Human Modeling for Ground Processing Human Factors Engineering Analysis

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Abstract— There have been many advancements and accomplishments over the last few years using human modeling for human factors engineering analysis for design of spacecraft. The key methods used for this are motion capture and computer generated human models. The focus of this paper is to explain the human modeling currently used at Kennedy Space Center (KSC), and to explain the future plans for human modeling for future spacecraft designs.

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1. INTRODUCTION

The Human Engineering Modeling and Performance (HEMAP) Lab originated due to the complex and challenging workspace design issues the Space Shuttle posed on technicians performing maintenance, modifications, and repair operations. The HEMAP Lab includes a motion capture system that captures biomechanical motions of humans and performs various detailed ergonomic analyses of high risk operations. With the previous knowledge, skills and capabilities developed during the Space Shuttle and Constellation Programs, the HEMAP Lab has evolved into a one of a kind state-of-the-art capability at KSC, which will prove to be very beneficial to design flight and ground hardware, and the related human tasks, to ensure safe, efficient, and effective ground, flight, and non earth terrestrial habitation and processing of future space systems. [1,2]

One recent and very important accomplishment of the HEMAP team was the analysis of the installation/removal (I/R) of four Avionics Boxes (AB) planned for test flights of the Orion crew module. Three technicians of varying stature were used to simulate the installation and removal of the four avionics components. One technician picks up the avionics box component from the hatch dive board and then passes the component to an Installation Technician (IT) while a third technician served as an installation/removal Quality Inspector (QI). Dozens of task scenarios were performed using many variations. Observations and data were collected real-time, through technician inputs, and via viewing and assessment of recorded playbacks of the tasks with ergonomic evaluation software applications.

The project requirements for this assessment were developed and agreed upon using customer requirements questionnaires and discussions. The purpose of this project was meant to aid in the identification of process improvements and possible tooling that could prevent occurrences of collateral damage and personnel injury caused by limited access, awkward postures, and/or limited field of view during avionics box I/R.

It was determined that the prime scope of this initial assessment would include overall access, gross motor tasks, visibility, and lateral reach. Detailed assessment of fine motor tasks, performed inside the cavities where the box is mounted, including reach to fasteners, arm/hand/tool access between components and their respective walls, and tool grasps within confined areas were not evaluated and were planned for extended studies.

2. METHODS

The HEMAP Crew Module (CM) mockup is an open-frame construction to allow visibility for the motion capture cameras. Accuracy of the fabricated mockup was checked against CAD data. Wood was used as the core of the CM floors, designed to be weight-bearing for multiple technicians and objects and nonslip. The wood was painted with fire retardant paint. Wire mesh was used to represent the workspace envelopes. This mockup method developed by the HEMAP is easily adaptable and is used for many other types of CM analysis and is extremely efficient at reducing costs as compared to a physical simulation that does not use motion capture immersed into a CAD model of the vehicle.

The motion capture system was used to capture various scenarios of real human participants simulating the installation of four avionics boxes (B1, B2, B3, B4) within a representative mockup. Each avionics box was constructed out of wire mesh and rods, according to their dimensional attributes. The weight being handled at any time by any technician was less than 2 pounds. (the true mass of the box is included into the biomechanical analysis). For the motion capture sessions, each subject and component were marked so motions would be tracked and viewed within the CAD electronic environments. See Figure – 1, 2&3

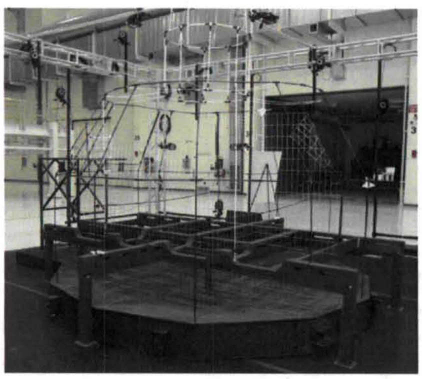

Figure 1 Mockup and Motion Capture

The inner configuration of the Crew Module (CM) included inner mold lines, curved aft bulkhead, side hatch opening, side hatch platform, forward bulkhead, docking ring, inner wall footprints; and other mounted components and wire/cabling. The work areas were broken down into five zones formed by the structure of the CM. Work areas utilizing removable platforms placed atop the structure were designated as A1 through A4. Areas with No Access (NA) were blocked for access by placing wire fence. The four boxes are labeled B1-B4. See Figure- 2.

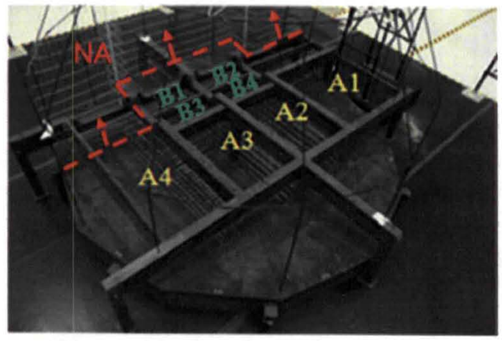

Figure 2 Box, Access, and Non Access Areas

Key features of the mockup were removable platforms which allowed the team to trial a variety of configurations for technicians to install the four avionics boxes either by working atop the platforms or with the platforms removed to allow working directly in the access areas A1-A4. Removable platforms were fabricated and placed atop the backbone structure openings (A1-A5) during portions of the motion capture tasks.

Technicians for this project were selected to closely represent a 5th Percentile and a 95th Percentile Army Anthropometric Survey (ANSUR) male in stature and weight, allowing analysis of a broad range of sizes, and covering possible technicians populations from a short to tall stature male. Female Technicians were not available at the time of the captures, so the software analysis did not include female ergonomic evaluations. See Table-1.

Table 1 Subject Height and Weight

Subjects	Height	Weight
5^{th} Percentile	162.1 cm	77.3 kg
5^{th} Percentile	163.3	65.5 kg
5^{th} Percentile	161.6 cm	65.9 kg
95^{th} Percentile	187.0 cm	101.0 kg
95^{th} Percentile	188 cm	99.5 kg

Technicians used for this project had experience in similar activities as part of Space Shuttle operations. One had performed tasks within the Orion ground test article, which offered insight and lessons learned to the team and other technicians regarding working in the nearly identical sized mockup performing similar handling tasks. The technician pool had received prior general training on proper general lifting techniques, using smooth and no sudden acceleration. Each technician was experienced with lifting critical, fragile components. The moderate width of each component allowed for standard hand separation. Technicians performed the motions at the HEMAP Lab under environmentally controlled conditions.

Technicians were able to remove particular portions of these platforms and stood in the access area or kneeled on the platform covering the access area. The A1 platform just interior to the side hatch opening was installed throughout all tasks and assessments.

Based on Customer input, all motion capture tasks assumed the use of a lifting/lowering device (LLD). The design of the lifting device had yet to be developed. For project evaluation, representation of a lifting device was simulated by a participant who guided the part over to the installation location. The part was suspended by cords as it was lowered into position by the technician.

Figure-3 shows two technicians kneeling on the installed platform A1 and A2 while installing avionics box 4 (B4). The technician holding the box is kneeling on the A2 platform, the technician simulating the box lifting/lowing device (box held by string) is kneeling on A1 platform.

Figure 3 Technicians Working from Platforms

Figure-4 shows a configuration which shows three technicians, one technician standing on platform A1 and simulating the box lowering apparatus, a second technician kneeling on A2 platform holding the box, and the Quality Inspector (QI) standing in the removed platform for A3.

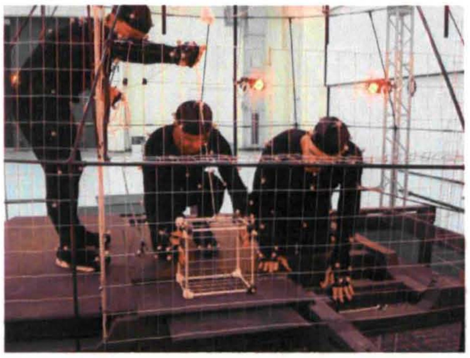

Figure 4 Three Technicians

3. Analysis

During and after performing various scenarios of real human participants simulating the installation of 4 avionics boxes within a representative mockup, pros and cons of the simulated process results were evaluated by the team who developed recommendations based on customer inputs, participant feedback, ergonomic/human factors analyses, participant visibility, and real-time and animation reviews. Included in the ergonomic/human factors analysis were the biomechanical lower back analysis, fatigue analysis, access, reach, and visibility, which included the participant inputs.

Technicians participated in several capture activities to simulate the installation, removal, and inspection of the four components. The technicians' feedback, Customer inputs, ergonomics, and process requirements were factors used to develop recommendations.

As motions were performed, they were captured within the HEMAP system and fed into two evaluation software applications. HEMAP used Siemens Jack to view live motions, shown as avatars within an electronic environment of the CM and components. Within Jack, as motions were occurring, the HEMAP Team was also able to perform preliminary real-time ergonomic analyses. Concurrently with Jack, HEMAP used recently integrated DELMIA to also view the live motions and electronic environment. After motion captures were recorded for later playbacks, each motion task scenario was reviewed and evaluated in each of the software analyses packages.

The renderings in Jack and DELMIA produced graphics differing primarily in avatar, or manikin, skins. The virtual environment of the CM and components were similar in that they were nearly incomparable in graphic quality, providing similar levels of details.

Even though HEMAP fabricated and used platforms within the mockup to simulate areas most feasible for future platforms, the actual platforms themselves do not appear in the electronic, computer environment. In screenshots representing platforms installed, it will appear as technicians are hovering at the top plane of the platform heights with their knees, prone posture, or feet if standing on actual mockup platforms. Likewise, graphics of the represented installation aid (actual cord tether in the physical mockup) does not appear in the electronic environment.

Moving the platforms in and out of the mockup were not evaluated for ergonomic, feasibility, or human factors assessment. For each motion capture evaluated, platforms were either installed or removed before the start of action began for recording and assessment purposes.

3.1 Task Sequence Analysis

During pre-task discussions, including review of the CM mockup and component configurations and tasks to be performed, the Team deduced that a particular order of component installations would be needed to allow technicians access in simulating fastening and installing the components. The list of feasible order of operations were followed during the motion capture analysis. Motion captures were performed with a variety of scenarios including platforms in, platforms out, 5th Percentile Installer, and 95th Percentile Installer.

3.2 Lower Back Analyses (LBA); Compression Forces

The National Institute for Occupational Safety and Health (NIOSH) has established a limit of 3400 Newtons (a unit of force required to impart acceleration of lift to the mass being lifted) as a safety limit for compressive force to the lumbar region of the spine. HEMAP references this value during evaluations within the ergonomic software evaluation applications to determine safe lifting ranges. All of the lower back compression, or Lower Back Analysis (LBA), forces experienced by the technicians during the Avionics Box tasks performed were below the recommended 3400N safe limit. This was primarily due to the simulation of the LLD installation aid which resulted in the components only being weighted to the mass of the mockup materials that were used to fabricate them. Jack's Low Back Compression Analysis tool is based on a complex biomechanical low back model which is described in published articles: [3] Raschke, U. (1994) and [4] Raschke, U., Martin, B.J and Chaffin, D.B. (1996)

3.3 Rapid Upper Limb Assessment (RULA)

The RULA tool which examines the upper body posture and arms did not provide additional insight into any of the tasks, as it always interpreted the tasks as a level 7 – a condition requiring immediate intervention to alleviate the posture. Since the components are configured below technician torsos and since the technicians cannot get level with the components during installations within the CM, it was expected by Human Factors Analysts that the upper limb forces and evaluations would reflect higher limits.

As experienced with similar shuttle processing, applying proper lifting techniques and padding to reduce contact stress during long task durations of carefully placing the avionics box, should prevent risks during these infrequent tasks.

3.4 Reach and Visibility

During each scenario, reach and visibility were evaluated as well as technician natural behaviors and technical limitations. Through discussions and performances of the tasks, the consensus of technicians is that these components will require torquing from the back side and, due to this, it will be necessary to work from the Aft Bulkhead with the platforms out to allow the torque-wrench swing required. See Figure-5 for the estimated view of the technician in the modeling software.

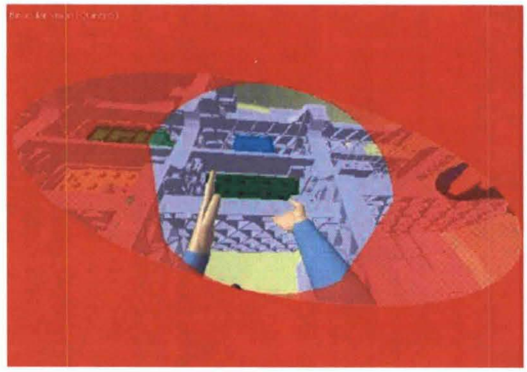

Figure 5 Estimated View of Technician

4. EXAMPLES

The section goes through one example which focuses mainly on the installation technician, and on the lower back stress.

4.1 Comparing Platfom In vs. Platform Out

This configuration did a comparison of the Installer Platform in versus out, with a 5th percentile installation technician of stature and wieght. The results showed that the Installation Technicians (IT) preferred to work with the Installer Platform out, while installing B3 and B4. This was confirmed after assessing results in the ergonomic analyses software.

A 5th Percentile IT experienced a lower back compression of 1597 Newtons (N) with the Installer Platform out and a lower back compression of 2123 N with the platform in. Therefore, both values of platform scenarios represented safe lifting ranges under 3400 N. Ultimately, being able to stand/kneel within the access area A3 and A4 cavity, nearest the components, allowed for more natural postures than when lying prone (Figure-8) on the platforms in the same locations. Figure-6 shows the analysis software Jack, and Figure-7 shows the analysis software DELMIA.

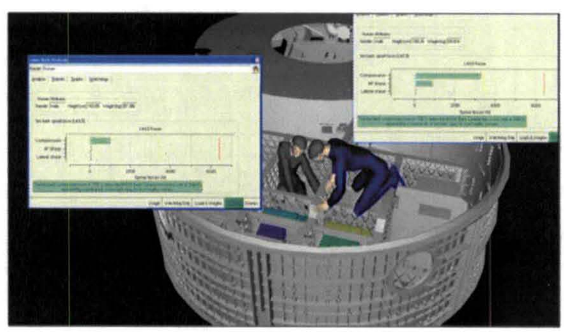

Figure 6 5th Percentile Installer in Gray

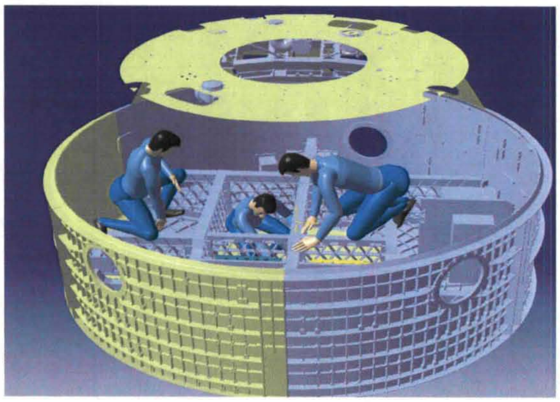

Figure 7 DELMIA Analysis of Installer Platform Out

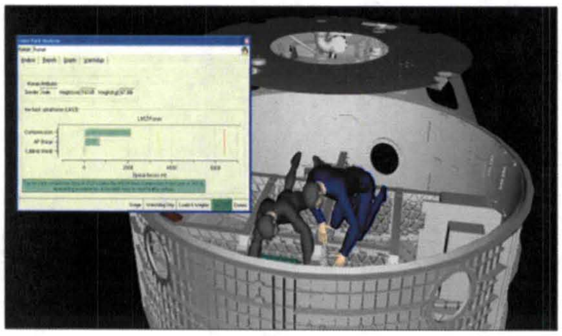

Figure 8 Technician Lying Prone

Figure 9 5th Percentile Inataller

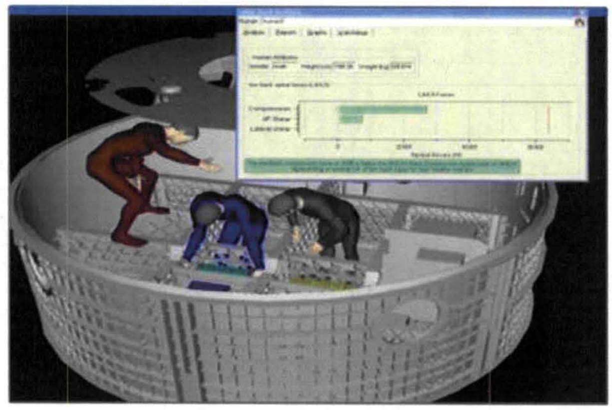

Figure 10 95th Percentile Installer in Blue

4.2 Comparing 5th vs. 95th Percentile Installer

Further comparisons were made between installing components B3 and B4 with a 95th percentile technician against a 5th percentile technician in stature and weight. It was determined that a 5th percentile technician should install the components as they are shorter of stature and are not forced to lean over as far into the avionics bays, which causes more strain on the lower back. A 5th percentile technician experienced a lower back compression force of 1597 N compared with a 95th percentile technician who experienced a lower back compression of 2695 N. Figure-9&10

4.3 Static Strength Prediction

Static Strength Prediction analysis of B1 and B2 installation/removal and quality tasks showed that a higher percentage of the population would be capable of performing the tasks with the platforms out than with the platforms in.

4.4 Reach

The subjects' arm lengths ranged from below the 5th percentile to the 90th percentile. From a lying prone posture on a platform or from kneeling or standing directly atop A2 and A3, each technician was able to reach down to the bottom of the box openings. However, reach within the avionics bays amid the components is a concern due to limited space which may not allow adequate hand/arm motions.

4.5 Visibility

Due to the components being placed in the centers of the avionics bays for the baseline assessment, technicians reported they were able to see to the lowest edge of the outer planes of each wireframe mockup component during installation and removal. The Jack and DELMIA firstperson eye view software evaluations also confirmed the effective visibility. Figure-11.

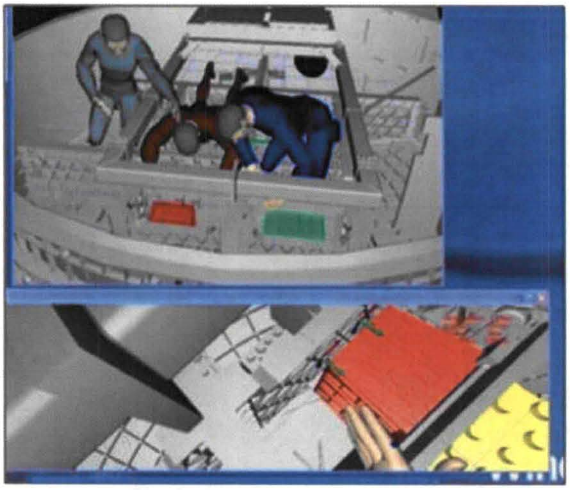

Figure 11 View of Box in Restricted Space

4.6 Other Analysis

Several other analyses were performed. For example for the boxes B1 and B2 further away from A2 and A3, technicians advised that they preferred to use the platforms to perform these tasks for B1 and B2. Lying on platforms would prevent technicians from having to reach across either the B3 or B4 components. Also having adjacent, A1 and A4 platforms installed allowed for tool placement and ability to stretch beyond A2 and A3 workspaces. Lying on the A2 and A3 center platforms helped to reduce strain on the lower back when reaching further away from the box opening. At these postures, additional pressure was placed on the knees and ankles, a trade willingly accepted by the technicians who did not experience pre-existing knee or ankle conditions that would be cause for further assessment.

Furthermore, motion captures were performed with a variety of scenarios including platforms in, platforms out, 5th Percentile Installer, and 95th Percentile Installer. Standing, kneeling, lying prone, bent or straight arms, etc. were analyzed. Additionally the Installation Technician (IT) and the Quality Inspector (QI) positions and locations were studied. During each scenario, along with biomechanical and static strength, reach and visibility were evaluated, as well as natural behaviors and physical workspaces and limitations.

5. WORKSPACES LIMITATIONS

For the purposes of the initial assessment of the Avionics handling, the boxes were centered within each cavity as overall handling, gross motor tasks, lateral reach, and visibility to the Aft Bulkhead were assessed.

Based on these designs, there was not enough space for a technician to thoroughly place his hands down the sides of each component due to the tight configurations. Even with bare hands and no markers, concerns were addressed regarding whether there would be sufficient room to manipulate tools on the sides of each of the component boxes. See Figure-12 and 13.

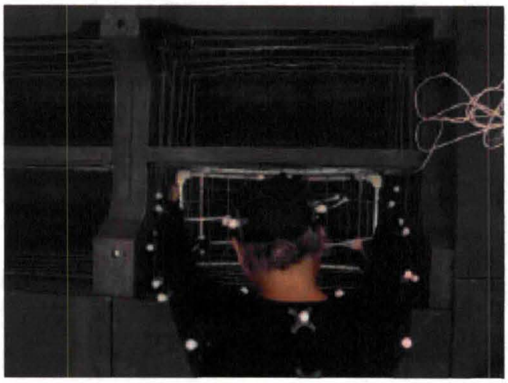

Figure 12 Restricted Access Around Box

Figure 13 Limited Hand Space

It was determined that more detail assessments would need to be performed to determine true physical workspace limitations and feasible handling methods for installations and removals. For this project primarily large body motions were assessed to determine whether technicians benefited from platforms being installed or not in handling these components. In addition, reach to the outward planes of the components and downward to the Aft Bulkhead, where the lowest fasteners would be, were determined to be feasible with the technician pool used and general placement of components within the centers of the cavities.

6. RELATED STUDIES

The Avionics Box Cold Plate Damage Prevention paper explains lessons learned from the Space Shuttle Program while describing the cold plate damage problems and the corrective actions for preventing future damage to aerospace avionics cold plate designs. [5]

During the Constellation program analysis was done for the Ares rocket to improve avionics box placement for the technicians. [6] In order to have the efficient and effective ground processing inside and outside the vehicle, all of the ground processing activities were analyzed. The analysis was performed by engineers, technicians, and human factors engineering experts with spacecraft processing experience. The procedure used to gather data was accomplished by observing human activities within physical mockups. Figure-14

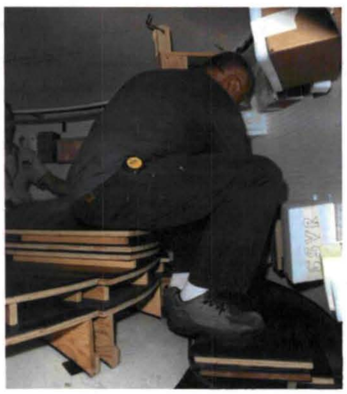

Figure 14 Designing Box Locations and Ground Support Equipment

Another study simulated the avionics box and avionics shelf configuration in a biomechanics laboratory at the University of Miami. [7] This study looked at lifting time, how close the box can be placed on target, the EMG muscle activity, and the forces to the L5/S1. The lifts were manually done with restrictions or no restrictions to the installed box with three different box weights, and two shelf heights. See Figure –15

Figure 15 University Study

7. LESSONS LEARNED

1. Technicians familiar with shuttle and crew module capsule ground test article processing were effective in providing lessons learned and valuable insights into various handling options of the four components which were performed and simulated during dozens of motion capture scenarios.

2. Having a lower stature technician perform the installation/removals closer to their bodies, offers less strains caused by bending on the back and legs, compared to the taller stature technician performing the same tasks.

3. The use of additional removable platforms in the CM are not recommended since these platforms would limit access and not enhance the postures.

4. Labeling of the platforms is recommended to assure proper positioning.

5. Non-protruding and non-interfering handholds would also provide benefits to handling the platforms within the confined environment.

6. Dimensions and thickness would be affected by maneuverability through the Side Hatch and interfaces with the CM.

7. Flexibility in horizontal platform maneuvering within the CM is also recommended in planning platform construction.

8. Having adjacent platforms installed for the Guiding and quality technician allow increased visibility and handling for their roles and provide additional staging surfaces.

9. Operations should afford the technicians the opportunity to take frequent stretching breaks during the task to increase circulation and rest stressed, fatigued muscles after holding postures static.

10. Foam padding should be used where practical, especially during long duration jobs, to minimize contact stress to tissues and muscles and to increase technician comfort in performing the installation and removal tasks.

8. FURTHER STUDIES AND FUTURE PLANS

8.1 Further Studies for Avionics Box Installation

Plans are to perform further studies to evaluate component configuration with the cavities, assessing fine motor and detail handling tasks. This assessment would evaluate components placed in exact locations to determine Feasibility of Hand/Arm Workspaces, Detailed Handling, Fine Motor Tasks (Hand/tool grasp), Collision Detection (Component placement within cavity), Visibility (Around components in cavities), and Detailed Reach (Inside cavities).

8.1 Future Plans

Provide the state-of-art biomechanical capabilities to design flight hardware to ensure safe and efficient ground, flight, and terrestrial processing of future space systems.

Improve the HEMAP capabilities to satisfy NASAs need for Research and Technology by partnering with and incorporating NASA, academia, and commercial state of art capabilities, methods, and expertise.

9. CONCLUSION

The HEMAP Lab has evolved into a one-of-a kind state-of-the-art capability at KSC, which will prove to be very beneficial for designing flight hardware, designing tasks, and analyzing stress, force and strain to ensure safe and efficient ground, flight, and terrestrial processing of future space systems.

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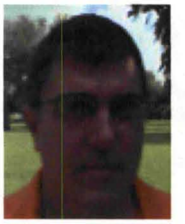
BIOGRAPHIES



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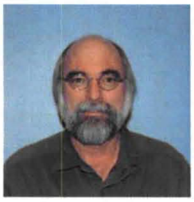

Brad A Lawrence *began his career in the U.S. Navy as a Cryptological Maintenance Technician. After his discharge he joined ITT in Dallas as a Field Systems Engineer. His responsibilities included maintaining computer systems for the City of Dallas and various major corporations. A few years later he transferred to Texas Instruments building and calibrating FLIR systems. In 1985 he accepted a job as a Video Systems Specialist on the Space Shuttle Program with Lockheed Space Operations Company. Holding the title of Computer Science Lead he now oversees the NASA Image Analysis Facility, Kennedy's Advanced Visualization Environments Lab and the HEMAP Motion Capture Studio. He obtained the NASA UNIX System Administration Certification and has earned the NASA Space Flight Honoree Award, Space Flight Team Award, and the coveted Silver Snoopy Award. Brad has received the Technical Achievement Award in 2004 from United Space Alliance and three NASA Director awards for dedication and innovation.*

Katrine Stelges *is an Industrial and Human Engineer (I&HE) with United Space Alliance with over 11 years' experience of implementing projects that have reduced risks, improved efficiencies, and applied user inputs and human factors criteria into practical solutions. She is currently the Principal Investigator for the Human Engineering Modeling and Performance (HEMAP) Lab. Stelges is a Lean Six Sigma Certified Green Belt, holds a M.S. in Management of Technology from the University of Miami, is pursuing a second M.S. in Industrial Engineering. Prior to joining I&HE, Stelges was a Materials and Process Engineer with USBI, currently USA's Solid Rocket Booster Element, and taught secondary physical science and chemistry for Brevard and Orange County public schools.*

MJ S. Ndiaye *is currently working on a Masters in Human Factors and Systems at Embry-Riddle Aeronautical University (Daytona Beach, FL). Her thesis assesses the effects of intelligent adaptive displays on fighter pilots. MJ joined United Space Alliance (USA) in 2007 as an Industrial & Human Engineer, and is currently working in the Human Engineering Modeling & Performance (HEMAP) Lab. Before joining USA, she was granted undergraduate and graduate Teaching/Research assistantships that allowed her to hone her research skills and satisfy her inquiring mind. MJ is keen on R&D and enjoys working on projects that involve designing space vehicles or habitats (i.e., ground crew performance and functionality, acceptability testing, and other habitability impacts).*

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Gena Henderson Ph.D., *serves as chief of the Engineering Support Services Branch within the Engineering Directorate at John F. Kennedy Space Center. This office is responsible for generation and management of business processes and documentation; generation and management of business metrics; records management; management of design and development technical reviews; export control; management of business reviews; management of office, laboratory and shop space database; knowledge management; management of the Kennedy Engineering Academy; and management of the Agency Lessons Learned program as a delegated function from the NASA Headquarters Office of Chief Engineer.*

Donald Tran *is currently working in the KSC Engineering and Technology Directorate at Kennedy Space Center. His work human factors work includes; improving the over 40 ground sub-systems designs for the Constellation Program Ground Operations Project, and improving the local and remote Control and Display screens for these subsystems. His work as a human factors engineer is aimed at improving ground processing operations, i.e., processing, maintenance, testing and inspection of flight hardware using ground systems.*

Tim Barth *is a systems engineer in the NASA Engineering and Safety Center (NESC), which was established to improve safety across NASA programs and projects by focusing on technical rigor and engineering excellence. Tim has worked at Kennedy Space Center (KSC) in a variety of engineering and technology management positions, and has led many successful teams and projects to improve the safety, efficiency, and effectiveness of space launch operations. Also Tim has led efforts to establish industrial and human factors engineering capabilities within NASA and contractor organizations at KSC.*