SpaceHuman: A Soft Robotic Prosthetic for Space Exploration

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Abstract

The project focuses on the human centered design approach for aiding crewed space operations in microgravity. The key element is enhancing the floating experience, while enabling humans to adapt in microgravity environments. The metaphor of the undersea world inspired the design of a body extension that can complement the interiors of Zero-G habitats. The analysis of the unique seahorse's tail structure became the insight into the overall biomimetic design. In fact, a seahorse tail enables movement, gripping and protection to the seahorse while floating. SpaceHuman is an additive prosthetic that can move around the body to grasp objects and handles in microgravity, protecting the wearer from injuries that might occur while floating in a confined habitat, while providing an adaptable and kinematically stable base. SpaceHuman has been designed through different computational design methods, to simulate its behavior in microgravity, and has been worn and tested on a Zero-G flight.

Author Keywords

Human Space Exploration; Biomimetic Design; Microgravity; Additive Prosthetic; Wearable Soft-robotic Device.

CSS Concepts

• **Human-centered computing~Human computer interaction (HCI)**; *Haptic devices*; User studies; Please use the 2012 Classifiers and see this link to embed them in the text:
https://dl.acm.org/ccs/ccs_flat.cfm

Introduction

The SpaceHuman project arose from the vision of a possible future in which humans will commonly live and work in space. This scenario requires, indeed, a deep insight in our design thinking today to enable a change and create an impact for human space exploration and better coping with the challenges implied by zero gravity environments. This work is an attempt to formulate a hypothesis about the possibility that in the future the human species will face a new great migration, but this time beyond the confines of our planet. Therefore, some questions arise. How will our habits and behaviors change? How should we reconfigure our physical structure to respond to the various gravity fields that we are going to experience?

SpaceHuman: a biomimetic design

On Earth, the configuration of our body responds exactly to the laws of gravity. Bipedalism is the main distinguishing feature of the human race and is characterized by a narrow base of support and an ergonomically optimal position thanks to the appearance of lumbar and cervical curves [5,7]. Here on Earth our body is our main reference system; in fact we can clearly distinguish what is above what is underneath, what is on our right and what is on our left. Our eyes, through their alignment and the image

Figure 1: Flyer floating in microgravity with SpaceHuman during a Zero-G flight parabola (Photographer: Steve Boxall).

Figure 2: SpaceHuman spatial configuration while floating with the user in micro-gravity. While floating, the gravity line does not assume its regular conformation since the main element defining it has disappeared.

processing capabilities of the brain, determine the distance and orientation of the horizon. In the absence of gravity, where some of the laws of statics and physics are altered or fail, our body no longer has this precise reference system. Lacking this reference system, the validity of the environment that surrounds us also disappears, and we no longer know nor, above all, need a floor or ceiling; our body is transformed into a floating element in a space no longer defined by the laws of gravity. Therefore, for adapting to a radical and sudden change in environmental conditions, we need to adopt a disruptive design response in order to address these new needs and requirements for sustaining human life in space. Indeed, the need to act on the body itself, perhaps providing an extension, seems an appropriate response to allow the exploration of such an extreme and unusual environment in a complete way, without leaving uncovered or exposed areas that will be essential for navigating reduced gravity environments [3,4,10].

Undersea world inspiration

The underwater environment, also used by NASA researchers and scientists to demonstrate their experiments on zero gravity simulations, is the perfect setting to observe floating organism and from which to take inspiration [8, 16]. In this case, among all the marine creatures that use their tail for swimming, the seahorse stands out. It has developed an extension of its body that does not perform solely the function of rudder or propeller for swimming. Indeed, seahorses use their tails to grasp objects in their environment while they camouflage to hide from predators and hunt for prey. Flexibility and resiliency are key features that enable these behaviors. The same features became the key aspects to implement and develop in a physical body extension that enhances body movement, gripping, and protection in microgravity. The analysis of the performances of a seahorse tail was studied in detail thanks to a research on "Why the seahorse tail is square" published in 2015 on the journal Science by Michael M. Porter, Dominique Adriaens, Ross L. Hatton, Marc A. Meyers and Joanna McKittrick [13].
SpaceHuman is therefore an additive prosthetic or otherwise definable as a "supernumerary robot".
SpaceHuman will be able to facilitate the use of space in zero gravity or reduced gravity by restoring the right motion and balance of our body and assigning a new function to a part of our body that until now has not been fully exploited [1,6,11]. Through air chambers specifically designed to be able to change their shape and bend along a reinforcing rib of the material, the astronauts and space tourists who will use SpaceHuman will be able to cling to useful surfaces inside orbital housings or in Lunar or Martian villages.
Each air channel is fabricated from a thin silicone layer that gives a great deformability. The morphology variation occurs through the inflation of these air chambers that are divided into three macro sections; each of these sections has 4 aligned elements of the same size, for a total length of 1.4 m (Figure 2). The subsequent sections have, respectively, a dimension equal to ¾ and ½ of the initial one. These air chamber lines are connected to air pumps that are activated following the behavior of the user's body and the surrounding environment. The various sections can swell independently and along one of the three lines, thus allowing the tail to obtain multiple configurations (see also Figure 3).

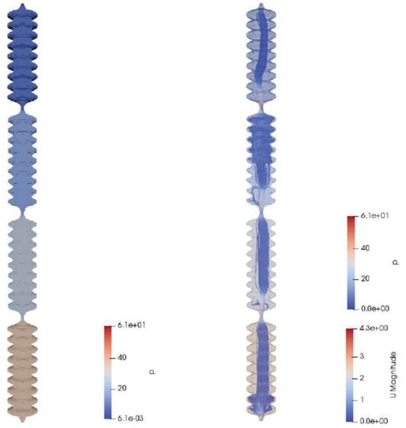


Figure 4: Computational Fluid Dynamics simulation results of SpaceHuman air chambers performed thanks to the coupling between OpenFOAM© Library and Grasshopper©.

State of the art

The main inspiration was derived by reviewing the actual Body Restraint Tether device with astronauts, described in Extravehicular Activity Operating Procedures (ESOP) for Astronauts [20]. The body-restraint tether (BRT) is a flexible 30-inch-long network of fabric-covered cables and ball joints that lock the astronaut's upper torso to a system of handrails installed around the station and is part of Space Exploration Equipment and Tools developed by NASA. However, the BRT system doesn't allow automatic activation and rigidity as it is not a robotic body extension. Also, it is mainly used for extra-vehicular activities (EVA) such as spacewalks and not for improving the operations inside the spacecraft. Researchers at the NASA Johnson Space Center (JSC) in collaboration with General Motors (GM) have designed and developed Robo-Glove, a wearable human grasp assist device to help reduce the grasping force needed by an individual to operate tools for an extended time or when performing tasks having repetitive motion. There is some prior art in soft robotics [15] for space exploration, such as the "Spatial Flux: Body and Architecture in Space" project developed at MIT Media Lab by researchers Chrisoula Kapelonis and Carson Smuts. The Space Flux project is based on the idea of a temporary architecture that coexists with the body. Through air chambers and pumps that activate the inflation of the structure, the user is trapped in the arms of the robot and can enjoy his or her own rest without the fear of floating freely in space [9]. Another example of shape-changing interfaces through pneumatically-actuated soft composite materials is PneUI, a project designed by MIT Media Lab and MIT EECS researchers [19]. The shape changing states are computationally controllable through pneumatics and pre-defined structures that lead to main four applications: height changing tangible phicons, a shape changing mobile, a transformable tablet case and a shape shifting lamp. Other tail inspired projects include “Arque: Artificial Biomimicry-Inspired Tail for Extending Innate Body Functions”, developed at Keio University Graduate School of Media Design by Junichi Nabeshima, Kouta Minamizawa, MHD Yamen Saraiji. However, this tail concept configuration is not meant to work in reduced gravity or in microgravity for human space exploration [12].

Computational performance based design

The SpaceHuman project has been entirely designed using computational design methods in order to achieve a high-performance solution. Different digital simulations have been performed using Finite Element Models directly associated to the parametric model of the tail structure. SpaceHuman consists of a trio of ribbed tubes made of translucent, flexible silicone. The ribs are actually 36 air chambers that can be inflated in different configurations by 12 battery-operated air pumps attached to a belt causing the tails to curve or lengthen in reduced gravity conditions (Figure 5). Air chambers sizes, membrane thickness as well as their assembly were parametrized to obtain a flexible computational model that led to optimization processes during the design phase and an ease of prototyping during the fabrication process. Fluid Dynamics simulation has been performed in order to optimize the dimensions and shape of each set of air chambers while evaluating the pressure differential inside them. The geometrical model has been parametrically coded in Grasshopper© [17] and, thanks to Butterfly plugin that utilizes OpenFOAM© Library, it has been converted into a FE Model able to simulate the airflow inside the

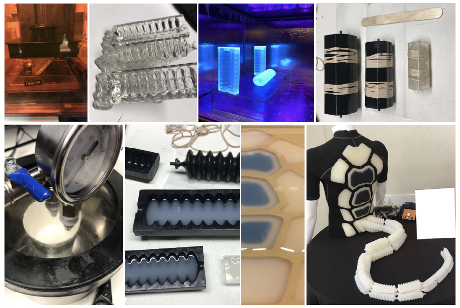
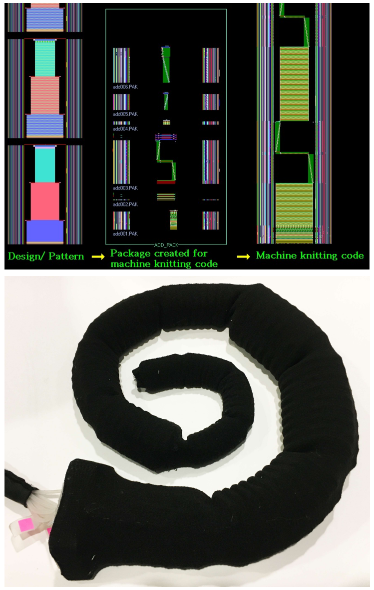


Figure 5: SpaceHuman fabrication steps and the prototype: 3D printing and curing of the molding, making of the silicon, casting and curing of the silicon, final assembly of the overall structure.



different air chamber sections. The algorithm allows to compare almost in real-time the deformations associated to different spatial configurations of the tail with their airflow (Figure 4). In particular, SpaceHuman is designed considering four chambers for each set to be inflated by each pump with a different flow rate and inflation time period. For the biggest air chambers, between the first and the last one, the results show a difference of about 80 Pascal. Therefore, this value has been used in the FE Model for analyzing the structural deformation of each air chamber membrane. This analysis gave the possibility to evaluate the behavior of the overall structural performance also considering different reduced gravity load conditions (lunar, Martian and microgravity).

SpaceHuman, being a soft-robotic wearable device, had to fulfill some requirements mainly given by the safety standards for the Zero-G flight and the overall comfort of the user. Silicone has been considered the preferred material not only for its ability to deform easily but also for being lightweight and extremely soft to wear. The fabrication process required several phases, mainly subdivided in the three main components of the prototype: air chambers, back protection, and cover sleeve. Fabrication of the air chambers required a set of 3D printed molds in which the silicone was poured and cast. In detail (see Figure 5 and 6), the process was: 3D printing of the and curing of the molds; degassing mixed silicon components; pouring Ecoflex 00-30 into the two part mold; extracting the cured silicone from the mold. The back protection on the wearable suit has been obtained by milling MDF sheets with a CNC machine, pouring Ecoflex 00-50 silicone into a mold and curing it. The machine knitted sleeve has been computationally designed through a professional software, provided by Shima Seiki, that allowed the definition of a specific design pattern for achieving a seamless uniform elasticity around the air chambers, for the entire length of the prosthetic, while enhancing the spatial deformation (Figure 6). Indeed the chosen knitting pattern was optimal to let the air chamber cross sections expand while keeping the length constant. Therefore, the textile sleeve is stretchable mainly along the tail cross sections allowing its deformation while containing the air chambers together.

Zero-G flight experiment

The prototype has been tested with different gravity conditions (microgravity, lunar and Martian gravity) in order to assess its performances in a simulated space environment (Figure 1). During the Zero-G flight, SpaceHuman has been tested as a choreography, meaning that each parabola had a predefined inflation combination. The reason of that choice relied mainly on safety, as the flyer was not an expert, and on specific research goals. Indeed, the authors prioritized the understanding of the microgravity floating experience with and without this soft-robotic prosthetics to understand the feasibility of democratizing the access to space to civils that don't have any astronaut training. In fact, during the parabolic flight, the no-expert flyer used a wearable bio-sensing tool in order to correlate the SpaceHuman performance with real-time physiological biomarkers, with an Empatica device E4, that showed the different stress levels during each parabolas. Moreover, given the fact that the combinations were set in advance for each parabola, the authors had the possibility to compare the numerical testing of the design phase with the flight recorded data related to each deformation of the tail. The authors are planning future Zero-G flight

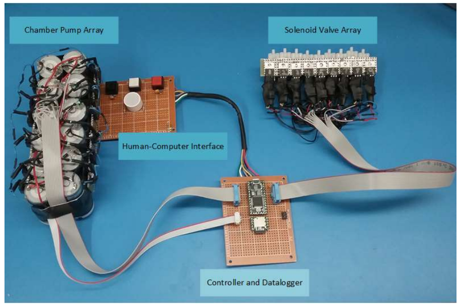


Figure 7: Electronics and Controls in the actual implemented version for the SpaceHuman Tail.

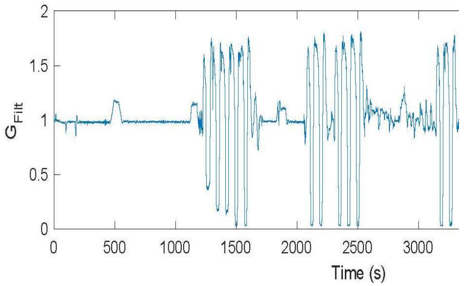


Figure 8: first G-levels (filtered) during the Zero-G flight experiment. In sequence: one Martian gravity parabola, two lunar gravity parabolas followed by several microgravity parabolas.

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experiments in which the tail will focus on reaching and grabbing specific targets thanks to an object tracking camera located on flyer's back.

Controlling the behavior of SpaceHuman during the Zero-G flight is accomplished by selectively inflating various combinations of chambers within a predetermined timing sequence. During each parabola the flyer manually activated a specific combination. To accomplish this, the controller activates pumps and controls solenoid valves to direct the airflow from inflating to exhausting the chambers. User interface was designed to be minimal, yet informative, to allow the user to easily execute experiments while in Zero-G and also know which tail sequence was on deck to deploy (Figure 7). In order to mimic a biological system, tail sections are inflated and exhausted in sequences to create an organic movement. In addition to certain combinations of large, medium, and small chambers being inflated (base, middle, and tip of the tail, respectively), there is also a distinctive timing characteristic that attempts to mimic a tentacle or seahorse tail movement. In particular, the base begins inflating first, followed by the mid-section, then the tip of the tail. Upon starting a sequence, the large chamber begins inflating immediately.

Results and future work

During the parabolic flight, a sequence of one Martian gravity parabola, two lunar parabolas, and 17 microgravity parabolas were performed. Figure 1 shows a flyer wearing SpaceHuman during a microgravity parabola. The prosthetic was acting as a propulsion system for changing the flyer orientation. The G-levels of the flights are represented as peaks (1.8g) in the graph below (Figure 8) where it is clearly recognizable as the hyper-gravity period before each parabola duration (0g). In the future vision in which our body will be the main control system of SpaceHuman, an in-depth analysis of flyer's physiological response correlated to the tail movements will be necessary to understand the level of comfort of the wearer. The results of this performed Zero-G flight showed an higher flyer's heart rate in correspondence of every hyper-gravity phase prior each reduced gravity parabola and some peaks when certain tail movements suddenly changed flyer's orientation in few seconds. The authors assume that an experienced flyer would have had probably a more relaxing experience.

Conclusion

The SpaceHuman project is an example of the evolutionary answers to the various low gravity environments that we are going to face, explore and live in the future. In the short term, according to different NASA and ESA astronauts' expertise, this project could become an extremely relevant asset to enhance stability and safety in microgravity and reduced gravity conditions. In particular, it could be used for gripping onto scientific racks and could be directly tested on the actual International Space Station, enabling mobility and motion through a microgravity habitat chamber, providing an "extra hand" to accomplish different tasks while avoiding injuries. In the long term, the SpaceHuman could evolve as an essential wearable soft-robot prosthetics that could also be connected to a spacesuit for facilitating safer EVA and spacewalks. Last but not least, it could give a contribute along with the vision of democratizing the access to space, enhancing the possibility of space tourism and research opportunities "on the field" for people without a specific astronaut training.

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