User-Centered Design: A Case Study on Its Application to the Tactical Tomahawk Weapons Control System

Sarah Rigsbee and William B. Fitzpatrick

*U*ser-centered design is an iterative design process that focuses heavily on the user and applies a top-down systems engineering approach that categorizes the overall system and user requirements into their various functions, subfunctions, and tasks. Decomposing systems into function and task components allows designers to gain a comprehensive understanding of users' needs, work, and decision-making processes. The information is translated into various design products, which are then leveraged to define user requirements that feed the overall systems engineering process. To illustrate the user-centered design process in a real-world application, we present a case study of the Tactical Tomahawk Weapons Control System, a component of the Tomahawk Weapons System that has provided the U.S. Navy with an unprecedented warfighting capability for more than 30 years.

INTRODUCTION

Human-systems integration (HSI) is a comprehensive program for integrating human requirements as part of an overall systems solution. HSI can be broken down into seven distinct specializations: manpower, personnel, training, human factors engineering (HFE), environmental safety and health, survivability, and habitability.[1] The goal of HSI is to optimize total system performance. HFE, which is a subset of HSI, can be used to design a human–computer interface (HCI). HFE is a field of study that seeks to understand the limitations and capabilities of human beings and apply that knowledge to designing systems for human use. One methodology used to implement HFE is user-centered design (UCD).

UCD is an iterative design approach based on the principle of centering the design process around the user, thus creating a user-centered design.[2] The process is carried out through several methods such as ethnography to study the user's jobs or task performance and user interviews and/or focus groups to elicit user needs and preferences as well as insights into design solu-

tions.[3] As part of the subfield of usability engineering, UCD has been developed for software design[4] and typically involves the following design approach: early focus on the user and tasks; empirical measurements using questionnaires, usability studies, and usage studies (focusing on quantitative performance data); iterative design using prototypes (where quick and rapid changes are made to the interface design); and participatory design, where users are directly engaged as part of the design team.
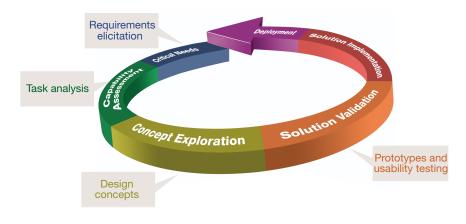

Figure 1. HSI within the systems engineering spiral.

The design process not only begins and ends with the end user but also includes consistent and repeated elicitation of users' feedback. User feedback is essential to ensure that the system design supports the operator's tasks and decision-making processes by providing, for example, the right information at the right time and in an intuitive manner. One facet of intuitive design is that the information is where one would expect it to be both temporally and spatially and is in a form that is easy to recognize and interact with. The UCD process helps define design requirements for the user and the system.

CASE STUDY: TACTICAL TOMAHAWK WEAPONS CONTROL SYSTEM

The Tactical Tomahawk Weapons Control System (TTWCS) is a component of the Tomahawk Weapons System, which has provided the U.S. Navy with an unprecedented warfighting capability for more than 30 years. The Johns Hopkins University Applied Physics Laboratory (APL) has served as the Technical Direction Agent for the Tomahawk Weapons System Program Office (PMA-280) for 28 years. Between 2004 and 2010, APL provided HFE support to PMA-280 by helping implement a UCD process and HCI design recommendations for the latest version of the TTWCS.

To illustrate how the UCD process can be applied to real-world programs, this article will describe each component of the UCD process and how that component was applied to the design of the next-generation TTWCS HCI. The design team followed a systems engineering approach[5] that mirrors the APL systems engineering loop described in this issue. The general UCD processes were integrated with the APL systems engineering loop and applied to the design of the TTWCS and the next-generation TTWCS HCI in the following phases (Fig. 1): requirements elicitation was used for the critical needs component; task analysis was used for the

capability assessment component; design concepts were used for the concept exploration component; and prototypes and usability testing were used for the solution validation component.

Tomahawk Development Background

As Tomahawk evolved (Fig. 2), greater capabilities and higher levels of automation were incrementally introduced into the weapons control system, culminating in the current version called the TTWCS. The TTWCS is a hardware and software system that is responsible for the initialization, planning, preparation, and launching of Tomahawk missiles in support of the Navy's power projection missions.

As the TTWCS evolved and further capabilities were introduced, the user interface also needed to evolve to support the new capabilities. Although it was deemed operationally suitable and effective, the HCI became less intuitive and did not fully support the nominal flow of the tasks required to complete a mission. The broad goals given by the sponsor for the user interface were to increase combat effectiveness, reduce operator workload, and improve situational awareness.

The sponsor believed that a solid HSI approach would help them achieve the desired improvements to
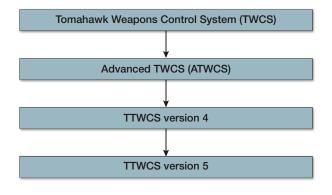

Figure 2. Evolution of the TWCS.

the user interface. Additionally, the HSI initiative also supported the DoD's "Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs" (DoD 5000.2-R).[6] This document states that programs shall initiate, early in the acquisition process, a comprehensive strategy for HSI to optimize total system performance, minimize total ownership cost, and ensure that the system is built to accommodate the characteristics of the user population that will operate, maintain, and support the system.

REQUIREMENTS ELICITATION

The UCD approach starts with a comprehensive understanding of the users and their environment. The old usability mantra "know thy user" is critical to the UCD process. Before entering into the world of the users, it is important that the interviewer understand the users' lexicon, system, tools, and environment so that the interview process is constructive and the interviewer is able to correctly interpret the true meaning of the feedback given. Identifying subject-matter experts (SMEs), or users who are former or current operators of the system, is essential to developing foundational background information on the roles relating to and supporting operations. One caution regarding SMEs is that they have a wealth of knowledge regarding existing or past systems and are often biased toward the original designs and procedures; this bias sometimes stifles a more creative or more forward-thinking approach. That said, SMEs are intimately familiar with the shortcomings of existing systems and can identify valuable data on user preferences and desired design features. SMEs can also direct designers to the second-most valuable source of information, existing key documentation.

TTWCS Requirements Elicitation

TTWCS operators use a computer workstation but do not share the same work environment with the typical office worker because they must adhere to various rules, regulations, and standard operating procedures that are unique to the Navy. TTWCS operators participate in additional activities including watches, training, and maintenance duties that could lead to fatigue and inefficient task switching. Knowing that the users are sailors in the Navy, and more specifically TTWCS operators, certainly helps designers to narrow down population differences, but they cannot be completely eliminated. Age, gender, cultural background, and other demographical differences within the pool of TTWCS operators are present and must be taken into consideration.

Interviews were performed onboard ships and in training facilities to elicit requirements from current TTWCS operators. The overarching purpose was to design the HCI to match the TTWCS operators' mental model of the system—how the users believe the system should operate and how they believe they should interact with the system to accomplish the overall mission. Because operators' mental models may vary, the interview process is critical in establishing a fundamental design base in order to support as many operators as possible. APL human factors experts had the opportunity to interview dozens of active-duty sailors and several trainers, and they found that operators' perspectives and feedback differed, especially by experience level. Through the interview process, demographic information as well as operators' mental models and opinions were obtained. As expected, opinions expressed by a senior chief with experience working with Tomahawk for 20 years was dramatically different from those of the inexperienced operator, a recent graduate from "A-school" (i.e., land-based classroom training after basic training for the Navy). Although the senior chief's knowledge is invaluable, understanding the cognitive challenges experienced by new operators helped direct the design team's focus toward the simplest common understanding of the system. Designing the interface to support inexperienced operators generally purports a more intuitive HCI and provides the added benefits of reducing cognitive workload and training time. Another group of stakeholders who can also be considered SMEs consists of members from the training community. The training community has great insight into what is easy and what is difficult to train. Areas in which training is difficult often are the least intuitive, carry the heaviest workload, and are most subject to errors. Focusing on and improving these areas benefits both the trainers (i.e., making it easier to train) and the operators (i.e., making it easier to learn). Copious notes were taken during the elicitation sessions (i.e., interviews), and the notes were then refined into explicit requirements that eventually led to a high-level design concept document.

TASK ANALYSIS

The task analysis phase (Fig. 3) of the UCD process closely examines the various underlying tasks performed by the operator in support of the functions and their requirements. The activities in task analysis first include defining the process and scope of considerations. The overall goal or mission of the system must be clearly identified and defined. In turn, the overall responsibilities of the operator must be determined as specific high-level requirements. The next step includes identifying the task categories and hierarchy and then decomposing those categories into subfunctions and subtasks. Workflows are based on this decomposition and then examined to determine low-level requirements. These
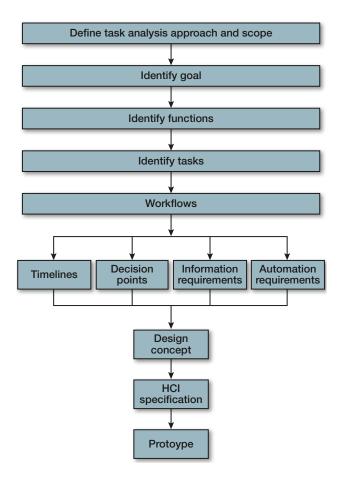
Figure 3. The TTWCS task analysis process.

the system. Each user workflow contains a diagram of steps, step descriptions, step triggers and products, swim lanes defining responsibility, information requirements for each step, and a description of how automation will be implemented. Note that no HCI is specified yet in this phase.

The effort of going from the top-level hierarchy (functions) to the subtask reveals what tasks the operator needs to perform to successfully complete a mission.

TTWCS Task Analysis

The overall goal or mission of the TTWCS is to deliver the appropriate ordnance by a specified time within a specific level of accuracy to a target. In turn, the TTWCS operator's overall responsibilities were determined as specific high-level requirements. These were then broken down into subfunctions that were translated into specific functional requirements and functions. For security and classification reasons, specific graphics and examples of the task analysis effort done on the TTWCS cannot be given. However, a sample functional task hierarchy is shown in Fig. 4. For each high-level task in the diagram, functional diagrams, task flows, and subsequent user workflows were defined.

DESIGN CONCEPTS AND ARTIFACTS

All information gained from the requirements elicitation and task analysis is fed into the development of a design concept in the solution validation phase of the systems engineering process. Three primary design artifacts are produced during this phase, the first of which is the high-level design concept document, which provides the basis and logic behind the user-interface design and guides the creation of an initial low-fidelity prototype. The high-level design concept document feeds into the HCI design specification document. The HCI design specification document provides an intro-

requirements drive the design concept, which is captured in a HCI design specification (described in the *Design Concepts and Artifacts* section) and then visualized and tested as the prototype.

For each top-level task hierarchy that is defined, functional task diagrams are developed to provide a basic representation of the task flows for the system. The analogy in systems engineering is the functional block diagram. Each high-level task diagram is further decomposed into sequential subtask flows, subtask descriptions, triggers, and an automation approach.

Each subfunction is further decomposed as appropriate. Additional diagrams are created to show the sequential flow of tasking at the subtask levels and to explain how a potential automation approach applies to each component. Finally, a subtask is defined with the purpose of showing the operator's interaction with the system, users, and any inputs from outside
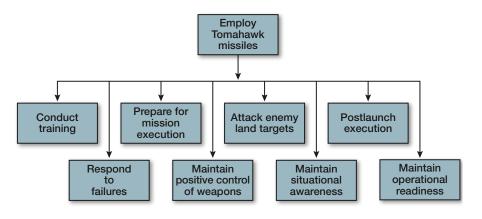

Figure 4. Top-level task hierarchy, e.g., systems functions.

duction and detailed screen layouts, colors, icons, and interaction methodologies. The third artifact is the user workflows.

TTWCS Design Concepts and Artifacts

From the interviews and previous task work, it was learned that the existing key documentation came in the following basic forms: Navy doctrines (e.g., Universal Naval Task List, Naval Tactical Task List, CCG1/4 Navy Mission Essential Task Lists, concept of operations, and operational tasking) and systems engineering documents (e.g., systems engineering plan, interface control document, system segment specification and system segment design description, and Tomahawk technical description document). The third source was historical design documents (e.g., task analysis, workflows, HCI specifications, and style guides). Fortunately, because of Tomahawk's longevity and well-instantiated systems engineering process, the documentation is plentiful.

The TTWCS high-level concept document was created using the aforementioned documents, the knowledge and information gained during the requirements elicitation, and the details from the task analysis. From the TTWCS high-level concept document, the TTWCS HCI design specification and TTWCS user workflows were created. Legacy user workflows were adjusted to represent the new interaction methodology.

PROTOTYPES AND USABILITY TESTING

Prototypes that can be utilized in UCD have three levels of fidelity: low, medium, and high. The purpose of using a low-fidelity prototype is to gather feedback in the early design stage and help validate the task analysis and user workflows. UCD design is iterative; that is, feedback from one usability test feeds design improvements to the next prototype and then the new prototype is once again tested to gain feedback. A low-fidelity prototype can be created using simple sketches of design concepts in a white board drawing, a paper-based sketch, or a presentation that could be shown to operators and other stakeholders for review.

A medium-fidelity prototype can then be created based on the feedback obtained from user reviews of the low-fidelity prototype. This prototype provides information that is more detailed and more dynamic in nature. It is once again presented to operators and other stakeholders to gain further feedback.

The next iteration of the prototype (i.e., high-fidelity) has an even greater level of detail and dynamic interaction and allows operators to actually operate the system and complete various, though limited, task flows.

Once all the feedback from testing of these prototypes is assimilated into the design, the design docu-

ments can be created. After the test and build phase is completed, the system and operator performance can be benchmarked to establish points of future comparison. To make the appropriate comparisons to earlier versions of the system (if there are earlier versions), benchmark testing is required; this consists of testing these versions by using the same task flows and metrics that will be used to test future builds. Getting performance data from earlier versions allows for establishment of benchmarks to illustrate measurable improvements. The most critical aspect of usability testing is the development of appropriate metrics. The metrics can be both objective (e.g., speed, accuracy) and subjective (e.g., NASA Task Load Index[7] and Situational Awareness Rating Technique[8]). The metrics must be applicable to all versions being tested and must be able to address the primary areas of interest that support the overarching goals of the system.

TTWCS Prototypes and Usability Testing

As the TTWCS program moved into the solution validation phase, a preliminary low-fidelity prototype was developed. This prototype began as a white board drawing and then evolved into a paper-based sketch and finally into a presentation that could be shown to Tomahawk operators and other stakeholders for review.

Benchmark testing, as described in the previous section, was conducted. APL played a vital role in the planning, experimental design, and execution of all benchmark and usability testing, ensuring development of appropriate metrics that supported the program's overarching goals of reducing workload and improving combat effectiveness and situational awareness.

A medium-fidelity prototype was then created based on the feedback obtained from user reviews of the low-fidelity prototype. This prototype was more detailed and more dynamic than the low-fidelity prototype. As with the low-fidelity prototype, this version was once again presented to TTWCS operators and other stakeholders to gain further feedback.

The high-fidelity prototype was created next. This version had even more detail and dynamic interaction than the medium-fidelity prototype and allowed operators to actually operate the system and complete various, though limited, task flows.

For each version of the prototype, user feedback was assimilated into the design, and design documents were created in parallel with the prototype and moved from draft to completion, corresponding with the levels of fidelity of the prototype. After the test and build phase was completed, performance of the system and operator were benchmarked to establish points of future comparison. The system was subjected to several other tests before actual deployment, and even after deployment, feedback is elicited from TTWCS operators to help guide follow-on builds.

RESULTS

Applying the UCD process to design the TTWCS graphical user interface was very successful. The design is currently in production and will be fielded in 2015. Preliminary testing showed improvements in workload, situational awareness, the number of missiles launched on time, the number of errors, and the amount of help required to operate the new interface with minimal training. By its very nature, UCD garners consensus from the entire stakeholder community early in and throughout the design process. This, in turn, allows the design and development to move forward smoothly. Users and stakeholders alike are looking forward to the deployment of the system they helped build. Moreover, those same users and stakeholders help spread a positive message regarding the improved interface, which results in a boost in the users' initial acceptance of the product.

REDESIGN IMPACTS AND LIMITATIONS/ CONSTRAINTS

It is important to highlight that although operators are consulted throughout the iterative systems engineering UCD process, it is imperative that the design team receive buy-in from the entire stakeholder community (e.g., training, program management, operational communities, etc.). Redesigning the HCI impacts far more than just the operators; it also impacts software, hardware, training, logistics, systems engineering, and, of course, the organization sponsoring the redesign. Providing the various stakeholders with a firm grasp of the upcoming changes allows them to provide their own feedback and make plans for the upcoming changes. Including multidisciplinary perspectives creates a better design and reduces the number of important details that may fall through the cracks and induce expensive redesign during the development phase. Allowing stakeholders to provide feedback early and often gives them a sense of ownership of and pride in the product. As part-owners of the design, stakeholders quickly became advocates. The programmatic side effect is that the vast majority of stakeholders end up pulling in the same direction and there is little debate regarding the direction of the design.

A caveat to the UCD process is that if the process is not well managed, the design can be derailed by stakeholders with strong opinions. Although it is important to gather a large amount of feedback, one needs to realize that single extreme data points are just that and cannot be used to determine the effectiveness or direction of a design. Gathering several ideas and examining them for overlaps and common themes is essential in the design process. Additionally, the design team must balance the user/stakeholder feedback with other factors and constraints. A classic example is the young operator who desires the same capabilities and HCI he/she enjoys on the modern gaming console (e.g., Xbox or PlayStation 3). The sailor may not be cognizant of the countless constraints that impact the design. In the case of the TTWCS, for example, additional constraints include legacy hardware (e.g., processors, workstations, and network infrastructure), which is often not conducive to running HCIs used in modern commercial applications. Additionally, there are also several other systems that the TTWCS must interface with both on and off the ship and these systems and interactions need to be included in design decisions. In addition, when designing a system that can cause fatalities, like TTWCS, safety and security issues are present and must be considered.

Another valuable point of interest is standardization. A common look and feel is always a goal when designing a user interface because it can reduce training time and errors by providing an interface that is similar to those of other systems familiar to the operator. When designing the HCI for the TTWCS, the design team followed several military standards and guidelines for human factors. For example, the military standard "Human Engineering Design Criteria for Military Systems, Equipment and Facilities"[9] establishes general human factors engineering criteria for the design and development of military systems, equipment, and facilities. The military standard "Department of Defense Interface Standard: Common Warfighting Symbology"[10] was designed to eliminate conflicts within various symbol sets and bring a core set of common warfighting symbology under one DoD standard.

SUMMARY

UCD is an iterative systems engineering design process that focuses heavily on the user, applying a top-down approach that decomposes the overall system, user goals, and requirements into their various functions, subfunctions, and tasks. Designers were able to gain a comprehensive understanding of the TTWCS operators, their work, and their decision-making process in the UCD task analysis phase. This understanding translated into various products including workflows, timelines, an HCI design specification, and HCI prototypes.

Although the UCD process is extremely valuable, the approach must be tempered with engineering aptitude that accounts for the entire system as well as other facets that users may not consider. The essence of HSI, HFE, and UCD is not to force the human to adapt to the system, but to design a system to fit and support the human.

REFERENCES

[1]Booher, H. R. (ed.), "Introduction: Human Systems Integration," in *Handbook of Human Systems Integration*, John Wiley & Sons, Inc., Hoboken, NJ, pp. 1–30 (2005).

[2]Norman, D. A., and Draper, S. W. (eds.), *User Centered System Design: New Perspectives on Human-Computer Interaction*, Lawrence Erlbaum Associates, Hillsdale, NJ (1986).

[3]Wickens, C. D., Becker, S. E., Liu, Y., and Lee, J. D., *An Introduction to Human Factors Engineering*, 2nd Ed., Pearson Prentice Hall, Upper Saddle River, NJ (2003).

[4]Nielsen, J., *Usability Engineering*, Morgan Kaufmann Publishers/Academic Press, San Francisco, CA (1993).

[5]Mayhew, D. J., *The Usability Engineering Lifecycle: A Practitioner's Handbook for User Interface Design*, Morgan Kaufmann Publishers/Academic Press, San Francisco, CA (1999).

[6]U.S. Department of Defense, "Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs," DoD 5000.2-R (5 Apr 2002).

[7]Hart, S. G., "NASA-Task Load Index (NASA-TLX); 20 Years Later," in *Proc. Human Factors and Ergonomics Society 50th Annual Meeting*, San Francisco, CA, pp. 904–908 (2006).

[8]Taylor, R. M., "Situational Awareness Rating Technique (SART): The Development of a Tool for Aircrew Systems Design," in *Proc. AGARD (Advisory Group for Aerospace Research & Development) AMP (Aerospace Medical Panel) Symp. on Situational Awareness in Aerospace Operations*, Neuilly-sur-Seine, France, CP-478, pp. 1–17 (1990).

[9]U.S. Department of Defense, "Military Standard: Human Engineering Design Criteria for Military Systems, Equipment and Facilities," MIL-STD-1472D (14 Mar 1989).

[10]U.S. Department of Defense, "Department of Defense Interface Standard: Common Warfighting Symbology," MIL-STD-2525B w/ CHANGE 2 (7 Mar 2007).

The Authors

Sarah Rigsbee

William B. Fitzpatrick

Sarah Rigsbee is an Associate Professional Staff member in the Force Projection Department. Ms. Rigsbee has provided HIS engineering, data analysis, and statistical analysis support for a variety of projects, including the TTWCS. **William B. Fitzpatrick** is a Senior Professional Staff member in the Force Projection Department who specializes in human factors. Mr. Fitzpatrick has applied his human factors expertise to numerous projects at APL, including the TTWCS. For further information on the work reported here, contact Sarah Rigsbee. Her e-mail address is sarah.rigsbee@jhuapl.edu.

The *Johns Hopkins APL Technical Digest* can be accessed electronically at **www.jhuapl.edu/techdigest**.