# ORBIT: Orbital Repairs By Innovative Technology

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## Abstract

The University of Maryland's Space Systems Laboratory has a long history with multiple design projects for small single-person spacecraft (SPS) intended for extravehicular operations. Since the SPS concept has been criticized as differing from teleoperators, suited-missions, and other space utility vehicle (SUV) models only by the ability of the operator to have direct vision ("eyes-on") of the worksite, "hands-on" interaction with the worksite, and simultaneous use of robotic arms. Testing will focus on identifying performance differences between the methods. To quantify effectiveness for each option, we performed a Fitts' Law tapping task in three hands-on environments: shirt-sleeve, space-suit arms, and SPS suit-arms, as well as two robotic control environments: one with direct eyes-on vision, and one using video screens for teleoperation. After each series of tasks, participants completed a short survey including the NASA Task Load Index (TLX) as well as a Cooper Harper rating. We hypothesized that a combination of hands-on control and eyes-on robotic control will be the most suitable design for an SUV. Experimentally, we found that within the hands-on control environments (shirt-sleeve, suit arms, SPS arms), there is not much variation in task difficulty, but that these environments were much easier to control than the robotic control environments. Among the robotic control environments, subjects performed better overall when using direct eyes-on vision, as opposed to teleoperation. Our findings suggest that combining eyes-on and hands-on interaction is both important and significant in SPS design and handleability.

**List of Abbreviations**

DOF = Degrees of Freedom
ERA = European Robotic Arm
EVA = Extravehicular Activity
HCI = Human-Computer Interaction
ISS = International Space Station
LEO = Low-Earth Orbit
MMOD = Micrometeoroids and Orbital Debris
NASA = National Aeronautics and Space Administration
NASA-TLX = NASA Task Load Index
ORU = Orbital Replacement Unit
RHC = Rotational Hand Controllers
SCOUT = Space Construction and Orbital Utility Vehicle
SPS = Single Person Spacecraft
SRMS = Shuttle Remote Manipulator System
SSRMS = Space Station Remote Manipulator System
SSL = Space Systems Laboratory
SUV = Space Utility Vehicle
WEI = Work Efficiency Index

# 1. Introduction

## 1.1. Motivation

A crucial component to space exploration is the use of extravehicular activity (EVA), where an astronaut must leave the shuttle or space structure and complete specific tasks attached to a tether on the shuttle or structure. While EVAs are important to the upkeep and function of any particular space vessel, executing an EVA is costly in multiple ways. The preparation necessary to perform an EVA is time-consuming, as are the post-EVA procedures. Astronauts must also mentally and physically prepare themselves to face the harsh conditions of space.

If humans are to continue exploration into space, it is clear that a new form of performing EVAs is needed. The overly taxing process of performing EVAs has been of great concern for researchers, as there is a desire to prevent and lessen the risk of accident while an astronaut is outside the confines of their vessel. It is essential that a safer way of performing EVAs be found and implemented so that astronauts are able to complete their tasks with less overhead and lower safety risks.

## 1.2. Introduction to and Current State of SUVs

One possible solution to making EVAs safer for astronauts is using a single-person space utility vehicle (SUV), a spacecraft concept aimed at limiting the risks associated with EVAs. The concept of using an SUV to improve the efficacy and quality of EVAs is a novel approach to assist astronauts in the ISS and other potential host vehicles. Extensive theory has been developed by Dr. David Akin of the Space Systems Laboratory (SSL) at the University of Maryland. The Space Construction and Orbital Utility Transport (SCOUT) is a single-person spacecraft (SPS) concept developed at the SSL as a potential alternative for EVAs [1].

FlexCraft is another example of an SPS. This concept is currently under further development for future flight tests in order to prove that the SPS is a better option than spacesuit for EVAs. Completing tasks in the FlexCraft resulted in better efficiency and safety when compared to regular spacesuits. The use of a SPS means that there is no need for pre- and post-mission procedures for the astronauts, effectively saving the 12 to 16 hour time needed to prepare the astronaut [2].

Current SUV designs revolve around the concept of protecting an astronaut from the hazardous space environment, resulting in designs where an astronaut will be able to exist in a small, fully encapsulated, single-person, shirtsleeve environment. SUV designs include other general features including a means of direct external viewing (e.g., windows or transparent dome) and controllable, dextrous robotic manipulators, the focus of this research project, for the completion of tasks during an EVA.

However, outside of Dr. Akin's research, there has been little development in the field of space utility vehicles. Some companies have attempted to design an SUV, but no model has been fully manufactured and validated for flight. Genesis Engineering Solutions, Inc. filed a patent application for an SUV concept [3], but have yet to produce a complete vehicle for testing.

### 1.3. Research Goals

This research project aims to explore the differences between the aforementioned SCOUT and FlexCraft concepts in order to produce a valid, well-tested alternative to current methods of performing servicing missions from the exterior of the host vehicle. The SCOUT vehicle has spacesuit-type arms attached to its structure, allowing the operator to directly interact with the worksite. Additionally, this SPS concept has robotic manipulators that the operator can use to supplement their activity at the worksite. This would require a unique method of control that will allow the user to have their hands in the suit arms while simultaneously guiding the robotic manipulators about the worksite. However, the FlexCraft design concept lacks these integrated suit arms, so the user is free to utilize standard hand controllers to move the manipulators. This research project aims to weigh the benefits of each design against one another.

# 2. Literature Review

## 2.1. EVAs and In-Orbit Activity

### 2.1.1. Pitfalls of EVAs

There have been at least two humans aboard the International Space Station (ISS) every single day from November 2nd, 2000 onwards [4]. As humans continue to expand their presence in low-Earth orbit (LEO) and beyond, the upkeep of the structures they inhabit grows ever more important for sustaining long-term human activities. While maintaining the ISS is primarily accomplished inside the habitat, it is not uncommon that such tasks would call for an astronaut to perform an extravehicular activity, commonly referred to as a spacewalk.

An EVA is defined by the United States' public space agency, the National Aeronautics and Space Administration (NASA), as "any activity performed by a pressure-suited crewmember in unpressurized or space environments" [5]. An excursion of this nature is an extensive, time-consuming process. The astronaut needs to ready their body for the harsh environment waiting for them beyond the confines of their in-orbit residence, and vice-versa as they re-acclimate to their shirtsleeves environment. Examining data from Expeditions 28 through 55, a period of roughly seven years, it has been calculated that, per EVA, an average of 23.1 hours are devoted to preparation, while an average of 7.4 hours are utilized for post-EVA activities [6]. Nearly an entire day of operations are lost in preparation for an EVA, inhibiting progress in scientific experimentation or other essential tasks aboard the station [6]. Additionally, the length of the preparation period for an EVA makes extremely time-sensitive emergency repairs impossible to perform without risking the safety of the astronauts involved.

An excursion in the outer-space environment also exposes astronauts to health risks. Since spacesuits typically operate at reduced pressure (4-6 psi) and 100% oxygen atmospheres to reduce loads on the wearer and simplify the life support system, astronauts are required to prebreathe before venturing outside of their vehicle. Prebreathing is the process by which astronauts deplete the nitrogen levels in their bloodstream by cycling pure oxygen through their respiratory system in an attempt to avoid decompression sickness, also known as the bends. Decompression sickness affects the musculoskeletal system and the central nervous system, either individually or together, and can cause numbness, tingling, joint pains, brain dysfunction, and even death [7]. Another risk associated with a human operating in the space environment is that of radiation exposure and micrometeoroids and orbital debris (MMOD). Exposure to radiation from cosmic rays and solar particle events can affect an astronaut's central nervous system and increase their likelihood of cancer-induced death [8]. MMOD have the potential to puncture a spacesuit, inducing depressurization that would be fatal to the astronaut [9]. Although the current survival rate of EVAs is 100 percent, a better method could be devised for protecting an astronaut from harm while operating in the space environment.

These aforementioned issues with performing maintenance EVAs are indicative of the need for a technology that accounts for and severely diminishes the risks, while also boosting mission efficiency.

### 2.2. Single-Person Spacecraft

The idea of a space utility vehicle was developed as a potential solution to the glaring issues with the current methodology for conducting a spacewalk. This vehicle concept has the theoretical benefit of being operated from a pressurized crew enclosure that acts as a space suit replacement, meaning there would be no need for the astronaut to perform a spacewalk [10]. By completing tasks from inside a SPS, time devoted to the task will decrease as the pre-procedures traditionally performed for an EVA are unnecessary. Included in the SPS is a cockpit outfitted with displays and controls which provide information to the crew during missions, further decreasing the time needed for the tasks [10].

Genesis Engineering Solutions, Inc. gives a detailed list of preliminary necessary SPS features that they have explored, including features such as an external bay to hold equipment, a berthing and docking mechanism, and a sun visor [11]. Additionally, in their guidelines for a design competition, they assert that the SUV should be able to accommodate users from 5th percentile females to 95th percentile males [12]. The vehicle must also maintain a suitable cabin atmosphere; often the SUV's atmospheric pressure and composition are consistent with those of either the spacecraft it will operate alongside or those of conventional spacesuits. Additionally, navigation, life support, and emergency safety systems must be implemented, and all of the above necessitates an onboard battery-powered system [1]. A service panel with inputs and outputs for servicing oxygen, nitrogen, water, and power levels is also necessary [11].The absence of gravitational forces will cause the crew member's body to shift into a natural weightless position. Weightless crew restraints are needed to keep them in place as they will be unable to remain in a seated position. Dr. David Akin and Dr. Mary Bowden's *Human-Robotic Hybrids for Deep Space EVA: The SCOUT Concept* outlines that the exterior of the vehicle should feature protection from MMOD and solar radiation [1]. It will also need a propulsion system for transit to and from the worksite as well as general maneuvering in space; both hydrazine monopropellant thrusters and pressurized nitrogen cold-gas propulsion have been proposed for this purpose. SUVs proposed for EVA often also feature the ability to interact with objects outside the vehicle via robotic manipulators or spacesuit arms and gloves attached to the hull of the vehicle.

#### 2.2.1. FlexCraft

The FlexCraft vehicle is a concept that has been developed and tested in order to prove the single person spacecraft is a better option than spacesuits for crew members to perform spacewalks. It is a single-person SUV with a cold-gas propulsion system for local maneuverability, and a life-support system to support one to three day sorties, depending on the battery power [13]. This vehicle integrates the use of robotic arms, but does not have EVA arms and gloves. Completing tasks in the FlexCraft has many benefits compared to in a spacesuit, including time, efficiency, and safety. The overhead time of an EVA requiring a spacesuit is between 12.5 and 16 hours [2], due to extensive pre- and post-mission procedures to prepare the astronaut. However, these procedures are not necessary if the tasks are completed within the FlexCraft, effectively decreasing the overhead time to less than one hour. A work efficiency index (WEI) is a common standard that measures and calculates EVA efficiency, as it specifically measures the task time divided by the overhead time. A promising WEI would preferably be a larger number [2]. FlexCraft has a WEI of 12, dwarfing the 0.39-0.43 efficiency rating of spacesuits [2]. While on spacewalks, astronauts are exposed to radiation and MMOD as well as experiencing fatigue, abrasions, bruises, and occasionally decompression sickness [10]. The FlexCraft offers a safer environment for the crew members, as they are more protected from solar radiation and MMOD, and have the opportunity to get food and water as well as use the restroom if needed.

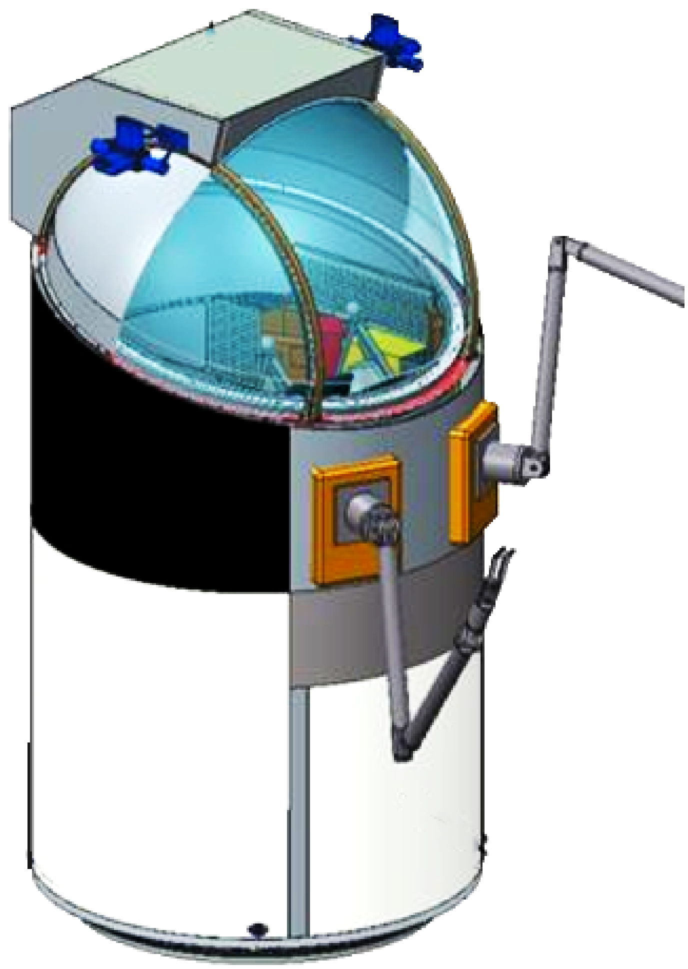

*Figure 1. FlexCraft Theoretical Model [14]*

One important feature of the FlexCraft is the sole use of robotic arms, not the combination of robotic arms and spacesuit arms and gloves. Gloves, in order to be integrated into a design, should be comfortable, and offer a large range of motion, and provide quick feedback to the user [2]. With current glove designs, these requirements are often not met. The bulk of layers required to retain pressure, insulate, and protect against debris inhibit feedback and restrict movement [2]. Equipping an SUV with gloves requires all of the same limitations as a space suit, such as the necessity for a prebreathing process, a low pressure environment, and health risks [2]. Thermal limits exist as well, as suit gloves cannot grasp extremely hot or cold surfaces for extended time periods.

As suit gloves are not integrated into the FlexCraft design, all of the tasks are completed by the robotic arms. The arms have interchangeable manipulators and end-effectors that are specific to the task at hand such as grasping/stabilization, cutting insulation, and connecting wires [15]. The manipulators can be made to be any size, with small manipulators able to reach places that gloved hands cannot. Other advantages of the robotic arms are the higher level of precision and repeatability than gloves, as well as the lack of reliance on muscles, allowing for an object to be held indefinitely without fatigue [2]. The FlexCraft, an SUV with robotic arms, is just one design of an SPS.

### 2.2.2. SCOUT

Space Construction and Orbital Utility Transport (SCOUT) was designed in 2003 as a system able to connect to the L1 Gateway that NASA was developing at the time [1]. The study focused on the necessary design elements to allow for an astronaut to complete three main tasks in a shirtsleeve environment: external operations, vehicle and habitability operations, and docking and berthing. The external task operations such as maintenance are best carried out by an exterior workstation, which includes spacesuit arms, two dexterous arm manipulators, and a grappling manipulator [16]. As solar radiation and MMOD are important concerns, hard suit arms similar to the ones on the AX-5 spacesuit [13] are used as well as Stuffed Whipple Shielding. This type of protection is a multi-layer shield consisting of layers of Nextel and Kevlar between the sacrificial bumper layer and the rearwall. The bumper layer breaks up the debris into smaller pieces with the other layers absorbing most of the impact, so minimal damage is done to the rear wall and vehicle [17]. The arms are mounted to the front of the upper torso of a fairly traditional space suit, which is integrated into the side of the SPS. A hemispherical bubble helmet is included for a panoramic view, and includes an adjustable interscye distance to accommodate a variety of astronaut widths [13]. An externally mounted bailout suit is equipped with a propulsion system in case of emergencies [16].

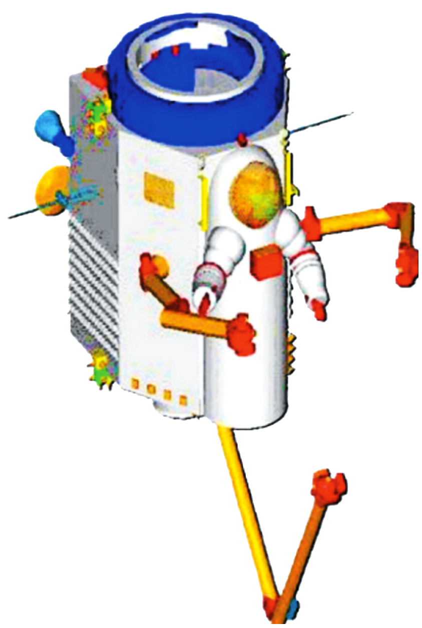

*Figure 2. Scout Theoretical Model [18]*

The interior operations of flight control and systems monitoring are best carried out with an interior work station, traditional controls, and displays in a cabin [10] with an interior octahedral diameter of 1.05 meters and a height of two meters [16]. Rotational hand controllers (RHC) offer a full range of motion to control the robotic manipulators, with some six degrees of freedom force controllers being commercially available, and some six degrees of freedom displacement controllers having been developed but not fully prototyped [16]. In an SPS, hand controllers cannot be used if the operator's hands are in the gloves at the end of the suit arms. Alternative forms of control such as gestural control, voice control, two person controls, and a remote teleoperator exist however.

A life support system capable of lasting twenty-four hours includes pressurized tanks for oxygen and nitrogen, and a lithium hydroxide canister to capture carbon dioxide [10]. In order to dock the vehicle, two identical, redundant docking interfaces are provided for safety and operation, as they allow for materials and personnel to transfer between connected SUV's. The entrance contains fluid, data, and electrical pass-throughs, and complies with the NASA clearance standard of 32 inches for crew transfer [10].

### 2.3. Weighing the Benefits of a "Hands-On" Approach

The current design configurations of FlexCraft and SCOUT hint at a disagreement over the necessity of having an apparatus that allows an astronaut to be "hands on" and interact directly with a workspace. "Hands on," in this case refers to the capability and freedom for the astronaut/end user to shift to using their own hands compared to simply relying on robotic manipulators. The project direction will veer towards the "hands on" approach that is present within the SCOUT design.

Currently, there is no direct empirical proof that concludes that using robotic manipulators in conjunction with physical human control is significantly better than simply relying on just robotic manipulators. It has been generally assumed in the past that while robots can perform tasks in the place of humans so that a life is not at risk, robots simply wouldn't be as reliable at performing a task than a human, so it was more beneficial to put an astronaut in a risky situation to perform an EVA. This assumption is reflected in a 1987 paper by K. Salisbury, summarizing the performance issues of robotic manipulators in space. Salisbury remarks that humans unconsciously combine prehensile, manipulative, and sensory functions in performing complex tasks but "in the robotic world, we are not yet so lucky as to be able to smoothly integrate these complex functions into a synergy of action" [20].

While this may have been the assumption in the past, that does not mean that this assumption is credible in the modern era. Advancements in the field of space robotic manipulators have been made since 1987. However with no empirical data accessible that determines whether a "hands-on" apparatus is necessary or whether having just robotic manipulators as the method of interaction is adequate, it is hard to deviate from the expectation that humans are able to perform tasks better than robotic manipulators and therefore, a "hands-on" apparatus is a necessary component for SUV design.

#### 2.3.1. Pursuing the SCOUT Design Concept

As this research project is aimed at designing a novel method for human interfacing with a worksite that maximizes efficiency, the SCOUT design concept has been selected for use in this project. It is the belief of this research team that the combination of suit arms and dexterous robotic manipulators best suits that goal. The suit arms provide a familiar work environment to astronauts acclimated to traditional EVAs, while the manipulators and their end effectors allow for greater precision and ease of repetitive movements. The robotic manipulators detailed in the SCOUT proposal are based on the Ranger robotic satellite servicing arm. A current iteration of Ranger is housed in the Space Systems Laboratory of the University of Maryland, the facility hosting this investigation, and thus would be available for testing. This means that the team would not need to spend time constructing and testing a model for the robotic manipulator outlined by the SCOUT proposal, and can instead begin to develop algorithms to control Ranger. The suit arms, themselves, will be based on previously-developed technology and are not a focus of this project.

### 2.4. Robotic Manipulators

Robotic manipulators are a class of robot designed for interaction with a worksite. They consist of many joints - either translational or rotary - assembled in a way that allows the arm a certain amount of degrees of freedom (DOF). The more DOF a manipulator has, the greater its capability for movement. At the end of the robotic arm is an end-effector, the part of the manipulator that interacts with a worksite. The end-effector is designed for executing tasks with specific interfaces [21]. Attached to the end-effector is the manipulator's wrist that orients the object being handled, which is in turn mounted to an arm that is responsible for moving and positioning the object [22]. Note that the term "arm" is generally used to refer to the robotic manipulator as a whole, not just one particular section of the robot.

#### 2.4.1. Robotic Manipulators in Space

Robotic manipulators must satisfy a certain set of criteria to be successful in the outer space environment [23]. For transportation to and from the worksite, the robotic apparatus must be capable of docking with a target spacecraft, with or without human intervention. At the worksite, the manipulators must be able to assemble complex space structures - an especially pertinent demand as the human presence in LEO and beyond is expected to expand. The robot should also be able to assist in routine inspection of such structures in space. As such, they should be sufficient at performing minor repairs without human assistance. However, these manipulators should also have the ability to assist humans in complex servicing missions. Although this may prove challenging, as different missions call for different tasks and tools, the robots may be equipped with different end-effectors for a variety of applications. For maximum efficiency of the robotic system, humans must also be trained on Earth to properly interact with and work alongside the robot.

Some of the above qualifications do not apply to robotic manipulators integrated with an SUV. For one, the manipulators would not have to dock with other spacecraft, as they would be strictly mounted to the structure of the vehicle. Nevertheless, it is worth studying prior examples of robotic manipulators, either verified for spaceflight or that have actually operated in space, to better understand the demands of such an apparatus in space.

One of the more notable robotic arms to have operated in the space environment is the Shuttle Remote Manipulator System (SRMS) [24]. Also known as the Canadarm, the robotic apparatus was retired along with NASA's Space Shuttle program in 2011, but had been in service since its inaugural flight in 1981. The manipulator assisted in the capture of payloads with the added responsibility of maneuvering them for both berthing and deployment. Besides its invaluable contributions to the United States' Space Shuttle program, the SRMS has also assembled various parts of the ISS and been utilized by astronauts during EVAs. The arm provided astronauts foot restraints to use as a work platform, allowing astronauts to more efficiently accomplish a broad range of tasks. Although the Canadarm was not equipped with the intricate work ability as would be required aboard an SUV, the adaptability of the system is worth noting. Over the course of its mission, the Canadarm manifested different iterations in an attempt to expand the arm's capabilities and features. As the SUV is designed with the intention of being docked to a host spacecraft or space station when not in use, it would be similarly easy to perform such upgrades to expand the capabilities of the vehicle.

Another example of a robotic arm meant to operate aboard the ISS, although not yet launched, is the European Robotic Arm (ERA) [25]. This system is able to grapple from base point to base point, moving itself to different workplaces along the ISS. Similar to the robotic manipulators to be included on a SUV, the ERA has been designed to perform tasks typically reserved for a traditional EVA. To that effect, the system is equipped for manual control by either suited astronauts in the space environment or astronauts within the pressurized environment of the ISS. Spacewalking astronauts can control the manipulator via a console outfitted with switches and LED displays such that it is easily compatible with their bulky, pressurized suits. If opting to control the arm remotely, the astronauts aboard the ISS will utilize a software application to control the arm while monitoring the camera views provided by the ERA. As this technology had been verified for flight, though not yet flown due to the end of the Space Shuttle program, it clearly demonstrates the need for a controllable robotic manipulator in EVA servicing tasks. Clearly the ERA is different from the task arms to be mounted on an SUV as it is free to grapple about its host station, but its usefulness in assisting with EVA operations is similar to what is expected of the SUV. However, the SUV would allow the astronaut greater precision and awareness in controlling the manipulator from an environment similar to that of the inside of a space station, while still having access to a direct line of sight of the work area.

The most relevant example of a ready-for-flight robotic arm, in terms of the scope of the project, is that of the Ranger Robotic Satellite Servicer [26]. The Ranger manipulator system is the basis for the SCOUT vehicle that is being used as the inspiration for this project. Though never flown, due to the tragic loss of the Columbia Space Shuttle in 2003, this robotic system has proven useful for Earth-based testing and verification of other manipulators. The twin manipulators are tested in a neutrally buoyant environment, and thus have been outfitted with components optimized for operations in that environment. Extensive time spent developing and testing the Ranger robotic system in the Neutral Buoyancy Research Facility of the University of Maryland have led to developments that could be transferred to an in-flight scenario. Perhaps one of the greatest contributions to space robotics was the development of a free flight system, including attitude estimation and control, that allowed for simulations in the neutrally buoyant environment to more accurately resemble the dynamics of space flight. This would be directly applicable to the future development and testing of the SCOUT system due to needing to test it in a free-flight neutral buoyancy environment. Additionally, much research has been expended on the development of the system's ability to perform the tasks expected of an astronaut on an EVA. The neutrally buoyant mock-up of the Ranger system was designed with the strict requirement that it must generate the same force and have the same reach capability as an astronaut in a space suit, ensuring it could perform such tasks. As this is the system on which the robotic manipulators aboard the SCOUT vehicle are based, it is valuable to utilize the arms for testing throughout this project.

### 2.4.2. Ranger Technical Specifications

As aforementioned, there currently exist a wide variety of robotic manipulators with an even broader array of applications. However, an SUV will require a specific type of robotic manipulator in order to fulfill its purpose as an efficient maintenance vehicle. This research project aims to build off the idea of the previously-discussed SCOUT and, as such, the technical requirements for the robotic manipulator outlined in that design concept will be examined in great detail.

The specific tasks that the robotic manipulators aboard the SCOUT spacecraft will perform have requirements of their own. Based on data from current EVA operations, it was determined that the maximum force required for a manipulator to insert or remove an Orbital Replacement Unit (ORU) was 90N [1]. This can easily be achieved by a Ranger-based arm, as it was calculated that, in the position with optimal mechanical advantage, the maximum force generated is 2620N [1]. Additionally, the Ranger apparatus was designed with the ability to apply 52.2N-m of nominal torque [1]. The mechanical ability of the two task arms on the SCOUT spacecraft alone is not enough to be successful in performing in-orbit activities. The SCOUT arms also require specific end-effectors to perform its predicted tasks. Currently, the spacecraft will be outfitted with a bare bolt drive, a parallel jaw mechanism, and a microconical end effector [1]. The bare bolt drive will give the manipulators the ability to drive bolts head-on. The parallel jaw mechanism functions as an adaptable device, as its fingers can hold a variety of positions, which allows it to fit around many different interfaces and be useful in many situations. The microconical end effector allows the manipulators to grasp robot-standard interfaces on the ISS. However, there does not currently exist a method for controlling the SCOUT task arms.

### 2.5. Control Concepts

The intention for providing dexterous robotic manipulators to supplement direct human-worksite interactions has an inherent challenge of developing a method of control. While the astronaut has their arms in the pressurized suit they do not have the ability to govern the manipulators with their hands as is traditional. Instead, a novel way of controlling the robotic arms must be developed that will allow the astronaut to simultaneously work with their own hands. To accomplish this the team intends to investigate concepts of gestural control and voice control, respectively.

#### 2.5.1. Gestural Control Methods

Traditional control input devices such as hand controllers could be used as a control method, but space mission complexity is increasing in a way that can soon become overwhelming to operators who use control input devices [27]. Due to this advancement, the idea of utilizing Human-Computer Interaction (HCI) such as voice-controlled robotic manipulators to lighten the burden astronauts have to complete projects while in outer space. Pursuing this area of research was decided upon due to its potential applicability in the future. Before discussing methods of HCI control, some requirements that any control scheme must meet to be viable are safety, reliability, accessibility, feedback, and commonality [27]. For experimentation within this project, the plan is to explore the options of gestural and voice-based control. To begin with, gestural control of robotic manipulators is usually done by capturing images of the human body's movements and translating that into motion of a robotic arm through inverse kinematic algorithms [28]. Some systems use commercially available technology [29], such as an XBox 360 Kinect, a device designed to translate the movement of a human into that of a video game character. This technology has also been considered for use in space [28]. The conclusion was that it might become usable in a more large-scale way if further research was conducted. It might even have some benefits over current methods, such as reducing training time. Therefore, it has been determined that pursuing research regarding this method would be a viable option.

#### 2.5.2. Voice-Based Control Methods

Another viable method of control would be voice control. This option concerns using speech to command the robotic manipulators to move in certain pre-programmed ways. There are many benefits to using voice control, including, but not limited to, hands-free control and consistency of the control method [27]. However, some downsides exist, such as interpreting different languages and accents, as well as changes in voices in microgravity. These potential issues have not stopped the technology from being more extensively researched than motion control for use in space. On top of being determined to be more accurate than motion signals [30], voice control in EVA applications has been studied at the NASA Johnson Space Center and even aboard one of the space shuttles [27], marking the only time voice controlled systems have been used on a spacecraft. Specifically, at the Johnson Space Center, voice controls were used to manipulate a robotic arm into performing a few different tasks, and this method was determined to be 85-95% accurate in recognizing the command and completing it. While this is not a perfect result, if improvements are made, this accuracy could increase. The latter experiment, on the space shuttle, was conducted in October 1990. Using their voices, the astronauts were able to control the CCTV cameras in the shuttle. They reported it to be a very convenient and useful tool to have on the space shuttle [27]. While the task may seem simple and the experiment was performed long ago, it still sets a precedent that this technology is indeed viable for use in space applications. This technology has even been commented to maybe be useful for EVA activity, perhaps while an astronaut has to perform one repair they can conduct another using their voice. In conclusion, voice controlled robotic manipulators are another extremely promising research area that we intend to explore.

### 2.6. Gaps in Research

The space utility vehicle, specifically the single-person spacecraft, is a fledgling concept. While the idea dates back to the twentieth-century, there is a lack of substantial work that has been done to validate the SUV as a beneficial addition to space exploration. Although there have been a handful of design studies and even fewer scale-models constructed, there has yet to be a large and coordinated effort to advance the concept of the SPS. Currently, EVAs are efficient enough to not warrant funding for research into an alternative method for conducting maintenance and servicing tasks. However, there have been no true tests of the SUV to confirm its validity as a viable alternative to EVAs. While certainly a successful development of a reliable control algorithm based solely on either gestures or voice commands would prove useful to the field of robotics as a whole, this team aims to extend this further. Should such a method of control be created over the course of this project, it will be exploited through human-factors testing to determine its overall benefit to in-orbit maintenance tasks that can be replicated on Earth's surface and, eventually, in the microgravity environment of a neutral buoyancy tank. It is the belief of the research team that data from such experimentation can be useful in comparison to EVA servicing mission statistics and provide conclusive results on the efficiency of SUVs.

# 3. Methodology

## 3.1. Purpose

Phase one of research will focus on determining which method of mission servicing is most optimal for the completion of EVA tasks. For this phase, a total of 5 methods will be tested. They include a shirt-sleeve environment, space-suit arms, SCOUT suit arms, FlexCraft on site robotic operation, and remote teleoperation with a video visual feed. This set of mission servicing methods was chosen based on a combination of which concepts were sufficiently developed and what is available for us to test. FlexCraft and SCOUT are the two most prominent examples of a possible design of an SUV, and with Ranger Satellite Services available to us at the SSL here at UMD, their respective servicing methods are ideal for this first phase of testing. In addition, spacesuits have historically been the preferred method of mission servicing. With the suit mockups used for testing in the neutral buoyancy facility here in the SSL at UMD available to us, spacesuits are also an ideal method to be tested. Remote teleoperation is also ideal for testing as it does not require a complex apparatus to run tests with the only features needed in addition to the robotic manipulator is some method of relaying live footage to the operator at a remote location.

## 3.2. Test Design

The design of our phase one testing will be built around each method of EVA maneuvering performing a Fitts' Law tapping task [28]. Fitts' Law is used to describe the relationship between speed and accuracy of motion, i.e., it predicts the time taken to “tap” a target object as a function of the ratio between the distance to the target and the width of the target. We will construct a Fitts' Law task board that allows us to test different distances and target sizes during our testing. This method will allow us to accurately quantify how well each method of EVA works.

There will be five different methods of testing. The first is a shirt-sleeve test in which we will teach subjects about the tapping task. This should be a quick test in which the subjects learn how to perform the test. The next test uses space-suit arms similar to those used to complete EVAs currently, so that we may compare our possible methods to the current EVA method. A third test uses SCOUT arms, which have less mobility than typical space-suit arms, but would, in the future, be used in conjunction with robotic arms to optimize performance time. The SCOUT concept tests the idea that human hands, eyes, and brain are all needed on sight to perform EVAs. The next method is the FlexCraft method, where subjects will perform the tapping task on sight using hand controls of the NBV robotic arm. This tests the idea that only human eyes and brain are needed on sight for EVAs. The final method is remote teleoperation, in which subjects will perform the Fitts' tapping task using hand controls of the robotic arms and a video feed instead of direct vision. This is used to test the idea that human hands, eyes, and brain are not needed on sight during EVAs.

We will teach the subjects the test in the shirt-sleeve environment, first. We will then give each subject on familiarization run with the task methods to make sure they are familiar with the task at hand and to also keep time of our test down. We will then proceed in order through the space-suit and SCOUT arm environments next given their similarity to the shirt sleeve environment. We will vary the order of the eyes-on and teleoperation environments so we do not skew our data as test subjects become more familiar with the robot the more they use it throughout the tests

NBV Arm Model

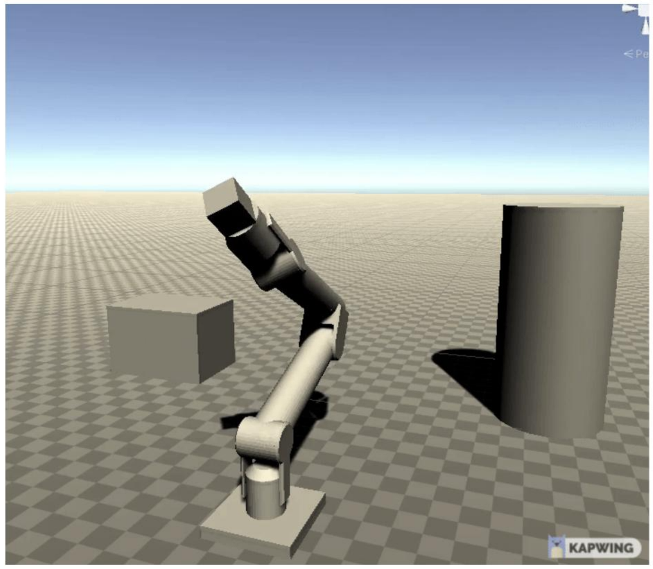


*Figure 3: NBV in Unity Gaming Engine*

### 3.3. Analysis

After further examination from the testing sequences and data collection, a standard for the "preferred" method will be evaluated based on a variety of factors. Favored outcomes include shorter task completion times and reduced occurrence of errors, which will be considered alongside numerous standardized testing scales to rank our approaches for operating an SUV.

This will be analyzed, as stated earlier, using Fitts' Law, which is given by

$$MT = a + b * log_2(\frac{2D}{W})$$

where *MT* is the average time taken to complete the movement, *a* and *b* are the constants for the intercept and slope, respectively, *D* is the distance from the starting point to the center of the target, and *W* is the width of the target. The actual difficulty of the task is quantified by part of the second term of the equation, given by:

$$ID = log_2(\frac{2D}{W})$$

This metric, *ID,* is called the index of difficulty. It defines the difficulty of various combinations of distance and target width. Both Fitts' Law and the index of difficulty follow a linear relationship with the time per movement. We will look at the time it takes for subjects to complete the tapping task in relation to how difficult each tapping task is for our analysis. This should be a linear relationship. The slope of the line, our *b*, tells us how much the time it takes to complete the task increases with the difficulty of the task, i.e. The intercept, *a*, corresponds with average movement times for each index of difficulty. We will prefer both a smaller slope and smaller intercept, as these indicate that the movement completion time does not increase too much with difficulty of task, and that the average movement times are not too high.

Data collection of this magnitude will require human testing and participants. Voluntary participants will be able to sign up via email and testing will be approved under the IRB standard and approval. The participants will be subjected to testing various approaches to performing tasks. Considering participants will be interacting with space suit arms and robotic arms, there is a visible learning curve to being able to operate the robotic manipulators or maneuvering the suit arms. Noticeably, it is difficult to quantify the learning rates to extrapolate a probability curve. To reduce bias and skewed data, a wider variety of testing subjects and sample sizes will be included. Quantifying learning rates and comfortability isn't as cut and dry as the other factors, so the NASA Task Load Index and Cooper Harper Scale will account for these "abstract" factors.

The NASA Task Load Index (NASA-TLX) determines Physical Demand, Mental Demand, Temporal Demand, Effort, Own Performance, and Frustration. The NASA-TLX is a questionnaire given to participants with a scaling factor on each question. Each question is weighted and the overall score is given from 0-100 [29].

The Cooper-Harper Scale rates the handleability of a system on a scale of 1 to 10, with lower scores being desirable. The flow chart below is presented to pilots following a testing procedure so that their experience can be quickly assessed.

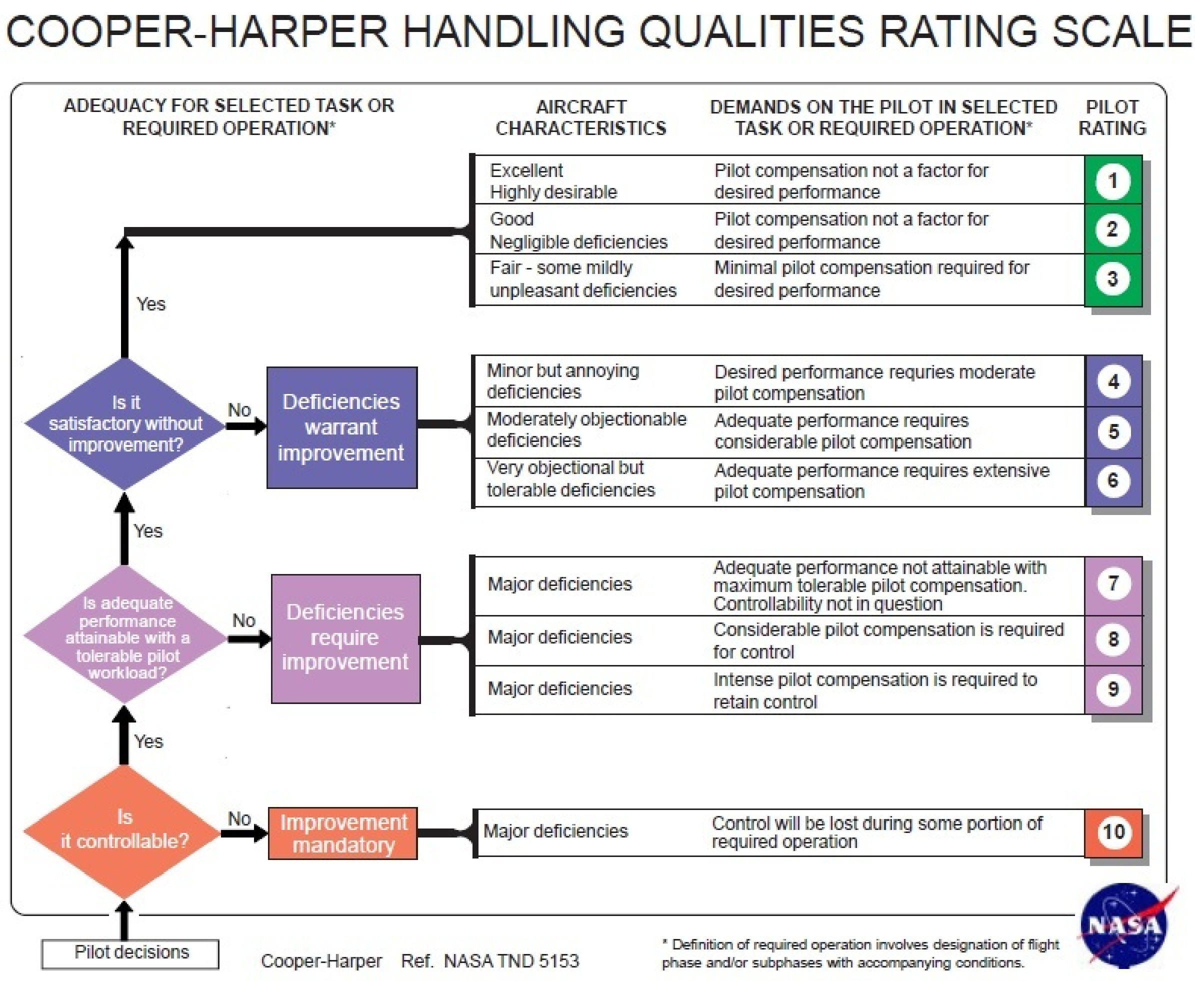


*Figure 4: Cooper-Harper Rating Scale [30]*

Analysis from the data collection will render crucial information about which method proved to be the most optimal solution or approach. Rather than taking the typical approach of a decision matrix, the results from each approach will be compared based on the time taken to complete tasks, the least number of errors, NASA Task Load Index, and Cooper Harper Scale.

The main goal of the data collection will purely be for research and analyzing methods that performed at a higher level in comparison.

## 4. Results

### 4.1. Fitts' Tapping Test Results

Analysis of the Fitts' tapping task data revealed that, on average, participants had the shortest total task completion times and individual movement times in the shirt-sleeve environment, with an average of total time T = 13.06 +/- 1.05 s. The suit arm environment took slightly longer on average, with T = 15.03 +/- 1.32 s. With the SCOUT arms, participants averaged T = 15.70 +/- 1.69 s to complete the task. When controlling the robot using direct eyes-on vision, the average task completion time was T = 253.91 +/- 26.20 s. Finally, the longest average task completion time was for the teleoperation control method, with T = 277.95 +/- 28.02 s. These uncertainties were computed with a 90% confidence interval.

Similarly, linear regression analysis of tapping test data across all participants and test environments revealed that the slopes of the Fitts' Law relationship increased with each test environment. The fitted slope *m* of the shirt-sleeve environment was m = -0.01. For the suit arm environment, the slope was m = 0.04, and for the SCOUT arm environment, the slope was m = 0.12. We then see a sharp increase in slope, computing m = 3.00 for the direct vision environment, and m = 3.40 for the teleoperation environment. The fitted intercept *b* does not increase with each test in the same way, however. For our hands-on tests, the fitted parameters give b = 0.79 in the shirt-sleeve environment, b = 0.68 in the suit arm environment, and b = 0.43 in the SCOUT arm environment. With the robot control tests, the fit gives b = 2.89 for the eyes-on control, and b = 2.63 for the teleoperation control.

Table 1 displays the averages and linear regression fit parameters for the Fitts' tapping task across all participants and test environments, with the calculated $R^2$ value. Figure 5 displays the average Fitts' tapping test completion times as well as the fitted slopes and intercepts for each test.

Fitts' Law Linear Regression Fit Parameters for All Environments

| Test Environment | Avg. Total Time (s) | Error (s) | Slope | Intercept | $R^2$ * |
|---|---|---|---|---|---|
| Shirt-Sleeve | 13.06 | 1.05 | -0.01 | 0.79 | 0.00 |
| Suit Arm | 15.03 | 1.32 | 0.04 | 0.68 | 0.01 |
| SCOUT Arm | 15.70 | 1.69 | 0.12 | 0.43 | 0.06 |
| Eyes-On | 253.91 | 26.20 | 3.00 | 2.89 | 0.15 |
| Teleoperation | 277.95 | 28.02 | 3.40 | 2.63 | 0.14 |

*Table 1: Average total test completion time with error, fitted slope, fitted intercept, and $R^2$ value for Fitts' tapping task. *Note that the $R^2$ values will be discussed further in Section 5.1*

Test Completion Time and Fitts' Law Fit Parameters Across Participants

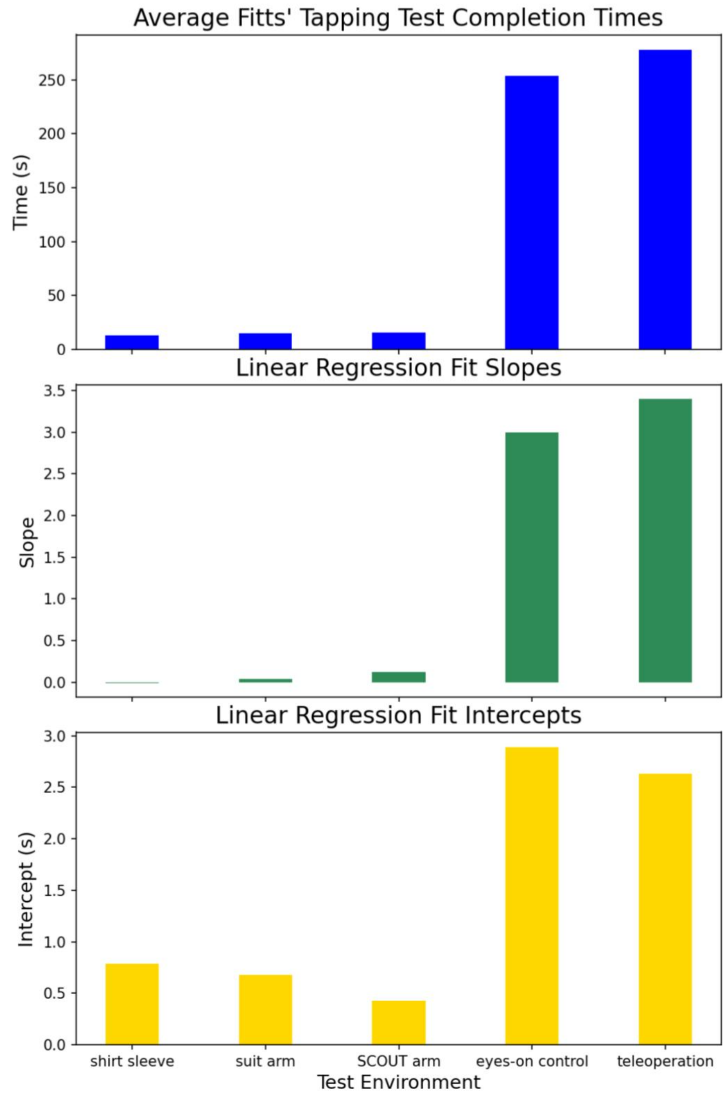


*Figure 5: Bar graph of Fitts' law average test completion times, and linear regression fitted slopes and intercepts for each testing environment.*

### 4.2. Post-Testing Survey Results

Figures 5, 6 and Table 2 report the relevant survey data we collected from test subjects using the NASA-TLX and Cooper-Harper Scale. The data was collected after each subject had completed the tests and will be used in conjunction with the Fitts' Law data in helping to judge the efficacy of each environment.

Figure 6 reports out the average NASA-TLX score in each of the six categories for each control environment, allowing us to see overall trends in the test subjects' perception of each test as they progressed through each environment. Table 2 is the tabulation of the results shown in Figure 6, with an overall average calculated for each environment, giving a numerical rating to judge east test by on a surface level. Figure 7 shows the results of the Cooper-Harper survey.

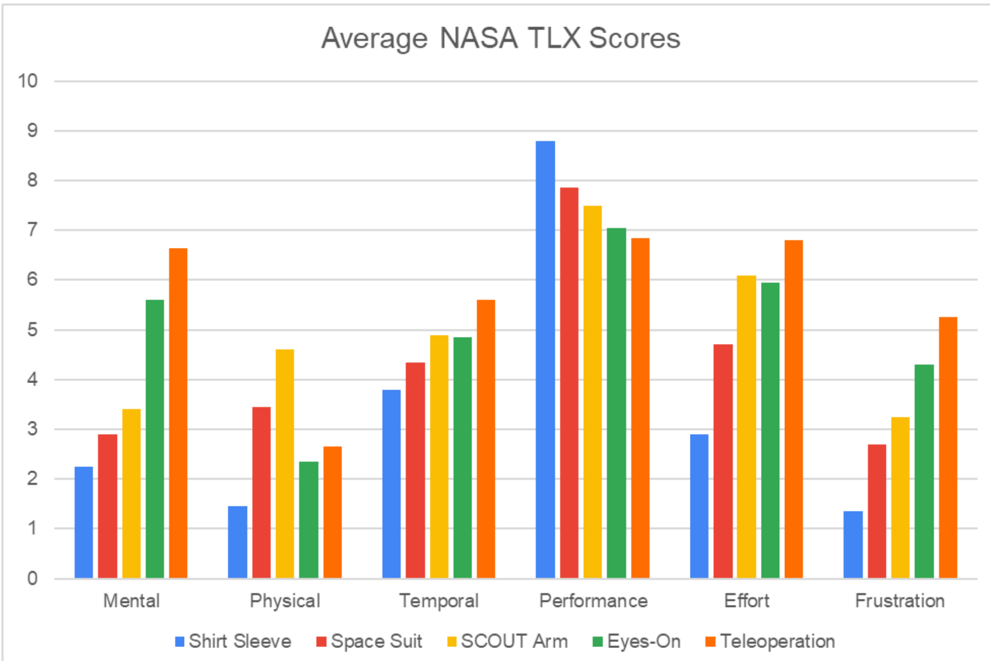


*Figure 6: Average NASA TLX scores for each testing environment,*

NASA TLX Average Ratings

| NASA TLX Category | Shirt Sleeve | Space-Suit Arm | SCOUT Arm | Eyes-On | Teleoperation |
|---|---|---|---|---|---|
| Mental | 2.25 | 2.90 | 3.40 | 5.60 | 6.65 |
| Physical | 1.45 | 3.45 | 4.60 | 2.35 | 2.65 |
| Temporal | 3.80 | 4.35 | 4.90 | 4.85 | 5.60 |
| Performance | 8.80 | 7.85 | 7.50 | 7.05 | 6.85 |
| Effort | 2.90 | 4.70 | 6.10 | 5.95 | 6.80 |
| Frustration | 1.35 | 2.70 | 3.24 | 4.30 | 5.25 |
| AVERAGE | 3.43 | 4.33 | 4.96 | 5.02 | 5.63 |

*Table 2: NASA-TLX average scores tabulation for each testing environment.*

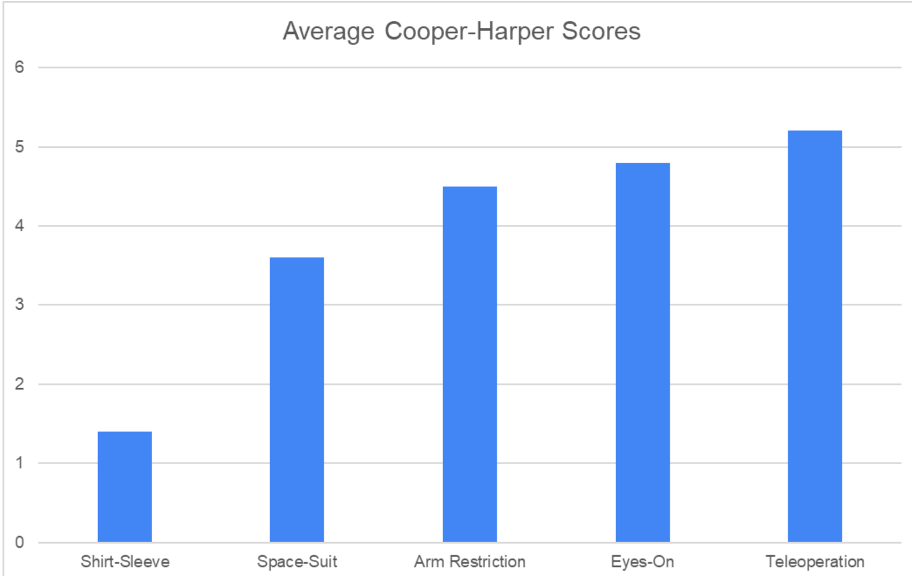


*Figure 7: Average Cooper-Harper scores for each testing environment.*

## 5. Discussion

### 5.1. Fitts' Law

To further discuss the results from the Fitts' tapping task, the percent increase between variables in the shirt-sleeve control environment and each subsequent environment was calculated. These values are tabulated in Table 3. It was found that the average total test time in the robotic control environments was 1844.18% longer in the eyes-on control environment, and 2028.25% longer in the teleoperation environment. This was to be expected because in the control environment, there are no obstructions to the participants' movement which would cause slower times. However, it was also found that the spacesuit arm environment and the SCOUT vehicle environment have faster times than either of the robotics environments. The suit arm environment had a 15.08% increase from control, while the SCOUT arm environment had a 20.21% increase from control. These results were also to be expected due to the space suit arms having low resistance, although they have more resistance than the short sleeve environment.

## Percent Increase of Fitts' Law Parameters

| Test Environment | Avg. Total Time % Increase from control | Slope % Increase from control | Intercept % Increase from control |
|---|---|---|---|
| Shirt-Sleeve | control | control | control |
| Suit Arm | 15.08 | 500 | -13.92 |
| SCOUT Arm | 20.21 | 1300 | -45.57 |
| Eyes-On | 1844.18 | 30,100 | 265.82 |
| Teleoperation | 2028.25 | 34,100 | 232.91 |

*Table 3: Calculated percent increase from shirt-sleeve control environment to each subsequent testing environment for average total time, fitted slope, and fitted intercept.*

While the fitted parameters from the linear regression for Fitts' Law can tell us numerically about our results, it is also important to visually examine the linear relationship of each testing environment. The slope and intercept must be inspected together, instead of separately, to get the full picture of what our data tells us. Figure 8 displays the Fitts' Law linear regression fits for each individual participant in each of the testing environments, while Figure 9 displays the fits for the combined participant data for each testing environment.

In Figure 8, we can see how "easy" each task was for each participant. Across the board, it seems that participants did not struggle with the three hands-on testing environments. The slopes for these lines (red for shirt-sleeve, orange for space-suit arm, and yellow for SCOUT arm) are all nearly horizontal, indicating that the index of difficulty for each movement did not affect the amount of time it took to complete each movement. This was the same across the board for all participants (see Appendix A for individual participant results), as well as in the combined data-sets fits in Figure 9. What was not the same, however, was whether or not the eyes-on robotic control environment (green) or teleoperation (blue) was more difficult for the participants to complete. We know from Figure 9 that overall the teleoperation task was more difficult than the eyes-on control task, as the blue line of teleoperation sits above the green line of direct vision. On the individual participant-level, however, this was not always the case. As shown in Figure 8, some found the teleoperation environment to be easier than the direct vision environment. This may be in part due to the order in which the participants learned the different testing environments. The first three were always completed in sequence: shirt-sleeve, space-suit arm, then SCOUT arm. We then randomly varied whether participants completed the eyes-on or teleoperation task next. Even though we gave participants practice time in each environment, the learning curve is not the same for everyone. Therefore, participants who completed the eyes-on control environment first may have still been “learning”, which is why the teleoperation task may have seemed easier to them. Randomly varying the order in which the participants completed these tasks should account for this variation, so we can still say that, overall the teleoperation environment was more difficult than the direct vision environment.

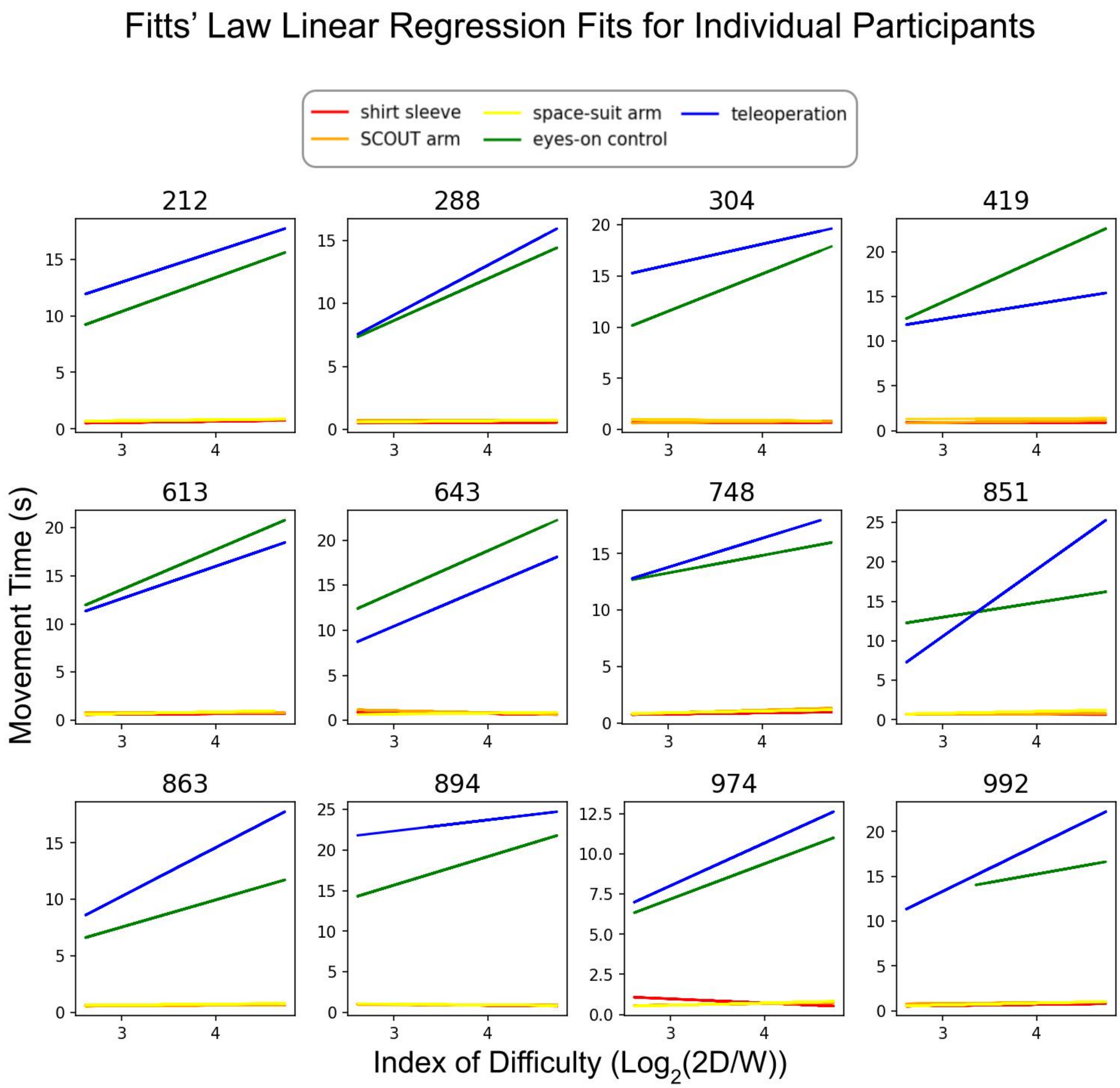


*Figure 8: Linear regression fits to individual participant data for each test environment. D is the button-to-button distance, W is the button width. Tests are differentiated by color. Participants are identified by a randomly generated 3-digit number*

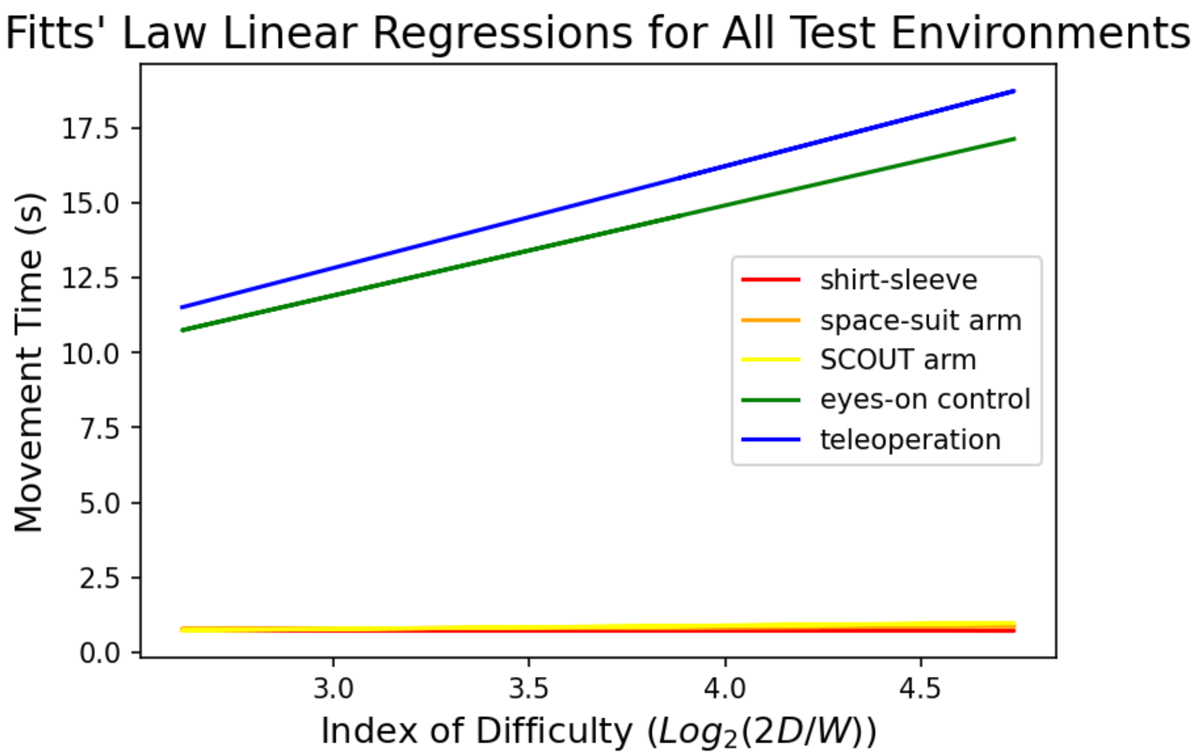


*Figure 9: Linear regression fits to combined data-sets for each type of test. D is the button-to-button distance, W is the button width. Tests are differentiated by color.*

Other variations in the Fitts' Law can be accounted for by the randomness of the test and the testing environment. During the tests for some participants, due to the randomness of the test, some participants had trouble looking at which light was on for the buttons. In addition to that, because of the testing environment, the patrons were less than an arm's length from the Fitts' tapping test board. Due to this close proximity, it was sometimes difficult to determine which button was lit up. This could affect future spacecraft designs like SCOUT. Due to the close proximity and limited range of visibility, it would be harder for the astronaut in the SCOUT model to do maintenance tasks that require a wider view.

We expected a wide variation of values for the Fitts' Law data due to a number of factors. If there were any left handed participants, there would be variation due to the testing environment only supporting right hand use, however all the participants that were tested were right hand dominant. As expected, there is a lot of variation in the Fitts' Law values for the use of the robotic manipulators. When controlling the arm, the participants could move the arm up, down, left, right, forward, backwards, as well as rotate it. However, the arm is not the same speed in all directions. Depending on the pathing the participants took, the Fitts' Law value would be greater and have more variation than the spacesuit arms environment. In addition to the arms, the participants were only given about 5 to 10 minutes to practice with the controllers for the robotic manipulator. However, some participants have had gaming experience, which affected the time it took to hit the buttons. For those participants who have video game playing experience with a device similar to the controller like an arcade stick, there was a smaller learning curve, and therefore could control the robotic manipulator with more ease.

During some of the tests, the participants were allowed to ask where the button was located during the teleoperations without direct vision, since it was hard to see some of the buttons on the camera. Due to this, the participants also had to take more time to ask and confirm. This indicates that the teleoperations without direct vision of the target would be ill advised. Due to the low visibility of the cameras, doing maintenance tasks without direct vision would be difficult. However, if the screens and the camera were higher quality, the teleoperations with no vision would be a semi-viable option for SUVs. However, before using robotic manipulators, there would need to be major improvements. The robotic manipulators would need to be upgraded so that the arm moves at all speeds in all directions and it would need to be comparable to the spacesuit arms environment to even be viable.

The low $R^2$ values presented in Table 1 and Appendix A would typically indicate that the independent variables in the regression model are not very good at explaining the variation in the dependent variable. This can occur for several reasons. One is that the relationship between the independent and dependent variables is weak or nonexistent. It could also mean that the model does not include all relevant independent variables or factors that could affect the dependent variable. A third explanation is that there is a high degree of random variation or error in the data, which reduces the ability of the model to accurately predict the dependent variable. Based on our discussion of factors that affect the variation in the data, and knowing that Fitts' Law is a linear relationship, it seems that the third option is the most likely explanation of our $R^2$ values.

### 5.2. NASA-TLX and Cooper-Harper Scale

The NASA-TLX asks test subjects to rate six different categories (mental demand, physical demand, temporal demand/hurriedness, subject performance, effort, and frustration) of their experiences on a scale of 1-10. In order to assess the experience of the test subjects in each environment, we looked at the average scores in each category across all five testing environments. Across all of our test subjects, there was a correlation between an increase in the mental demand, temporal demand, effort, and frustration of the testing environments and a decrease in the performance of the test subjects.

The bar graph in Figure 6 illustrates these findings. Looking at the tabulation of the bar graph results in Table 2, as expected, the shirt-sleeve environment was the "easiest" control environment. The more important metrics come from comparing the Space Suit environment, since it is most similar to an EVA, and the teleoperation environment since it has the highest NASA TLX Score on average. There was an overall 129.3% increase in mental demand, a

28.7% increase in temporal demand, 44.6% increase in effort, and 94.4% increase in frustration. A 23.2% decrease in physical effort and -12.7% decrease in performance was also observed.

Overall, the TLX data indicates that even with a sharp increase in the overall workload and stress put on test subjects, there is a relatively low effect on a test subject's ability to perform a task. The TLX data does also suggest that even with the significant increase in test subject stress and workload, there were little to no additional performance benefits to be gained.

In addition to collecting survey data using the NASA-TLX, we also surveyed our test subjects with the Cooper-Harper scale. This was used to judge how optimal each control environment is on a scale of 1 to 10, with a 1 being the most optimal and a 10 being the least. As shown in Figure 7, as expected, the shirt-sleeve environment is the most optimal and teleoperation being the least. These results generally agree with the NASA-TLX data, with an increase in Cooper-Harper scale correlating with an increase in mental demand, effort, and frustration as well as a decrease in performance.

### 5.3. Next Steps

Following the conclusion of the Fitts' Laws test, a second phase of research and prototype development could follow. Phase two of research would depend largely on the results of testing conducted in phase one, and, following the team's hypothesis that the SCOUT arm environment would be the most suitable, would aim to flesh out and sophisticated the SCOUT arm environment. Should the results of phase one testing indicate that teleoperation, suited worksite interaction, or robotic manipulators being operated directly on-site are optimal for servicing missions, the project will be re-evaluated and a new course of study will be devised.

Should the conclusions drawn by phase one testing point to the combination of suit arms and robotic arms as being most beneficial for traditional EVA operations as hypothesized, the project will enter phase two of its development. The purpose for this phase is to investigate which method of control will allow an operator the greatest efficiency in performing routine maintenance tasks. Gestural control, voice control, and a combination of the two will be tested against one another in an attempt to produce a maximally-efficient design for worksite interaction from within an SUV.

#### 5.3.1. Potential Test Design

Assuming the combination of suit arms and robotic arms is the most beneficial, a SUV mockup would be built. The SUV would be waterproofed in order to be tested in the Neutral Buoyancy Tank with scuba divers. It is unlikely that the design will include a control board or electronics in order to keep the divers safe from electrocution. The mockup would also include the integration of spacesuit arms and robotic arms, the latter being controlled by a gestural control algorithm or voice-based control algorithm.

To perform these tests, we would need to develop either gestural or voice control software for our SCOUT-style testing. To develop these methods of control, a graphical simulation of the Ranger robotic servicing arms would be utilized for refining the precision of the control methods. A simulation is preferable for prototyping as it allows for repeated, efficient testing; meanwhile, testing the physical Ranger arms would require scheduling time to utilize the laboratory and maneuvering the manipulators about the facility to establish a workspace. Once the simulation would be performing accurately, the control methods would be applied to the physical Ranger arms for further refinement. Should there still be apparent errors, we would continue iterating through this process of developing first in a virtual environment and then applying to the real model.

In addition to the utilization of a graphical simulation of the Ranger arms, a model of the full, SCOUT spacecraft would be developed and implemented into the Unity environment. This will allow for a realistic, gravitational simulation of the spacecraft as a whole. This would allow testing to be done prior to the mockup being lowered into the Neutral Buoyancy Tank. Such testing has the potential to answer pertinent questions about the spacecraft concept concerning the reach of the manipulators, how close the spacecraft can get to a workstation and still have full utilization of its manipulators, and whether suit arms would suffice in close-quarters. Experimenting in the computer environment would allow for many important questions to be answered before performing the test in the Neutral Buoyancy Tank, which can be time-consuming and costly. This would make the time spent in the water more efficient, and allows for testing of the suit arms and manipulator combination rather than of the spacecraft as a whole.

The divers and robotic arms would work in tandem to complete tests using a mockup satellite similar to that on the ISS. Tests may include pushing buttons, moving loads, and grasping elements for extended periods of time.

#### 5.3.2. Potential Results and Analysis

The results and method approach path chosen in phase one determine the specific approach for phase two. After the development and tedious testing of this approach, it would then be tested and analyzed similarly to the basic tests and criterion of phase one. The same factors such as time taken to complete tasks, probability of errors, and various testing scales would be implemented once again.

Testing would follow the similar standard procedures to those outlined in 3.2 and 3.3 above. It would still involve voluntary participants with the newly developed test mockup. A common testing factor could include the NASA Task Load Index to evaluate Physical Demand, Mental Demand, Temporal Demand, Effort, Own Performance, and Frustration. In conjunction with the task load, the Cooper-Harper Scale could be taken in consideration to estimate the handleability of a system display.

Overall, there are clear next steps and procedures that could be taken to examine the control methods tested in our project, and to further investigate the efficacy of SPS vehicles.

## 6. Conclusion

In order to determine the best control method for SUVs, multiple different environments were tested using the Fitts' tapping test, the NASA Task Load Index, and the Cooper-Harper scale. These tests were done to compare the different methods of performing maintenance tasks on the exterior of host vessels with SPS. SCOUT and FlexCraft have their own unique control methods that were tested. In the results, it was found that the base environment, the shirt-sleeve environment, had the fastest times and were the most consistent. This was followed in speed by an environment similar to SCOUT, using space suit arms. These hands-on environments were very comparable to the shirt-sleeve environment. The slowest times were obtained by the teleoperation control of the robotic manipulator, which is similar to the FlexCraft environment.

Our results show that the difficulty level of tasks did not vary much within the hands-on control environments (shirt-sleeve, suit arms, and SPS arms), suggesting that the SCOUT arm shoulder-joint restriction does not significantly impede a subject's ability to move. We observed that these three environments were easier to maneuver compared to the robotic control environments. In the robotic control environments, the subjects performed better when they had eyes-on control instead of teleoperation, indicating that the ability to have direct vision is important to task handleability. Overall, these findings indicate that a combination of hands-on and eyes-on interaction could create the best SPS design.

For the future, further tests should be done with more efficient robotic manipulators to give a more accurate comparison for which method would be more efficient. In addition to that, further tests should be done, testing different control methods. Only controllers were used to move the robotic manipulators, so gestural controls and voice controls should be tested. If those methods prove to be effective, it can be tested to see if a combination of the hands on site and the robotic manipulators with different control methods can be used to manufacture an effective SPS.

## 7. Acknowledgements

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## Appendix A - Individual Participant Data

### Fitts' Law Linear Regression Fit Parameters for Shirt-Sleeve Environment

| Participant ID | Total Time (s) | Slope | Intercept | $R^2$ |
|---|---|---|---|---|
| 212 | 11.58 | 0.11 | 0.24 | 0.27 |
| 288 | 9.79 | 0.02 | 0.47 | 0.13 |
| 304 | 12.55 | 0.01 | 0.67 | 0.00 |
| 419 | 16.31 | -0.01 | 0.93 | 0.00 |
| 613 | 12.18 | 0.06 | 0.42 | 0.11 |
| 643 | 13.93 | -0.14 | 1.30 | 0.29 |
| 748 | 16.37 | 0.11 | 0.48 | 0.12 |
| 851 | 12.38 | -0.04 | 0.82 | 0.02 |
| 863 | 11.52 | 0.01 | 0.59 | 0.01 |
| 894 | 16.45 | -0.12 | 1.37 | 0.13 |
| 974 | 11.25 | -0.26 | 1.75 | 0.14 |
| 992 | 12.42 | 0.13 | 0.19 | 0.35 |

### Fitts' Law Linear Regression Fit Parameters for Suit Arms Environment

| Participant ID | Total Time (s) | Slope | Intercept | $R^2$ |
|---|---|---|---|---|
| 212 | 13.99 | 0.09 | 0.42 | 0.26 |
| 288 | 13.04 | -0.01 | 0.78 | 0.01 |
| 304 | 14.04 | 0.10 | 0.39 | 0.30 |
| 419 | 18.34 | 0.13 | 0.50 | 0.29 |
| 613 | 14.56 | -0.01 | 0.85 | 0.00 |
| 643 | 16.16 | -0.23 | 1.76 | 0.34 |
| 748 | 20.37 | 0.24 | 0.19 | 0.24 |
| 851 | 13.28 | 0.05 | 0.55 | 0.03 |
| 863 | 10.96 | 0.06 | 0.38 | 0.11 |
| 894 | 17.64 | -0.01 | 1.00 | 0.00 |
| 974 | 11.89 | 0.09 | 0.32 | 0.19 |
| 992 | 16.08 | 0.09 | 0.55 | 0.08 |

## Fitts' Law Linear Regression Fit Parameters for SCOUT Arms Environment

| Participant ID | Total Time (s) | Slope | Intercept | $R^2$ |
|---|---|---|---|---|
| 212 | 14.48 | 0.08 | 0.49 | 0.05 |
| 288 | 12.63 | 0.08 | 0.38 | 0.15 |
| 304 | 16.62 | -0.07 | 1.18 | 0.03 |
| 419 | 24.71 | 0.03 | 1.21 | 0.00 |
| 613 | 14.64 | 0.18 | 0.14 | 0.20 |
| 643 | 13.70 | 0.11 | 0.35 | 0.10 |
| 748 | 18.98 | 0.15 | 0.47 | 0.09 |
| 851 | 17.10 | 0.23 | 0.14 | 0.27 |
| 863 | 12.24 | 0.07 | 0.42 | 0.08 |
| 894 | 16.90 | -0.11 | 1.37 | 0.09 |
| 974 | 12.24 | 0.14 | 0.15 | 0.19 |
| 992 | 14.17 | 0.22 | -0.02 | 0.68 |

## Fitts' Law Linear Regression Fit Parameters for Eyes-On Robotic Control Environment

| Participant ID | Total Time (s) | Slope | Intercept | $R^2$ |
|---|---|---|---|---|
| 212 | 227.45 | 3.00 | 1.40 | 0.62 |
| 288 | 205.31 | 3.32 | -1.32 | 0.40 |
| 304 | 246.14 | 3.64 | 0.66 | 0.20 |
| 419 | 318.94 | 4.74 | 0.16 | 0.33 |
| 613 | 292.48 | 4.15 | 1.13 | 0.27 |
| 643 | 298.19 | 4.62 | 0.36 | 0.18 |
| 748 | 259.45 | 1.55 | 8.65 | 0.06 |
| 851 | 261.30 | 1.85 | 7.43 | 0.16 |
| 863 | 169.00 | 2.41 | 0.32 | 0.48 |
| 894 | 331.80 | 3.52 | 5.13 | 0.31 |
| 974 | 160.12 | 2.20 | 0.60 | 0.35 |
| 992 | 276.74 | 1.87 | 7.79 | 0.07 |

## Fitts' Law Linear Regression Fit Parameters for Teleoperation Environment

| **Participant ID** | **Total Time (s)** | **Slope** | **Intercept** | $R^2$ |
|---|---|---|---|---|
| 212 | 273.20 | 2.72 | 4.82 | 0.27 |
| 288 | 221.23 | 3.94 | -2.74 | 0.44 |
| 304 | 300.52 | 2.04 | 9.94 | 0.04 |
| 419 | 252.58 | 1.67 | 7.51 | 0.20 |
| 613 | 270.04 | 3.35 | 2.58 | 0.30 |
| 643 | 259.27 | 4.42 | -2.83 | 0.31 |
| 748 | 278.62 | 2.56 | 6.11 | 0.09 |
| 851 | 321.26 | 8.48 | -14.86 | 0.62 |
| 863 | 251.24 | 4.32 | -2.67 | 0.45 |
| 894 | 422.46 | 1.37 | 18.23 | 0.01 |
| 974 | 181.24 | 2.65 | 0.07 | 0.41 |
| 992 | 303.77 | 5.11 | -1.99 | 0.41 |