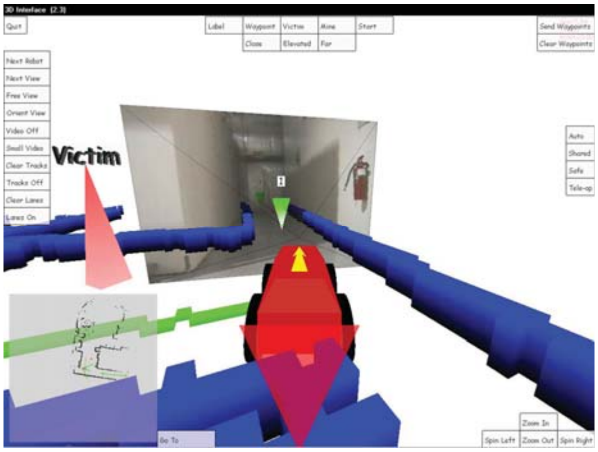

Figure 1: Interface used for Search and Rescue

shared understanding between the human and robot, we provide a cognitive spatial map that captures only the outline of relevant structure and abstracted, normalized hazard data.

The goal is not, as with most robot operator control interfaces to maximize richness of data, but rather to generate abstractions that correspond to the user's cognitive needs and eliminate everything else. To achieve this, an assemblage of perceptual algorithms on the robot and representational intelligence on the interface is necessary to reduce the output of a host of sensors and algorithms into a simple, yet appropriate display. See Figure 1 where the hallway is abstracted into a series of simple occupancy lines. Green cones indicate the robot's future path whereas green lines indicate the previous path. A red triangle shows an action affordance by indicating that the back is blocked. The vertical prism stands tall to increase the saliency of a critical feature – in this case a human which has been found.

F. Select representations that reflect operator attention, expectancy and value.

In designing computer mediated visualization, perceptual and cognitive factors come into play. Detection and discrimination have largely perceptual components; recognition involves cognitive factors including contextual elements as well as aspects of long term memory. Wickens' four factor theory [13] is useful in understanding this process. Selective attention encompasses factors of *salience*, *effort*, *expectancy*, and *value*. Salience is a bottom up process that helps to differentiate a stimulus or set of conditions from others. Expectancy and value clearly are knowledge driven and also play a role in operator perception and cognition. Effort is a factor in that if much effort is required on the part of the user, then the user may tend to "miss" changes. Finally, perception proceeds through a combination of selective attention and analysis of the features of an event or stimulus. From a design perspective, the representations, icons, and abstractions used must be different enough from one another and from background to aid perception. From a long term memory perspective, those perceptual representations including icons and metaphors that are an expected part of the user long term memory lead to shorter training time, better retention, and faster response times.

IV. Case Study

A. A Robot Threat Seeking Mission.

In experiments conducted for the DoD Joint Ground Robotics Enterprise (JGRE), the INL provided military operators tasked with detecting and localizing a chemical simulant a human factored control display interface with an advanced hazard mapping system. The experiment was designed for participants to detect and localize a chemical hazard within underground bunkers at Fort Leonard Wood. Participants for this experiment were from the Edgewood Chemical and Biological Center (ECBC) and the CBRNE School. In particular, the participant pool consisted of 10 individuals who had extensive training in emergency response, with half of them also having significant prior robot training. The operator group was comprised of 7 soldiers (2 officers, 5 NCOs) and 3 civilians, who were CUGV trainers/operators.

This experiment compared the INL's AUTOBOT with the Army's state-of-the-art chemical unmanned ground vehicle (CUGV). The CUGV is an iRobot™ PackBot Explosive Ordnance Disposal (EOD) that has been augmented to support a variety of hazard detection sensors. The CUGV is operated through an interface that uses two hockey-puck shaped actuators and a variety of levers and switches. The robot is fully tele-operated, except that the arm can move into predetermined positions with the click of a button. The interface has been augmented over a traditional PackBot interface to show the readings of the various sensors attached to the robot. The point of this paper is not to compare features of these two systems in detail, but to explain how perceptual and cognitive principles were used in the AUTOBOT application to enhance system performance.

The AUTOBOT implements integration of robust behaviors, hazard sensors, and interaction techniques. Operator workload is decreased because the operator does not have to rely upon overly complex control devices nor constantly monitor obstacle avoidance, navigation, and path planning. Within this paradigm the AUTOBOT uses a suite of sensors that enable the robot to generate a detailed map of multiple hazards within the environment, including threat areas and safe zones. This is congruent with principles of Seigel and White's cognitive map. Environmental hazards are abstracted by color coding from green to yellow to red. Each color corresponds to a human safety limit. Within a particular color, the level of color intensity/shading is used to indicate the direction of the hazard gradient. These gradients key the operator to higher hazards areas.

B. Perceptual and Cognitive Design Principles.

The interface used for the experiment leverages aspects of perception and cognition, including 3D rendering by shading, structure through movement; the use of an intuitive, easily understood metaphor for control; and building of a spatial cognitive map [3]. By conducting surveys of end-users, it was

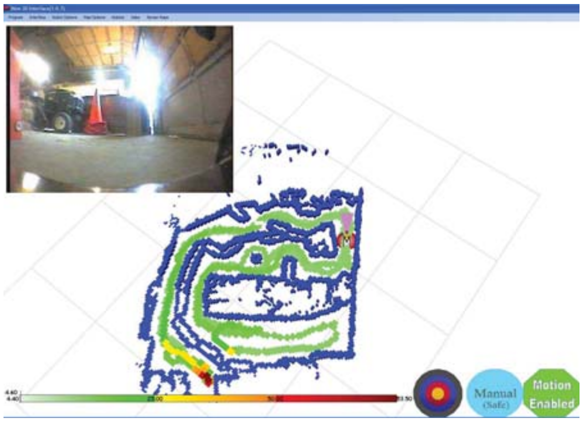

Figure 2. Screenshot obtained during chemical detection experiment

possible to develop icon-based representations that support Wickens model; possessed saliency, required a low degree of effort for subjects to discriminate changes in representation of the robot world. Figure 2 [20] presents the system as tested at Fort Leonard Wood.

To accomplish this, the user was provided with control actions consistent with mission objecties and learned patterns for searching environments, The blue boxes represent walls and obstacles produced by the laser mapping system on-board the vehicle. The path/location of robot is plotted with chemical sensor reading displayed as a green (clean) to red (contaminated) color. The purple fan in front of the robot represents field of view. Actual view of robot camera is shown on the top left of the picture [20].

A series of icons was developed to assist in the search process. Each of these icons could be mapped back to the metaphor of a search and rescue dog. “Look here,” and “go there” icons were used. Not only was the metaphor one to which the operators were easily trained, the results demonstrated that the use of this particular control metaphor resulted in detection times that were half as long and accuracy twice as great when compared with contemporary display and control practices for the use of robots in threat detection tasks. As part of the presentation strategy, sensor data were abstracted and presented to operators.

The U.S. Army TRADOC Operations Research Agency, TRAC-MTRY(2008) summarizes the results of this study in the following way:

“The laser-mapping capability is a clear illustration of a technology leap from state-of-the-art systems. The obvious difference in accuracy, standardization, and net-centered usefulness between an automatically digitally rendered, email-able, and GIS reference map and a hand-rendered map is a dramatic leap in capability. The clarity of spatial information as well as the transportability of the digitally mapped areas is far superior to the variations seen in hand-rendered maps. This technology may easily lead to the development of tactics, techniques, and procedures (TTPs) to catalogue the layout of certain urban regions in a theatre of operations and make data available to a networked force. With this capability, one can easily envision a digital map with a hot spot instantly available to all troops in a network-centric battlefield. A strong advantage of the mapping system is that all maps, regardless of the operator, have the same basic structure, can be GIS registered and may be computer archived. ”

The autonomous behaviors also reduced (operator) workload, physical and mental effort, and were enthusiastically endorsed by participants. Interestingly, it was only the experiment performed with the AUTOBOT where 100% of the participants reported full trust in the system. In previous studies that involved radiation detection, search and rescue and detection of land mines, the level of trust had been lower. The major difference between the chemical detection experiment and the others was not a difference in mapping, localization, or navigation, but rather a gross simplification of the visual representation and tasking options provided to the human. In other words, trust was generally increased by simplifying the interface.

V. Discussion and Conclusions

Roboticists and systems designers need to be mindful regarding principles of human sensation, perception, and cognition. Human factors are highly applicable to mission performance and are best engaged before rather than after system performance problems are discovered Many of these principles are available in the open literature, but must be applied through rigorous experimentation. Reducing user ambiguity and providing simpler user control are hallmarks of good human factors in design. .

In order to enhance the utility of currently fielded systems, it is necessary to improve the reliability and value of behaviors such as navigation, mapping, path planning, self-directed search and dexterous manipulation. The robotics community has long been preoccupied with the endeavor to create better behaviors. In reality, it is equally important to work towards greater operator acceptance, understanding, and usability of robot behavior, and this can best be accomplished through adherence to the principles of human factors engineering.

This paper has sought to focus on how human performance and acceptance aspects of HRI can be supported through consideration of human factors principles for perception and cognition. As the robot’s role evolves from that of mobile sensor suite to trusted team member, the nature of HRI changes. Design that leverages what we know about attention, perception, expectancy, and response compatibility can be used to support that change. User requirements are contextually driven, but consideration of context alone is not enough. In order to make the robot an acceptable resource we must consider a) the operator, b) task context and c) mission requirements. We must make our representation, abstraction, and control of *the robot in the world* congruent with operator expectancy and information processing needs. In so doing, we have the opportunity to make the robot valuable in applied settings. Finally, sound design principles, - even those with a basis in sensation and perception - without the proper craftsmanship will not lead to overall improvements in usability and performance. It is incumbent on the designer to include the end user in the process, consider multiple factors and influences present in field settings, and to employ metaphors that complement systems performance. Finally, this process must be guided by an iterative process of real world performance testing with human subjects.

REFERENCES

[1] Cogniron, the Robot Companion, URL *http://www.cogniron.org/About.php*, accessed May 2008.

[2] C. Bartneck, and Y. Kanda, HRI “Caught on Film,” Human Robot Interaction (HRI), Proceedings of the 2nd ACM SIGCHI/SIGART Conference on Human-Robot Interaction (HRI 07), Washington DC, USA. pp. 177-184, 2007.

[3] D. J. Bruemmer, D.A. Few, H. Hunting, M.C. Walton, C. Nielsen "Virtual Camera Perspectives within a 3-D Interface for Robotic Search and Rescue," In *Proc. of the ANS / IEEE 11th Annual Conference on Robotics and Remote Systems for Hazardous Environments*, Salt Lake City, UT, Feb. 12-15, 2006.

[4] D. J., Bruemmer, C. W Nielsen, D. I. Gertman, “How training and Autonomy Effect Results in a Dirty Bomb Experiment,” Proceedings of the 3rd ACM/IEEE International Conference on Human robot Interaction, Amsterdam, pp 161-168, 2008.

[5] R. W. Proctor, and K. L Vu in Jacko and Sears, Editors, Human Information Processing: An Overview for Human Computer Interaction, *The Human Computer Interaction Handbook*, Lawrence Erlbaum Associates, New Jersey, pp 35-51,2005.

[6] J. Thomas and K. Cook, “Illuminating the Path: The Research and Development Agenda for Visual Analytics,” prepared for the Department of Homeland Security, National Vision and Analytics Center, published with support of the IEEE, New Jersey, 184 pp, 2005.

[7] W. J. Freeman, “The physiology of perception.” Scientific American, February Vol 264, (2) Pgs. 78-85.1991

[8] E. R. Tufte, (2001) *The Visual Display of Quantitative Information (Second Edition)*. Graphics Press, Cheshire, CT, 2001. 197 pp, hardcover. ISBN0-9613921-4-2, 2001.

[9] A. Stewart, and D. Travis, Guidelines, Standards, and Style Guides, in *The Human Interaction Handbook*, Jacko and A Sears, Ed., L Lawrence Erlbaum Assoc, pp 991 -105,2003.

[10] B. Schneiderman, *Designing the User Interface*, Addison Wesley, 639 pp, 1997

[11] D. Bruemmer, D. Few, M. Goodrich, D. Norman, N. Sarkar, J. Scholtz, M. L Smart, B. Swinson, and H. Yanco, “How to Trust Robots Further than We Can Throw Them,” *Conference on Human Factors in Computing Systems (CHI2004),* 1576-1577, 2004.

[12] J. Nielsen, *Usability Engineering,* Interactive Technologies pub, 1993.

[13] C. D. Wickens, J. D., Lee, Y. Liu, S. E. Becker-Gordon, *An Introduction to Human Factors Engineering*, Prentice Hall, New Jersey. 587 pp,2004.

[14] J. M Zacks, and B Tversky, “Event Structure in Perception and Cognition,” Psychological Bulletin, Vol. 127, no. 1, 3-21,2001.

[15] B. Tversky, “Cognitive Maps, Cognitive Collages and Spatial Mental Models.” In Spatial Information Theory – A Theoretical Basis for GIS, Proceedings of the European Conference COSIT ’93, pp. 14-24. Springer-Verlag, Elba,1993.

[16] C. Ware *Information Visualization*, Academic Press, New York, 436 pp, 2000

[17] M. R. Endsley, and D. J. Garland, *Situation Awareness Analysis and Measurement*, Lawrence Erlbaum Associates, New Jersey, 2000

[18] C. D. Wickens, “Situation Awareness: Review of Mica Endsley's 1995 Articles on Situation Awareness Theory and Measurement,” Journal of the Human Factors and Ergonomics Society Volume 50, 3, June 2008 , pp. 397-403(7)

[19] J. J Gibson, *The ecological approach to visual perception*, Boston, MA: Houghton Mifflin, 1979

[20] T. Anderson, et al., “CBRN SUGV Field Test and Evaluation of Intelligent Autonomous Behaviors at Fort Leonard Wood,” US. Army TRADOC Operations Research Agency Technical Report, TRAC-MTRY, Monterey CA, 2008.