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Three-Dimensional Simulation: Microgravity Environments and Applications

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Most, if not all, three-dimensional and virtual reality (VR) software programs are designed for one-*g* gravity applications. For space environment simulations, where gravity is of the order of 10^{-6} *g* or for all practical purposes nonexistent, one must be able to generate simulations that replicate microgravity effects upon simulated astronauts. Unfortunately, the software programs utilized by NASA do not have the ability to readily neutralize the 1-*g* gravity effect. This preprogrammed situation causes the engineer or analysis difficulty during microgravity simulations. Therefore, microgravity simulations require special techniques or additional code in order to apply the power of three-dimensional graphic simulations to space-related applications. This paper discusses the problem and possible solutions to allow microgravity three-dimensional/VR simulations to be completed successfully without program code modifications.

Introduction

THE latest generation of simulation software programs delivers much visual power for design and analysis. In recent years many of these powerful simulation tools have become available on the market to assist and enhance design and analysis by engineers and ergonomists. Advances in PCs, which are much faster, more powerful, and relatively inexpensive compared to PCs a few years ago, have made it possible to run many of these software tools on desktop computers instead of the more expensive engineering workstations. The factors just listed, in addition to improvements in the software programs themselves, are the main reasons that three-dimensional/virtual reality (VR) simulation is beginning to be used more and more around the world for a variety of problem-solving applications. NASA is no exception. NASA is interested in ergonomic and other considerations concerning human and human/hardware functions in space environments.

One type of simulation tool being used is microgravity three-dimensional/VR graphics with ergonomic function analysis. This type of simulation can be used to design and investigate a new piece of hardware or even model a system design and then perform ergonomic analysis. Also, three-dimensional simulation can carry out a variety of analytical and verification functions such as finite element analysis, time studies, accessibility, maintainability, and system safety issues. Simulation is an excellent tool for communication between various scientific groups; in addition, simulation can be used as a communication tool with nonscientific departments in an organization. For instance, three-dimensional simulation allows an organization to bring employees from all functions into the design process much earlier. High-level three-dimensional/VR simulation is being used for training purposes, hence allowing the organization's best technology and personnel to be widely used in a number of locations at any one time.

Graphical three-dimensional simulation modeling facilitates engineering's ability to design hardware, equipment, and to validate human capabilities such as reach, clearance, and vision. Simulation allows human motions to be prototyped for a wide range of people sizes so that many of the ergonomic aspects of a task or job can be evaluated prior to building or purchasing hardware or equipment.[1] The use of such software, with ergonomic functions, allows engineers to quickly and effectively evaluate manual assembly tasks to improve cycle times and eliminate/reduce injuries, and it can be used for training purposes. The simulation is capable of being used in conjunction with a wide range of other analytical tools, for instance, the manual application of the RULA assessment tool for determining incorrect postures.[2]

Literature Review

A literature search was centered around research dealing with three-dimensional/VR simulation of microgravity applications. In particular, the search was interested in three-dimensional/VR simulation of microgravity ergonomic and/or physiological applications as they apply to humans during work.

Schagheck and Trach[3] report on cooperative efforts with the Russians and long-term microgravity work on the Russian Space Station *Mir*. The report explored long-duration microgravity research, but there was no report concerning three-dimensional/VR simulations being utilized nor does the report mention ergonomic or physiological analysis. Another paper by Fujii et al.[4] reports that microgravity has adverse effects on human physiology and psychology. Further they report that the longer the duration the greater the microgravity effects and the more serious the health problems become. The objective of this research was an investigation into the generation of artificial gravity by the manned artificial gravity research ship. There was no mention of physiological research or analysis nor was there any three-dimensional/VR simulations mentioned. Another report by Convertino[5] reported on artificial microgravity research on humans. This research did not actually fly the subjects but rather used continuously six-degree-head-down tilt of subjects. The research concerned fit and unfit subjects, peak oxygen uptake, and blood plasma volumes. There was no mention of computer-generated simulations to predict actual subject physiological response to such testing. Hence, overall during the literature search there was no research found that reported on three-dimensional/VR simulation of ergonomic and/or physiological analysis of microgravity applications.

Research Methodology

The research method used for this microgravity study includes simulations of two different space system models: a generic space station module (Fig. 1) and a corresponding NASA computer-aided design (CAD) model space vehicle, the U.S. Space Laboratory (Fig. 2). The research includes the simulation of modeled humans carrying out various tasks. These simulated tasks allow the modeled worker to be exposed to various physiological stressors while

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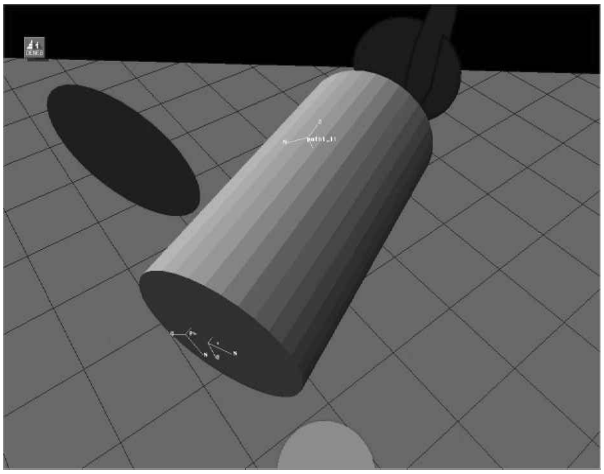

Fig. 1 Generic space module model with disks.

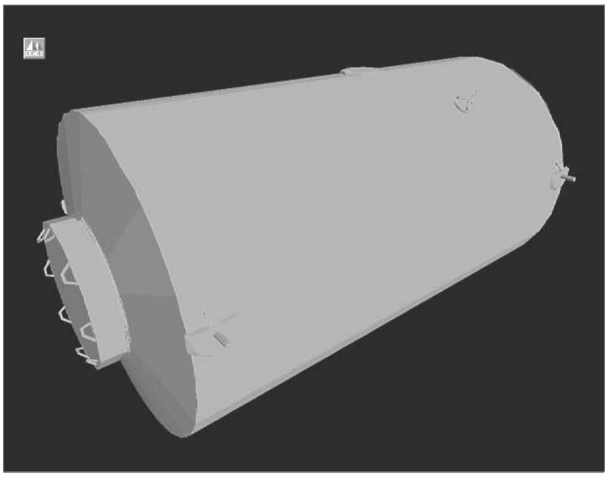

Fig. 2 U.S. space lab module model.

carrying out simulated manual tasks. In both cases the simulation software generated and collected data on the various ergonomic stressors and reported those back for further analysis as necessary. The laboratory is an on-orbit space platform designed for the specific purpose of carrying out scientific experiments in a microgravity environment.

Delmia ERGO Simulation Software

The primary analysis tool utilized for this research was the three-dimensional simulation software package produced by Delmia Corporation based in Auburn Hills, Michigan. The software, ENVISION®/ERGO, is a powerful design and analysis tool with the following capabilities: two- and three-dimensional CAD; design capability for working models of processes and tooling; and the design, simulation, and analysis of various systems. The Delmia software utilizes real-time three-dimensional animation technology to simulate and analyze products, processes, and systems while providing ergonomic and physiological analysis. These tools provide optimization capabilities for the design, mechanical, industrial, and system engineers. Also the package is useful for research and analysis by ergonomists. The software is capable of supporting virtual reality devices.

While using this type of simulation software, engineers and ergonomists can proactively address human interface issues that impact the ability of a wide anthropometrical range of simulated humans to carry out tasks and maintain a proposed space or other design. Four immediate benefits are as follows: 1) While in the design stage, design engineers and ergonomists can virtually eliminate the time and costs of expensive rework or design change. 2) Simulation also eliminates costly and time-consuming physical mockups. 3) Engineers reduce time-to-fly by visualizing and validating components digitally before the product design is frozen and/or before committing resources. After the simulation is validated, engineers can use the product and process models for training, maintenance, and documentation. 4) Ergonomics, anthropometry, physiology, and safety issues can be analyzed and addressed while the system is still in the design stage. This type of digital analysis can eliminate or reduce expensive redesign and delays.

Ergonomic and physiological functions included in many of the three-dimensional and VR simulation packages are listed here. These are the functions most frequently used for ergonomic studies: 1) visualize the feasibility of certain tasks, 2) reach and grasp, 3) bend and reach, 4) eye windows to view what the model sees, 5) Kcal prediction model—energy expenditure, 6) motion time measurement, 7) RULA posture analysis, 8) NIOSH lifting guidelines, and 9) anthropometry switching for the human models.

Human Simulation

For this research the simulated human is referred to as an astronaut. The astronaut model generated by the computer is an articulated representation of the human body. The number of degrees of freedom is normally 86 but can be increased up to 128 by modeling fully articulate hands. The designer or analyst can change astronauts by varying gender and anthropometry (Fig. 3): this allows the design of workplaces for a range of astronaut. Fifth-, 50th-, and 95th-percentile anthropometry characteristic male and female astronauts are preprogrammed in the simulation software.[6] However, simulated individuals can be modeled to meet specific human physical characteristics.

Three-dimensional graphic simulation tools can be used for space vehicle design and analysis. In the case of Delmia, this software allows the systems designer or ergonomists to prototype human motion within a work area using a proprietary graphical motion programming paradigm.[6] The software allows a NASA ergonomist or engineer to design and/or set up the motion sequences for simulated space module astronauts or subsystem by using the graphical programming method. A motion sequence then is an ordered collection of postures where the user manipulates the model astronaut's limbs using task-based and graphic programming. A posture contains information regarding the joint values, attachments, and analysis. With this programming method a motion sequence consists of an ordered collection of worker postures generated by the designer. The designer generates simulated astronaut postures by computer software manipulation of the worker's limbs. The software program uses a combination of forward and inverse kinematics. For instance, if the worker posture exceeds the reach of the astronaut's arm the simulated body's inverse kinematics provides a solution by automatically bending the astronaut's torso. Software capabilities are provided for developing time standards and studying the ergonomics of a job related to moving objects, energy expenditure, and posture analysis using percentile-based, fully articulated three-dimensional human simulated models.[1]

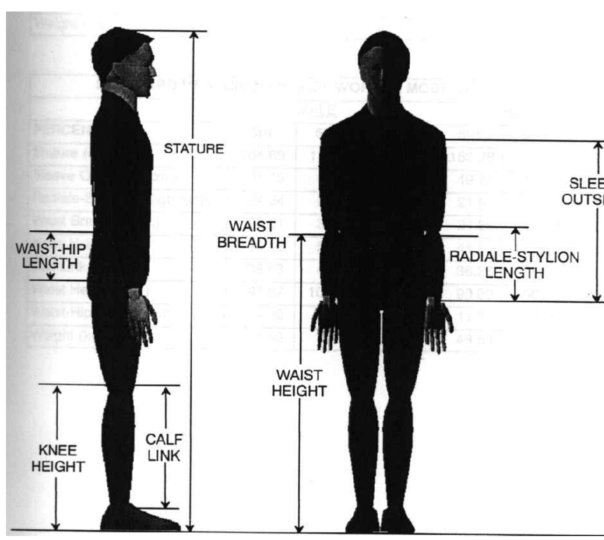

Fig. 3 Anthropometric model.

Microgravity Simulation Methodology and Discussion

The methodology utilized for this phase of research included preliminary and advanced analysis. Both preliminary analysis and advanced analysis methods used Delmia ERGO software as the primary data-gathering tool.

The preliminary analysis consisted of designing a rudimentary space vehicle for the astronaut's work environment. This initial vehicle was designed as a 5×10 m double-walled cylinder with perpendicular closed ends. The astronaut was a 50th-percentile female generated by the software program, and she had 86 deg of freedom. There was no particular reason for selecting the 50th-percentile female human model; we could have selected the smallest, 5th-percentile female, to the largest, 95th-percentile male, astronaut to carry out this initial analysis.

The advanced research analysis was conducted around a properly scaled NASA U.S. Space Laboratory module. The module consisted of the outer shell of the space vehicle with the interior modeled by experiment racks. The graphical realism of the interior walls was accomplished by wallpapering inside walls to simulate the actual U.S. space module interior. Several of the racks were embellished with three-dimensional models of experiments, which were capable of being taken out of the racks and moved to other locations by the astronaut. The simulated astronaut was the same 50th-percentile female as used in the preliminary analysis.

The Delmia software package, like all simulation programs, expects and is programmed to orient and analyze the simulated human with 1-*g* influence. Naturally the simulated human would be typically oriented in an upright position with the worker or astronaut's feet firmly attached to a horizontal surface perpendicular to the gravitational force, say, the ground. The simulated human can freely move about, under the influence of gravity, and is limited to two-dimensional travel without mechanical assistance almost exactly like a real human. This can pose an interesting problem for the engineer or analyst involved in microgravity simulation where the simulated human should float similarly to a neutral buoyed underwater diver. In space there is no up or down, and the astronaut is free to move in three-dimensional rather than the typical two-dimensional environment we are accustomed to here on Earth.

Several different methods can be utilized to simulate the astronaut in a microgravity environment. The first method is to attach the simulated human model to a vertical or horizontal surface (Fig. 4), and then store this first posture in the program path. A posture is a snapshot of a particular activity and is used by the Delmia software to store critical information utilized to generate the simulation sequence. Posture generation is the beginning point for the simulation. Next the engineer should manually, by pull-down and pick screens and mouse action, translate the simulated astronaut to the next point in the space environment. This could be the ultimate destination or some intermediate point in between.

The second posture position, and ensuing moves of the astronaut, can be accomplished by several means. One method is to position a temporary surface, such as the thin disk seen in Fig. 1, at a point where the engineer wishes the simulated astronaut to move to and then simply attach the astronaut to that point. Then the temporary surface can be deleted or made invisible (Fig. 5), thus leaving the astronaut at the proper position. Another method, and perhaps the most straightforward and simple, is to translate the simulated astronaut by mouse manipulation. With the simulation program running in Delmia's ERGO, go to TEACH, there select BODY, then select JOINT MOVE. In JOINT MOVE there are three options: 1) translate-x, 2) translate-y, and 3) translate-z. Pick one of these three with a left mouse button click, and then with the "−" or "+" buttons move the astronaut into the appropriate position. Then select either of the other two translate buttons for appropriate placement. The step size of the incremental moves for any of the three translations can be adjusted for precise astronaut placement.

Once the simulated astronaut is placed in the proper location, the engineer or ergonomist can manipulate the astronaut by conventional means in order to simulate the task requirement moves needed at that posture (Fig. 6). Then the posture can be saved, and the process repeated until the work sequence is completed. At any point the postures can be played back for actual model simulation.

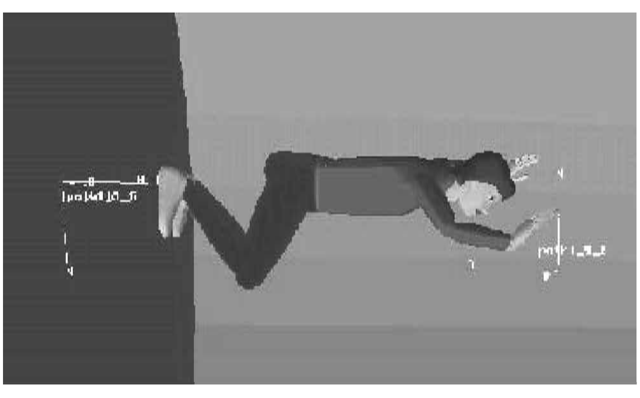

Fig. 4 Virtual human microgravity simulation in Envision/Ergo.

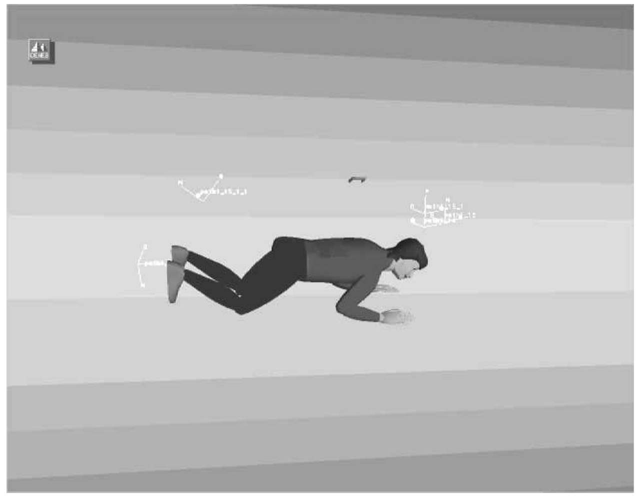

Fig. 5 Astronaut attached to invisible disk.

Fig. 6 Example of simulated astronaut manipulation.

Future Research

A kilocalorie (Kcal) prediction model, such as the energy expenditure via Garg's Prediction model,[6] is programmed in the simulation software package and is very useful for calculating the amount of energy expended. Also, on an ongoing basis the energy expended could be collected by time periods and charted to track progress of continuous methods improvement and its effects on astronauts. The Kcal prediction model can be used to get an estimate of the Kcal consumption for various manual tasks. The purpose of this tool is to make sure that a proposed task is within the astronaut's capabilities. The metabolic energy expenditure is a physiological measurement for determining the task intensity that can be continuously performed by an astronaut. By examining the energy requirements for a task, the system designer can assess the capacity of an astronaut to perform the task, establish duration and frequency of rest periods, and evaluate alternative work methods in case the work is determined to be too strenuous.

The Kcal model assumes that the work can be broken down into simpler tasks. Once the work has been divided, the average Kcal rate for the whole job can be estimated by summing the energy requirements for those tasks and the energy required to maintain the posture. Then this sum is averaged over time.[6]

The Kcal prediction tool was not used in this first phase of microgravity research. Kcal expenditure calculations for people performing work are important in that the calculations can predetermine whether a task or work cycle is too physically intensive for continuous activity. However, this function is designed for 1-*g* applications, and it is unknown how accurate the data would be, considering that they were generated in a simulated microgravity application. This is a topic of continuing research.

Summary

The simulated human astronaut is central to this investigation just as the real astronauts are the essential resource in an actual space flight. The simulated astronaut is a 50th-percentile female and is utilized for both the generic and U.S. lab models.

Several methodologies for microgravity simulation of astronauts were presented. These methods do not require program code writing or adjustments. These methods utilize the ease and power of the computer system and software to make these required commands, thus, writing code automatically embedded in the simulation.

The design of the module or workstation, hardware, and vehicle support equipment can only be competed while examining the inherent human factor in the design process. Design engineers have traditionally relied on expensive and time-consuming mockups to evaluate designs and workplaces. To avoid these expenses, it is important to evaluate available design alternatives early in the design stage. Three-dimensional simulation of astronauts where the software carries out motion, reachability, anthropometry, biomechanics, and ergonomic analysis is extremely important. The ergonomic benefits of an optimum-designed space vehicle can result in significant reduction in the design effort and related costs in both time and money.

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References

[1] Nayar, Narinder, "DENEB/ERGO—A Simulation Based Human Factors Tool," *Proceedings of the 1995 Winter Simulation Conference*, Association for Computer Simulation, New York, 1995, pp. 427–431.

[2] Hunter, Steve L., "Ergonomic Analysis: 3-D Simulation of Cellular vs Functional Manufacturing Systems," Ph.D. Dissertation, Industrial and Systems Engineering, Auburn Univ., AL, April 2000.

[3] Schagheck, R. A., and Trach, B., "Microgravity Research Results and Experiences from the NASA Mir Space Station Program," NASA, 2000, pp. 73–89.

[4] Fujii, T. S., Suzuki, T., Toyobe, M., Hamami, H., Tauchi, H., Nitta, K., and Kibe, S., "Concept for a Manned Artificial Gravity Research Ship," Society of Automotive Engineers, TP, March 1999.

[5] Convertino, V. A., "Changes in Peak Oxygen Uptake and Plasma Volume in Fit and Unfit Subjects Following Exposure to a Simulation of Microgravity," *Acta Physiologica Scandinavica*, Nov. 1998, pp. 235–251.

[6] Deneb Robotics, Inc. (Delmia Corp.), "IGRIP/ENVISION/ERGO Software Manual," Auburn Hills, MI, 1998.

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