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Development of an Integrated Human Factors Toolkit

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ABSTRACT

An effective integration of human abilities and limitations is crucial to the success of all NASA missions. The Integrated Human Factors Toolkit facilitates this integration by assisting system designers and analysts to select the human factors tools that are most appropriate for the needs of each project. The HF Toolkit contains information about a broad variety of human factors tools addressing human requirements in the physical, information processing, and human reliability domains. Analysis of each tool includes consideration of the most appropriate design stage, the amount of expertise in human factors that is required, the amount of experience with the tool and the target job tasks that are needed, and other factors that are critical for successful use of the tool. The benefits of the Toolkit include improved safety, reliability and effectiveness of NASA systems throughout the agency. This report outlines the initial stages of development for the Integrated Human Factors Toolkit.

DEVELOPMENT OF AN INTEGRATED HUMAN FACTORS TOOLKIT

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1. INTRODUCTION

Human Factors is the discipline devoted to optimizing the integration of human abilities and limitations into systems design to achieve safe, reliable, and effective performance. All of these objectives are critical for NASA to achieve its mission. Human factors is thus an integral part of the design and development process of NASA systems. However, in order to achieve successful integration of human factors considerations, they must be integrated throughout the design process. Systems engineers who do not have expertise in human factors must recognize when human factors is needed, how it should be applied, and when specialized expertise in human factors must be recruited.

This report describes the initial stages of development of an Integrated Human Factors Toolkit (IHFT). The IHFT is proposed as a utility to assist systems engineers in the identification of human factors needs in a project, the selection of the most appropriate human factors tool, and the implementation of that tool. Optimal tool selection depends on the:

- requirements of the system under development,
- current stage of system completion,
- resources available, and
- expertise of the project team.

Once a tool is selected, the toolkit also provides advice on how the tool can be implemented to maximize its effectiveness. By facilitating the integration of human factors needs into the project and improving tool use, the IHFT can improve the safety, reliability and effectiveness of the resulting system designs. It also can reduce the amount of time required to implement human factors, thus improving the productivity of the design process.

2. HUMAN REQUIREMENTS

Human performance can be divided into several components, including physical performance, information processing, and human reliability. Physical performance refers to the safety and speed at which physical tasks can be completed. Safety is important for several reasons. Severe injury removes employees from the workforce despite investments in training and experience throughout their years of service [1]. Injury can result from a single case of overexertion [2] or an accumulation of musculoskeletal damage from repeated movements [3]. The development of injury depends on a complicated interaction of multiple workplace, physical, and organizational factors that must be considered in detail to minimize the risk of injury [4]. Models of physical human capabilities have been created and combined with toolkits for biomechanical evaluation to create systems that can predict capabilities such as reach, fit, fatigue, and injury risk [5].

Speed is also critical. Not only does speed have a direct effect on productivity, but it can also have more insidious effects on safety and reliability. Fatigue increases the likelihood of injury [1], in part because of an increased probability of using incorrect postures and in part because of reduced integrity of fatigued muscles. Fatigue can also reduce coordination, increasing the probability of error in tasks requiring accurate manual control, such as interacting with a console interface.

Information Processing refers to the ability of a system user to perceive all of the information needed to complete job-related tasks, interpret and analyze that information, and make appropriate decisions, all while maintaining an acceptable level of mental workload. There are several computational models that have been developed to predict human information processing performance. The Man Machine Integration Design and Analysis System (MIDAS) was created by a joint US Army - NASA Ames team [6]. MIDAS includes models of basic IP processes such as perception, memory, decision making, motor behavior, routine action, and skill, but does not include higher-level processes such as problem solving, learning, language, motivation, emotion, or imagining. The model can be used to predict performance times and levels of mental workload, as well as evaluating competing design alternatives [7]. MIDAS has been validated in many situations such as air traffic control with encouraging results [8]. There are also several commercially available modeling systems, such as the MicroSaint family from Micro Analysis and Design.

Some of the landmark techniques in Human Reliability Assessment (HRA) are described by Kirwan [9]. HRA can be decomposed into several consecutive stages. First, the tasks required to complete a job successfully must be analyzed in sufficient detail to accomplish the project goals. This level of detail depends on the stage of system development and the focus of the analysis. Once the tasks are analyzed, possible errors must be identified, represented, assessed, quantified, and reduced. Techniques for achieving each of these stages have been developed. Many of these are based on a framework developed by Rasmussen [10], which divides human behaviors into three types:

- skill-based: automatic behavior based on well-learned procedures requiring little attention for activation,
- rule-based: procedural behavior that can be followed based on a deterministic set of rules, and
- knowledge-based: event-specific behavior that depends on context and involves problem solving processes.

3. COMPILATION OF THE TOOL LIST

It is essential that a general use Human Factors Toolkit contain all of the tools that should be considered for use by engineers and designers across NASA. This includes both those tools that best satisfy the expected needs of the engineers and designers to efficiently and effectively conduct their analyses as well as those that are preferred because of previous use and training. In order to insure that the tool compilation meets these needs, a comprehensive search for human factors tools from a variety of domains was conducted. Several domains were considered, including a variety of Department of Defense (DOD) collections, academic sources, literature review, surveys of current NASA employees and contractors, and personal communications (see Table 3-1). Several sources provided analysis of the tools in their inventories, either conducted by the tool developer or by independent observers.

3.1 Sources

DoD – The Department of Defense maintains an evolving compilation of human factors tools through the Defense Technical Information Center (DTIC). Originally developed by the Human Factors Engineering Technical Advisory Group in 1994, it continues to be updated as new tools are identified. Tool reviews include basic information on appropriate uses, hardware requirements, processing procedures, output formats, contact information, and validation references.

ONR – The Office of Naval Research Science and Technology Office established a Manning Affordability Initiative to prepare for expected reductions in manpower for naval systems. By encouraging the integration of human factors into the systems engineering process, they hoped to accommodate the reduced manpower without a corresponding reduction in system effectiveness. The tool analyses include descriptions of the tool capabilities, expertise requirements, hardware specifications, and constraints. There are also descriptions of how each tool fits within the Systems Engineering process and suggestions for how each tool complements and is complemented by other human factors and systems engineering tools.

Eurocontrol: Eurocontrol is a European organization dedicated to the safety of air navigation throughout that continent. As part of its mission, it has created a human factors group to investigate human factors issues in future air traffic management systems development (HIFA). HIFA has created an interactive program to assist in the selection of human factors tools throughout the systems engineering design process for managers, designers and human factors practitioners. Brief descriptions and contact information are presented for each tool.

NASA: The National Aeronautics and Space Administration Office of Safety and Mission Assurance has compiled a preliminary list of tools used by human factors practitioners throughout the agency. Tools are added to the list by practitioners, along with references and links to more information from other sources. No analysis of each tool is provided. Additional NASA tools were identified through surveys at Kennedy Space Center of NASA employees and contractors from Boeing, Lockheed, and United Space Alliance.

NAV AIR: The Office of the Navy AIR Training Systems Division maintains a comprehensive list of publications authored by its researchers. Many of these publications describe the use of human factors tools in the areas of decision making and team training.

DISA: The Defense Information Systems Agency manages the Human Systems Information Analysis Center (HSIAC). In addition to providing services, HSIAC also maintains a gateway to resources on human factors methods, tools, and techniques.

FAA: The Federal Aviation Administration Technical Center contains links to many resources used by the FAA to integrate human factors into the design process of air traffic management systems and cockpits. There is considerable overlap between the needs of the FAA and NASA and the tools described in many of the FAA documents are useful sources for the NASA toolkit.

Compendex*Plus: A general search for additional documents was conducted using the digital library resources at KSC and at Florida International University. These sources were used to identify additional tools as well as conduct more in depth analysis of the tools that were identified in the previous sources (see section 4 for more information on the tool analysis).

3.2 Human characteristics addressed by HF Tools

As the tools were compiled, they were differentiated according to the human characteristic(s) that each one addressed. Six major categories were identified. Each major category was further divided into subcategories to isolate the specific target of the tool. Table 3-2 presents the major categories and the subcategories contained within each one.

Table 3-1. SOURCES REVIEWED FOR HUMAN FACTORS TOOLS

Source	Description	Reference
DoD	Compilation of human factors tools by the DoD - Human Factors Engineering Technical Advisory Group (HFE TAG)	http://dtica.dtic.mil/ddsm/
ONR	Compilation of human factors tools by the Office of Naval Research Science and Technology - Manning Affordability Initiative (ONR S&T MAI)	http://www.manningaffordability.com/S&tweb/Index_hse.htm
Eurocontrol	Compilation of human factors tools by Eurocontrol - Human Factors Integration in Future ATM Systems	http://www.eurocontrol.int/eatmp/hifa/index.html
NASA	Compilation of human factors tools by NASA Headquarters - Office of Safety and Mission Assurance	http://humanreliability-pbma-kms.intranets.com
NAV AIR	Publications from the Office of the Navy AIR - Training Systems Division	http://www.ntsc.navy.mil/
DISA	Tools and resources from the Defense Information Systems Agency - Human Systems Information Analysis Center	http://iac.dtic.mil/hsiac/
FAA	Information resources from the FAA Technical Center	http://www.tc.faa.gov
Compendex*Plus	Library database of scholarly engineering publications	http://www.ei.org/eicorp/eicorp

Physical: Tools that address physical requirements and limitations were divided into five categories: overexertion injury, repetitive trauma, fatigue, reach/fit, and toolkits. Overexertion injury refers to a musculoskeletal injury that is sustained as a result of an exertion that exceeds the capacity of the individual. These tools rely on biomechanical models of the musculoskeletal system to determine at what level of exertion users are likely to be injured. Some calculate a risk score indicating an estimate of the injury risk. Others present the quantitative values calculated by the model and rely on the analyst to interpret the data.

Repetitive trauma refers to musculoskeletal injuries that result from the cumulative effects of many small exertions. These tools consider the major risk factors that have been linked to repetitive trauma injuries and assist the analyst in quantifying the degree of risk inherent in a system design. Some of these tools calculate cumulative risk scores that combine the risks identified from each risk factor. Others are checklists that simply highlight the risk factors that are present. Some of these tools provide recommendations based on the results to reduce the risk of repetitive trauma injury.

Fatigue can affect system performance in two ways. Fatigued workers work slower and with reduced quality. This can reduce the efficiency or effectiveness of the system. Fatigue can also increase the likelihood of a user experiencing an injury due to overexertion or motor control error. Tools that address fatigue try to identify fatigue that results from either metabolic energy expenditure or lack of sleep. They can provide a risk score or present the metabolic levels and require the analyst to interpret them.

Reach and fit tools address the anthropometric characteristics of the human components of the system, the physical dimensions of the system layout, and the requirements of the human-system interaction. In general, reach/fit tools evaluate CAD layouts of the system, adding manikin representations of human users using a distribution of population dimensions to insure that any movement requirements are feasible given the physical requirements of the tasks. These tools can include evaluation of cones of vision, collision detection, analysis of clothing requirements for extreme environments, and other considerations.

Toolkits provide a variety of analysis methods, generally assembled from the general literature but with a consistent interface and the ability to share data. The consistency allows multiple analyses to be conducted without repeated data entry and allow analysts to learn a single interface model.

Information Processing: Tools that address information processing were divided into four categories: perception, situation awareness, decision making and mental workload. Perception tools evaluate the ability of the human user to perceive the physical characteristics of the system. Multiple modalities can be addressed, but generally include visibility, audibility, and tactility. Some tools also consider perception between team members for the purpose of coordinating activities and command & control.

Situation awareness (SA) tools evaluate the accuracy of the user's mental model of the important characteristics of the current state of the system and his or her ability to project that model into the future. There are a wide variety of situation awareness tool types. Query insertion tools ask the user relevant questions at periodic intervals to determine how aware of the important characteristics he or she is. Other tools use subjective scales, requiring users to use introspection to rate their awareness of the situation on a variety of dimensions. Some attempt to determine the SA using physiological characteristics. If a critical cue is displayed, responses such as event-related potential can be measured directly to determine if the cue was noticed. Performance-based tools correlate certain aspects of performance with SA. Finally, observer ratings have subject matter experts (SMEs) observe the user's performance and measure the SA based on the appearance of specific behaviors.

Decision making (DM) tools are used to investigate the details of the decision making process applied by users to identify modifications to the system, additional training, or decision support systems that can be applied to improve system performance. In general, a detailed interview must be conducted to identify the cognitive processes that lead to target behaviors.

Mental workload refers to the amount of a user's mental capacity that is occupied during system operation. These tools resemble SA tools in that they can use subjective scales, physiological measures, performance-based measures, or cognitive models. Mental workload tools have been customized to a variety of situations and there is a wide variety of tools available.

Human Reliability and Error: Because of the extreme consequences that can result from human errors, there is a great need to measure human reliability and predict the types and probabilities of errors that may occur. Tools for evaluating human reliability address one or more stages of the analysis process listed in Table 3-2. In order to analyze human reliability, it is useful to analyze the tasks, identify all possible errors that can occur, analyze the consequences of the errors, and predict the likelihood that each error may occur. Error analysis tools can use cognitive models, operator interviews, incident reports, and/or statistical techniques. Some human reliability tools also assist the analyst in identifying ways to reduce the likelihood or magnitude of errors that occur. Usability tools are specifically designed to evaluate error types and probabilities in human-machine interfaces.

Manpower, Personnel, and Training: Manpower, personnel, and training (MPT) tools are used to determine the number of people required to achieve satisfactory performance from a system, what kinds of people are required in terms of skill sets, abilities and authority, and what training would improve system performance or reduce manpower requirements.

Static Resources: There are many handbooks, guidelines, and standards that have been created within the Department of Defense and in general industry to address human factors requirements. Resources were obtained from US DoD, US federal agencies, European organizations, NASA, and private organizations.

Comprehensive Modeling Tools: Comprehensive models attempt to describe all of human behavior. They can be used to predict actual behavior, test theoretical hypotheses, and model populations. For the toolkit, models that attempt to predict actual behavior were considered. Task network models do not explain why behaviors occur, but predict the times that activities require and probabilities of successful mission completion. Cognitive architecture models begin with first principles of human cognition and thus do attempt to explain the mechanisms of behavior. They can predict what behaviors are likely to occur and can be matched with task networks to predict time and reliability as well. Digital human models create simulations of physical aspects of humans to predict the most likely movements and paths taken by humans to accomplish tasks and can be linked with biomechanical models to predict injury risk.

Table 3-2. MAJOR CATEGORIES OF HUMAN CHARACTERISTICS TARGETED BY
HF TOOLS AND THE SUBCATEGORIES IDENTIFIED WITHIN EACH

Physical	Information Processing	Human Reliability and Error	Manpower, Personnel, and Training	Static Resources	Comprehensive Modeling Tools
overexertion injury	perception	task analysis	manpower	handbooks	task network models
repetitive trauma	situation awareness	error identification	personnel	standards	cognitive architecture models
fatigue	decision making	error analysis	training	guidelines	digital human models
reach/fit	mental workload	error quantification			
toolkits		usability evaluation			

4. TOOL ANALYSIS

As each tool was identified, a detailed analysis was conducted to determine how it could be applied most effectively within the systems engineering process at NASA. Several factors were determined to be critical components as to whether a particular tool could be applied to a particular design effort.

4.1 Expertise

The expertise required to use the tool is an essential consideration. Tools differed significantly in the amount of knowledge of human factors fundamentals that is necessary to use them effectively. For example, modeling a task using a cognitive architecture model is impossible without considerable

expertise in cognitive engineering. On the other side of the spectrum, using a repetitive trauma checklist to evaluate a computer workstation can be accomplished with virtually no knowledge of human factors. Each tool falls along a continuum between these two extremes. Performance-based mental workload tools are easy to implement without human factors expertise, but selecting a performance measure requires a familiarity with the components of mental workload and the types of tasks that draw from each mental resource. Systems engineers should not select tools that require more human factors expertise than is available on the design team.

Another type of expertise that must be considered when selecting a tool involves use of the tool itself. Some tools can be used effectively after a short perusal of the manual. These tools have intuitive interfaces and/or simple processes. Subjective mental workload scales, risk-scoring repeated trauma tools, and many human error tools require little tool expertise. When selecting an unfamiliar tool, it is necessary to select one that does not require past experience to use effectively. Some vendors recommend training classes that can last up to 2 weeks. Projects operating within time constraints may not be able to take advantage of these tools.

A third type of expertise is the familiarity with the requirements of the job being analyzed or designed. In some cases, the analyst can effectively use a tool while observing the end user perform the job without really understanding what is happening. Many of the physical tools fall into this category. However, others require intimate familiarity with how and why each step of the job is performed. Analysts who do not have access to experienced end users and are unfamiliar with the job under study must select a tool that can be implemented without such knowledge.

For each of these types of expertise, the toolkit should provide some insight into how much is needed in order to accomplish the goals for which the tool is intended. In many cases, it depends on details of the project that do not generalize to all uses of a tool. However, the toolkit can provide guidance that helps an analyst determine if he/she has sufficient expertise in order to effectively use the tool for its intended purpose.

4.2 Stage of Development

Tools are generally developed for application at a particular stage of system development. Six phases of human factors application have been integrated into the NASA Systems Lifecycle Stages (see Figure 4-1). While gathering user requirements, tools can assist designers to understand what the needs of the system are, how previous versions have failed to meet expectations, and to identify potential constraints. Tools that address this phase cannot require analysis of specific design components.

During conceptual design, tools can help designers compare alternative design approaches, interaction metaphors, high level architectures, and physical layout schemes. Physical tools that predict injury based only on general task requirments can be implemented here. Mental workload tools that estimate workload based on models of task dynamics and do not require SME interaction can also be useful.

During detailed design, much of the interpersonal communications, interface designs, and workstation layouts are largely determined. Tools that evaluate display legibility, fault trees, and repetitive trauma checklists can be useful here. Tools that use high fidelity simulations to identify design constraints and bottlenecks can be implemented to significantly reduce the costs of redesign once physical mockups are completed.

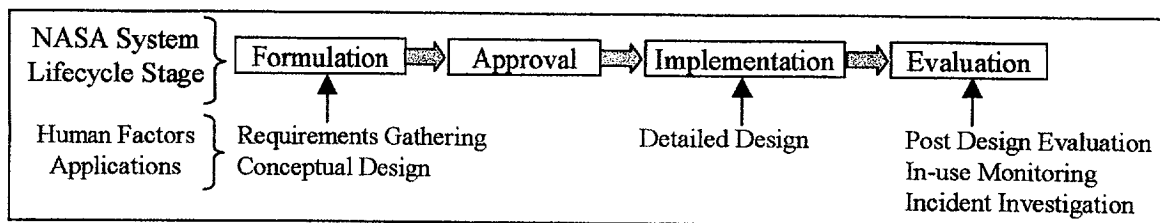| NASA System Lifecycle Stage | Formulation ⇒ Approval ⇒ Implementation ⇒ Evaluation |
| Human Factors Applications | Requirements Gathering Conceptual Design ... Detailed Design ... Post Design Evaluation In-use Monitoring Incident Investigation |

Figure 4-1. INTEGRATION OF HUMAN FACTORS INTO THE NASA SYSTEM LIFECYCLE

After the design is completed and a physical system has been constructed, tools that involve analyzing user performance directly can be used to identify deficiencies before the system is launched. Performance-based workload measures, situation awareness tools, statistical error quantification tools and video-based physical tools are most effective to evaluate completed designs.

Some tools are designed to monitor systems over time during use. At this phase, it is critical that tools are not intrusive so they do not impair user performance. This is critical both because it would invalidate the results and because it could sacrifice the effectiveness of the system during the evaluation. Instantaneous subjective workload scales, continuous safety sampling, and ergonomic workstation checklists are intended for in-use monitoring.

Several tools, particularly those that determine the cause of human errors, are designed to be used during incident investigation. Examples include root cause analysis and cognitive task analysis. During the investigation process, access to users who were involved in the incident is usually required.

4.3 Resources

Selection of an appropriate tool must also consider the resources required to obtain sufficient accuracy and precision in the results. The most basic resource is cost. Tools that are owned by the federal government or are available at no cost should be selected over a tool with similar capability that costs tens of thousands of dollars. The range of tool prices varies considerably. The toolkit lists prices for fixed price tools and facilitates the request for quotes for tools that are flexibly priced.

Time is often a more constrained resource than money. Tools vary in the amount of time required to complete various types of analyses. Often the time requirements are proportional to the scope of the analysis. For example, fault trees that address every aspect and component of a design take considerably longer than an identical fault tree focused on just a partial set of components. However, the toolkit can provide general insight into the time requirements for analysis at various levels and provide comparisons among tools that provide similar analysis.

4.4 Access

The toolkit can also facilitate access to the tool and tool-related support materials. Links to tool vendor contact information, web sites, and training registration can facilitate getting started once a tool has been selected. Links to independent validation studies and tool analyses such as can be found at the ONR Manning Affordability Initiative web site can be very helpful during tool selection. Contact information for experienced users at NASA can help in the selection process as well as during use of the tool.

5. CONCLUSIONS

In order for NASA to design systems that successfully consider human capabilities, it is essential that human factors is integrated into the systems engineering process. The inclusion of human factors can be greatly improved through a utility that assists systems engineers in the selection and application of human factors tools. The IHFT is an effort to provide this assistance. The toolkit allows systems engineers to retrieve a set of human factors tools, along with advice on implementation of each tool. The selection criteria and advice are customized for the project, including its stage of development, resources available, and the expertise of the design team. Use of the IHFT will improve the safety, reliability and performance of systems throughout NASA.

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