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Optimizing Biology Research Tasks in Space Using Human Performance Modeling and Virtual Reality Simulation Systems Here on Earth

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ABSTRACT

A new method, combining virtual environment simulation technologies with unique human performance modeling software is being used to design, test and evaluate procedures for future biology experiments aboard the International Space Station (ISS). The Man Machine Integration Design and Analysis System (MIDAS) simulates human performance through seven underlying architectural components. The models interact producing results such as astronaut work load and experiment success rates given environmental inputs and timing constraints. Graphical models of biology research equipment and samples are provided by the Virtual Glovebox (VGX), a state-of-the-art simulation system mimicking the real Space Station systems. Human-in-the-loop experiment simulation using the VGX also enables validation of human-environment interactions predicted by MIDAS. This combination of human-in-the-loop (VGX) and human-out-of-the-loop (MIDAS) simulation presents a novel and extensible method for developing procedures which are optimized for the unique space environment, equipment and timing constraints faced by astronauts. This research demonstrates optimized procedural specifications predicted by the MIDAS software.

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INTRODUCTION

The era of the International Space Station (ISS) has finally arrived, providing researchers on Earth a unique opportunity to study long-term effects of weightlessness and the space environment on structures, materials and living systems. Many biological experiments planned for ISS will require significant input and expertise from astronauts who must conduct the experiments, follow complicated assay procedures and collect biological samples. The Life Sciences Glovebox Facility (LSG), a contained reach-in environment, will be used to shield astronauts from vapors, fluids and biological samples and will provide a workspace for experiment-unique equipment.

A significant need exists for quantifiable data to guide the space-experimentation aboard the International Space Station due to the time constraints (and subsequent workload increases) faced by mission specialist performing experiments in space. Human performance modeling, a computational software set of tools under development at NASA Ames Research Center, has been proposed as a cost-effective and safe research method to obtain quantifiable data, identify system vulnerabilities and develop mitigation strategies associated with operator workload, task and procedural timing in advanced aerospace concepts [1]. In addition, virtual reality systems have been used successfully to train skilled operators, including astronauts, in a variety of complex work tasks [2]. To make the most of the limited time available for science research aboard ISS, it is essential to incorporate new tools, such as Virtual Reality (VR) training and human performance modeling, into the procedure development and training regiments. At this time, however, quantitative data do not exist regarding the real benefits of VR training for many types of tasks [3]. Furthermore, human performance modeling of systems, although successful in areas of aeronautics and nuclear power plant operation, has not yet been developed and demonstrated for operator environments such as the ones astronauts face when doing biology research tasks in space [4, 5, 6].

The fundamental hypothesis of this research is that Human Performance Modeling tools combined with virtual environment training systems can significantly reduce astronaut workload and training requirements thereby speeding the time to completion for important research tasks aboard the ISS. Three cooperative methodologies aimed at identifying required tasks and procedures for completing biological research aboard the ISS are combined to accomplish this goal. They are 1) a physical mock-up of the Life Sciences Glovebox Facility (LSG) and its associated equipment, 2) the Space Life Sciences Virtual GloveboX (VGX) and 3) a human performance modeling tool, the Man Machine Integration Design and Analysis System (MIDAS). Used cooperatively, these systems can assist in the creation, testing and optimization of procedures for biology research aboard ISS.

Combining these three disparate systems to create an integrated set of tools for developing, optimizing and testing/training procedures for biology research tasks in space has presented a number of technical, operational and software development hurdles to overcome. In this report, we outline these hurdles and present a novel integrated solution.

BACKGROUND

THE NASA LIFE SCIENCES GLOVEBOX (LSG)

Many of the science research experiments astronauts conduct aboard ISS require a glovebox to contain equipment, tools and materials and to protect astronauts from any type of biological, physical or material hazard involved in the experiment [7, 8]. Astronauts may also use a glovebox to protect sterile biological experiments from contamination. When deployed, the LSG provides the crew with a pull-out workbench for performing biology experiments in space (Figure 1). It is equipped with holding racks and an air-lock attachment for contained specimen transfer. Glove ports on two sides allow up to two operators to work together on experiments inside the box. A suite of experiment-unique equipment and supplies have been developed which take into account the unique microgravity environment in space and the unique constraints

Figure 1. *Engineering model of the Life Sciences Glovebox Facility with air-lock module attached on the side. The LSG is pictured in its deployed position, pulled out from the Space Station Rack.*

imposed on the astronauts both from the environment restrictions and through the glovebox interface [9].

THE NASA VIRTUAL GLOVEBOX (VGX)

The NASA VGX combines elements of aerospace flight simulator technologies with new medical simulation systems to provide a versatile, virtual environment for training astronauts in biology research tasks [2]. A stereoscopic display station projects high resolution images to a screen in front of the operator. The operator reaches under the screen, seeing a virtual representation of his/her hands and the internal environment of the glovebox (Figure 2). The VGX will extend existing Life Sciences research and training

Figure 2: *A Stereoscopoic Display Station uses two digital projectors and polarized optics to provide an ultra-high resolution immersive environment for the VGX of about the same size as the working space of the Life Sciencs Glovebox Facility. An operator reaches under the projected screen to see a virtual representation of his/her hands and the inside of the glovebox.*

activities within familiar virtual environment systems to include tasks that require fine eye-hand coordination.

Today, astronauts prepare for life science experiments through a series of training videos, visits with scientists and practice experiments using Earth-based mock-ups and real biological specimens. The opportunities for these full-scale mock experiments are rare and, due to the heavy work loads astronauts face when preparing for their missions, it may be weeks or months between their last practice experiment and the actual procedure performed in space. Developing crew training requirements for specific payloads is a significant challenge and making training efficient is essential to provide focus on safety and research objectives [10]. The need to incorporate new virtual reality technologies into astronaut training for life science experiments is clear. Technologies like the VGX will build on the current training schedules of astronauts and promise to reduce required training time, streamline the process and also reduce the number of live specimens required for preparatory experiments.

HUMAN-IN-THE-LOOP METHODOLOGY (HITL)

Various research tools exist to study human performance with complex systems ranging from objective and quantifiable methods to subjective and qualitative assessment. The objective research methodologies that currently exist to study human-system performance extend from Human-in-the-Loop (HITL) methods such as high fidelity simulations to lower fidelity simulations with humans still performing behaviors "in the loop". A recent HITL methodology is the environment as represented by the VGX. The use of HITL simulation has been proposed as a methodology for examining human-system performance in a safe and controlled environment in many research communities including military, surface transportation, and aviation communities [11]. This technique has proven to be successful in accomplishing the goal of safely and realistically evaluating human-system behavior but has the disadvantage of being very complex and costly, often times prohibiting its use.

HUMAN-OUT-OF-THE-LOOP METHODOLOGY (HOOTL)

A second methodology, human-out-of-the-loop (HOOTL) simulation, is one that utilizes computer models of human performance as the human agent interacts with new technologies and procedures [4]. HOOTL simulation tools are computer-based simulation processes where human characteristics, taken from years of research from respective fields, are embedded within a computer software structure to represent the human operator interacting with computer-generated representations of the human's operating environment [12, 13, 14]. The dynamic, integrated model of human performance enables predictions of emergent behavior based on elementary perception, attention, working memory, long-term memory and decision-making models of human behaviors. This modeling approach focuses on models of human performance that feed-forward and feedback to other constituent models in the human system depending on the context that surrounds the virtual operator [4]. Since the human operator responsible for interacting in these systems is replaced by a computer representation in the actual system evaluation, the risks to the human operator and the costs associated with system experimentation are greatly reduced: no experimenters, no subjects, and no testing time [4]. In addition, the predictions of human performance produced by these models can be generated at an earlier time during the design phase of advancing technologies.

Human Performance Modeling

Human performance modeling is a general term that includes many forms of modeling representations. These representations can take both static and dynamic forms. Static models are theoretical representations and commonly use behavioral information gathering techniques [15], cognitive task analysis [16-18], and work domain analysis techniques [19] to predict operator-environment interactions. Static models also include models of operator characteristics such as visual, cognitive, attentional, situation awareness, or static workload models [20-23]. Some static models also maintain human motion and posture simulation/prediction models [24]. In general, these static models of human performance follow conceptual flow patterns of human tasks may not fully account for environmental variations that could change operator performance.

Dynamic human performance models have attempted to incorporate the operator characteristics of static models with environmental characteristics to produce emergent output characteristics [25]. Dynamic models utilize cognitive task analysis processes in developing an understanding of the cognitive and performance demands required for work activities [26]. The emergent characteristics from dynamic models have traditionally taken the form of workload predictions, situation awareness predictions and procedural and task timelines [4]. One of the more developed dynamic cognitive-behavior modeling tools, the Man-machine Design and Analysis System (MIDAS) operates in this manner.

Man Machine Interaction Design and Analysis System (MIDAS)

MIDAS, a dynamic human performance modeling system, was co-developed by NASA Ames Research Center and the US Army for military related applications. The architecture of MIDAS has made it a good modeling

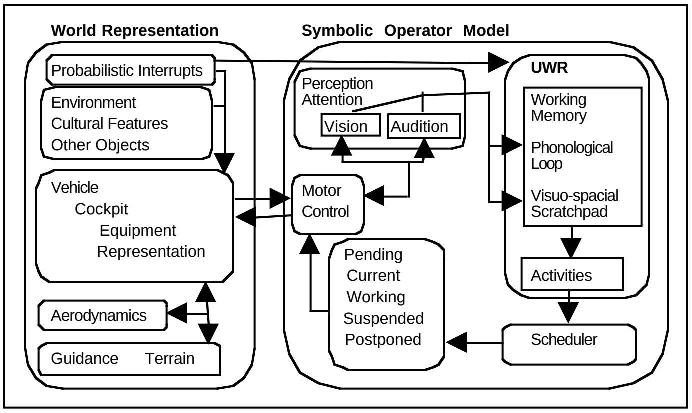

Figure 3*. Flow of the MIDAS software tool. A World Representation incorporates the outside environment, vehicle and physical systems and feeds input into the Symbolic Operator Model. Inputs are processed through the Updateable World Representation (UWR) cognitive models. The UWR processes this information as well as audio and visual sensory input information to schedule tasks. Motor output of the virtual operator feeds back to update the World Representation. The cycle is repeated for the duration of the simulated procedure.*

system for easily incorporating new operational domains (Figure 3). The software simulation is based on "first principles" of human performance [12]. In essence, a simulation of the external environment is combined with a virtual human operator. The activities of the virtual operator are determined by underlying models of human performance: physical, memory representation, attentional control, activity representation, task activity, and decision-making. Together with the results analysis system, these models interact together to produce predicted human behavior that is based on environmental influences [13].

RESULTS: INTEGRATION OF LSG, VGX AND MIDAS FOR TASK OPTIMIZATION

Procedures developed for the National Airspace System (air traffic control and human flight systems) utilize human performance modeling technologies early in the design phase to identify sources of human error and optimize procedures for success. Here, we describe the application of these technologies to develop and optimize experimental procedures that mission specialists will perform in the LSG aboard the Space Station. However, in order to apply these tools, a high-fidelity database integrating procedures and the human/environment interface must exist. The VGX provides the required database and also includes a realistic immersive environment for studies comparing real human performance with predictive models. Real mockups of the LSG hardware and equipment are available to complete the circle and offer full validation of both virtual environment and predictive modeling results. The biological experiments simulated in the VGX are translatable directly into procedures for the LSG; and the predictive modeling of MIDAS is translatable directly to optimize procedures for the LSG. In this way, MIDAS may be used to streamline existing procedures and develop new protocols for biological experiments that will be performed aboard the ISS.

A number of technical accomplishments were required in order to develop MIDAS and the VGX for application to LSG experimental procedures. Further accomplishments were also made in the integration of these systems to create a novel solution to the problem of optimizing procedures for the LSG. The accomplishments are enumerated as follows:

1. *Visualization: a new consideration for difficult to study domains*. A strategy was developed to provide visualization of human performance in a difficult to study domain, the LSG
2. *Model creation for VGX and MIDAS simulation systems.* A method for creating and modifying models of real-world objects from the LSG or from engineering models was developed.
3. *Porting models and environments from VGX to MIDAS methodologies*. A method for translating VGX models and simulations into MIDAS simulations was developed.
4. *Procedural specification and task translation for the VGX and MIDAS*. Real science tasks, identified by procedural specifications, were translated into quantitative programming for the VGX and MIDAS.
5. *Integrated solution and simulation*. Definition of a working prototype was achieved to demonstrate the application of this integrated set of tools.

1. VISUALIZATION: A NEW CONSIDERATION FOR DIFFICULT TO STUDY DOMAINS

Domains that are difficult to study are those that occur in environments not readily available for human experimentation or that utilize very specialized and expert performers. The glovebox domain aboard ISS is one such environment due to its inaccessability and the microgravity environment which can effect human performance. A new approach in the application domain of the human performance model will be its ability to assist in the visualization associated with procedural completion. Visualization has been identified as a critical component for validating the human performance simulation through an examination of the completion of a set series of procedures and tasks [27]. Visualization for Space Station glovebox experiments, also refers to the creation of an accurate rendition of an operator as that person engages in procedural completion in space. Thus, with a MIDAS simulation, a mission specialist will be able to watch the procedural sequence required to complete a given task in the Space Station glovebox. This may provide an enabling strategy for training behaviors in difficult to study domains.

2. MODEL CREATION FOR VGX AND MIDAS SIMULATION SYSTEMS

The VGX software incorporates elements of modeling, simulation and training into an intuitive virtual environment user interface. This methodology requires accurate geometric models of all real-world objects that operators will encounter in the work environment. The MIDAS system, requires the same geometric model database as well as human performance models. As the design and development of the LSG Facility continues, the most up-to-date models of the LSG and associated equipment must be incorporated into both of these simulation systems.

A number of models were created with Computer Aided Design tools and reflect the current state of the LSG design (Figure 4). Engineers also must build experiment-specific equipment and supplies for each space experiment. This may involve modification of off-the-shelf hardware, microscopes for example, or the creation of completely new systems such as the Mass Measuring Device whose counterpart on Earth, the scale, cannot work in the microgravity of space. In every case, this new equipment must translate quickly and seamlessly to the VGX and to MIDAS in order to provide accurate modeling and performance metrics for LSG procedures. A database of virtual tools for LSG

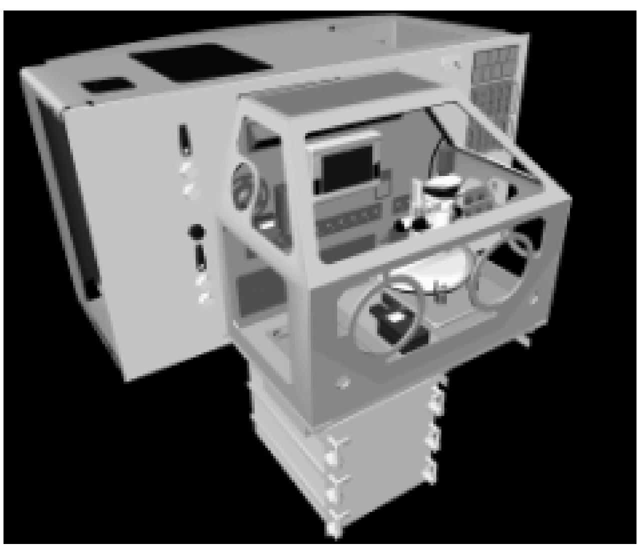

Figure 4: *The VGX model environment with animal habitat module attached below and Space Station mounting rack behind. The 3-D models of equipment are created from hardware design models, photographs or from actual physical equipment and must be simplified to allow for the fast render times required for real-time immersive environment simulation.*

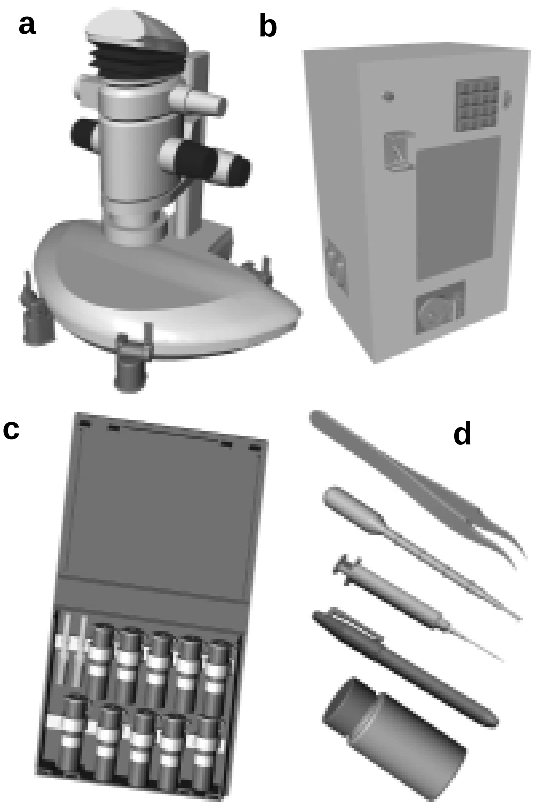

Figure 5: *Models are created from LSG equipment, supplies and experiment-unique tools. Equipment includes items such as the microscope (a) and small-mass-measuring device (b). Tools can be experiment-unique like the plant pollination kit (c) or they can be common lab tools such as vials, pens, tweezers and pipettes (d).*

equipment has been created for the VGX (Figure 5). The ability to add/remove and arrange LSG equipment and tools in a virtual environment allows for fast and easy assessment of optimal equipment configurations and use of the limited space within the LSG.

3. PORTING MODELS AND ENVIRONMENTS FROM VGX TO MIDAS METHODOLOGIES

Currently, both the VGX and MIDAS software systems run on Silicon Graphics workstations and use OpenGL under Open Inventor development libraries for visualization and geometric model representation. This similarity in computer platform and software facilitate portability of models, environments and code modules between software packages. At this time, a set of geometric models and one experimental environment have been ported from the VGX to MIDAS. Further work will address code sharing between these software packages, allowing for parallel simulations of LSG tasks with and without humans in the loop.

An important component of the VGX software, its simulation engine, borrows heavily from physically-based modeling tools and medical simulation tools which are already in use at the National Biocomputation Center at Stanford University [28]. Within this simulation environment, operators can easily manipulate objects within the VGX. Importantly, operators can also observe objects that move realistically (*e.g.* floating, falling and tumbling) in the simulated gravity or microgravity environment. Rigid objects collide with one another and if they are normally connected/disconnected or are hinged (*e.g.* vials with caps, boxes with lids or scissors) then they must interface and move in the same way as their real counterparts.

The MIDAS simulation system incorporates many of the equipment parameters supplied by the VGX simulation software. In addition, basic pick-and-place capabilities for simulated human interaction are required. Once geometric models are ported to MIDAS from the VGX, functional representations must be added. Equipment such as microscopes and video monitors must have discrete state components such as "On/Off" power buttons and indicator lights. Objects in the scene that contain biological samples or tools must have the ability to open, close or be moved within the environment by a virtual human operator. All these object states are programmed into the MIDAS system and specifications are identified from the real objects and equipment in the LSG. With the addition of a human model JACK™, the MIDAS environment and models behave similarly to those in the VGX, thus approximate a real LSG workspace.

All virtual environment simulators intended for training purposes need accurate methods for measuring user performance and for evaluating the quality of skill transfer from virtual task to real-world performance. Due to the many parallels between LSG tasks and surgical tasks, the VGX can use performance and evaluation metrics similar to those employed for surgical simulation [29]. Performance characteristics are also part of the MIDAS output. Porting performance metrics between MIDAS and the VGX creates an integrated system for human performance modeling with MIDAS and validation of those performance metrics with HITL studies using the VGX.

4. PROCEDURAL SPECIFICATION AND TASK TRANSLATION FOR THE VGX AND MIDAS

Accurate training and modeling tools require more than geometrically correct models and behaviors of those models that emulate the real capabilities of equipment. Procedural specifications are necessary which capture the accurate timing, work requirement and related control sequences for complete experimental tasks. For the LSG, procedures are nominally developed through many iterations using real mock-ups of equipment on Earth. Basic research tasks, such as processing biological samples or running experimental equipment, are put together for the LSG from procedures that scientists use in their labs to perform similar Earth-based research. Tasks that are relatively simple on Earth, such as changing food and water in animal containment units, preparing samples for viewing under a microscope or even simply initializing microscope, can become very complex in the microgravity of space in the confined work-space of the LSG. Further translation of these tasks from LSG procedures into VGX or MIDAS procedures requires the addition of workload assessment and timing for those sub-tasks associated with the overall procedure. A microscope-turn-on procedure has been selected as an initial simulation. This procedure has been taken from specifications and timing characteristics for the real equipment and will serve as the baseline for future, more complex, MIDAS/VGX modeling efforts . Success criteria, timing, and sequence/priority of sub-tasks for turning on the microscope and video monitor and preparing a sample for viewing were identified and programmed into the MIDAS system. With this accurate procedural specification, full simulation of the procedure and predicted human performance outputs were made possible.

5. INTEGRATED SOLUTION AND SIMULATION

An initial integrated scenario has been developed that uses MIDAS to simulate a microscope-turn-on procedure in the LSG. Models developed for the VGX were translated from the VGX system to Core MIDAS. Objects required for the procedural simulation included a stereoscopic microscope, video monitor, experiment boxes, vials for biological samples and a digital timer.

The procedural specification required JACK™ to scan the environment, identify objects and follow a realistic microscope turn-on and evaluation procedure. Missions specialist operations manuals indicated that experimenters must complete a pre-defined series of steps to successfully initiate the microscope, the camera, the monitor and initiate the timer to track the performance time of the experimental procedure. These steps were encoded in the MIDAS operational environment.

The output from the procedural simulation in MIDAS is shown in Figure 6. Visual and auditory inputs were measured during the simulation (top two graphs in Figure 6). JACK scanned the environment for 5 seconds to identify its content. A timer went off after 10 seconds providing auditory input to cue the microscope turn-on procedure. Spatial cognitive processing was required for JACK to turn on power, lights, video monitor and camera for the microscope system. Motor output for arm, hand, and head movement are also shown. No verbal cognitive processing was required for this procedure; however,

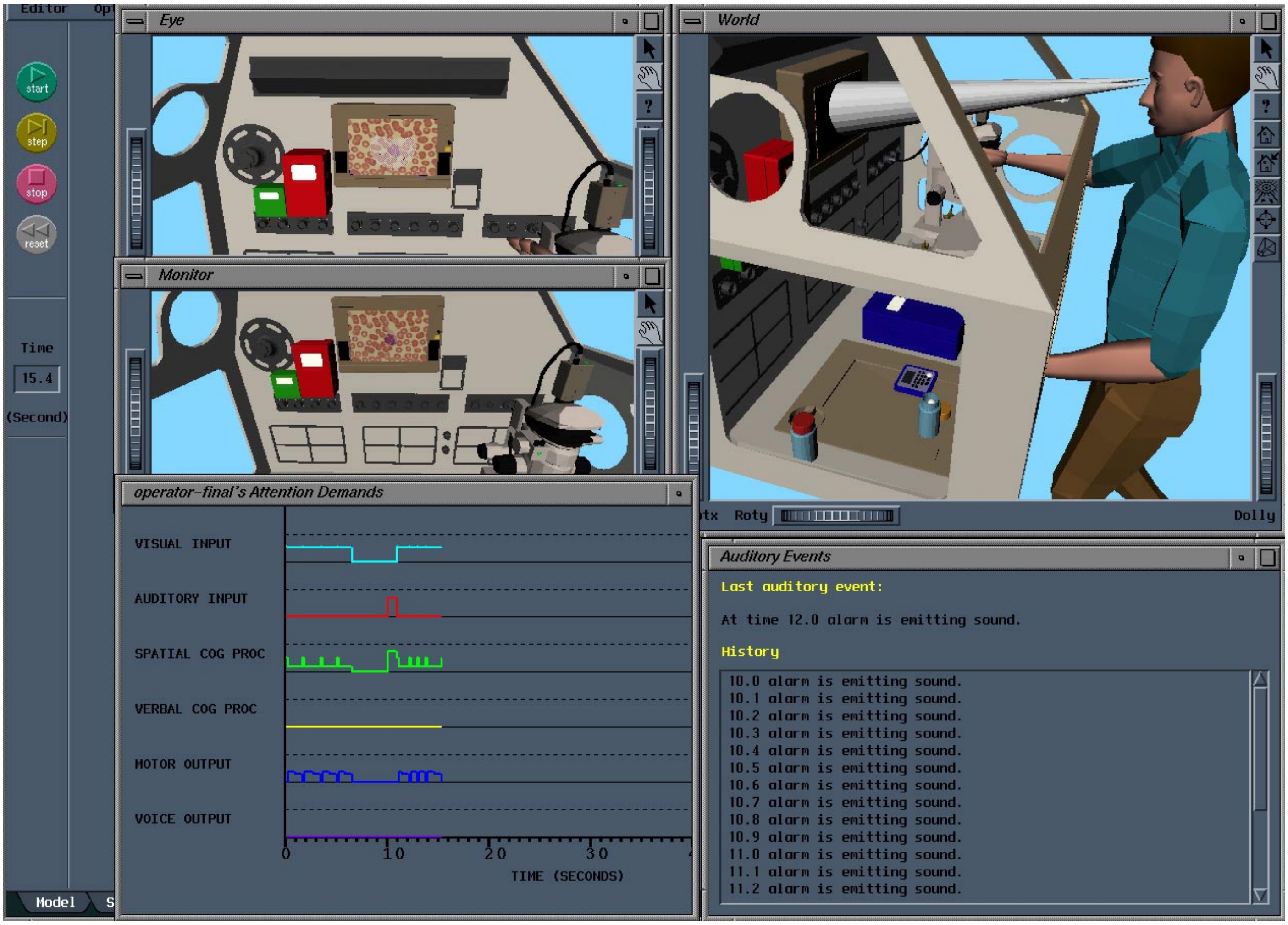

***Figure 6**. The successful integration of the LSG and Core MIDAS envir-onments. This graphic demonstrates the view from JACK's eye (top left), the view of the monitor (middle left), JACK's workload (visual and auditory input, spatial and verbal processing, and motor and voice output), JACK's world view (or VGX in this case) (top right), and the auditory events that occurred during the scenario (bottom right).*

verbal cues will become part of future simulation studies. This scenario demonstrates the compatibility between the VGX and the MIDAS software tools and provides support for further examination of JACK cognitive demand predictions.

This initial scenario demonstrates that HPM simulations can be used at an early stage in the development of a product, system or technological development to identify workload and timing concerns. The initial scenario development process has demonstrated a number of advances. The first is from the HPM standpoint. The initial model that was developed demonstrates that the MIDAS software tool previously used only for aerospace applications in its current form can be applied to novel environments such as the experimental condition engaged in by astronauts aboard the ISS. A number of key issue were identified to augment and refine the initial scenario to increase the realism associated with the performance of the astronaut.

A number of the anticipated refinements include augmenting the realism associated with object interactions, implementing performance modifiers and contour detection, and identifying and implementing sources for accurate system performance. The system model development process allows the designer of the product, system or technology to fully examine many aspects of human-system performance with new technologies. Validation through human-in-the-loop simulations using the VGX and real LSG mock-ups are required prior to accepting the output of any computational model.

CONCLUSIONS

Operator training and expertise, well-defined procedures and tightly controlled timing are critical to the success of any biological experiment. These requirements, coupled with the high workload demands and the high stress placed on mission specialists, greatly reduces the probability of success for biological experiments performed in the LSG unless procedures are developed to maximize operator performance and account for the unique constraints imposed by the space environment. Human performance modeling provides a quantitative method for optimizing procedures, identifying performance vulnerabilities and predicting the success of experiments given a variety of procedures and conditions. This initial study to model human performance with the Core MIDAS system using the VGX environment demonstrates these capabilities and will yield procedures for mission specialists that are optimized for success.

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