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The Future of C2

An agile, user-centric approach to combat system concept design

Track: HUMAN FACTORS ENGINEERING

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ABSTRACT

Purpose of this paper is defining a framework for the "Warfighter-Centered Design" (WCD) of new concepts for naval combat systems. This framework explicitly takes into account the business value of WCD with respect to safety, optimal manning and reduced lifecycle costs. WCD improves safety because lack-of usability can lead to serious consequences; the analysis of the accident of USS Vincennes clearly shows that the combat system exhibited serious usability problems both in estimating the altitude trend of an air track and in the IFF identification. WCD holds also a significant economic value because it reduces the lifecycle costs related to ship manning and training and allows optimal solutions to the evolution to asymmetric and littoral warfare. Warfighter-Centered Design is not a methodology or a set of techniques, but an integrated approach to product concept design that focuses explicitly on the needs and limitations of the warfighter. It is based on user involvement, iterative prototyping and user-based assessment and it can focus on the different levels of the Command Information Centre organization and consoles.

INTRODUCTION

The concern of designing usable systems has quite a long history and it can be traced back to the early seventies. This issue has been addressed first by specifying guidelines [1] and general rules to follow in system design. However, this strategy can be hardly defined as effective: human-computer dialogue principles [2] are few and too generalist and the validity of specific design guidelines [3] is limited to narrow sets of application domains. A decade later the main contribution of applied psychology to the field was the predictive models of human-computer interaction behaviour [4]. However, the validity of predictive models (ex. GOMS, TAG) is limited to expert, error-free performance. While psychology has given an important contribute in understanding the capabilities and limitations of fundamental human functions such as cognition, memory [5], perception [6] and attention [7], modern computer systems pose a bigger challenge: the cooperative work and decision making in networked organizations. The increasing importance of the whole usage context in a number of domains has led to the development of different sets of methods for the engineering of usable systems. They can all be defined as "user-centered". First definition of User Centered Design appears in the work of Donald Norman [8] as an iterative process based on the understanding of the context of use and employment of user-based evaluation. Human factors engineering [9], usability engineering [10], scenario based design [11] and contextual design [12] all belong to the user-centric family; user-centered design is part of Human Factors contribution to system engineering. For our domain, naval combat systems, we will call it from now on "Warfighter-centered" design (WCD).

THE USABILITY OF NAVAL COMBAT SYSTEMS

Usability is one of the architectural qualities of a combat system, among maintainability, safety, adaptability, reliability, scalability, etc [13]. It is currently defined (Figure 1) as "quality in use"[14]: "*the extent to which a product can be used by specified users to achieve specified goals with safety, effectiveness, efficiency, satisfaction in a specified context of use*". Two important issues are addressed by this definition:

1. Usability can be measured: its metrics are derived from its sub-concepts of **safety**, **effectiveness**, **efficiency** and **satisfaction**.
2. Usability can be defined only for certain users, tasks and environments. These three factors are commonly defined as the **context of use** of the system**.**

Usability is therefore directly related to the context in which it is used. The characteristics of the operational context (the combination of warfighters, operational tasks and external/system environment) play a fundamental role in establishing the degree of utility and usability of the

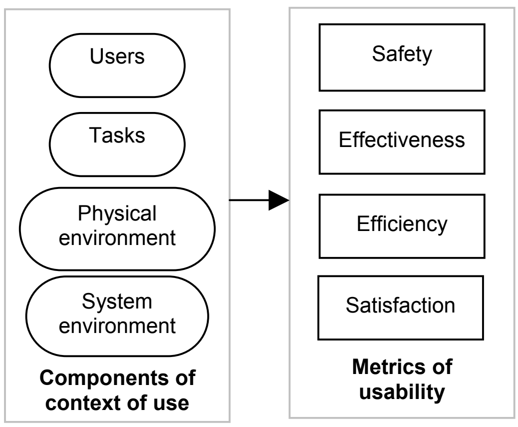

Figure 1. **Quality in use**

combat system. The product must fit to the purpose it has been designed, for both to experienced and novice/infrequent warfighters, periodic and episodic tasks, ordinary and unexpected events and so on.
For example, in designing the man-machine interaction of combat systems, great attention should be addressed in preventing sources of safety-critical errors, which often relate to infrequent tasks, yet critical for crew survival or mission accomplishment. Consequences of bad system design can be really hard and they will be showed with the help of the accident case of the "*USS Vincennes*".

ANATOMY OF AN ACCIDENT: VINCENNES, 1988

On July 3, 1988, the US cruiser "CG-49 Vincennes" is patrolling the Strait of Hormuz, in order to protect merchant ships, together with "FFG-14 Sides". Their tactical data grids are connected through the Link 11 network.
At 7:20 am. Captain Will Rogers of Vincennes launches a helicopter with the order to fly north and report on the Iranian gunboat activity; One hour and half later the helicopter reports traces of enemy anti-aircraft fire from the gunboats. At this point Cpt. Rogers decides to establish an engagement with the enemy vessels and at 8:52 he sets full speed. About one hour later, the Iranian gunboats are under the fire of the US cruiser.
At the same time (9:47) an Airbus airliner, Flight 655, takes-off at Bandar Abbas runway (Iran). Its course unfortunately heads straight to Vincennes that is in the middle of a surface engagement. Flight 655 is wrongly classified as 'military' through the IFF on board of Vincennes and Roger announces that he will shoot if the target comes closer to 20 miles. Vincennes tries to communicate with the aircraft on the emergency frequency, but without success. Two minutes later (9:56), the track appears to descend and two SM-2 are fired against the aircraft. The crew immediately realizes the mistake from the size of the cloud of debris, but it is too late. What happened? Who's the responsibility if 290 people die because of an error?

Human and system responsibility

Immediately after the tragedy, both USA and Iranian authorities blame each other for the responsibility of the accident. Captain Robert Hattan, the commanding officer of the nearby frigate Sides, claims that [15] Rogers was overly aggressive and this created the unfavourable situation that led to the tragedy. Rogers' ship had been nicknamed "Robocruiser" for its attitude, which was evidenced that morning as it opened fire on gunboats that had allegedly fired at or near the Vincennes' helicopter. By creating such a charged and confusing atmosphere, some argue, Rogers made it much more difficult to accurately determine whether Flight 655 posed a genuine risk to the Vincennes or not. However, as Admiral Vern Clark, the then-Commander of the Joint Chiefs of Staff states at the US Congress [16]: "the U.S. rules of engagement strongly emphasize that each commanding officer's first commitment is to the safety of his ship and crew. Ships' captains are expected to make forehanded judgments, and if they genuinely believe they are under threat, to act aggressively".

One thing is certain: Captain Rogers has been given bad information about the radar contact. All of his decisions were made in the Combat Information Center (CIC): he had to rely on the data provided by his officers to make the final choice, and the data was wrong. Not only he was told that the craft was descending (and not ascending, as it actually was) but he was also told that the craft's Identification, Friend or Foe (or IFF) reading was Mode II (military) and not Mode III (civilian, as it actually was). Two inexperienced member of his crew relied too much in the system and provided the wrong data to the CO [17]. On the frigate *Sides*, Hattan believed *his* data (clearly showing Flight 655 IFF mode III) to be incorrect because on the Vincennes *they* simply couldn't be wrong [18].

Why did sailors of both platforms rely so heavily on the Vincennes' combat system? Because when released, this system was the top-end for anti-air warfare purpose: it was designed, as was most of the 1980s Navy, for a massive "blue" (or open) water battle with the Soviet Navy; as such, it can track hundreds of missiles and airplanes. However, this complexity came into conflict with the quality in use of the system. In particular, two features of the combat system caused the accident: visualization of altitude of tracks and the IFF function.

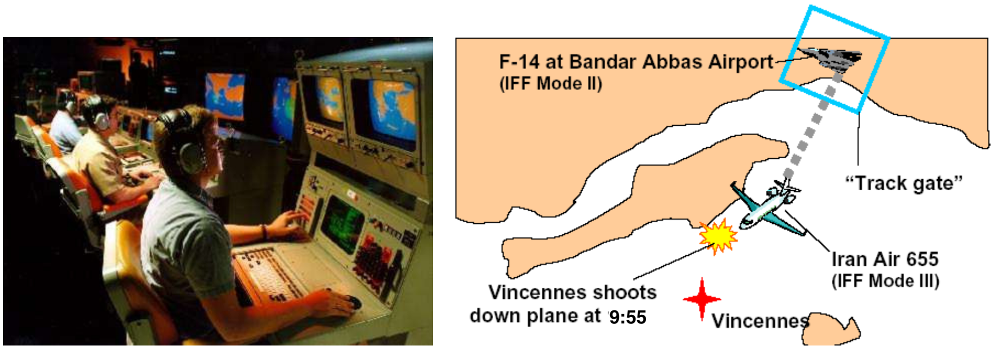

Figure 2. (a, on the left). The Vincennes' CIC. Note the three large 42 x 42" displays and the smaller 12" display below. (b, on the right) Diagram that shows the IFF tracking gate position that caused the error [19].

Altitude

One engineer working on the Aegis combat display system recognized the complexity of the information it provided—specifically, the confusing way to read altitude [20]. Although three large displays show every contact, "to get speed, range, and altitude," the operator must explicitly punch up that information, which is subsequently displayed on a tiny 12-inch monitor (figure 2,a, the lower part of the console). Most importantly, this display does not include the track's altitude rate of change, forcing the operator to compare data taken at different times and make the calculation in his head, on scratch pads, or on a calculator—maybe during an engagement. Unfortunately, the design issue raised up that engineer was not taken into consideration by his management. Had that display been added, the *Vincennes*' over-excited Tactical Information Officer might have seen the correct trend of Flight 655 altitude and the disaster could have been avoided.

IFF

The second error - reporting an IFF Mode II (military) rather than the correct III (civilian) - can be similarly explained through bad system usability. While the radar operator was examining the oncoming contact (Flight 655) with his trackball cursor, the IFF displayed its reading from the last "tracking gate" location. This "gate" is essentially a box that the ship's radar monitors for various signals (such as IFF); if it isn't explicitly moved, it stays in place. Thus, while the civilian Airbus plane was correctly emitting an IFF Mode III signal, the radar picked up the IFF Mode II signals from an F-14's still at the Bandar Abbas Airport (figure 2, b). Had the system been better designed so as to either facilitate moving the tracking gate, or to give a warning should one select a contact outside of the tracking gate, the disaster likewise might have been avoided.

BUSINESS VALUE OF THE WARFIGHTER-CENTERED APPROACH

Improved safety and reliability

The Vincennes case study brings strong evidence of the importance of combat system usability for safety and reliability purpose.

Safety and reliability is mainly addressed by the Safety Analysis discipline [21]. The objective of the system safety discipline is to achieve a minimal level of risk within the constraints of operational effectiveness, time and cost. Main contribution of this discipline is defining a modelling and analysis process by which the risk deriving from the usage of complex systems can be elicited and quantified. Human can be outside or inside of the scope of the analysis, with some limitations [22]. The first limitation regards how much we can predict the sources of human error in the combined breakdown of causes (FTA) or consequences (FMEA of Event Tree). The second limitation is estimating the hazard probability: it is only possible for typical warfighters' tasks and workload. Third, analytical techniques cannot say how to reduce the risk related to human error.

The Warfighter Centered Design and the Safety Analysis discipline share similar concerns in reducing the risk and they are therefore complementary: Safety analysis provides the means to model and prioritise the hazards coming from human-machine interaction, while WCD provides the design approach for reducing the degree of risk related to the human-machine hazards with the highest priority.

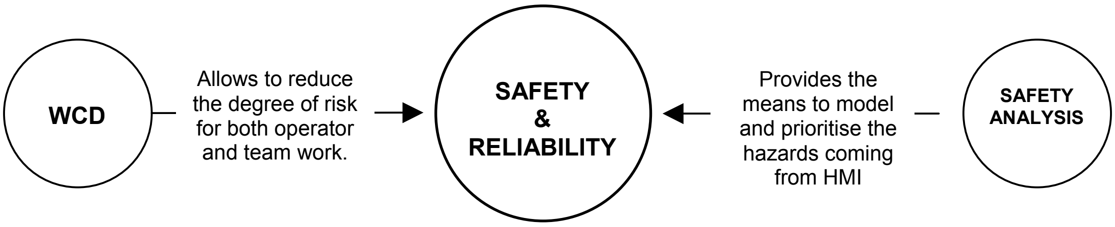

Figure 3. Interaction of WCD and safety analysis in achieving system safety and reliability

Optimised manning

Navies worldwide face today the challenge represented by these three operational trends:

(1) *From* blue water – *to* → littoral (brown water) scenarios.
(2) *From* symmetric – *to* → asymmetric (ex. terrorism, piracy) warfare.
(3) *From* combined – *to* → joint- and coalition-based operations.

At the same time they face cuts in the programs budget and the need to reduce manning on the ships. All of this requires a major change not only at the system level (combat and shipwide), but also in the organization of the CIC and the job specification of each of its components.

The ICE program [23,24] shows that it is possible with a WCD approach to completely redesign the concepts for the room layout, the team composition and job specification in order to bring the number of people from 22 to 10 while retaining and also improving ship combat capabilities.

Life-cycle cost reduction

Reduced manning, together with cross-training, is one of the top priorities of the navies after the end of the cold war, which determined a drastic need to reduce the global lifecycle costs. Reduced manning is a complex issue, involving an evolution both at the organizational, doctrinal and technological level. Through the warfighter-centered approach we can redesign the CIC room addressing all of those levels. For example, assuming that a CIC room has a crew of about 22 people, reducing it to 10 can save 700.000 € per year and 170.000 € for the initial training. For the whole lifecycle, the global saving amounts to about 15 millions of euros.

- Reduced manning:

$V_{reduced\ manning} = (n_1 - n_2) \times \textit{yearly personnel cost} \times \textit{number of years} = (22 - 10) \times 50.000 \times 25 =$ 15.000.000 € for the whole system lifecycle, given:

n_1=22 team members in the CIC room;
n_2=10 team members in the redesigned CIC room;
an average personnel costs of 50.000 € per year for each team component
and an average life cycle of 25 years.

- Reduced training:

$V_{reduced\ training} = ((n_1 \times weeks\ of\ tr._1) - (n_2 \times weeks\ of\ tr._2)) \times\ cost\ of\ training =$

$= ((24 \times 6) - (10 \times 3)) \times\ 4200 = 176.400$ €, given:

Weeks of tr_1 = average time spent in training with the former system
Weeks of tr_2 = average time spent in training with the new system
Cost of training = total cost in € of one week of training for each crewmember.

A FRAMEWORK FOR THE WARFIGHTER-CENTRED APPROACH

We showed in the introduction how guidelines or human performance modelling are not sufficient in the achievement of usability. The optimal strategy is applying a warfighter-centered design approach that takes into account the strengths and limitations of humans and machines in a specific operational context.
Our framework defines the business value of the warfighter-centered design for naval combat systems in achieving improved safety and reliability, optimal manning and reduced global life cycle costs. In the conclusive part we will detail the principles, the key activities of warfighter-centered design and how it can focus at different levels of the CIC and console design (Figure 4).

Warfighter-Centered design is therefore not a methodology or a set of techniques: it is an integrated approach to naval combat system development that focuses especially on making systems usable and safe. It is a multi-disciplinary activity that requires iteration of design solutions and evaluation; its integration to interactive systems design enhances effectiveness and efficiency and counteracts possible adverse effects of use on human safety and performance.

The warfighter-centered approach is especially suited to designing and validating new concepts and solutions. The demonstrators and prototypes developed can be used as to verify the goodness of requirements, which are later transferred to product development.

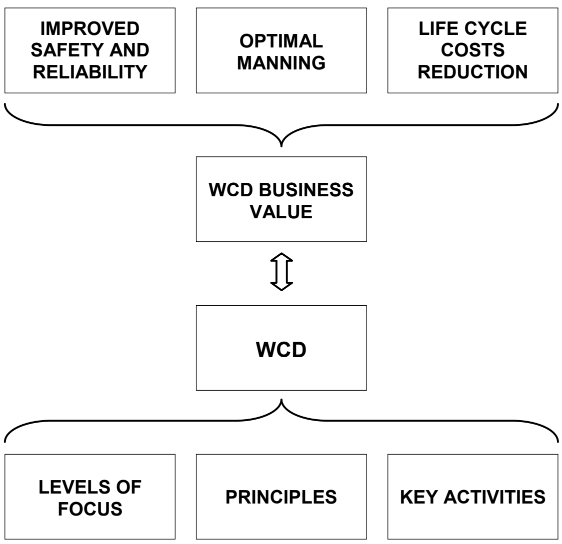

Figure 4. Framework for Warfighter-Centered Design

WCD focus levels.
The Warfighter-Centered approach can be applied at different aspects of the CIC crew/room and consoles (figure 5). Methodologies and techniques are chosen depending on those aspects of the system and context of use that are taken into account:

- **Team composition** is defined through the analysis of current organization and the parallel evolution of doctrine and automation. Descriptive and formative models support this task [25] that must be carried out together with users and operational experts.
- **CIC room layout** is consequently defined in order to accommodate the chosen CIC operational roles within the space. Verbal and visual communication must be taken into account.
- **Shared room displays** must be designed in order to provide the right amount and quality of information when needed. Their position in the space must be related to the CIC consoles layout.
- **Task allocation** is defined based on task characteristics respect to human/system capabilities and limitations.
- **Decision support tools** must be designed for supporting human tasks and reduce the human workload.
- **Console ergonomics** characteristics of input and output devices must be chosen considering the nature and frequency of the tasks.
- **Training/simulation concepts** must be designed in order to provide support for decision making and training with the CIC. Simulations of operational scenarios address the training need of the crew in coping with infrequent and unexpected events.

Table 1. Different aspects of CIC/Console design levels

CIC level	Console level
Team composition	Task allocation
CIC room layout	Decision support tools
Shared room displays	Console ergonomics
Training/simulation concepts	

It is not compulsory to address all of these aspects at the same time. For example, specific

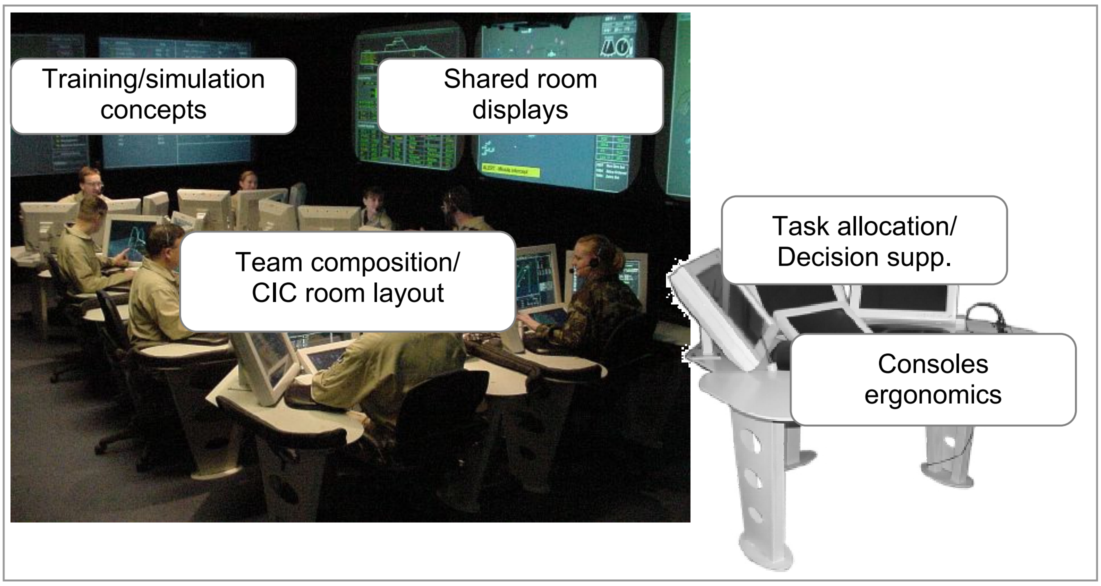

Figure 5. Different aspects of CIC and Console design [24]

business needs or budget constraints can restrict our focus at the console or at the CIC level. However, it is possible to start focusing at the console level and migrate later to a full-scale Warfighter-Centered design approach.

Principles and key activities of warfighter-centered design

Warfighter-Centered design is defined by four principles and key activities [26]:

Table 2. WCD principles and key activities for naval combat systems

WCD Principles		WCD key activities
1	Allocation of function	1) Identification of critical tasks
2	User involvement	2) Specify task requirements
3	Iteration	3) Design prototypes
4	Multi-disciplinary teams	4) Evaluate designs

(I) An appropriate allocation of function between operators and systems. This division of labour involves the appreciation of human capabilities and limitations, as well as a thorough grasp of the particular demands of the task. Factors like reliability, speed, accuracy, flexibility of the answer, cost and safeness should be carefully individuated.

(II) The active involvement of users. The optimal strategy is utilising warfighters who have recent insight into the operational context of naval combat systems. In concept system development the extent of user involvement comprises two high level activities: elicitation and analysis of user knowledge of task and environment and user-based evaluation of the demonstrators. This is the most critical issue for the combat system domain, since obtaining real, well trained users can hardly be defined as an easy task. Nevertheless, a close cooperation with the navies is an increasing trend in product design and an acceptable level of user involvement can be achieved.

(III) Iteration of design solutions. The purpose of prototyping is not just experimenting architectural solution like in RUP [27], but entailing the feedback of end-users within the iteration process. The warfighters accomplish operational tasks using the prototype in a usability lab; the feedback from this validation is used to further evolve the requirements for the design solution.

(IV) Integrated, multi-disciplinary design team. The user-centered approach to combat system concept design is a collaborative process that benefits from the active involvement of the various stakeholders, each of whom has both insights and expertise to share and needs to fulfil. The design team must include at least:

- Warfighter (his presence is mandatory),
- Navy officer,
- Human factor expert,
- Training and support expert,
- Software/system engineers.

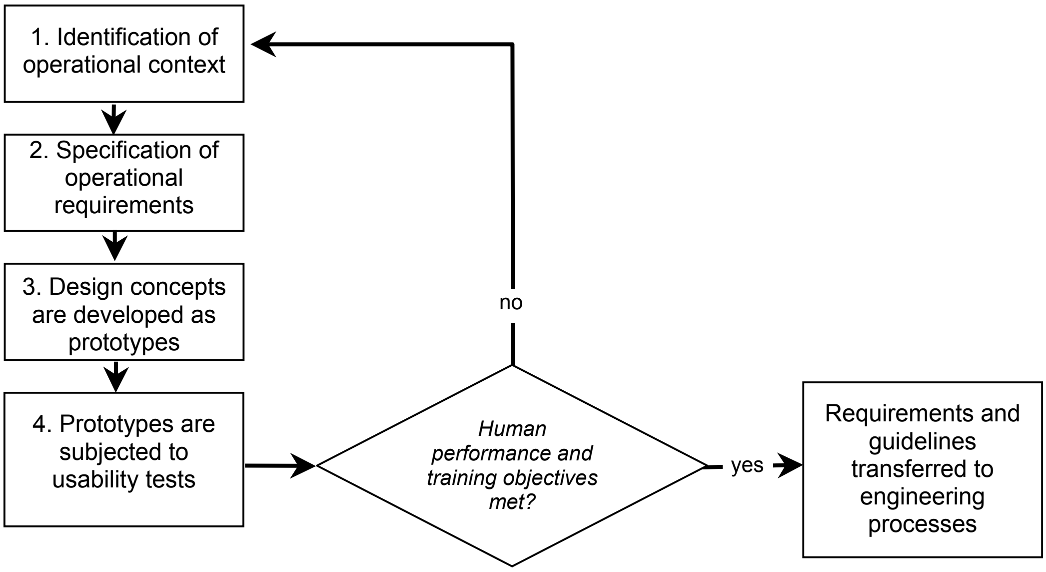

Figure 6. WCD key activities

The WCD key activities for concept design are (figure 6):

1. Identification of the operational context of critical tasks. Critical tasks are identified for the proposed system respect to users, task characteristics and environmental constraints: tasks are carried out by users with a specific profile (ex. different degrees of previous experience, operational training, physical limitations), with specified goals, procedures and frequency, under specified environmental constraints. This knowledge must be extracted from doctrine and warfighter experience.

2. Specification of operational requirements. Operational and usage scenarios are defined. Job functions are allocated to systems and warfighters and a new task structure is specified. Use cases and other product requirements are defined. Human performance and training objectives are stated in order to provide measurable criteria for assessment.

3. Design concepts are developed as prototypes. Prototypes are developed according to the operational requirements. Prototypes can have different degrees of fidelity realism, spanning from a paper prototype to a working computer prototype.

4. Prototypes are subjected to usability tests. Warfighters carry out simulated operational tasks with the system prototypes and the human performance/training objectives are measured in order to evaluate the fit-to-purpose of the design concept.

When the design solution is judged to be enough fit-to-purpose, the requirements and the product development guidelines are transferred to the system/software engineering processes related to product development.

DISCUSSION

While in commercial sectors like computer manufacturing, telecommunications and software engineering the iterative, multidisciplinary, user-centered approaches have gained more and more foothold, the military sector currently presents a different situation. The relevance of involving users within a multidisciplinary design has been often ignored and this issue applies especially in the naval domain. We lack business cases as in aerospace, which has been already taking into account the integration of human factor for 50 years. Pilots have been for years more exposed to safety and usability issues than sailors. However, things are changing:

the evolution of the context of warfare involves faster response times and higher uncertainty in recognition and identification tasks. This issue raises the need of a warfighter-centered approach in designing naval combat systems. However, a strong difference emerges between the new and the old continent; human factors research in USA is mainly driven by major research programs targeted at developing and evolving requirements later transferred to the USN fleet; as a European firm, we confront with human factors engineering 'below the line', on a daily basis, within the product development process for a wide range of customers, mainly medium and small sized navies. This difference of business context makes the adoption of a large scale approach to human factors engineering improbable if not unnecessary; our approach is participative, facilitating the active customer involvement and short prototyping-evaluation iterative cycles.

This design process is consistent with the evolution of the tendering process from the "us-versus- them" paradigm (focused on formal requirements acceptation) to integrated procurement and project teams. An integrated project team is also a suitable frame for establishing a multidisciplinary effort consistent with the outlined WCD principles.

CONCLUSIONS

We defined a framework for the Warfighter-Centered design of new concepts of naval combat systems. We explicitly included in this framework its business value with respect to safety, optimal manning and reduced life-cycle cost; usability issues can seriously compromise the safety of a combat system, as the description and the analysis of the accident of USS Vincennes clearly showed. Moreover, the warfighter-centered approach holds a significant economic value for the navies, because it reduces the lifecycle cost related to ship manning and training and it allows an optimal manning with respect to the changing nature of naval warfare and operational scenarios. Littoral and asymmetrical operational context require an organizational, doctrinal and technological evolutionary leap through an integrated approach to product concept design focusing explicitly on the needs and limitation of the warfighter. This approach is based on user involvement, iterative prototyping and user-based assessment, focusing at the different levels of the CIC organization and consoles.

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