IMPROVING WORKING CONDITIONS FOR ASTRONAUTS

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Abstract

While in microgravity, astronauts are preoccupied with physical restraint, which takes attention away from the maintenance task or scientific experiment at hand. This may directly lead to safety concerns and increased time for extravehicular activity, as well as potentially inhibit or corrupt data collection. A primary concern is the time it takes to manipulate the current restraint system. The portable foot restraint currently in use by NASA employs a series of pins in order to engage the system or release in an emergency. This requires considerable time for the user to detach, and there is an increased risk of entanglement. If restraint operating time could be reduced by 50%, the astronaut's assigned experiment time could be increased an average of 100 minutes per mission. Another problem identified by NASA included the inability of the current system to release the user upon failure. Research and design was conducted following the Six-Sigma DMEDI project architecture, and a new form of restraint to replace the existing system was proposed. The research team first studied the customer requirements and relevant standards set by NASA, and with this information they began drafting designs for a solution.

This project utilized electromagnetism to restrain a user in microgravity. The proposed system was capable of being manipulated quickly, failing in a manner that released the user, and being electronically controlled. This active electronic control was a new concept in restraint systems, as it enabled an astronaut to effectively "walk" along a surface while remaining restrained to it. With the design prototype and a limited budget, a rudimentary test assembly was built by the team, and most of NASA's specifications were met. With recommendations from NASA, the research team concluded by developing potential material and design solutions that can be explored in the future by Purdue University or other parties.

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IMPROVING WORKING CONDITIONS FOR ASTRONAUTS:

An Electronic Personal Restraint System for Use in Microgravity Environments

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INTRODUCTION

An important human factor in a microgravity environment is the astronaut's ability to restrain and affix him or herself in place in order to transfer force to the work at hand.

Many different restraint systems are in use during space flight and depend on whether the user is participating in extravehicular activity (EVA) or intravehicular activity (IVA). Systems must be designed to support the user in a wide variety of tasks ranging from operating a microwave to installing a new module on a satellite.

Current Systems

Restraint systems currently employed in microgravity environments are mechanically operated. These mechanical restraints are manually engaged and disengaged by the astronaut in order to sustain a safe and functional work environment. As the astronaut prepares to begin a task during EVA or IVA, he or she begins by placing each foot in a restraint that utilizes a Velcro-based pad or locking pin mechanism. A problem with these systems is their inability to allow the user to quickly detach from the restraint surface in case of an emergency. A second problem identified by NASA is that the current system requires a significant amount of time to engage and disengage. This takes away from critical mission time that could be spent focusing on the task at hand. NASA also reported in some rare cases astronauts becoming entrapped in the current system. Not only does this create an extremely dangerous scenario, but if an emergency should arise, the user has little control over solving the mechanical malfunction (Watson & Dunn, 2002). According to NASA, the ideal scenario would incorporate a nonmechanical restraint that would release the user upon failure. This

holds true for both EVA and IVA (R. Trevino, personal communication, September 8, 2009). Considering this, the proposed design improvement would have to comply with requirements outlined in NASA Standard 3000 (1995) along with requirements specified by NASA engineers.

SOLUTION EXPLORATION

With the given requirements, the scope of the design began to take shape. The design would encompass research of a nonmechanical, personal, portable restraint capable of being engaged and disengaged with little effort by the user. In addition, the team developed a system that allows the user to move his or her feet along the vehicle's surface while maintaining a secure point of contact with that surface. Aside from the immediate improvements, the design would also reduce the amount of time spent manipulating the restraint. This translates to added mission time and productivity.

From Mechanics to Electromagnetism

The team proposed that the new system utilize a series of electromagnets strategically placed in the sole of a lightweight composite "boot." Each electromagnet would be independent of the others and controlled by the user via an external control box that regulates all settings and translates the results to the restraint. This would allow the user to engage and disengage both feet by the touch of a button. Ideally, the user would need only to navigate to the restraint surface, hover over the surface, and engage the system with minimal effort. In addition to ease of operation, each composite sole would use a set of independent microswitches located near the heel. These switches create a simulated "walking" motion for the

astronaut. With each step taken, the switches activate and deactivate the electromagnets, maintaining at least one secure foot at all times. The control system would consist of a “stationary mode” and a “mobility mode.” Depending on the intentions of the user, he or she would select the preferred mode, engage the magnets, and continue with the task at hand.

Meeting NASA Human Factors Requirements

NASA Standard 3000 specifically outlines the requirements for the construction of any space vehicle or equipment that requires human interface. Some of the personal restraint guidelines are listed below.

- Restraint forces shall be reasonably distributed over the body to prevent discomfort and shall not require conscious effort to remain constrained.
- All personnel restraints shall accommodate the specific population of users for whom the system is to be designed.
- The personnel restraint system shall be capable of being cleaned and repaired on-orbit.

Foot restraints are specifically addressed in the document, and the following guidelines were of particular interest to the team:

- All foot restraints shall maintain foot position to allow the crewmember a complete range of motion (roll, pitch and yaw).
- Attachment interfaces for foot restraints (portable-to-portable and fixed-to-fixed) shall be interchangeable throughout the space module.
- The portable foot restraint shall be capable of being installed and removed easily.
- Foot restraints shall be attached or donned with minimum effort.
- Rapid ingress/egress shall be inherent to all IVA foot restraints.
- All foot restraints shall minimize danger of entrapment. A positive means of releasing the foot from the restraint shall be provided.

Figure 1. Load requirement vector diagram for IVA restraint.

Lastly, load requirements were of particular importance to the contacts at NASA. See Figure 1 for an illustration of restraint loads.

- The restraints shall withstand a torsion load (horizontal twisting) of 200 Nm (150 ft-lb) as a minimum with the torsion vector normal to the floor.
- Foot restraints shall be designed to withstand a tension load (vertical pulling) of 445 N (100 lbf) as a minimum.

The proposed electromagnetic design was then weighed against preexisting restraint systems as well as other alternatives, as can be seen in Table 1 below.

Addressing System Compatibility

The team realized that an electromagnetic restraint was an excellent alternative to current designs. If the system should malfunction at any time, the device would fail in a manner that released the user from the workstation with high reliability. This directly addresses and prevents the risk of entrapment. In addition, initial restraint donning time could be significantly reduced, and repeated restraint activation time could be reduced to a fraction of a second. The system also provides a lightweight alternative over the bulky plate restraints utilized currently during EVA, and it interfaces with a wide array of footwear, such as shoes, socks, and/or boots. This is an added bonus when addressing applicability.

Design Type	Cost	Weight	Power Draw	Capable of Mobile Restraint	Time needed to Manipulate	Use Rigidity	Emergency Release Capability	Ease of Operation	Integration Complexity	Load Distributed Evenly	Restraint Continued Unconsciously	
Skylab Grid	-	-	+	+	-	+	-	+	-	+	+	6
Foot Loops	+	+	+	-	+	-	+	+	+	-	-	7
Electromagnetic (non-mechanical)	-	+	-	+	+	+	+	+	+	+	+	9
Pin-attachment	-	-	+	-	-	+	-	-	+	+	+	5
Total +												

Table 1. Comparison of possible systems with respect to NASA Standard 3000 requirements.

SYSTEM DEVELOPMENT

Once a wearable electromagnetic restraint system had been chosen, the team was faced with the challenge of creating a system that was safe, easy to manipulate, comfortable, and that met many, if not all, of the standards set forth in NASA Standard 3000. The foot attachments, or “boots,” were designed concurrently with the supporting electronics system.

Boot Structure

For the structures, recycled high-density polyethylene, a dense plastic resembling Teflon, was chosen as the foundation structure because it was very machinable, relatively cheap, and softer than some other structures. The particular magnets were chosen primarily because they were designed as industrial lifting magnets and would be compatible with many different magnetic or at least ferrous structures. An initial concern with the electromagnetic design was the effects of electromagnetic interference (EMI) on surrounding electronics. Conductive shielding was coated around all noncontact surfaces of the electromagnet to reduce this effect. The first detailed structure design that was chosen can be seen in Figure 2.

Electronics Structure

In the control circuit, a power circuit (12VDC) was operated by an actuating circuit (6VDC) so that high-current and low-resistance power could flow straight to each magnet. A “mode select switch” changed between “stationary” and “mobile” modes by either turning both magnets on or activating control to the microcontroller, respectively. When in mobile mode, a series/parallel

relay was activated that switches both magnets to parallel circuit architecture. This switch allowed for optimum current flow through the magnets regardless of the operating mode. The microcontroller used BASIC code to read inputs from the switches at each boot and activate the magnets accordingly. The code followed architecture as reflected by Figure 3. An important feature of this schematic was the emergency power break switch that, when pressed, cut the power to all circuits in the system, instantly disabling the restraint. The switch did not damage any part of the system, so if the user wished to reactivate the restraint, the switch could be pressed again. Circuit breakers were installed on all primary circuits to account for any possible overcurrent condition from the source or if the electromagnets shorted out.

Figure 2. Final restraint design.

Figure 3. Software decision flowchart.

Failure Analysis

After both initial designs were created, the team outlined a list of failure modes to analyze where the system could possibly fail and potentially improve upon it. This was organized by the use of failure modes and effects analysis (FMEA) charts. It was noted by the team that the majority of failure modes were basic electrical problems (open, short), which could be prevented by robust wiring and construction (such as the use of heat shrink or shielding). In addition, most failure detection methods were reliant on the user to notice the fault. For example, if a fault involved the loss of operation of one magnet, the user's foot would be unrestrained, a condition that is instantly perceptible.

With regard to structures, straps were moved to an attach point within the sole structure to prevent possible detachment. A back plate was added for heel stability. A rubber pad on the lower surface was removed to allow for better magnetic performance due to the smaller gap between the restraint and the restraint surface. The boot was shortened by 1 inch to accommodate for more general foot sizes, and the magnet was repositioned to more closely align with the forward center of mass (Mc) of a 95th percentile man. The standard defined that positioning the magnet 2.5 inches from the back plate would allow the magnet to take all vertical loads absorbed by the standard male (Elenitsky, 2005).

With regard to the control system, the FMEA demonstrated that the system would be more reliable if the microcontroller

Figure 4. System electronics schematic.

were isolated from the stationary mode system. An isolation relay was added to the schematic to accomplish this. After some preliminary testing, it was determined that the microcontroller could not output enough power to actuate the relays, so an inverting transistor array had to be implemented in the control signals. An alarm was added to the programming of the microcontroller to alert the user that the main magnet power was disconnected, which strongly increased detectability of power failures. The final system schematic is shown in Figure 4.

TESTING

When manufacturing of the finalized design was completed, the team began testing the product to determine if the project goals were met. Tests included magnet load capability with respect to effective gap, load performance with indirect load (applying torque to the system), and manipulation times (donning/doffing of the device).

Load Testing

A gap performance test was done to establish a magnet profile for current testing and so that future design changes would be more compatible with surface contact distances. The magnet was activated with thin, calibrated, plastic shims between it and the attractive surface and loaded until failure. Results of this test with respect to theoretical magnetic performance can be seen in Figure 5. It was noted that the selected electromagnet's peak load capacity was less than theoretical, but its performance with respect to effective gap was predictable. This performance is defined by a derivation of Ampere's law combining electromagnetic force and air gap (L^2), shown in the equation below (Underhill, 1914).

$$F = \frac{\mu^2 N^2 I^2 A}{2\mu_0 L^2}$$

Figure 5. Load capability with respect to the electromagnet gap.

Figure 6. Load testing apparatus.

Vertical load tests began by establishing magnet performance while integrated with the sole structure. This was done using a vertical load test bench designed by the team. The boot was activated and attached to an iron-alloy steel plate that was fixed to a movable engine hoist. The magnet (or straps, depending on the test) was then fixed to a ground anchor (see Figure 6). Load capability was measured by increasing tension in the hoist line until the point of magnet detachment, and then recorded.

The second vertical load test verified the normal vertical load capabilities of the electromagnet while integrated in the boot structure. This test was to determine whether the system would meet NASA's requirements for load. The mean of 39.5 pounds-force (lbf) was less than the desired holding force of 50 lbf per magnet, and therefore, it was a requirement not met by the design. It was also noted that magnet strength had been significantly reduced from the results seen during gap profiling (see Figure 5). Because of this result, the team conducted further tests to explore what would reduce the strength of electromagnets theoretically rated at 100 lbf.

The third load test was designed around the team's theory that torque moments from each strap were drastically reducing the magnet's effective holding strength. Instead of placing the ground anchor around both straps, as seen in Figure 6, the anchor was connected to either the front or back and loaded until failure. The test resulted in a significant difference in torque capabilities, as summarized in Figure 7. These results demonstrated to the team that the magnet was not configured in a manner that enabled maximum efficiency because the user was able to apply a greater amount of torque from the front strap than the magnet was able to withstand. This information allowed the team to develop designs that would counteract this result, which are mentioned later.

Figure 7. Torque performance at each strap location—note 95th percentile human center of mass.

Figure 8. Distribution of boot detach times.

Manipulation Testing

The final series of tests were to determine if donning/doffing times of the product met the goals set by NASA and the team. Thirteen subjects were asked to attach both boots while keeping one hand affixed to the boot in air. The test was done in this manner to simulate attaching the boots in a microgravity environment, where the user could not rely on the device to remain stationary while attached. The same test was repeated for the user's ability to remove the restraint. The results of the tests for boot detachment can be seen in Figure 8. The goal of time reduction was to reduce product manipulation by 50%, or 60 seconds. The time distribution demonstrates that the team significantly reduced manipulation time in both the mean and maximum cases by 84% and 69%, respectively, exceeding the team's goals.

Test Conclusions

The reduction in time supported the implementation of electromagnetism into restraint technology, while load capabilities of the magnet demonstrated the need for a different magnet configuration. Observing the difference

in torque from each strap persuaded the team to recommend placing a magnet under each strap, instead of one magnet being under the center of mass of a standard male. This would allow load from the straps to be directly transferred to the magnets without any moment. The team compiled all results and operational testing to compare to baseline data acquired from the customer. It was shown that the current restraint system has a conformity percentage of 40% of total requirements, while the results demonstrate that the team's product meets 90% of system requirements. The requirements and system comparison can be seen in Table 2.

RECOMMENDATIONS FOR FUTURE DEVELOPMENT

Through experimentation and literature research, the team acquired a significant amount of information regarding future changes to the project. The first and most prevalent was the overestimated performance of the electromagnets. When first purchased, the magnets were stated to be capable of lifting 100 lbs of steel. However, during testing, it was demonstrated that only about 60% of this strength was seen. This could have been due to a number of factors, including magnet mating surface condition and other environmental variables. Through testing torque load, the team observed that the magnet being attached to the structure allowed for many additional moments to be applied to the magnet, as demonstrated in Figure 7. The team chose the magnet placement after researching center of mass for a 95th percentile male (Elenitsky, 2005). The center of mass source determined that in order for the magnet to efficiently take loads absorbed by the user, it should be placed 2.5 inches from the back of the heel, very close to where the magnet was integrated. For future

editions of the product, the team decided that having two magnets placed under the strap locations would offer the best performance. Load from each strap would be directly transferred to the magnet without any resulting torque. As with any design, the alternative magnet placement presents issues with strap attach methods and power capabilities, but perhaps electromagnets with different geometry could be chosen to solve those problems.

If this product were to be implemented in the future, the team recommended several material changes that could assist in the integration phase. The team conducted research on soft magnetic composite (SMC) materials, in which soft iron is embedded into composite fabric. This allowed composite structures to exhibit some of the behaviors of common metals. If the core structure of the shoe were switched to SMC, a more complex but aesthetic design could be accomplished out of lighter materials. The floor station or panel would then be magnetized rather than magnetizing the boot (Jack & Hultman, 2003).

In addition, the team was unable to test in real or simulated microgravity environments, so several variables remained uncertain. One variable was the force required to actuate the contact sensors. The sensors apply a back force of several ounces, and while such a small force may be overcome by momentum, theoretically a user is unable to apply any force without some other form of restraint to absorb or redirect that force. The team proposed that the control switches be replaced with ultrasonic or infrared distance measuring equipment. That form of sensor can be compacted to near the size of the contact microswitch, but it requires no actual contact for actuation. Furthermore, the system would eliminate any

Goals/Customer Requirements:	Pre-existing System	Proposed System
Restraint forces shall be distributed over the body to prevent discomfort	Conformance in pin attached method Non-conformance in footloop/bar method	Conformance
System shall not require conscious effort to remain constrained	Conformance in pin attached method Non-conformance in footloop/bar method	Conformance
System shall be capable of being cleaned and repaired on-orbit	Conformance	Conformance
Attachment interfaces for restraints shall be interchangeable throughout space module	Conformance	Conformance
Foot restraints shall be attached or donned with minimum effort	Non-conformance in pin attach method Conformance in Footloop/bar method	Conformance
Rapid ingress/egress shall be inherent to all IVA foot restraint	Non-conformance in pin attach method Conformance in Footloop/bar method	Conformance
All restraint shall minimize danger of entrapment	Non-conformance in all methods	Conformance
Foot restraints shall be designed to withstand a tension load of 100 lbf	Conformance	Non-conformance
Donning/Doffing time shall be less than 50% baseline	120 seconds	Conformance Est. Ave. (95%): 30 seconds

Table 2. Performance of pre-existing system versus proposed electromagnetic system with respect to NASA Standard 3000 requirements.

moving parts, and it could engage the electromagnets at a predetermined distance (instead of 0) to allow for no time delay between foot placement at restraint.

A simulated microgravity test environment would also allow the team to confirm donning/doffing times for the system. During the experiment phase, test subjects were asked to hold on to each boot while attaching it to simulate that in a micro, or sub-1G, environment, the boot might not just stay on the floor or in front of the user. This hindrance did not have a significant effect on manipulation times, but effectiveness of the attach/detach methods as well as the mobility system could be confirmed only through testing in an actual (or better simulated) microgravity environment.

The technology demonstrated in this project could also be utilized to serve areas other than microgravity restraint. The team reviewed other problems presented by the NASA researchers and found that tool handling was an issue, especially during EVA. The electromagnetic device could be used to secure tools to a panel or other surface by means of magnetism. The control system could then be used to sense when a user was attempting to remove or place a tool and enable or disable the magnetic fields accordingly.

CONCLUSION

Because of the nature of a microgravity environment, astronauts who desire to actuate or apply force are required to be restrained. These restraints take time and

attention away from the user, which potentially lead to safety concerns or inaccurate data. It was decided that user restraint utilizing electromagnetic force was a suitable alternative to mechanical means, as the product would fail in a safe manner and allow for near-instantaneous restraint times. In addition, the team developed a novel control system that would allow the user to “walk” while remaining restrained. A prototype was assembled, but initial testing determined that the magnets were not performing to their rated strength because of the torque being induced by the sole structure. However, the measured time required to don the system and quick release function performed as NASA requested. In addition, the mobility function that the team created could revolutionize astronaut capabilities. The team used data from these experiments to draft new designs that would maximize magnetic performance in future versions. While the team failed to achieve the goal of meeting all of the requirements set forth by the customer’s standards regarding manned spaceflight, the team did accomplish an accessory goal, which was to develop a technology demonstrator. The system performed as designed, and it simply needed minor enhancements to accomplish all goals and requirements. When and if future parties are capable of obtaining more resources than were available to the team, the data and designs gained from this project can be used to accelerate future technologies in the field of manned space exploration.

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Figure 9. Final operational system prototype.