

# **Integrating Supernumerary Robotic Limbs onto the xEMU spacesuit to enhance Astronaut capabilities and efficiency in Extra-Vehicular Activities**

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Extra-Vehicular Activities (EVAs) are considered one of the most complex operations an astronaut can perform during a spaceflight mission. Coordinating and executing EVAs are complex and costly affairs that are a necessity for any space vehicle; this is especially true for expanding the longevity of a spacecraft, like that of the International Space Station (ISS). A key challenge in planning EVAs is the amount of time an astronaut has to complete a series of tasks, which is inversely related to their metabolic load. Prior studies have determined that the biomechanics of a spacesuit wearing astronaut play a significant role in their metabolic load. In addition to this concern, another key challenge for astronauts conducting EVAs is to have access to a rigid tether to enable them full access to both of their arms when conducting a specific task. We propose the incorporation of a pair of wearable robots, called Supernumerary Robotic Limbs (SuperLimbs), which would be mounted on the xEMU's Square Boss Interface (SBI), positioned such that each SuperLimb is on either side of the astronaut's center of mass. The use of SuperLimbs during an EVA allows the astronaut to safely and efficiently move across a spacecraft in EVA. The SuperLimbs grab EVA handrails for securing the astronaut's body, and guide the astronaut from one work location to another (thus reducing their overall work load). The incorporation of SuperLimbs onto the xEMU spacesuit forms a cooperative human-robotic system that can be modeled as a quadruped with two human arms and two SuperLimb grippers. Trajectory planning and control algorithms are developed as a quadrupedal locomotion problem, where the SuperLimbs act as followers while the astronaut operator is the leader. Furthermore, the quadruped human-robot system enables multiple points of contact at any point in the EVA, creating a secure bracing condition for the astronaut user that enhances both stability and controllability.

CCS CONCEPTS • Human-centered computing • Human-intention detection • Human-Robotic Leader-Follower cooperative locomotion

**Additional Keywords and Phrases:** Space robotics, Supernumerary Robotic Limbs, Quadruped Locomotion, Trajectory Analysis, Zero-gravity bracing

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Figure 1: Front (left), Right (center), and Top (right) view of the xEMU/Supernumerary Robotic Limbs integration concept

## 1 INTRODUCTION/MOTIVATION

Extra-Vehicular Activities (EVAs) are considered the most complex and costly operation that can be conducted during a spaceflight mission. These operations are a necessity in spaceflight operation because *human spaceflight systems are inherently complex and require direct human intervention in order to be maintained*. An entirely separate discussion can be made on the complexity of a human-supported spaceflight system, like that of the International Space Station (ISS) over that of a Mars Rover. Regardless, stakeholders, like that of NASA, ESA, etc. must accept significant costs/risks with each EVA operation that is carried out. The follow section describes key areas of improvement that can be addressed with the to-be proposed solution.

### 1.1 Metabolic Load Mitigation

A key area of improvement that is actively being researched by space agencies, like NASA, are that of maximizing the allowable time a single EVA can be conducted [1]. By maximizing the allowable time an astronaut has, more tasks can be performed in a single EVA and the safety margins in terms of oxygen capacity are expanded. The constraint that limits allowable EVA time is directly related to the metabolic load induced by the spacesuit-wearing astronaut [2,3]. We can claim *solutions to reducing the biomechanics of an astronaut in an EVA are highly effective in expanding allowable EVA time*.

### 1.2 Rigid Tether Utilization

Current industry practices require astronauts to use one of their arms as a brace while using the other to perform a task in microgravity environments [1]. This practice clearly shows an undesirable working condition for any astronaut, as this can provide an inefficient working configuration that can consequentially increase metabolic load, general strain, and task time. There are however, unique solutions that do exist as rigid tethers provided to astronauts. One of which is use of a portable rigid tether, which can be cumbersome to carry around, while the other is cooperation with the Remote Manipulator System (RMS), which can be physically limited and time consuming to orient correctly [4].

### 1.3 Lifting/Support Assistance

One common task that can be expected in planetary EVAs is that of lifting objects. Obviously, the act of lifting and holding an external object warrant increased metabolic loading. Through analysis of human performance, lifting an object by the arms introduces moments, which requires strength to overcome. This balancing act consequentially increases metabolic loading. Another common task that can be expected in a given planetary EVA is that of kneeling and standing. We can expect astronauts to frequently lower themselves to the ground to closely examine or work on some external object. The act of kneeling and standing requires an astronaut to overcome the weight and spacesuit physical constraints, thus resulting in increased metabolic load [2,3].

## 2 INTEGRATION OF SUPERLIMBS ON THE XEMU SPACESUIT PLATFORM

We propose the incorporation of wearable robots, called Supernumerary Robotic Limbs (SuperLimbs), onto NASA's next generation spacesuit platform, the xEMU, to dramatically expand the capabilities of astronauts in EVA (see Figure 1). For example, on the ISS, astronauts must physically move themselves between worksites by use of EVA handrails positioned throughout the exterior; with SuperLimbs, the act of transfer operations can be completely offloaded from the astronaut. The SuperLimbs autonomously/cooperatively grab the EVA handrails and move the astronaut towards the desired worksite. Both hands of the astronaut are available for conducting a mission, rather than holding a handrail. The use of SuperLimbs provides astronauts with the capability of a portable rigid tether anywhere on the ISS, improving worksite ergonomics.

Additionally, SuperLimbs can provide significant benefits to planetary EVA operations. The metabolic loading and general strain from lifting, kneeling and standing can be significantly mitigated by the incorporation of SuperLimbs on the xEMU. The SuperLimbs can provide the astronaut with a second set of appendages that can grab and hold an external object, whereby on that same notion, the SuperLimbs can also help an astronaut lower/raise themselves without much physical effort from the astronaut. The SuperLimbs may also be able to provide additional key benefits not yet discovered until planetary EVAs become a reality and more areas of improvement can be identified.

### 2.1 Mechanical Interface

The xEMU spacesuit contains a Square Boss Interface (SBI) located around the waist of the spacesuit. This specific interface is designed to allow any external tools or attachments to be mounted to the spacesuit [5]. We plan to install two SuperLimbs on either side of the SBI so that it can be assured to hold a handrail with at least one SuperLimb at all times during a transition to another handrail.

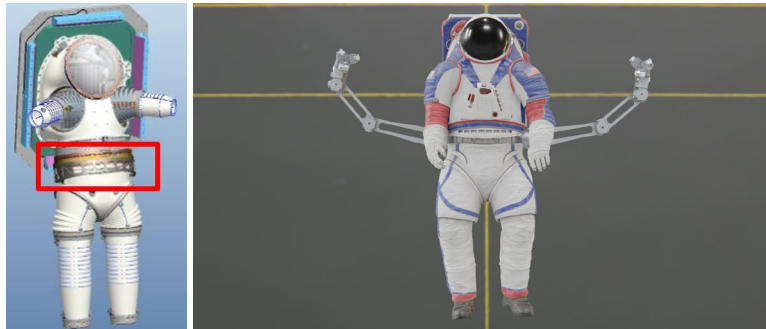


Figure 2: Location of the SBI on the xEMU [5] (left) and SuperLimbs attachment on the xEMU (right)

### 2.2 Human-Intention Detection

In order to establish an effective human-robotic leader-follower relationship, we must develop a methodology for allowing astronauts to command the SuperLimbs in a natural and intuitive manner to achieve a desired task. For this specific application, we took inspiration from how astronauts propel themselves during Intra-Vehicular Activities (IVAs) [6]. They simply push or pull handrails towards the direction they want to move. When the astronaut does the same while the SuperLimbs are holding handrails, the SuperLimbs feel some force and moment acting at their bases and the endpoints. Measuring these force and moment the SuperLimbs can detect the intention of the astronaut as to which direction he/she wants to move. See Figure 3. These signals can be then directly translated into a control command for the SuperLimbs.

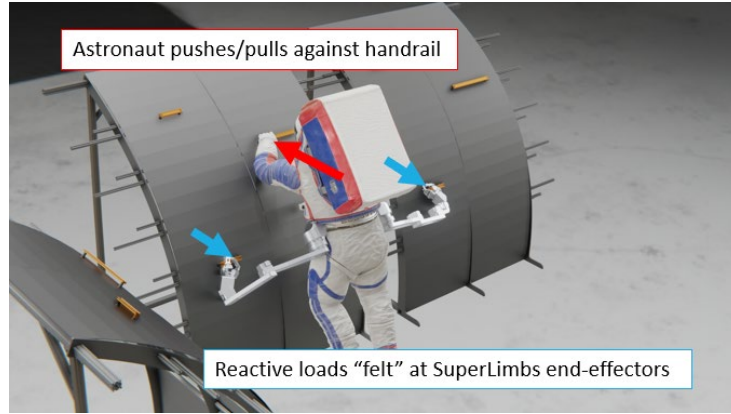


Figure 3: Human-Robot Interaction scheme for Human-Intention Detection

### 2.3 Human-Leader, Robot-Follower Cooperative Locomotion and Task Planning

In order to create autonomous, cooperative movement from the SuperLimbs, we model the astronaut-SuperLimbs system as a quadruped consisting of two SuperLimbs and two human arms. The quadruped structure allows for stable, secured bracing of the astronaut. While the astronaut-SuperLimbs system moving across the outside surface of ISS, for example, the four limbs are coordinated by holding handrails in an optimal sequence so that it can move towards a desired direction and securing bracing the body at all times. We treat the human arms as a leader and the SuperLimbs as a follower in coordinating the four limbs. We can solve the statically stable system (given a transient pose) with a space of possible solutions to move/orient the astronaut's COM in a desired direction (stable push). Each pose taken after each subsequent infinitesimally small movement can be also solved as a series of stable pushes and strung together to create the overall trajectory [7]. With the incorporation of optimization parameters subject to operational constraints on the SuperLimbs (keep-out-zones, singularity avoidance, etc.), the space of possible solutions for each transient pose reduces to an optimal solution. Additionally, the contact state plays a crucial role in task planning for the trajectory. Certain contact states (point contact, line contact) reduce the overall controllability of the system and should be avoided whenever possible.

## 3 FORWARD ACTIONS

Figure 4 shows an ISS Exterior Section Mockup for early-stage evaluation and testing of the proposed approach. To understand the Human-Robotic relationship, we must be able to properly map measured changes in forces/moments within the SuperLimbs in a given arbitrary configuration with a desired velocity by the astronaut. As mentioned earlier, performing a static balance of the closed-loop kinematic chain can satisfy this mapping. However, due to the unique application of human-in-the-loop input and response, a physical experiment needs to be conducted to validate the theoretical principles. To conduct this experiment, we developed a full-scale mockup of an external surface expected on the ISS as well as that of the SuperLimbs rigidly attached to a human subject. On the ISS mockup, handrails subjected to geometry as defined by the Human Integration and Design Handbook (HIDH) are equipped with load cells at the bases where they mount to the structure [8].

Likewise, the interface between the base of each mockup SuperLimb and that of the human are instrumented with load cells. Experiments are expected to be conducted in the coming months. The measured changes in forces with that of prescribed loads from the human subject can be compared against the theoretical framework established. Pending results from this experiment will help dictate which areas to address in the design of the control input taxonomy.



Figure 4: ISS Exterior Section Mockup (left), mounted EVA handrail (center), and SuperLimbs mockup (right)

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