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FROM LEGACY C^2 SYSTEMS TOWARD MISSION-CENTERED DESIGN: TOMAHAWK MISSILE WEAPON CONTROL SYSTEM

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Abstract

Through a sequence of research studies the User-Centered Design workgroup at the Space & Naval Warfare Systems Center San Diego (SSC-SD) has identified a set of design principles captured in a Mission-Centered Design (MCD) approach to developing Human Computer Interfaces (HCIs). This approach has been applied to emerging designs for the next generation land-attack Tactical Tomahawk Weapon Control System (TTWCS). A Task Manager display was implemented as a key HCI design feature to address cognitive requirements for supervisory control by providing an explicit mission process representation. The representation is used to convey mission process, status, and guide attention across simultaneous tasks. The interface supports the cognitive function of mission process situation awareness as well as providing an efficient mechanism to navigate to existing TTWCS interfaces. A recent study indicates a potential reduction in both cognitive and motor workload with Task Management assistance. An operational scenario-based laboratory evaluation of a future TTWCS HCI design with Task Management and decision support aids required a single operator vice the traditional four operators to perform simultaneous planning, execution, and missile control tasks. The improved HCI design produced high performance levels with minimal workload even with only 6 hours of difference[1] training.

Mission-Centered Design

Mission-Centered Design (MCD) is the military analogy to Work-Centered Design (Osga 2003a) which focuses design on the work or mission process while reducing procedure-induced workload and training requirements. The resulting system design can be an enabler for crew-size reduction by reducing task workload. MCD focuses analysis and design requirements on the complete set of mission products the warfighter must produce through the planning, execution, and monitoring phases of the mission. This design approach contrasts with a functional or data-focused design that requires the operator to navigate through complicated function-oriented menus to monitor task status and produce task products. The MCD process incorporates the User-Centered Design (UCD)(Henry 1998) process cycles of Analysis, Design, Implementation, and Development. Similar to UCD, MCD involves users early and frequently in all phases of the design. However, MCD is more similar to Usage-Centered Design (Constantine & Lockwood, 1999) in that the analysis focuses more on the operators' tasks than the operators' characteristics. While MCD recognizes the importance of understanding the expectations of users, we have found it is more important to understand the tasks the user must perform and the capabilities and constraints of the systems they must use to perform these tasks. The tasks define what needs to be accomplished to be successful and the constraints define the boundaries the users must work within. The notion of constraints stems from ecological (Vincente 1999, 2002) design processes and defines the level of flexibility that will be provided in the system. Being very similar to and sharing characteristics of the above mentioned design process, this paper does not try to define MCD as a new process but rather presents some design axioms we have found useful and then presents results of

[1] Difference training in the military is the training required to allow an operator to migrate from a current software version to a newer version. It is commonly measured in days or weeks, not hours. Furthermore, HCI differences where noted by some as the primary difference training requirement in fielding the current TTWCS v4 software.

implementing this process in redesigning the TTWCS user interface. As with most design processes, MCD begins with an analysis phase where a common hurdle is defining the granularity and specificity of task definitions.

Design Axiom 1: Explicitly represent the mission process within the interface.
Within the MCD context, systems can be designed to visually depict mission goals and processes. This visualization has been described as a "Goal-Explicit" work interface system (Osga 2003b) in which user supervision of tasks is aided by visualization features representing tasks, process, and task responsibility. The goal of design is to capture mission processes in a way that represents the most generally accepted process. The nature of the process, whether flexible, rigid, or a combination of both is determined by the type of process, consequences, automation reliability, and user preferences. In general, mission processes which are closer to the target in terms of weapons delivery require high reliability, rapid progression, and process rigidity to ensure common quality across shooting platforms. Processes related to planning, operations, or strategic thinking require increased flexibility and options.

Design Axiom 2: Focus on mission products to bound the task analysis scope.
Mission (work) products should direct and bound the task analysis. Products enable the design team to develop a common understanding of the granularity of the task analysis to be performed. These task products range from automated command and control (C^2) reports to automated planning, targeting, and weaponeering solutions. Typically, questions arise across design team members as to the definition of a product. We define a task product to be something of value to the customer in support of the work process - requiring no or minimum further work. If further work is required with a product, then the product is likely an interim result that is the output of a process step which, when combined with other task steps, will produce a final task product. These interim products may be appropriate but often rather are an indication that further analysis is required to understand the user's true goal in performing the task. The design team should be certain the product is defined as concretely as possible before proceeding further with the analysis.

Often, at the onset of the product analysis, the original task product definition will lack the proper substance, meaning the product description is not very tangible. For example, in the military environment, a task product may be expressed as the development of some type and level of situational awareness. Focusing on the report, solution, or decision the situational awareness will be used to produce is often helpful in developing more tangible and focused product descriptions. Maintaining this focus on task products keeps the analysis centered on the mission goals. When the focus on goals is combined with effective visualization support and human engineering the result is an HCI design that supports effective supervisory control of the mission products.

Design Axiom 3: Focus on task goals and products, not on current methods.
The approach to MCD contains steps similar to traditional Task Analysis, however, the end goal is not to capture and re-use a current process, but to capture mission goals and products and improve the mission process to obtain these products. Thus, the initial analysis should only focus on these products and any constraints that must be observed when producing the products. This will allow more optimal methods to be realized for developing and tracking the production of these products.

Design Axiom 4: Allow for variable levels of automation.

Another important aspect of design involves accommodating variable levels of automation in the creation of mission task products. With increasing automated support, HCI requirements are focused on human-system cooperation during the creation, review and use of mission products. The designer must ensure the operator defined level of automation is represented in the visible interface. This contrasts with a functional design in which automation merely dumps data into windows for manual review.

Human-Computer Interface Features

The interface model that we have constructed in our MCD process contains three layers of supervisory control, each providing a different level of inspection into the mission processes. These layers include:

1. Multi-mission, multiple-tasks (Figure 1),
2. Single mission, multiple tasks (Figure 2),
3. Single task, detailed support (Figure 3).

The HCI allows the user to display general task status across multiple missions, task process status within a single mission, or detailed product support within a given task. The levels allow users with different roles in the Command & Control hierarchy to use a common interface, making the sharing of task status information explicit. This allows users to collaborate on problem solving tasks instead of data sharing tasks. Figures 1-3 depict navigation layers as the user moves between these three supervisory control layers. The design goal is to present consistent navigation methods that are easy to train and repeated through many types of tasks as well as across mission domains. The top-level view (Figure 1) contains columns that represent various Land Attack mission roles assigned to the platform (ship). Icons in the individual rows represent assigned tasks within that mission role. The second layer (Figure 2) depicts a single platform's Tomahawk Strike missions displayed within the Tomahawk Strike process. The individual missions are represented in the first column as they were on the higher level, followed by a sequence of product steps depicting the strike process, and finally by a set of task information columns. The color coding of the product steps alerts the operator to the product's level or completion and issues associated with the quality of each product. Selecting a product step allows the users to respond to these system requests or to simply review the product at their own discretion. The automated product support sophistication can vary from highly structured and precise, to an information blackboard with relevant product information. The product completeness depends on the automation available to create the product. The level of operator involvement depends on workload, mission demands, and the commander's trust in the automation. In many cases, users desire multiple solutions ranging from best practice to poor in order to collaborate with the system output. Thus, the supervisory control role of the operator varies between products and across platforms as defined by command doctrine. These roles vary from completely autonomous product delivery, to supervisory product approval, to constraint-based product editing, to manual product creation. In some cases the '80% effective' draft product solution presented by the system is used due to competing tasks and demands, while in other cases the user has lower workload and can edit and fine-tune the product.

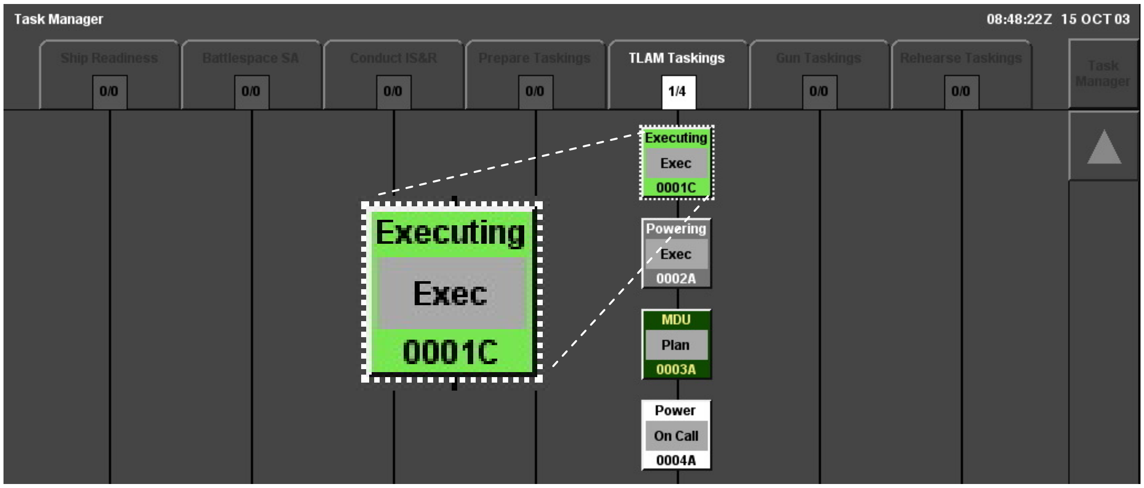

Figure 1. The Level 1 display shows seven columns of Land Attack mission roles. In this example there are four tasks within the Tomahawk Strike mission role. Each icon displays overall task status by the top line of text and the background color coding. Click on a columns tab to drill down to the Level 2 view (Figure 2) of that mission role. Double click on an icon to drill down to the Level 3 task status display (Figure 3).

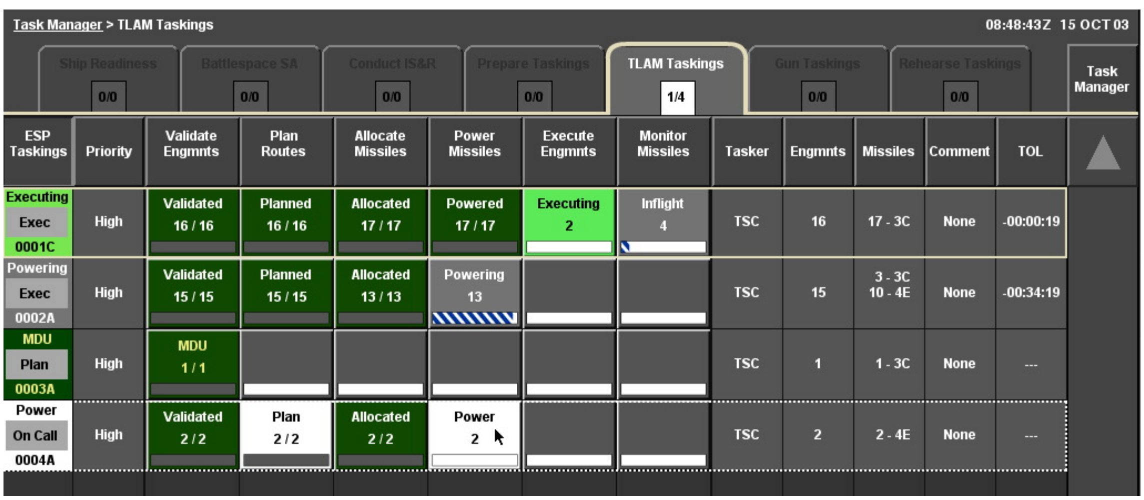

Figure 2. Level 2 displays the four Tomahawk Strike tasks but now includes for each task the status of each step in the Tomahawk Strike process in columns 3-8. The first column is the same general tasks status icon as displayed in the Level 1 display. The second column is the tasking priority. The final five columns provide general strike information. Double click any step within any task to see the Level 3 display (Figure 3) providing detailed status information about the completion of that step.

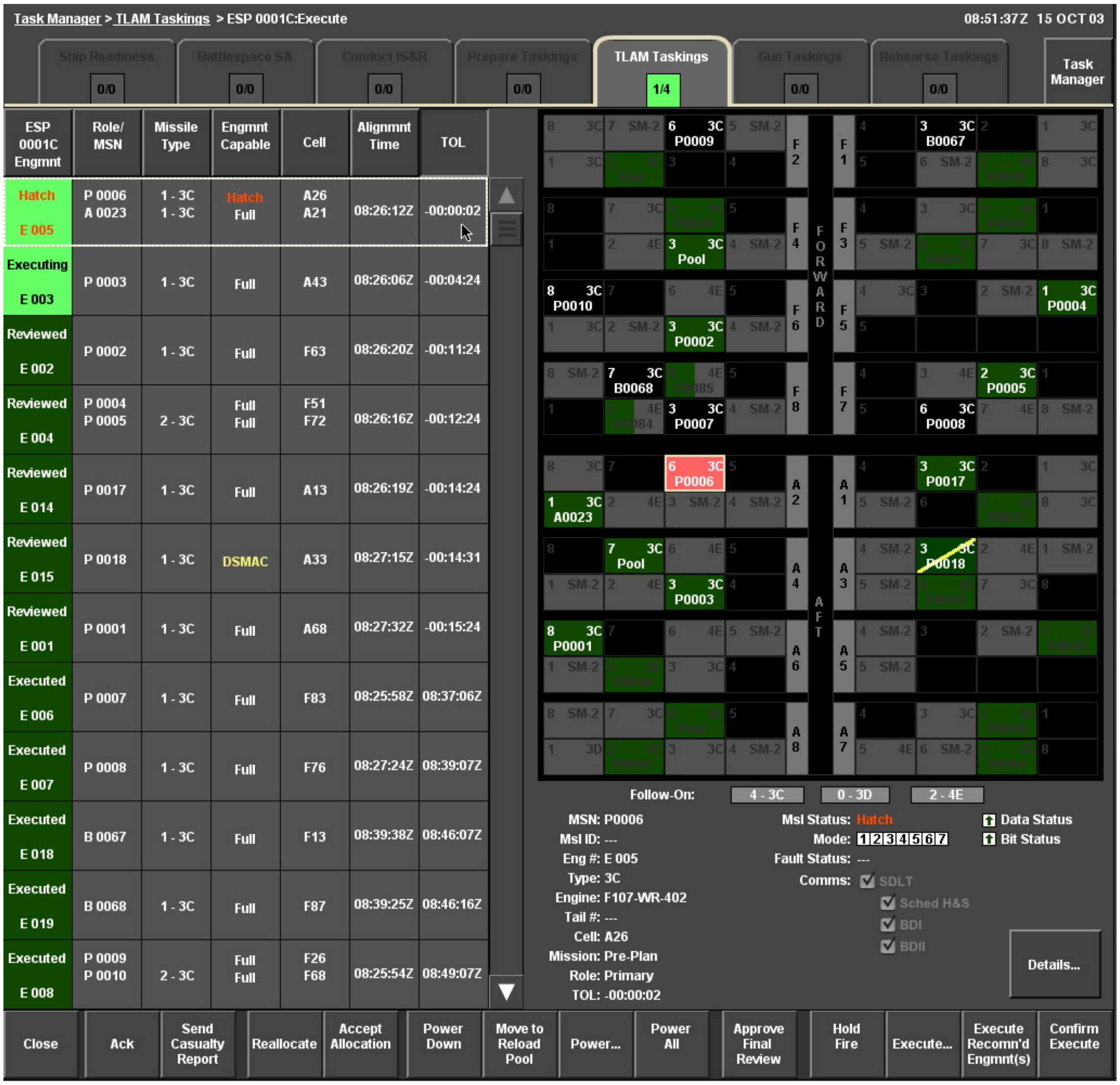

Figure 3. The Level 3 display shows the detailed status of a single step of a single task. This figure shows the Execution status of the first row task in Figure 2. Each row on the left represents an individual engagement within this task. The first two engagements are currently executing. The matrix on the right represents the physical layout and inventory of the ship's missile launchers. The actions button across the bottom provide the functionality the operator may employ.

Function vs. Task-Based Navigation

While human-factors design processes promote a focus on the user tasks, designers and programmers often decompose task products into a series of commonly occurring functions. Although the result is more concise and efficient to develop software, the representation of the mission or task is then lost to the end user in the final HCI design. Users are required to use vigilance and cognitive skills to determine what tasks need to be performed, to determine the product(s) required for that task, to determine the sequence of functions required to produce these products, and then maintain a knowledge of the windows or menus used to access these functions. This is commonly solved through training, documentation, paper checklists, sticky notes, etc. Anytime these peripheral "cognitive crutches" are seen being used by an operator it is a good indication that the HCI is not supporting the entire work domain process. Even if successfully trained, the operators' cognitive and motor (navigation) workload may be significantly increased.

The task product steps Level 2 (Figure 2) of the MCD navigation hierarchy will be used to demonstrate the subtle but important difference in task-based navigation vs. function-based navigation. Given that legacy military systems typically provide a functional HCI navigation method, the challenge to designers is the transition from a purely functional approach to a task-based approach. The Tactical Tomahawk Weapon Control System (TTWCS) has been the focus of study for HCI improvement under an Office of Naval Research sponsored project. Designs of various HCI components were developed through structured laboratory research (incorporating mission and user-centered design), then presented to the system prime contractors for implementation into future software upgrades. A two-stage improvement process was formulated in which the Level 2 supervisory control layer would be upgraded first in TTWCS version 5, followed by the lower supervisory control levels in subsequent software builds. Figure 4 depicts this process of first upgrading to a task-based navigation format, then adding the drill-down layers to task-based information results. In the legacy design, automation generally populates existing data-centric windows that are accessed by their functional descriptions. These data types do not directly map to mission tasks, requiring the user to translate mission goals and tasks into the functional "language" of the HCI. The result is the operator must remember the content and functionality contained within each window. Commonly, the operator must also integrate the data contained across several windows in order to review task products and monitor process status. This monitoring and manipulation of multiple windows in a limited display space further adds to cognitive and motor workload. The first level of HCI design upgrade shown in Figure 2 (center column) allows the user to monitor process status and navigate in a task-based fashion, however the task product completion and delivery must be done using the existing data-driven set of windows and their functionality. The second phase of upgrade (right column) provides a decision support information set that becomes tailored to the task selected by the user. Early phases of usability testing were conducted on these task-based HCI improvements to determine their benefit in relation to the previously proposed functional design.

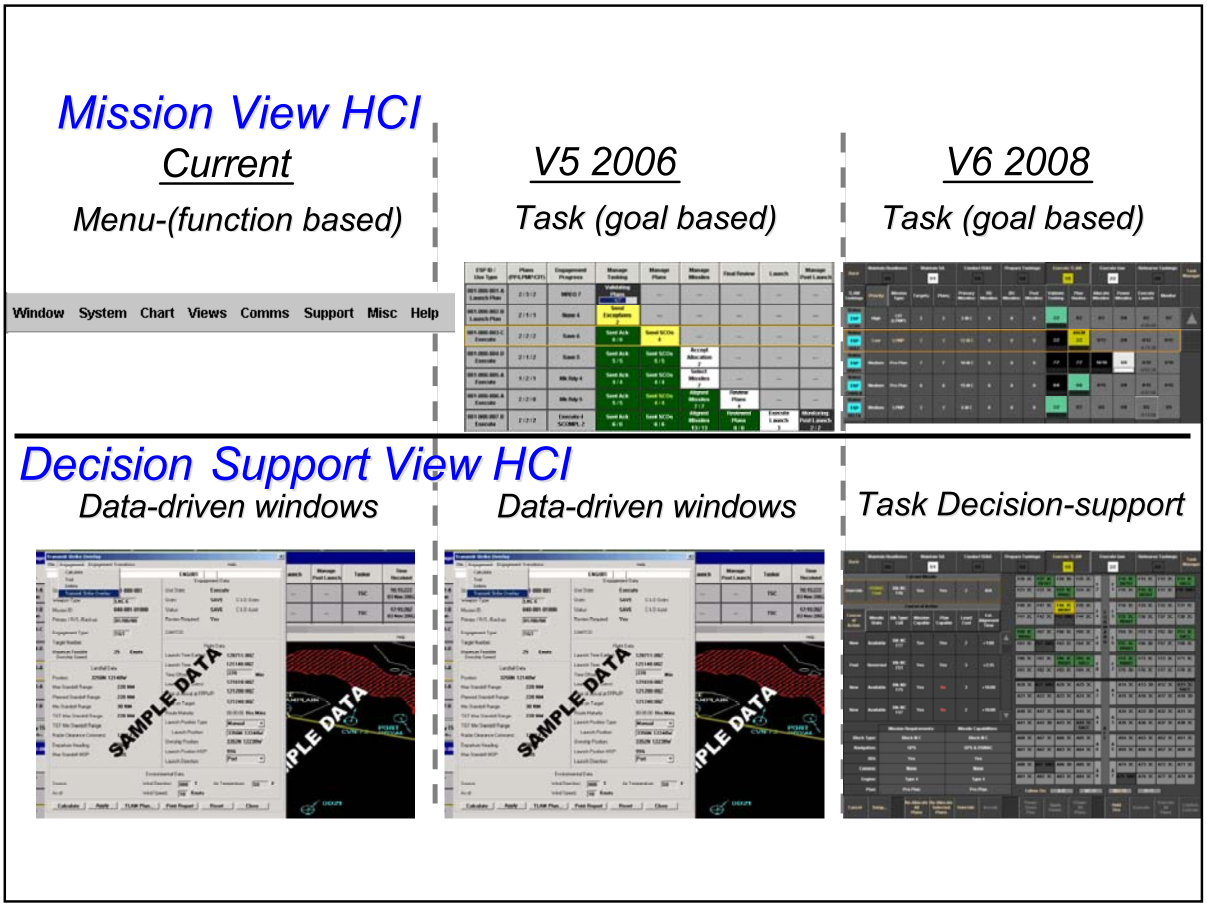

Figure 4. Design Evolution from Function-based to Task-based across versions of Tactical Tomahawk Human-Computer Interface. The Task Manger in v5 provides status information across simultaneous tasks and navigation to the windows required to complete any step the operator selects. The v6 software will replace the multiple existing data-centric windows with individual task product-based decision support displays.

Usability Testing

Usability testing ranges from paper prototypes to working simulations of systems through actual system models. This process fosters user involvement throughout the entire analysis and design process. Additionally, users are brought in frequently to provide feedback in user focus group or during usability testing. Their feedback is then iterated back into the analysis and designs. The analysis and designs must be presented to the users in a form they are familiar with as opposed to requirements, flow diagrams, or software documentation. This presentation commonly takes on the form of a paper or software HCI prototypes. An initial low fidelity TTWCS Task Manager (task-based HCI) was presented side-by-side with the previous function-based TTWCS v5 prototype to 10 current Advanced Tomahawk Weapon Control System (ATWCS, Tomahawk system prior to TTWCS) operators. Each operator subjectively predicted the task-based Task Manager would provide better performance and provided suggested improvements for the Task Manager interface. This series of formative usability tasks provided the justification for the prime contractor integrate the Task Manager into current TTWCS prototype for more objective analysis. An independent usability test was conducted by Brooks (2003, in press) to produce objective data comparing the function and task-based versions of HCI navigation for TTWCS. It should be noted that while objective measures were collected, this test was performed as another usability test vice an experimental study. Thus, the small sample size limits the ability to draw statistically significant conclusions. A summary of the Brooks study and results are presented here.

Nineteen participants from the United States Navy force (9 surface force and 10 submarine force) and two participants from the United Kingdom Royal Nave force participated in the usability test. Surface, submarine, and UK participants were each tested separately (i.e, there were 3 rounds of testing). The participants were all current Advanced Tomahawk Weapon Control System ATWCS trained operators with little if any TTWCS experience. Participants ranged from Tomahawk operators to supervisors. The usability test compared the TTWCS v5 function-based prototype with the proposed TTWCS Task Manager task-based prototype. The two designs were evaluated on cognitive workload requirements, task navigation times, and participant subjective feedback. The presentation of the two versions were balanced to avoid a learning effect. The participant was trained on one version, completed the scenario using that version, and then completed the questionnaire evaluating that version. The participant then repeated the process using the remaining prototype.

Cognitive Workload

Cognitive workload was evaluated through a secondary task measure. The primary task was to complete a scenario containing a series of Tomahawk Strikes. The secondary task was to read a digital time off a card and then determine if the hands of the clock would make an acute or obtuse angle and state this to the test administrator. Participants were asked to perform this secondary task whenever they had an opportunity during the scenario. Being able to perform more secondary tasks correctly would provide an indication of increased residual cognitive workload.

The results show that participants were able to perform more secondary tasks with the Task Manager prototype than with the function-based prototype. On average, participants were able to complete approximately 60 more secondary tasks with the task manager, almost doubling the performance compared to the function-based prototype. This increased residual in cognitive workload indicates operators will have more left over resources to take on additional strikes and/or the new TTWCS missile monitoring tasks not evaluated in this study.

Task Navigation

Motor workload was evaluated by the time required to complete the three primary stages of the Tomahawk Strike process: plan creation, missile selection, and execution review and approval. The time required to perform each of the major phases was reduced using the Task Manager prototype. In the planning phases the time was reduced on average by approximately 10 seconds, approximately one minute in the missile selection phase, and approximately three minutes in the execution phase. Combined, this results in a reduction in task navigation times across the entire mission from approximately 15 minutes to 11 minutes.

Subjective Feedback
Subjective Questionnaires were used to evaluate feedback regarding the importance, value, and quality of the Task Manager design enhancements. The system designs were rated on factors such as ease of use, learnability, confidence, managing tasks, engagement planning, launching weapons, post launch and use of color. User satisfaction ratings were reported as significantly higher for the new task-based HCI compared to the function-based version across each dimension of the rating scale.

Fleet Operability Test
A separate study evaluated 10 individual ATWCS operators in their ability to perform a high workload, real-world set of simultaneous Tomahawk taskings. This was evaluated inside a 90-minute scenario using an HCI with Levels 1-3 (as defined in this paper) of supervisory control support. This same scenario would today be manned by a team of 4 operators, and would be performed over a period of hours to avoid the workload of simultaneous taskings. Operators were evaluated on their ability to execute launches on time, their ability to answer situational awareness probes, and subjective workload ratings. The 10 participants collectively performed over 99% of their launches on time with low to average workload ratings through the scenario. For more details on this evaluation the reader is referred to Williams (2004) in the proceedings of this conference.

Conclusions
Results across multiple usability tests appear promising in support of improved performance with reduced workload, but larger data samples are required for better statistical analysis. Across multiple tests, users appear to favor the new Task Management HCI features in the performance of mission duties. Current ATWCS trainers evaluated further predict dramatic reduction in training times compared with the current HCI training requirements. Cognitive workload reduction allows possible team re-sizing and restructure supporting increased mission loads and reduced mission timelines. Further usability study is planned to continue to improve and evaluate MCD HCI features and to introduce these improvement into future TTWCS versions.

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From Legacy C2 Systems to Mission-Centered Design:
Tactical Tomahawk Weapon Control System

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CCRTS June 2004

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  - PMA-282 Tactical Tomahawk Weapon Control System (TTWCS)
  - IWS3C Naval Guns

Mission-Centered Design Distinctions

- Like UCD, MCD is an iterative process of Analysis, Design, Implementation, Deployment
- Focuses on mission products
  - Less focus on user characteristics or responsibilities
  - Focus on tasks as a by-product of the products
- Early and frequent user involvement throughout the process

Why TTWCS Needed MCD

- Crew Size Reduction
- Workload Reduction
- Training Reduction
- Better and more consistent performance
- Increasing mission requirements
- Increasing system complexity and functionality

Some MCD Design Axioms

1. *Focus on mission products to bound the task analysis.*
2. *Focus on task goals and products, NOT on current methods.*
3. *Do NOT allow task allocation to impact task analysis.*
4. *Explicitly represent the mission process within the interface.*
5. *Allow for variable levels of automation.*
6. *Avoid function based decomposition and analysis.*

Mission Products Bound the Task Analysis

- Analyze down to the level of tasks having products.
- What is a product?
  - Something of value to a customer with little or no additional work required from the producer.
  - Product should be tangible.
    - Intangible products lead back to a functional based design

Example TTWCS Products

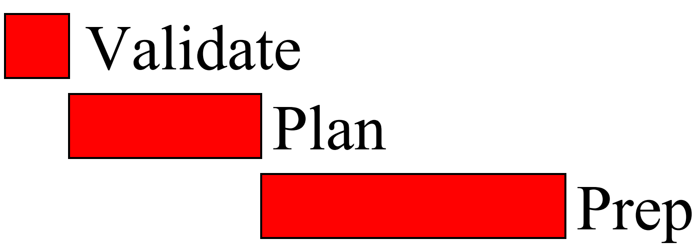
- Validation Report
- Strike Coordination Overlay
- Line Item Reports
- Post-Launch Report
- Missile Message
- Post-Strike Report

Focus on Goals Not on Current Methods

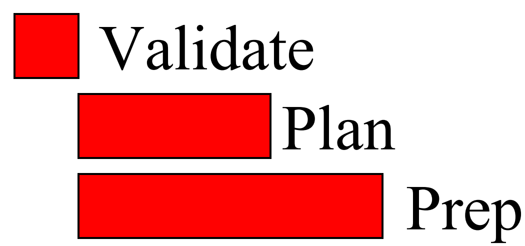
- Current method normally a by-product of previous constraints
- Want revolutionary not evolutionary improvements
  - Normative - how it was designed
  - Descriptive - how it is used
  - Formative - how it should be designed and used
- Must find ways to develop alternatives or you get stuck in local maximums

Example - Prep Missiles First

- Prepping of missiles is on the critical path.
- Historically waited until planning was completed to prepare missiles.
- Recommending once the strike is validated that missiles are prepped while planning is being done.



Serial



Parallel

Goal Explicit Interface

- Tasks
- Processes
- Products
- Responsibilities
- Automation
  - Domain Consistency
  - Reliability
  - Time Availability

SPAWAR UCD Team

User-Centered Design

Goals, Tasks, & Steps

Task Manager > TLAM Taskings 08:05:29Z 1

Ship Readiness	Battlespace SA	Conduct IS&R	Prepare Taskings	TLAM Taskings	Gun Taskings	Rehearse Taskings
0/0	0/0	0/0	0/0	1/4	0/0	0/0

ESP Taskings	Priority	Validate Engmnts	Plan Routes	Allocate Missiles	Power Missiles	Execute Engmnts	Monitor Missiles	Tasker	Engmnts	Missiles	Comment	TOL
Powering Exec 0007B	High	Validated 3 / 3	Planned 3 / 3	Allocated 5 / 5	Powering 5			TSC	3	5 - 3C	None	-00:15:31
Planning Exec 0008A	High	Validated 3 / 3	Planning 3	Allocated 5 / 5				TSC	3	2 - 3C 3 - 4E	None	-00:21:15
Validate Exec 0009A	High	Validate 1 / 1	Planning 1	Allocating 1				SLT 1	1	1 - 4E	None	-00:16:31
MDU Plan 0010A	High	MDU 1 / 1						TSC	1	1 - 3C	None	---

Allow for Variable Task Allocation and Levels of Automation

- Users will decide how to employ automation.
- Users will decide how to allocate tasks.
- If you do not support this they will find a work around (increasing workload) or your system will be seen as inflexible and will meet resistance.
- Everyone has an opinion on organization, don’t get wrapped up arguing about this instead of analyzing tasks.
- Automation availability and reliability will continue to change beyond your control.
- Important to show the current automation settings and allocations, especially if dynamic.

Automation Level Coding

Task Manager > TLAM Taskings 08:05:29Z 1

Ship Readiness	Battlespace SA	Conduct IS&R	Prepare Taskings	TLAM Taskings	Gun Taskings	Rehearse Taskings
0/0	0/0	0/0	0/0	1/4	0/0	0/0

ESP Taskings	Priority	Validate Engmnts	Plan Routes	Allocate Missiles	Power Missiles	Execute Engmnts	Monitor Missiles	Tasker	Engmnts	Missiles	Comment	TOL
Powering Exec 0007B	High	Validated 3 / 3	Planned 3 / 3	Allocated 5 / 5	Powering 5			TSC	3	5 - 3C	None	-00:15:31
Planning Exec 0008A	High	Validated 3 / 3	Planning 3	Allocated 5 / 5				TSC	3	2 - 3C 3 - 4E	None	-00:21:15
Validate Exec 0009A	High	Validate 1 / 1	Planning 1	Allocating 1				SLT 1	1	1 - 4E	None	-00:16:31
MDU Plan 0010A	High	MDU 1 / 1						TSC	1	1 - 3C	None	---

Mission vs. Function Based Design

- *Functional Design breaks the task procedure down into the engineers mental model -- HCI = SW Architecture*
- *Mission-Centered Design presents the goals and intent in the user's mental model -- HCI = Goals & Products*

VCR Example - *Decide to record a specific program*

Function Oriented	Task Oriented
Press "Menu"	*Select "Record football game"*
Tab down 3	*See Today's Options*
Press "timer set REC lock"	*Select Desired Date*
Tab down 2	*See Options*
Select "Enter program"	*Select Desired Game*
Move cursor to start time	
Press "Enter key" etc....	

TTWCS HCI Design Evolutions

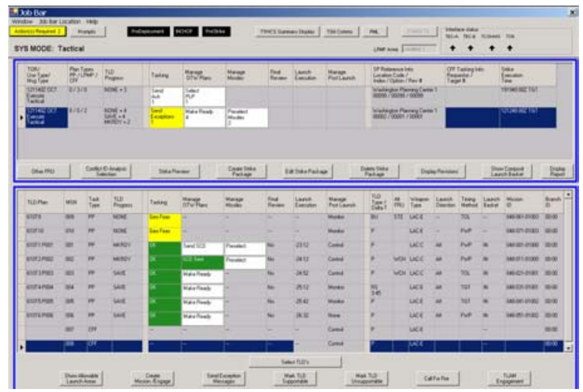
Current

Menu (function based)

Window System Chart Views Comms Support Misc Help

V5 2006

Task (goal based)



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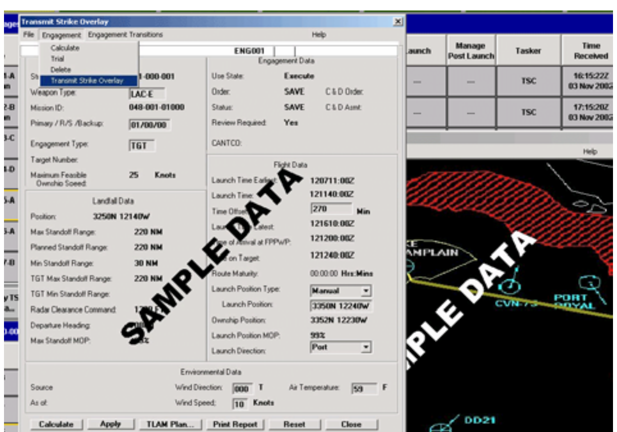
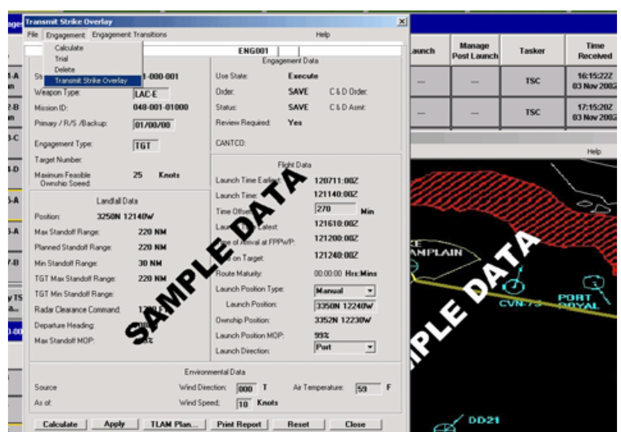
Task (goal based)

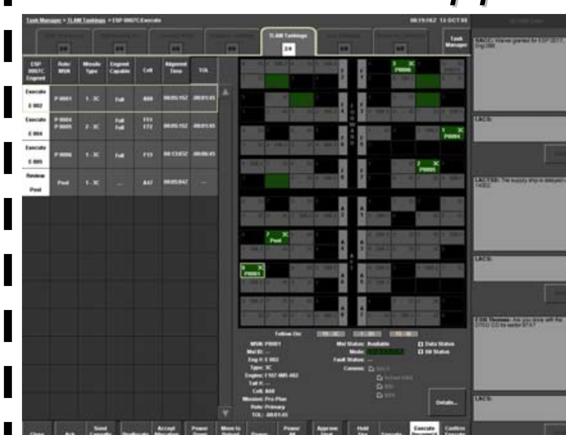
Data-driven windows



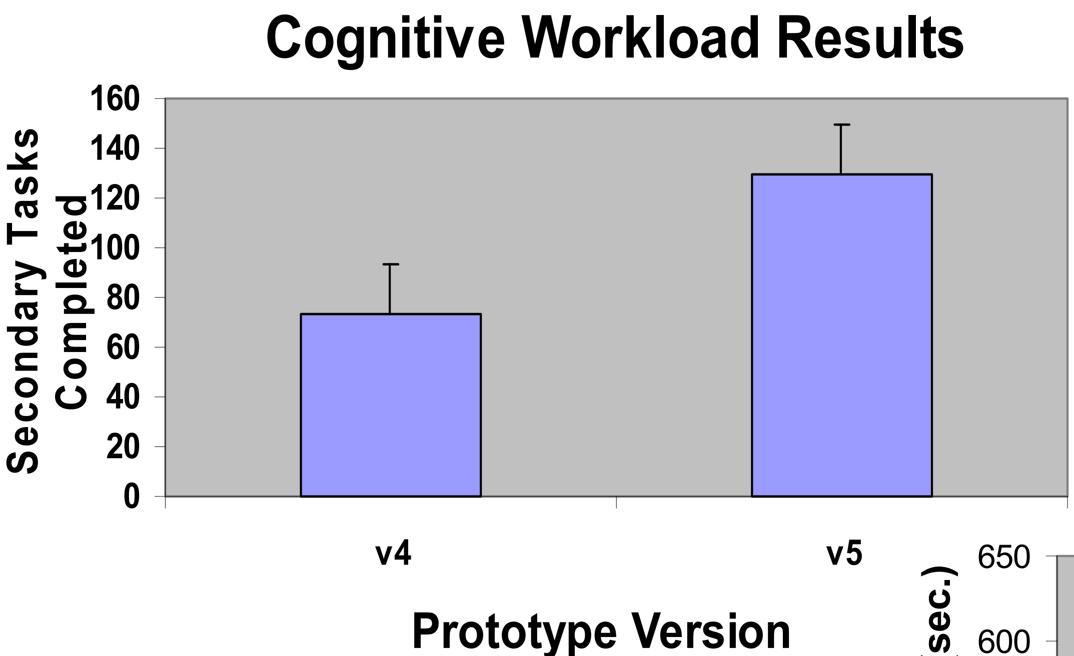
Data-driven windows

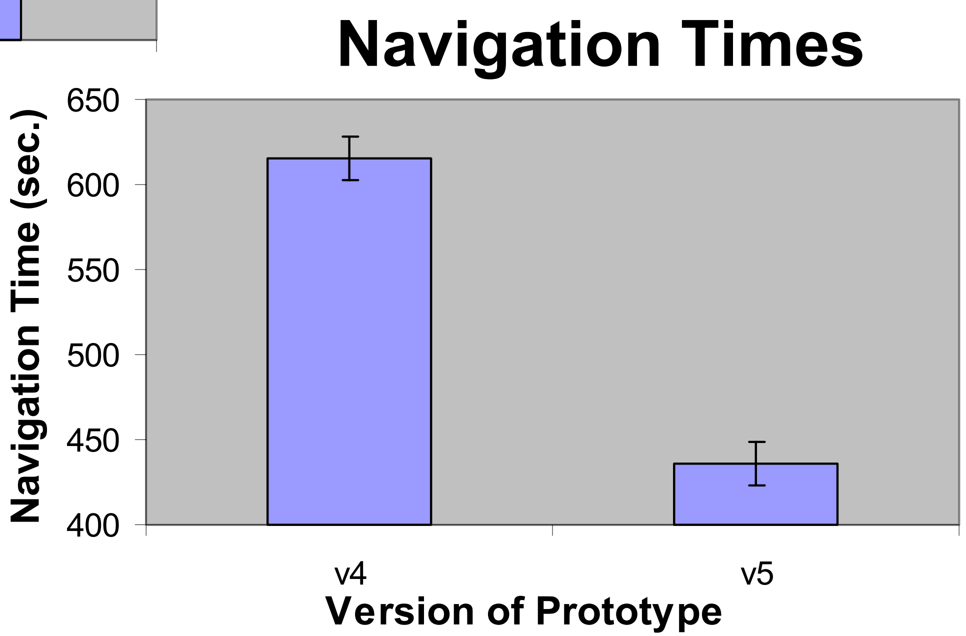


Task Decision-support



Lockheed-Martin Usability Testing





Fleet Operability Test

- Performance
  - HCI supported a single operator performing a complex scenario with accurate, timely performance of tasks and reporting
    - 99.0% on time launches (309/312)
    - Still room to improve on alerting during simultaneous task processing
- Situation Awareness
  - Performed better on higher level SA questions
    - Often anticipated upcoming events
    - Least effective in locating requested information
- Workload
  - Participant ratings indicated manageable workload across the scenario
    - Ratings were correlated with SME-rated taskload, indicating an understanding of the situation

Land Attack Combat System FNC Team

- Government Labs
  - SPAWAR Systems Center - San Diego, CA
  - NAVSEA - Dahlgren, VA
  - NAVAIR - Orlando, FL
  - Naval Submarine & Medical Research Lab, Groton, CT
- Industry & Federally Funded Labs
  - Johns Hopkins Applied Physics Laboratory, MD
  - Pacific Science & Engineering Group Inc., CA
  - Southeastern Computing Consultants Inc., VA
  - Lockheed Martin Advanced Technology Labs, NJ
  - Lockheed Martin Mission Data Systems, PA
- Universities
  - University of Virginia
  - University of Michigan

Advanced Technology Laboratories