Astronaut-Centric Analysis of a Jetpack with Integrated Control-Moment Gyroscopes for Enhanced Extravehicular Activity Performance

by

Celena Dopart

B.S. Aerospace Engineering
Worcester Polytechnic Institute, 2012

Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of Master of Science in Aeronautics and Astronautics at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY June 2014

© Celena Dopart 2014. All rights reserved.

The author hereby grants to MIT and The Charles Stark Draper Laboratory, Inc. permission to reproduce and to distribute publicly paper and electronic copies of this thesis document in whole or in part.

Signature redacted

Author .........................................................
Department of Aeronautics and Astronautics

Signature redacted

May 22, 2014

Certified by . . .

Jeffrey A. Hoffman
Professor of the Practice of Aerospace Engineering
Thesis Supervisor

Signature redacted

Certified by . . .

Kimberly F. Jackson
Member of the Technical Staff, Draper Laboratory
Thesis Supervisor

Signature redacted

Accepted by . . .

Paulo C. Lozano
Chair, Graduate Program Committee
Astronaut-Centric Analysis of a Jetpack with Integrated Control-Moment Gyroscopes for Enhanced Extravehicular Activity Performance

by

Celena Dopart

Submitted to the Department of Aeronautics and Astronautics on May 22, 2014, in partial fulfillment of the requirements for the degree of Master of Science in Aeronautics and Astronautics

Abstract

As a stepping-stone towards eventual human exploration of Mars, NASA plans to explore low-gravity objects. Since the surface environments encountered on such missions would limit the independent mobility of astronauts, a maneuvering unit that offers counter reaction forces and torques during movements and tasks will likely be required. The next-generation maneuvering and stability system proposed in this research incorporates control moment gyroscopes (CMGs) into an extravehicular activity (EVA) jetpack device currently being considered at NASA Johnson Space Center (JSC). This Mobility Augmenting Jetpack with Integrated CMGs (MAJIC) system will offer rigid attitude control not previously required for EVA tasks.

This research project was designed to: (1) assess EVA task motions, astronaut dynamics, and mission concepts to support the objective comparison of the original jets-only Jetpack system and MAJIC, and (2) analyze the performance of both systems based on user evaluations of the two control configurations. An EVA task list with associated motions and tools was compiled to develop a relevant mission concept of operations that would inform the subsequent research objectives. A method for analyzing astronaut dynamics during these EVA tasks was developed and used to compare system stability of the proposed (CMG-augmented) vs. current (jets-only) control systems. The combined astronaut dynamics and controls models formed a full simulation that was integrated into a Virtual Reality (VR) environment at JSC to offer a platform for two human evaluations comparing the proposed and current control systems.

Although computational analyses demonstrated increased attitude stability and decreased fuel consumption consistently across all missions and EVA tasks, results from the user evaluations were mixed. In the preliminary user evaluation, users showed overwhelming preference for MAJIC during worksite EVA tasks.
that incorporated astronaut motions, but no trend for piloted missions that did not incorporate astronaut motions. The results of the follow-up user evaluation indicate that benefits of MAJIC are more pronounced in certain mission scenarios, including ones in which mass and moment of inertia properties are increased (e.g. when tools are used). Future work should explore these mission scenarios further and continue development of motion capture capabilities to include full-body actuation and contact models within the virtual reality environment.

Thesis Supervisor: Jeffrey A. Hoffman
Title: Professor of the Practice of Aerospace Engineering

Thesis Supervisor: Kimberly F. Jackson
Title: Member of the Technical Staff, Draper Laboratory
Acknowledgements

It has been my pleasure and privilege over the past two years to have many wonderful people in my life. To these individuals, I owe endless thanks for help and support during the completion of this thesis. You have all helped me maintain my sanity.

First and foremost, thank you to Jeff. Without your guidance and encouragement, I would not have had as fulfilling an experience here at MIT. Discovering my future advisor was a former astronaut made for an incredibly exciting start to this adventure. That excitement has remained with me over these two years and I am grateful to have had the opportunity to work with you. I learned so much and I thank you for your countless words of wisdom and envy-inducing stories – you have time and again reinforced my dream of becoming an astronaut.

To Kim, you are the reason that this thesis is complete—weeks early, no less—and that it is a comprehensive, coherent body of work. From answering the most menial questions (I know I need to make MATLAB do this, but ...how?) to helping me stay relaxed and composed (the first day of a conference is supposed to be dedicated to skiing, right?), you have kept me on track and in line throughout this entire process. I am honored to be your first advisee, and hope any future ones work twice as hard and are half the trouble.

To the rest of my Draper advisors, supervisors, and colleagues, thank you not only for your technical and programmatic guidance, but also for making this experience unforgettable:

Michele, for training runs at altitude and hiking through a torrential downpour; Bobby, for your steadfast insistence that Word is superior to LaTeX; Kevin, for letting me hold the V2Suit’s IMU hostage for weeks on end; Jared, because working on this project alone would have been an entirely different experience; and Todd, because I know the future of this work, whatever it may be, is in capable hands.
Thank you also to Draper itself, for the generous IR&D and UR&D funding. The support has provided me with extraordinary research opportunities, not to mention my rent, food, and beer – the only four things a grad student really needs.

To those at NASA Johnson Space Center’s Virtual Reality Lab, thank you not only for your invaluable assistance setting up and running our evaluations, but also for introducing us to the best barbeque in town. To those at Draper Houston, thank you for being our line of communication with JSC, and for introducing us to the other best barbeque in town.

Outside of my MIT, Draper, and JSC research bubble, thank you:

To Houston friends, for filling my summer with Texas-style fun even though I thought I would melt whenever I stepped outside; DC friends, for making my visits home so perfect that going back to school was more difficult each time; and Boston friends, for reminding me that weekends do exist even as a grad student.

To Harvard Stadium, Summit Avenue, and the numerous destination decks that kick-started my days, thank you for proving three times a week that with the right perspective and enough hugs anything after 7:30 AM is a breeze.

To my family, who have believed in me turning my childhood fantasies into reality, thank you for absolutely everything you are to me and everything you do. Specifically:

Alethea, for the years of sisterly ‘wisdom’ you bestowed (inflicted?) upon me. I am tough because of you and still think you are the coolest older sister a girl could have. Dad, for making the decision to come to MIT a given even when it was hard, and for the Star Wars marathons that undoubtedly fueled my obsession with space. Mom, for being the best example of a strong, independent woman a daughter could hope for, and for making me spanakopita every single time I come home.

To all the other people and places that made my time in Cambridge a little more joyous:

Bikram Boston and Prana Power studios, for relieving my stress and helping me find balance; Life Alive, for the mouth-watering Mystic Mountain; Alfonso Cuarón, for Gravity’s perfectly timed PR campaign for jetpacks; Swissbäkers, for quiche, bacon, and coffee; and my bicycle, for saving me hours upon hours of commute time.

And finally, thanks to you, dear reader. If you are not mentioned above, I hope you have found your way here because this work has changed the future of space exploration and has catapulted my research team to aerospace fame, or at least saved us from obscurity.

...A girl can dream.
# Table of Contents

Abstract ........................................................................................................................................................................ 3
Acknowledgements ......................................................................................................................................................... 5
Table of Contents ......................................................................................................................................................... 7
List of Figures .............................................................................................................................................................. 11
List of Tables ............................................................................................................................................................... 13
Acronyms ...................................................................................................................................................................... 15

1. Introduction and Background ................................................................................................................................. 17
   1.1 EVA Mobility Near Low-Gravity Environments ................................................................................................. 18
   1.2 Maneuvering Units ................................................................................................................................................ 20
   1.3 Thesis Overview ................................................................................................................................................. 22

2. Astronaut Dynamics Model ................................................................................................................................... 23
   2.1 Astronaut Body Model ........................................................................................................................................ 23
      2.1.1 GEBOD ......................................................................................................................................................... 23
      2.1.2 EMU and Jetpack Mass Properties Augmentation ....................................................................................... 25
   2.2 Astronaut Dynamics Model ................................................................................................................................ 28
      2.2.1 Development .............................................................................................................................................. 28
5.2.2 Part 2 (ISS EVA) Description .................................................................................................................. 79
5.3 Evaluation Results ........................................................................................................................................... 82
  5.3.1 Part 1 (Obstacle Course) Results ............................................................................................................. 82
  5.3.2 Part 2 (ISS EVA) Results ......................................................................................................................... 85
  5.3.3 Human Interface and Application Feedback ............................................................................................. 89
  5.3.4 Evaluation Conclusions .......................................................................................................................... 90
5.4 Summary .......................................................................................................................................................... 91

6. Summary and Conclusions ................................................................................................................................. 92
  6.1 Thesis Review .................................................................................................................................................. 92
  6.2 Limitations and Future Work ....................................................................................................................... 94

Appendix A: Preliminary Evaluation Questionnaires .......................................................................................... 97
Appendix B: Follow-Up Evaluation Questionnaires ........................................................................................... 103
Appendix C: ANOVA Tables ................................................................................................................................ 107

References .............................................................................................................................................................. 109
List of Figures

2.1 Body Models .......................................................... 25
2.2 Overall System Center of Mass Location ....................... 27
2.3 Astronaut Body Model .............................................. 29
2.4 Simple Motion ....................................................... 32
2.5 Simple Motion Torque Profile .................................... 33
2.6 Hammer ............................................................... 36
2.7 EVA Power Tool ...................................................... 36
2.8 Smart Power Tool .................................................... 36
3.1 Process of Developing Missions from Building Blocks ....... 41
3.2 Jets-Only and CMG Attitude Errors for Mission Building Blocks ........ 43
3.3 Asteroid Sampling Mission Trajectory ......................... 50
3.4 Incapacitated Crewmember Rescue Grasp ...................... 51
4.1 EDGE-Rendered Astronaut and Jetpack on Itokawa Surface .... 55
4.2 User’s Initial View of the Asteroid Obstacle Course .......... 57
4.3 User Preference of Control Config. from the Obstacle Course Runs .. 60
4.4 Box Plot of Fuel Consumption for Obstacle Course Run ........ 62
4.5 User Preference of Control Config. from ISS EVA Videos .......... 62
4.6 Average User Rating of Five Potential Operational Functions ..... 64
5.1 Forearm Unit Comparison .......................................... 70
5.2 Torso Unit Comparison ............................................... 72
5.3 Simulink Block Incorporating Real-Time Motion Capture into the Astronaut Dynamics Model................................................. 74
5.4 Attitude Error Over Time.................................................. 76
5.5 Maximum Attitude Error vs. Astronaut Size........................ 76
5.6 Heads-Up Display with Improvements Indicated.................... 79
5.7 User with VR Helmet, Chest Plate, and VN-100 IMU on Right Armband................................................................. 80
5.8 User Preference of Control Config. from the Obstacle Course Runs.. 83
5.9 Box Plot for Fuel Consumption.......................................... 84
5.10 User Preference of Control Config. from the Motion Capture Runs... 86
5.11 Box Plot of Max. Attitude Error......................................... 87
5.12 Box Plot of Max Attitude Error for ISS EVA Runs.................... 88
5.13 Box Plot of Fuel Consumption for ISS EVA Runs.................... 88
List of Tables

2.1 Model Astronaut Size .......................................................... 24
2.2 EMU and Jetpack Assembly Mass Breakdown .................................. 26
2.3 Whole System Mass Breakdown .................................................. 27
2.4 Tool Specifications and Descriptions ........................................ 35
2.5 EVA Task Descriptions ............................................................ 37
3.1 Task Profiles ............................................................................. 46
3.2 Fuel Consumption ...................................................................... 48
3.3 Monte Carlo Results ................................................................... 52
4.1 Operational Functions .................................................................. 59
5.1 Range of Astronaut Masses ........................................................ 75
5.2 Maximum Attitude Error .............................................................. 86
C.1 Obstacle Course Fuel Consumption ANOVA Results ..................... 107
C.2 ISS EVA Attitude Error Without Tool ANOVA Results .................... 107
C.3 ISS EVA Attitude Error With Tool ANOVA Results ....................... 107
C.4 ISS EVA Fuel Consumption Without Tool ANOVA Results ............. 108
C.5 ISS EVA Fuel Consumption With Tool ANOVA Results .................. 108
Acronyms

AMRV = Astronaut Maneuvering Research Vehicle
AMU = Astronaut Maneuvering Unit
ANOVA = Analysis of Variance
ATB = Articulated Total Body
CMG = Control-Moment Gyroscope
COM = Center of Mass
D-RATS = Desert Research and Technology Studies
DOF = Degree of Freedom
DOUG = Dynamic On-Board Ubiquitous Graphics
EDGE = Engineering DOUG Graphics for Exploration
EMU = Extravehicular Mobility Unit
EVA = Extravehicular Activity
GEBOD = Generator of Body Data
HITL = Human-in-the-Loop
HUD = Heads-up Display
HUT = Hard Upper Torso
IMU = Inertial Measurement Unit
ISS = International Space Station
JSC = Johnson Space Center
LCVG = Liquid Cooling and Ventilation Garment
LSS = Life Support Subsystem
LTA = Lower Torso Assembly
MAJIC = Mobility Augmenting Jetpack with Integrated CMGs
MMSEV = Multi-Mission Space Exploration Vehicle
MMU = Manned Maneuvering Unit
MOI = Moment of Inertia
NASA = National Aeronautics and Space Administration
NEA = Near-Earth Asteroid
NEEMO = NASA Extreme Environment Mission Operations
PLSS = Primary Life Support System
SAFER = Simplified Aid for EVA Rescue
SSA = Space Suit Assembly
VR = Virtual Reality
Chapter 1

Introduction and Background

While the immediate future of human space exploration is undecided, NASA intends to eventually send humans to Mars. As a stepping-stone towards this goal, a number of potential missions to explore zero- or low-gravity environments have been proposed or discussed, including asteroids and Martian moons. To maximize performance of astronauts during extravehicular activity (EVA) in these unfamiliar environments, an advanced maneuvering unit will likely be required. Previous EVA tasks that made use of an independent maneuvering unit consisted primarily of satellite capture, satellite repair, and rescue maneuvers. In these new non-ISS and non-Space Shuttle environments, however, astronauts will likely be performing tasks that require precise motor control, such as sample collection and equipment deployment. A jets-only mobility system would have to fire thrusters to counteract the changes in center-of-mass (COM) and moments of inertia (MOI) that result from astronaut movement, negatively affecting task performance. This research proposes incorporating control-moment gyroscopes (CMGs) into a jets-only mobility device currently being considered at NASA Johnson Space Center (JSC).

CMGs are constant-speed rotors with a gimbal that changes the direction of the rotor’s angular momentum vector. A single CMG provides one attitude degree of freedom (DOF) and the most common configurations, including the
pyramid array in this research, consist of at least four CMGs. These momentum-exchange devices are electrically powered and thus consume no fuel. Additionally, CMGs provide a continuous range of motion where jets are limited by the minimum thruster valve on-off time. The Mobility Augmenting Jetpack with Integrated CMGs (MAJIC) proposed in this research will conserve fuel and offer the rigid attitude control that is necessary for these new missions but not provided by any past or current maneuvering unit.

1.1 EVA Mobility Near Low-Gravity Objects

NASA has long had goals to send humans to Mars, with recent plans projecting achievement within the next three decades. A number of stepping stones towards this eventual human Mars exploration have been discussed, including crewed asteroid missions, return to the moon, and exploration of Martian moons [1-2]. These missions are argued to be more realistic in the short-term since they could happen sooner than a manned landing on Mars, cheaper as a result of less required delta-v, and safer than a Mars landing [3]. Additionally, these missions do not merely offer programmatic and operational benefits of human venture beyond Earth orbit; they have the potential for more practical applications as well, such as extraction and utilization of resources and planetary defense and asteroid impact mitigation [4]. The scientific potential is also compelling in terms of better understanding the solar system.

In many of these environments, the gravity is too weak to allow astronauts to walk on the surface. Instead, they will require some form of mobility technology – one that is robust and flexible in order to benefit both current missions and any of these future missions that might reach fruition. Several different EVA technologies have been developed and studied to aid in this objective, including translation lines, EVA booms, and rope tethers [4-9].

A translation line device allows setup and use of several translation lines on a planetary, lunar, or asteroid surface, which are deployed from a central surface-anchored hub [4]. These lines can provide a method of translation and stabilization within the specified “corridor” of translation line-anchor deployment.
EVA booms are modeled after the robotic arm’s boom on the ISS and can serve as a robotically controlled translation aid when one end is attached to NASA’s Multi-Mission Space Exploration Vehicle (MMSEV) or a similar EVA exploration platform and the other is attached to the astronaut. A boom can also be attached to two translation lines or anchored surface mounts to allow a restraint for performing tasks along the length of the boom. Finally, the boom can be “walked” along the surface by an EVA crewmember by releasing one end and using it as a restraint [5]. A drawback for these two methods of surface translation and stabilization is that both require local anchoring. Techniques do exist to anchor the boom, the translation line’s central hub, or even the astronaut to the surface. These include driving in pitons, firing penetrators that resist extraction, screwing in large area augers, welding tie-downs into metal, ice, or silicate rock, using fluked anchors, and burrowing completely into the regolith [6]. In some cases, for example if an asteroid is metal-rich and magnetized, a magnetic anchor could be used [7]. However, the success of all these anchoring methods depends heavily on the composition and characteristics of the destination surface [8].

A pair of MIT researchers have offered a method for EVA surface exploration that eliminates the problem of surface composition [9]. The method “lassoes” two ropes around the circumference of an asteroid and harnesses an astronaut between them. The harness contraption enables the astronaut to slide along the two ropes, acting as tethers that offer stabilization and the freedom to move about the entire circumference. However, movement will be constrained to the corridor between the two ropes, significantly limiting the scope of exploration. Further, this method is limited to small bodies like asteroids, and is not feasible for Martian moon missions.

What all these methods also have in common is the necessity for some level of setup, whether by anchoring central hubs or by looping ropes around an asteroid before the main EVA objectives can be achieved. This drawback, in addition to the other disadvantages previously mentioned, underlies the motivation for the current research. A manned maneuvering unit offers full range of exploration of the destination surface, does not depend on the composition or character of the
surface, provides a method for translating to and from a home-base spacecraft, and eliminates the need for initial setup to begin EVA tasks.

1.2 Maneuvering Units

Over the years, a number of maneuvering units have been developed, tested, and used. The first personal propulsion unit that NASA astronauts used in space was a hand-held compressed air gun unit that proved troublesome in testing in 1963. Its cumbersome handling qualities and quick fuel depletion resulted in the unit never gaining popularity for EVA use [10]. Even while the hand-held unit was being developed and tested, research was progressing on backpack-like systems for advanced mobility during EVA. The first of these jetpack systems was developed by the US Air Force in the 1960s, and completed in April 1966. Called the Astronaut Maneuvering Unit (AMU), it had self-contained life support, telemetry, communications, propulsion, and stabilization systems [11]. The first unit flew on Gemini 9 in June of 1966 and was to be tested on a spacewalk by pilot Gene Cernan [10]. Unfortunately, due to safety concerns during the EVA, the system was never tested.

Another personal maneuvering unit test bed, the Astronaut Maneuvering Research Vehicle (AMRV), was analyzed aboard Skylab in the M509 experiments [12]. Like the proposed MAJIC system, the AMRV incorporated CMGs into its design. The purpose of the M509 experiments was to evaluate the utility of several astronaut maneuvering techniques to further establish design requirements for future maneuvering units [13]. The AMRV eventually developed into the Manned Maneuvering Unit (MMU), but the evolved design abandoned the inclusion of CMGs. This was due in part to limits of CMG technology and also because simply providing effective mobility capabilities was a priority over rigid stabilization for EVA missions at the time.

The MMU, evolved from the AMRV, was designed at NASA JSC. This self-contained propulsive backpack unit was used several times during the Space Shuttle era, both in testing and in practice [10]. However, after three flights it was retired from use for two main reasons. First, most EVA tasks were able to be
completed without the MMU by using the robotic arm, translating with handholds, using tethers and restraints, or leveraging the maneuverability of the space shuttle itself. Additionally, the 1986 Challenger accident prompted new safety rules that would require expensive changes to the existing MMU [10].

The MMU was succeeded by a smaller, simplified version called the Simplified Aid for EVA Rescue (SAFER). SAFER was designed for emergency self-rescue in cases where an astronaut becomes detached from a safety tether and no vehicle can provide rescue capability. SAFER is worn by every International Space Station (ISS) crewmember using the Extravehicular Mobility Unit (EMU), one of the current spacesuits used on the ISS. However, as the name suggests, SAFER is for emergency use only and is not intended to provide primary EVA mobility.

NASA JSC is considering the development of a Jetpack device that will evolve the SAFER concept from a contingency unit into a primary maneuvering unit by leveraging the existing avionics system, redesigning the mechanical and propulsive systems, and adding hands-free functionality [14]. This concept will reintroduce the capabilities of the MMU and will certainly have applications for low-gravity missions; however, maintaining rigid attitude control to provide a stable work platform has not been a primary design requirement thus far. Jetpack’s 24 cold-gas thrusters that respond to translation and attitude commands will need to constantly fire to compensate for changes in inertia, center-of-mass location, and induced torques, resulting in motions that could interfere with tasks requiring fine motor control.

Consequently, this research pursues the use of CMGs where the MMU did not and incorporates these attitude control devices into the Jetpack. The objective is to offer greater attitude stability to EVA astronauts during all stages of an EVA in a weightless environment while conserving fuel.
1.3 Thesis Overview

This thesis investigates potential improvements offered by a CMG-augmented mobility unit in the context of current and future EVA missions. Two objectives are specifically addressed:

Objective 1: Assess EVA task motions, astronaut dynamics, and mission concepts to support the objective comparison of JSC's jets-only Jetpack system and MAJIC

Objective 2: Analyze the performance of both systems based on user evaluations of the two control configurations

This thesis addresses these objectives in six chapters. Chapter 2 discusses the development of an astronaut dynamics model used throughout the thesis as a means for analysis and additionally describes an investigation of EVA tasks, tools, and methods. This investigation is used to inform the concept of operations for MAJIC developed in Chapter 3. This concept of operations provides reference mission scenarios that are analyzed for fuel consumption and attitude stability by integrating the astronaut dynamics model with a simulation of the jetpack control system. Chapters 4 and 5 outline preliminary and follow-up user evaluations, respectively, and present trade-offs between jets-only and MAJIC system designs based on simulation data and user feedback. Chapter 6 summarizes the research, discusses the limitations, and presents recommendations for future work.
Chapter 2

Astronaut Dynamics Model

An astronaut dynamics model was developed to simulate EVA tasks of interest and calculate whole-body center of mass, moment of inertia, and torque profiles. These three outputs were integrated into a larger comprehensive system simulation environment that includes CMG and jet control algorithms. The two primary inputs into the astronaut dynamics model are human body parameters and basic motions, both of which are defined based on a simple astronaut body model. The development of these inputs, the astronaut body model, and the astronaut dynamics calculations are detailed in this chapter.

2.1 Astronaut Body Model

2.1.1 GEBOD

The unsuited astronaut body parameters were computed using the GEBOD (Generator of Body Data) program [15]. The program, developed at Wright-Patterson Air Force Base, calculates body segments' geometric and mass properties based on subject's gender, height, and weight, specified either by percentile or user-input values. The tool uses regression equations and is based on an Articulated Total Body (ATB) 17-segment human model. Regression equations are a widely used method in anthropometry for predicting unknown body dimensions from known ones, and use an existing database of measurements taken from human subjects. GEBOD utilizes four groups of
regression equations to determine the body dimension set, joint location coordinates, segment volumes, and principal moments of inertia. Each group of equations includes two sets that this research utilizes: male adult subjects and female adult subjects. For a more in-depth description of the program's calculations, see [15].

With GEBOD, the astronaut dynamics model can be modified for analysis of any size astronaut. Three astronaut sizes, summarized in Table 2.1, were chosen for this research's main analysis to encompass the range of sizes possible with NASA's current size restrictions: a minimum size female astronaut, an 'average' astronaut, and a maximum size male astronaut. The minimum size astronaut uses NASA's minimum height restriction of 1.49 m (58.5 in) and GEBOD's 5th-percentile female weight of 45.3 kg (99.9 lbs). The 'average' astronaut is modeled after the astronaut size currently used at Johnson Space Center for mechanical development of the Jetpack, which is an 81.6 kg (180 lbs), 1.83 m (72 in) male. The maximum size astronaut uses NASA's maximum height restriction of 1.93 m (76 in) and GEBOD's 95th-percentile male weight of 95.3 kg (210 lbs). These parameters are used with GEBOD to compute mass properties for the 14 segments of the simple astronaut body model used for this research. While the majority of the analyses in this document are based on these three astronaut body sizes, the methods developed with this research can be reanalyzed using any sizing specifications desired. Section 5 discusses simulation sensitivity to astronaut sizing.

<table>
<thead>
<tr>
<th>Size</th>
<th>Gender</th>
<th>Weight (kg)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>Female</td>
<td>45.3</td>
<td>1.49</td>
</tr>
<tr>
<td>Average</td>
<td>Male</td>
<td>81.6</td>
<td>1.83</td>
</tr>
<tr>
<td>Maximum</td>
<td>Male</td>
<td>95.3</td>
<td>1.93</td>
</tr>
</tbody>
</table>

While the astronaut body model mimics the 17-segment GEBOD model, adjustments were made to account for the astronaut's limited flexibility within
the Extravehicular Mobility Unit (EMU), the pressurized space suit astronauts wear during EVA. As shown in Fig. 2.1, GEBOD's 2, 3, 4, and 5 segments are combined into one main "torso" segment (L2) in the astronaut body model. The combination of these segments accounts for the rigidity of the torso, neck, and head of the EMU and restricts the independent mobility of the four segments. The two body models, with their respective numbering schemes, are illustrated in Figures 2.1a and 2.1b.

![GEBOD Human Body Model](image1)

(a) GEBOD Human Body Model

![Astronaut Body Model](image2)

(b) Astronaut Body Model

Figure 2.1: Body Models

### 2.1.2 EMU and Jetpack Mass Properties Augmentation

Anytime astronauts venture outside their vehicle for an EVA, they wear a pressurized space suit to protect their bodies from the harsh environment. The suit used for Shuttle operations and current International Space Station operations is the Extravehicular Mobility Unit (EMU), which provides environmental protection, mobility, life support, and communication for crewmembers during EVA. It is an integrated assembly comprised of two major subsystems, the Life Support Subsystem (LSS) and the Space Suit Assembly (SSA), as well as other accompanying support and supplementary gear [16].

The two subsystems can be divided into seven main components. The Liquid Cooling and Ventilation Garment (LCVG) consists of liquid cooling tubes that maintain desired body temperature and ventilation ducting to return vent
flow to the LSS. The Hard Upper Torso (HUT) provides the structural mounting interface for most of the EMU (helmet, arms, lower torso, Primary Life Support System (PLSS), display and control module, and electrical harness). The Arm Assembly includes the shoulder and elbow joints, as well as the wrist connection to the Gloves, which are relatively self-explanatory. The Lower Torso Assembly (LTA) contains the brief/waist assembly, legs, and boots, each comprised of flexible sections to allow for joint mobility. The Helmet is made of a clear polycarbonate bubble, neck connection, and ventilation pad. Currently, the EMU also includes a SAFER attachment that provides emergency mobility in the event of separation from the vehicle or station. For this research, the SAFER assembly is replaced with JSC’s Jetpack assembly, which includes the Jetpack mobility unit as well as the PLSS. The masses of these assemblies are listed in Table 2.2 [16-17].

Table 2.2: EMU and Jetpack Assembly Mass Breakdown

<table>
<thead>
<tr>
<th>Part</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Cooling and Ventilation Garment (LCVG)</td>
<td>2.94</td>
</tr>
<tr>
<td>Hard Upper Torso (HUT)</td>
<td>12.29</td>
</tr>
<tr>
<td>Arm Assembly</td>
<td>7.87</td>
</tr>
<tr>
<td>Gloves</td>
<td>2.31</td>
</tr>
<tr>
<td>Lower Torso Assembly (LTA)</td>
<td>20.72</td>
</tr>
<tr>
<td>Helmet</td>
<td>8.23</td>
</tr>
<tr>
<td>Jetpack Assembly (including PLSS)</td>
<td>119.3</td>
</tr>
</tbody>
</table>

The unsuited astronaut body model discussed in the previous subsection is augmented with the mass properties of the EMU and the Jetpack Assembly. The part masses from Table 2.2 are added to their associated segment mass, shown in Table 2.3, and segment inertias are increased proportionately with mass increase. The center of mass locations are assumed unchanged for all segments except the torso, which is adjusted to incorporate the added mass and dimensions of the Jetpack Assembly. This is done based on the known dimensions of the JSC model astronaut, the overall system center of mass (Fig. 2.2), and the calculated center of mass of an unsuited JSC model astronaut. Comparing these three known values, multipliers were computed to account for the overall system center of mass for different sized astronauts and alternate
body positions. The adjusted whole-body center of mass location is in the torso; that segment's center of mass is shifted higher up and slightly back by the selected multipliers in order to account for the Jetpack's mass properties.

![Figure 2.2: Overall system (JSC astronaut, EMU, Jetpack Assembly) center of mass location](image)

<table>
<thead>
<tr>
<th>Segment</th>
<th>Description</th>
<th>Associated Parts</th>
<th>Combined Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Upper Torso/Central Torso/Head/Neck</td>
<td>Helmet, HUT, Jetpack Assembly, LCVG</td>
<td>174.31</td>
</tr>
<tr>
<td>1</td>
<td>Pelvis</td>
<td>LTA, LCVG</td>
<td>17.51</td>
</tr>
<tr>
<td>3a</td>
<td>Upper Arm</td>
<td>Arm Assembly, LCVG</td>
<td>4.33</td>
</tr>
<tr>
<td>4a2</td>
<td>Lower Arm</td>
<td>Arm Assembly, LCVG</td>
<td>3.04</td>
</tr>
<tr>
<td>5a2</td>
<td>Hand</td>
<td>Glove</td>
<td>1.67</td>
</tr>
<tr>
<td>3b</td>
<td>Upper Arm</td>
<td>Arm Assembly, LCVG</td>
<td>4.33</td>
</tr>
<tr>
<td>4b2</td>
<td>Lower Arm</td>
<td>Arm Assembly, LCVG</td>
<td>3.04</td>
</tr>
<tr>
<td>5b2</td>
<td>Hand</td>
<td>Glove</td>
<td>1.67</td>
</tr>
<tr>
<td>7a</td>
<td>Thigh</td>
<td>LTA</td>
<td>15.17</td>
</tr>
<tr>
<td>8a</td>
<td>Calf</td>
<td>LTA</td>
<td>6.02</td>
</tr>
<tr>
<td>9a</td>
<td>Foot</td>
<td>LTA</td>
<td>1.49</td>
</tr>
<tr>
<td>7b</td>
<td>Thigh</td>
<td>LTA</td>
<td>15.17</td>
</tr>
<tr>
<td>8b</td>
<td>Calf</td>
<td>LTA</td>
<td>6.02</td>
</tr>
<tr>
<td>9b</td>
<td>Foot</td>
<td>LTA</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>Total Mass</td>
<td></td>
<td>255.27</td>
</tr>
</tbody>
</table>

27
2.2 Astronaut Dynamics Model

The primary purpose of the astronaut dynamics model is to compute the center of mass, moment of inertia, and torque profiles associated with a given astronaut body model and prescribed motion. These outputs are used in the overall system simulation in order to calculate the required control actuation to maintain stability during various motions.

2.2.1 Development

The code for the astronaut dynamics model is adapted from a previously designed model created to simulate astronaut self-rotation [18]. The 37 degree-of-freedom (DOF) astronaut body model is defined in the code as 14 chain-linked segments as shown in Figure 2.3a, with the pelvis (segment L1) as the base. Each segment consists of a point mass at the segment's center of mass with a corresponding moment of inertia. Segment reference frames are defined at the base joint of the corresponding segment; for example, the reference frame for the pelvis, segment L1, has its origin at the base of the pelvis, joint 1. This pelvis reference frame, or the 1-frame, is the frame from which whole-body properties are defined. Every other link is a 'child' link to the pelvis 'parent', and this pattern continues outwards to the feet and hands, which have no corresponding 'child' links of their own.

Figure 2.3b shows the astronaut body model side view depicting the location of the Jetpack frame of reference (Point J). Point J is the origin of the J-frame, which is coincident with the entire system center of mass in the neutral position where the legs are straight down and the arms are straight down by the sides.
Any motion is defined by joint position, velocity, and acceleration. The kinematic modeling of the motions in this code is based on quaternion representation of rotation, rather than the Euler angle representation. A quaternion's four quantities enable singularity-free mathematical representation of orientations, and are thus preferable to the three-quantity Euler angle method. A quaternion, \( q \), has one real part and three imaginary parts, written as

\[ q = q_1 + q_2 i + q_3 j + q_4 k \]  

(2.1)

An orientation can be represented as a quaternion rotation,

\[ q_{rot} = \begin{bmatrix} \cos(\theta/2) & \sin(\theta/2) \end{bmatrix} e^T = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix}, \]  

(2.2)

where \( \theta \) is the angle of rotation about the axis \( e \) described by \( e = [e_1 \quad e_2 \quad e_3]^T \).
The angular velocities \((\omega_x, \omega_y, \omega_z)\) and angular accelerations \((\alpha_x, \alpha_y, \alpha_z)\) can be calculated using the quaternion derivatives through the matrix equations

\[
\omega = \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = 2Q^T \dot{q} \tag{2.3}
\]

\[
\alpha = \begin{bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{bmatrix} = 2Q^T \left( \ddot{q} - \frac{1}{2} \dot{Q} \omega \right) \tag{2.4}
\]

where

\[
Q = \begin{bmatrix}
-q_2 & -q_3 & -q_4 \\
q_1 & -q_4 & q_3 \\
q_4 & q_1 & -q_2 \\
-q_3 & q_2 & q_1
\end{bmatrix} \tag{2.5}
\]

To map motions from one segment to the next in the linked astronaut body model, a transformation consisting of a rotation matrix based on each segment’s orientation and a translation based on its lengths is used. Based on each joint’s quaternion orientation written as \(q_{rot}\), the rotation matrix from the previous link to the current joint’s link is:

\[
R = \begin{bmatrix}
2q_1^2 + 2q_2^2 - 1 & 2q_2q_3 + 2q_1q_4 & 2q_2q_4 + 2q_1q_3 \\
2q_2q_3 - 2q_1q_4 & 2q_1^2 + 2q_2^2 - 1 & 2q_3q_4 + 2q_1q_2 \\
2q_2q_4 - 2q_1q_3 & 2q_3q_4 - 2q_1q_2 & 2q_1^2 + 2q_3^2 - 1
\end{bmatrix} \tag{2.6}
\]

Linear velocities can then be calculated by a forward propagation from link 1 to link \(N\),

\[
V_{L_i} = \sum_{j \in P_i} R_j^i \left( V_{L_j} + \omega_{L_j} \times L_{ij} \right), \quad i = 1, \ldots, N \tag{2.7}
\]
The summation is performed over the set of parent links, \( P_i \), for the given link, and \( L \) is the distance from frame \( i \) to frame \( j \). Linear accelerations can then easily be found by differentiating. In this research, the astronaut's body is fixed with respect to the inertial frame. In other words, to an outside observer, the astronaut does not rotate or translate as a result of the movement. This simulates the function of the control algorithm, providing stability to astronauts while they work in zero- or microgravity environments. Thus, the base link (pelvis, \( L_1 \)) has zero angular and linear velocity and acceleration, and equation 2.5 can be fully solved.

The joint torques, \( t \), are then found using the backwards recursion from the original code [18]:

\[
\tau_i = \sum_{j \in C_i} R_j^i \tau_j + \tau_i^*, \quad i = N, ..., 1,
\]

(2.8)

where \( \tau_j \) maps the torques of the child joints, \( C_i \), to the current joint \( i \), and \( \tau_i^* \) is the torque due to coupling forces applied to link \( i \) by link \( i - 1 \) and \( i + 1 \) and the rotation of the reference frame. External torques and forces can be included in this calculation by applying a torque or force to a designated joint. This functionality is utilized in the next subsection by applying torques and forces to the hand segments to simulate tool use.

Using Eq. 2.8, the net torque about the J-frame origin required to maintain the fixed inertial position is computed, and the center-of-mass location and moments of inertia are calculated as well as the body position changes. These three outputs are computed with respect to the J-frame.

2.2.2 Example Analysis

The following section offers an analysis of a simple motion trajectory to demonstrate the astronaut dynamics model. In this simple case, there are no external forces or external torques. In this motion, both arms swing upward from the neutral straight down position to directly outward from the chest, and the
speed of the motion is varied to demonstrate the resulting changes in the torque profile. Figure 2.4 depicts the initial and final body positions for the defined motion. The star represents the whole-body center of mass, and the transition from 2.4(a) to 2.4(b) reflects the change due to the altered arm position.

![Figure 2.4: Simple motion](image)

Three simple cases are run using the described motion. The three cases differ only in the length of time to complete the motion: the slowest at 10 seconds for case one (Figure 2.5a), 5 seconds for case two (Figure 2.5b), and the fastest at 1 second for case three (Figure 2.5c).

As is expected from the defined motion, the required torque is entirely about the J-frame y-axis. In other words, if the astronaut were unrestrained, raising the arms would cause the astronaut to tilt forward. Additionally, the maximum torque increases as the speed of the arms increases, from 0.64 Nm for a 10 second motion to 6.43 Nm for a 1 second motion. The torque profiles shown in Fig. 2.5 are the astronaut dynamics input to the CMG-augmented Jetpack system simulation.
2.3 EVA Assessment

2.3.1 Motion

Because one of the main inputs to the astronaut dynamics model is motion, a preliminary astronaut task list has been compiled to include various tasks that might be enacted during an asteroid EVA. The task list provides necessary inputs for the astronaut dynamics model, including external forces and torques, mass properties of any corresponding tools, and definition of the motion trajectory. The task list is organized by grouping similar tasks and motions.
together, and is expected to ultimately help pinpoint Jetpack control modes based on intended task type.

Limited information is available concerning tool specifications, corresponding motions, and external force and torque data; however, guidelines described here will be used to continue populating a generalized task list and offer minimum and maximum torque limits for each task. The maximum external torque to which a crewmember can comfortably react while in free float is just under 70 N-m (50 ft-lb), and the maximum external force is just under 220 N (50 lbf) [19]. Impulses for each can be higher, but generally astronauts are instructed to avoid exceeding the limits. In terms of motion characteristics, arm movements will likely be the most common, given the type of motions seen on EVA (repairs, geological sampling, equipment deployment). Most arm motions remain within the immediate work envelope of the astronaut’s chest, defined as roughly between the shoulders, between the eyes and navel, and within the forward reach of the arms with a slight bend.

Since near-Earth asteroid (NEA) exploration is one of the EVA areas that would likely benefit from a CMG-stabilized Jetpack system, an initial task assessment was based on prior NEA mission analysis programs, namely the NASA Extreme Environment Mission Operations (NEEMO) and Desert Research and Technology Studies (Desert RATS, or D-RATS). Missions from both programs included analyses of task procedures and tool use, and given the science goals of NEA exploration, these primarily consisted of geological sampling methods [4]. Between the two programs, three categories of sampling techniques were tested: surface sampling, soil sampling, and depth sampling [4]. Surface sampling consists of hand, bag, or contact surface pad collection, soil sampling consists of clamshell device or scoop collection, and depth sampling consists of core tube or drive tube collection [20]. The three categories have generally increasing levels of reaction forces. Surface sampling—picking up a rock, for example—tends to have the lowest reaction force, while depth sampling—deploying a drive tube into the ground, for example—tends to have the highest. However, there are some exceptions; a small surface sample may
require a hammer to separate it from a larger rock, which creates a significantly higher impulse.

While specifications for the aforementioned sampling tools are not readily available, several tools from the EVA Tools and Equipment Reference Book have been chosen as representative EVA tools for this research. An EVA Hammer, an EVA Power Tool, and a second “Smart” Power Tool have been selected to offer a range of external impulses, forces, and torques. Selected tool specifications and descriptions are included in Table 2.4 and shown in Figures 2.6-8 [21].

<table>
<thead>
<tr>
<th>Tool</th>
<th>Mass (kg)</th>
<th>Length (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammer</td>
<td>0.91</td>
<td>27.94</td>
<td>Tool used for disconnect and jam removal with fiberglass shaft and brass head to damp the shock of hammer blows.</td>
</tr>
<tr>
<td>EVA Power Tool</td>
<td>1.33</td>
<td>29.85</td>
<td>Battery-powered, two-speed/four-torque unit with forward/reverse switch. Used for any EVA task that requires a portable torque device.</td>
</tr>
<tr>
<td>Smart Power Tool</td>
<td>5.44</td>
<td>36.83</td>
<td>Hand-held, battery-powered, microprocessor-controlled device with regulated torque and revolution. Parameters are keyed in by the user and electronically regulated by the tool.</td>
</tr>
</tbody>
</table>
A task list compiled from these tool specifications, the minimum and maximum guidelines described in the beginning of this section, and the task procedures learned from NEEMO and D-RATS missions offer a concise resource from which motion inputs for the astronaut dynamics model were easily compiled. The task list mentioned earlier, organized by task type, is given in Table 2.5. It includes the task, description of the motion, and the maximum resulting torque from the standalone astronaut dynamics model (using a maximum sized 210-lb, 76-in astronaut). For each task in Table 2.5 involving a tool, the mass properties of the tool were incorporated into the hand segment. These motions were then be combined into various motion profiles and integrated into the system simulation environment for analysis.
### Table 2.5: EVA Task Descriptions

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
<th>Magnitude of Maximum Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Category I: Using Tools</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hammer</td>
<td>The bent right arm swings down to the front, impacts with a 100N impulse to correspond with a hammer strike, and swings the arm back to the starting position. Modeled with hammer in hand.</td>
<td>59.54</td>
</tr>
<tr>
<td>Min Torque Power Tool</td>
<td>Bent right arm holds the power tool within the work envelope in a stationary configuration with the power tool powered up to its minimum torque (20.3 Nm).</td>
<td>20.30</td>
</tr>
<tr>
<td>Max Torque Power Tool</td>
<td>Bent right arm holds the power tool within the work envelope in a stationary configuration with the power tool powered up to its maximum torque (135.6 Nm).</td>
<td>135.60</td>
</tr>
<tr>
<td><strong>Category II: Reaching for or Passing Tools</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hand to Hip Reach</td>
<td>Bent arm swings downward from work envelope to slightly back past the left hip and returns.</td>
<td>8.87</td>
</tr>
<tr>
<td>Hand to Hip Reach With Tool</td>
<td>Same as “Hand to Hip Reach,” but modeled with a heavy tool in hand. Tool used is the Smart Power Tool.</td>
<td>29.66</td>
</tr>
<tr>
<td>Hand to Side Reach</td>
<td>Straight right arm swings horizontally from out to the side to straight forward, then returns.</td>
<td>16.58</td>
</tr>
<tr>
<td>Hand to Side Reach With Tool</td>
<td>Same as “Hand to Side Reach,” but modeled with a heavy tool in hand. Tool used is Smart Power Tool.</td>
<td>39.87</td>
</tr>
<tr>
<td>Overhead Reach</td>
<td>Bent right arm swings from work envelope up to over the head and returns.</td>
<td>9.21</td>
</tr>
<tr>
<td>Overhead Reach With Tool</td>
<td>Same as “Overhead Reach,” but modeled with a heavy tool in hand. Tool used is Smart Power Tool.</td>
<td>32.76</td>
</tr>
<tr>
<td>Overhead Two-Arm Reach</td>
<td>Both bent arms swing from work envelope up to over the head and return.</td>
<td>18.42</td>
</tr>
<tr>
<td>Overhead Two-Arm Reach With Tool</td>
<td>Same as “Overhead Two-Arm Reach”, but modeled with a heavy tool in both hands. Tool used is Smart Power Tool.</td>
<td>49.88</td>
</tr>
<tr>
<td><strong>Category III: Miscellaneous</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip Flexion</td>
<td>Both legs swing from straight down to straight out in front, and back.</td>
<td>154.33</td>
</tr>
<tr>
<td>Knee Bend</td>
<td>Both knees swing from bent position to straight down, and back up to starting bent position.</td>
<td>37.96</td>
</tr>
</tbody>
</table>
2.4 Summary

The astronaut dynamics model discussed in this chapter provides the foundation for the analyses comparing JSC’s Jetpack design to the MAJIC design that follow in the remainder of this thesis. The EVA task and tool investigation provides a framework for mission scenario development that supports these analyses. Developing the capability to compare the two systems based on astronaut EVA motion disturbances and not only on mission trajectory and navigation adds a level of focus to the analysis. This astronaut dynamics model offers a more detailed and comprehensive comparison of system performance in the context of actual EVA tasks.
Chapter 3

Mission Analysis

The astronaut dynamics model developed in Chapter 2 is used in conjunction with a control model developed using MATLAB/Simulink [22]. The control model calculates the jet and CMG commands based on the astronaut dynamics model torque, moment of inertia, and center of mass profiles, as well as mission specifications such as trajectory, velocity, and control mode [22]. For a more detailed description of the control model, please see [23]. This system simulation allows for a comprehensive analysis of astronaut motions during a wide range of mission scenarios and trajectories. Missions are defined by an astronaut motion profile, a mission trajectory and timeline, and the specified control mode. In this chapter, a number of mission scenarios are analyzed using the comprehensive model to compare attitude error and fuel consumption between the original jets-only attitude control system, and the proposed CMG-augmented MAJIC control system. Additionally, two approaches are presented to generate and analyze sample missions, which will be utilized in a Monte Carlo simulation to determine optimal size for the CMGs.

To guide these analyses, a concept of operations for MAJIC is presented, which includes several scenarios that would benefit from the system’s stiffer work platform and reduced fuel consumption. These scenarios span a range of work environments and tasks, including asteroid or Martian moon surface sample collection, equipment deployment, International Space Station (ISS) or
satellite servicing and repair, rescue maneuvers, and contingency EVA on spacecraft not equipped with built-in EVA handholds.

3.1 Concept of Operations

As demonstrated in Chapter 1, there is not merely one mission concept for future manned space exploration. Given that the MAJIC system offers benefits that are widely applicable to many different mission types, a concept of operations was developed to demonstrate these benefits in comparison to the jets-only system. Multiple mission concepts and desired EVA capabilities were researched and refined in order to provide an extensive demonstration of applications [24]. Portions of each were then analyzed in simulations [25] to quantitatively illustrate the benefits of MAJIC over JSC’s Jetpack system.

3.1.1 Mission Selection

The survey of current and future EVA goals presented in Chapter 1 resulted in five broad mission types, developed from a compilation of motions from the task investigation completed in Section 2.3:

1. Asteroid exploration and surface sampling
2. Contingency EVA on non-shuttle or ISS spacecraft
3. Routine satellite and ISS servicing and repair
4. Emergency self-rescue
5. Translation to and from worksite

This is not a comprehensive list of potential applications for the MAJIC system, but a generally representative range of mission types. Asteroid exploration and sampling is of future interest to NASA, and current methods for EVA stability and task completion would not provide adequate support for such missions. Likewise, EVA methods and techniques have been developed for ISS and Shuttle applications, so the possibility of contingency EVA on new spacecraft would require new methods for operational support not reliant on ISS or Shuttle footholds, handholds, and structural familiarity. In addition to
providing for new applications, MAJIC can take over in several areas of current operations as a next-generation mobility unit. Whether by allowing astronauts to bypass the tedious job of traversing via handholds, replacing the need for robotic arm manipulation of end-effector footholds, or offering more control and guarantee of safety in the case of emergency separation, MAJIC can provide more efficient and more stable solutions to current EVA applications.

3.1.2 Mission Building Blocks

Given that each of these five missions could cover a wide array of specific tasks and tools, with potential overlap between missions, a number of simplified “mission building blocks” were identified to address the different steps in a mission. Each block represents a general example of a specific portion of a larger mission. The five mission building blocks are:

1. Translation
2. Tool retrieval
3. Attitude correction
4. ISS servicing EVA task
5. Asteroid sampling task

Like the five mission types chosen at the beginning of this section, these five building blocks are not a complete list of the tasks performed within every mission. However, given the similar nature of many ISS servicing tasks, the unprecedented characterization of what an asteroid sampling task will specifically encompass, and the almost universal applicability of translation, tool retrieval, and attitude correction across mission type, these five blocks are a sufficient representation of applications for this analysis.

These five mission building blocks can be combined in numerous sequences to represent examples of the five mission types. Figure 3.1 shows this process.
3.2 Block Analysis

To demonstrate the benefit of the MAJIC system over the jets-only jetpack system for the five mission types, each of the five building blocks were analyzed individually with the comprehensive model that provides attitude stability and fuel consumption metrics [22]. As described in this chapter’s introduction, the comprehensive model combines the astronaut dynamics model with a control model. The astronaut dynamics model’s torque, moment of inertia, and center of mass profiles are analyzed in conjunction with the control model’s jets-only or CMG-augmented control configuration and specified mission trajectory. For each of the five mission building blocks, a representative task was created based on an astronaut motion profile (body movements and any associated tools) and a mission scenario. The average model astronaut (see Table 2.1) was used for all scenarios. Mass properties of any associated tools or samples were incorporated into the astronaut dynamics model (for tool specifications, see Table 2.4). Table 3.1 describes the task profiles for each block, and the remainder of this section discusses the results of the analysis.
Figure 3.2: Jets-only (top) and CMG-augmented (bottom) attitude errors for each building block
Figure 3.2 (cont): Jets-only (top) and CMG-augmented (bottom) attitude errors for each mission building block.
Figure 3.2 (cont): Jets-only (top) and CMG-augmented (bottom) attitude errors for each mission building block

(e) Asteroid sampling
The simulation results include attitude error and fuel consumption. Figures 3.2a-e show the results for each attitude control system for the five mission building blocks.

<table>
<thead>
<tr>
<th>Mission Building Block</th>
<th>Mission Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translation</td>
<td>Astronaut traverses a series of 20 specified points in 3D space in 10 minutes (total distance: 50 m). No motion within the body reference frame.</td>
</tr>
<tr>
<td>Tool Retrieval</td>
<td>Right arm reaches down to hip tool belt, retrieves Smart Power Tool (5.44 kg). [9] One minute later, right arm replaces tool back into the tool belt, and returns to initial position. Stationary at worksite.</td>
</tr>
<tr>
<td>Attitude Correction</td>
<td>Correction from an initial roll error of +7°. No motion within the body reference frame.</td>
</tr>
<tr>
<td>ISS Servicing EVA</td>
<td>Series of arm motions. Stationary at worksite. (This motion profile is not meant to accurately depict a specific servicing task, rather to encompass a broad range of arm motions and repetition.)</td>
</tr>
<tr>
<td>Asteroid Sampling EVA</td>
<td>Hammer (0.91 kg) retrieval, three hammer blows to asteroid surface, left hand retrieves dislodged sample, hammer returned, sample bag retrieved, sample placed in bag, returned to tool belt. Stationary at worksite.</td>
</tr>
</tbody>
</table>

For the translation mission building block (Fig. 3.2a), the added CMG array offers several degrees of extra rotational stability and much less "bang-bang" jet control. The attitude control in the jets-and-CMGs case present just a slight disturbance that is quickly compensated, whereas the jets-only case reaches higher errors and has continuous oscillation of about 4 degrees.

Apart from purely exploratory missions, almost every EVA will include some tool use, making tool retrieval a very common task. The tool retrieval building block plots in Fig. 3.2b illustrate similar results to the translation block – the CMGs quickly return the attitude error to zero after a quick, smooth correction. In the jets-only case, as soon as the first motion commences, the
attitude oscillates with the jets overcorrecting and compensating time and again. The MAJIC control system quickly cancels out the disturbance torques, enabling the astronaut to use both hands for tasks without needing to hold onto anything for stability.

The differences between the two control system responses when completing an attitude correction maneuver (Fig. 3.2c) are slight, but still present. The CMG system compensates more quickly and settles out precisely at zero error, while the jets-only system takes a little bit longer and also gradually passes zero error and continues to accumulate error. If the timeline were extended, the jets plot would show a deadband between -2 and +2 degrees of attitude error, while the CMGs case keeps the attitude precisely at zero.

The top graph in Fig. 3.2d displaying the attitude error of the jets-only configuration during an ISS servicing EVA starts with a slowly oscillating error, but then shows zero error after a spike at 0.5 seconds. This is actually a product of the control algorithm used, and indicates that the attitude rate error became too high, forcing the controller to essentially ignore the attitude error in order to bring down the rate error. Thus, this ISS servicing task is effectively uncontrollable with the jets-only configuration. At about 80 seconds, the attitude error falls down to zero in the CMG case, indicating a large deviation in attitude error similar to the one that the jets case saw. However, the system recovers quickly, and within 10 seconds has regained complete control. The MAJIC control system, thus, is able to quickly and smoothly correct during an EVA task, even when there are large disturbances.

For this asteroid sampling task in Fig. 3.2e, the magnitude of the attitude errors are similar (~2°) across the two control systems; however, the jets-only configuration accumulates a significant drift offset from zero error. While the MAJIC system returns the astronaut to exactly zero error quickly and smoothly after each maneuver, the jets-only system is unable to do so.

Fuel consumption for each mission building block was also analyzed using the closed-loop simulation. Table 3.2 indicates a 100% fuel savings (no fuel usage) for tasks that require only attitude control. Even for the translation task,
there are still significant fuel savings as a result of the added CMG control. (It should be noted that the model iteration used in this chapter does not account for momentum desaturation of the CMGs. Desaturation capabilities were developed later and are explained in the Chapter 5 analyses).

<table>
<thead>
<tr>
<th>Control System</th>
<th>Translation</th>
<th>Tool Retrieval</th>
<th>Attitude Correction</th>
<th>ISS EVA</th>
<th>Asteroid Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets Only (kg)</td>
<td>0.59</td>
<td>0.22</td>
<td>0.010</td>
<td>0.35</td>
<td>0.42</td>
</tr>
<tr>
<td>Jets and CMGs (kg)</td>
<td>0.33</td>
<td>0.00</td>
<td>0.00044</td>
<td>0.00</td>
<td>0.00087</td>
</tr>
</tbody>
</table>

*Propellant Mass Reduction (%)* 43.73 100.00 95.79 100.00 99.79

The fuel consumption and attitude stability results show that MAJIC offers benefits over a flexible range of mission types and tasks. However, the system must still be optimized for the astronaut to be most efficient and productive during each of these different mission concepts. Such a multiple-part optimization might include navigational aids or control modes to enhance certain capabilities during different parts of these missions, and the integration of these aids into various interfaces for the user. The possibilities for navigational aids were addressed as part of a user evaluation completed in August 2013 intended to obtain feedback of the MAJIC system from potential end users. The design and results of this evaluation are detailed in Chapter 4.

### 3.3 Mission Analysis for CMG Sizing

The system simulation used to analyze the EVA tasks in Section 3.2 is further used as a platform for a trade study to determine CMG size. As demonstrated in 3.2, the MAJIC system reduces fuel consumption. The CMG array can be sized based on the mass saved from reduced fuel without altering the overall mass of the system. To justify anything heavier than that specified mass, however, a trade study was completed based on added stability, power.
and energy consumption, and fuel. This section presents the system setup developed for this CMG sizing trade study.

In order to determine the optimal size and design for the CMG array in the MAJIC system, some of the same motions and tools and a similar analysis to those presented in Section 3.2 were used. The model iteration used in this section, however, included power and energy analyses in addition to fuel consumption and attitude error. Results of several different missions were compared based on these four main parameters: total propellant consumption, peak CMG power consumption, total CMG energy consumption, and attitude error. Each parameter had a corresponding performance weight that could be adjusted based on priority; for the preliminary sizing study, however, each weight was set equal to 1.

Two different approaches to the mission construction were developed for the sizing analysis: one that analyzed a wide array of arbitrary compilations of EVA motions and trajectories, and one that analyzed a narrower scope of more detailed and mission-relevant motions and trajectories. The first method automatically compiled an EVA motion profile from the motion library for a specific mission duration, allowing for numerous combinations of motions for a thorough, randomized analysis. The second approach used three specific missions to test the various sizes of CMG arrays, varying only the astronaut size.

For the first method, the code had four main options for motion compilation: low, medium, high, and clumped. The low option designated one motion every minute, medium designated one motion every 30 seconds, and high designated one motion every 10 seconds. The clumped option designated two, three, or four consecutive motions every minute. If a motion called for a tool, a tool was also chosen randomly. Finally, the astronaut size was also designated as minimum, average, or maximum (see Section 2.1 for descriptions). These various options allowed for a wide array of sample EVA missions to be automatically created to test the limits of the range of CMG array sizes.

For the second method, the three missions were chosen based on expected relevance and benefit of the MAJIC system: solar array inspection, asteroid
sampling, and incapacitated crewmember rescue. This allowed for a more realistic mission profile and a simpler platform for comparison, but also narrowed the scope of the analysis.

The solar array inspection was chosen to demonstrate the use of the MAJIC system for a task that cannot currently be done with ease on the ISS. In this mission, the astronaut translates from the first solar array wing at the truss, outward along the wing mast. When the astronaut reaches the end, he or she then traverses perpendicularly 3.4 meters, and then returns to the truss in a line parallel to the first trajectory (and to the mast). The astronaut repeats this pattern for the entire 35 by 12 meters of each of the four solar array wings on one half of the ISS. Currently, the robotic arm is the only way to offer safe access to the solar arrays, as there are no handholds on the structure.

The asteroid sampling mission (shown in Fig. 3.3) combines extensive translation with fine motor control tasks that draw on MAJIC’s fuel saving benefits as well as its attitude stability benefits. The human profile used for this sample mission assumes a motionless astronaut for most of the navigation around and towards the asteroid. Once the astronaut is on final approach towards the asteroid, the Jetpack and astronaut system will undergo a series of
torque and moment of inertia (MOI) changes that include three slightly adapted motions from the task list in Table 2.4. The three motions are Hand-to-Hip Reach, Hand-to-Hip Reach With Tool, and Hammer. When the astronaut is about a minute away from the asteroid, the astronaut reaches with an empty right hand from within the work envelope down to a hip tool belt (4 s motion), takes some time to locate and release the hammer from the tool belt (10 s), returns the right hand with the hammer up to the original position in the work envelope (4 s), waits to reach the asteroid surface (~30 s), and then completes one hammer motion cycle to the asteroid's surface (2 s) which includes an impulse force upon impact.

The final mission scenario simulated the rescue of an incapacitated EVA crewmember, demonstrating the use of MAJIC even with added mass and significantly altered center of mass and moment of inertia. The mission assumed an incapacitated average sized astronaut (see Section 2.1 for size description) has been physically grasped by the rescue crewmember and is being held facing forward with a slightly lower center of mass than the rescuer (i.e. the rescuer adopts a standard "lifeguard" rescue grasp as in Fig. 3.4). The rescue crewmember then turns 180 degrees towards the airlock and translates in a straight line there.

Figure 3.4: Lifeguard rescue grasp used by astronaut in incapacitated crewmember rescue mission [26]
The two different methods for the CMG sizing analysis were used to run a Monte Carlo simulation, which used repeated random sampling for analysis. The first method randomized all parts of the mission, from mission trajectory and duration to motion profile, astronaut size, and tool specifications. The second randomized only the astronaut size and mission type from only the three specified. Results using either, however, can offer distinct insight into the trade space being explored.

The primary Monte Carlo analysis for MAJIC was completed using the specific mission scenario framework. For the solar array inspection scenario, the optimal CMG had a mass of 1.10 kg, a flywheel speed of 14000 rpm, and a maximum gimbal rate of 46 rpm. For the incapacitated crewmember rescue scenario, the CMG was optimally sized at 1.48 kg, with a flywheel speed of 19000 rpm and a maximum gimbal rate of 52 rpm. The surface sampling scenario resulted in a CMG of 0.98 kg, a flywheel speed of 25000 rpm, and a maximum gimbal rate of 49 rpm. These results, summarized in Table 3.3, showcase the validity of incorporating CMGs into the jetpack design. In all three mission scenarios, the final CMG array weighed less than 6 kg—a feasible addition to the structure, especially when further considering fuel savings. For a more detailed explanation of the implementation, analysis, and results of the Monte Carlo simulation for MAJIC’s CMG sizing, see [23].

<table>
<thead>
<tr>
<th>Mission Scenario</th>
<th>Mass (kg)</th>
<th>Flywheel speed (rpm)</th>
<th>Max. gimbal rate (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Array Inspection</td>
<td>1.10</td>
<td>14000</td>
<td>46</td>
</tr>
<tr>
<td>Crewmember Rescue</td>
<td>1.48</td>
<td>19000</td>
<td>52</td>
</tr>
<tr>
<td>Surface Sampling</td>
<td>0.98</td>
<td>25000</td>
<td>49</td>
</tr>
</tbody>
</table>
3.4 Summary

The goal of the MAJIC system is to provide flexibility across different missions by offering enhanced attitude control, stiffer worksite stability, and reduced fuel consumption. A concept of operations was developed to include a number of potential future missions for which MAJIC would be beneficial, and each sub-task (or mission building block) was shown to provide better stability and lower fuel use. The implications from these results demonstrate a number of distinct benefits of MAJIC over the Jetpack system. Added stability provides easier navigation and translation for astronauts, and could not only provide a means for translation to remote targets like asteroids, but also an alternative to traversing on the ISS with handholds. Additionally, with the system correcting for any disturbances, the astronaut will not need to hold on or be restrained for many tasks. This hands-free capability allows the astronaut to retrieve tools stably during translation and prevents the astronaut from needing to locally tether. This has a number of benefits, including saving astronaut time and energy, while simultaneously reducing surface disturbance.

These computational benefits are bolstered by the CMG sizing analysis, which offers results of optimally sized CMGs for various missions. The CMGs chosen successfully complete the mission, out-perform the jets-only control system, and have a small enough mass that physical incorporation of an array into the Jetpack design is feasible. Chapter 4 shows how two of the analyzed CMG systems perform in a user evaluation.
Chapter 4

Preliminary User Evaluation

The mission analysis results in the previous chapter illustrate potential concrete benefits of the MAJIC system over the Jetpack system based on fuel reduction and increased attitude stability. In actual application of the system, however, the system will be piloted by human users rather than exclusively by autopilot as in the simulation. The inclusion of a human controller in the system introduces a number of new concerns: whether the fuel reduction and attitude stability increase with the MAJIC system hold with an imperfect pilot; whether the attitude stability differences are noticeable by human pilots; and whether the perceivable differences in the two control configurations are enough to warrant the introduction of CMGs into the system.

These concerns were addressed in a user evaluation completed over a three-month period in the Virtual Reality Lab (VR Lab) at JSC. The design of the user evaluation was influenced by the results of the mission building block analysis in Section 3.2; portions of the evaluation drew upon several of the mission scenarios analyzed. The evaluation was designed to gauge user preference and get feedback and recommendations from potential end users and customers by allowing the user an immersive virtual reality piloting experience with both the original jets-only control configuration as well as MAJIC’s CMG-augmented configuration. This chapter details the VR Lab’s graphics environment, evaluation design, and results of the preliminary user evaluation.
4.1 Virtual Reality Graphics Environment

The VR Lab at JSC has a number of unique capabilities that enabled a human-in-the-loop (HITL) evaluation to gauge user preference and performance between the two attitude control systems. Engineering DOUG Graphics for Exploration (EDGE) is a powerful graphics rendering software package used primarily in the VR Lab for simulated ISS EVA and SAFER training. The rendered scene created for the evaluation included a detailed model of the asteroid Itokawa, models of marker cones for evaluation tasks, and a model of an astronaut with the MAJIC system (seen in Fig. 4.1). Cameras and lights were controlled to display different perspectives and angles and highlight certain aspects of the rendered scene.

Figure 4.1: EDGE-rendered astronaut and Jetpack on Itokawa surface

There are myriad possibilities for customizing EDGE scenes. For this evaluation, the main camera view was attached to the astronaut's helmet for a true first-person piloting experience. A heads-up display (HUD) was created to
display pertinent information to the user in real-time while flying the system. The comprehensive MAJIC simulation environment communicated with EDGE via the d_comm C library, allowing real-time data transfer between EDGE and MATLAB/Simulink to drive the graphics based on the MAJIC model and user inputs. For more detailed information regarding the integration of the MAJIC model with the VR Lab simulation environment, see [27].

The graphics scene for the piloted obstacle course was rendered so as to give the user a 360° view of the virtual environment, including a model of the asteroid Itokawa. Users used a GamePad Pro hand controller to control positive and negative translation in all three axes, and these inputs were fed into the control model from which the resulting dynamics of the system were calculated and subsequently updated in real-time in EDGE.

4.2 Evaluation Design

Using the EDGE-MAJIC simulation environment developed in the VR Lab, a comparative user evaluation of the MAJIC vs. the JSC Jetpack systems was designed. The evaluation consisted of three distinct parts: a human-in-the-loop real-time piloted obstacle course, videos of simulated motion disturbances, and a user interface questionnaire and discussion. The subjects were volunteers and included four astronauts. The three parts are described in detail below.

4.2.1 Part 1 (Obstacle Course) Description

The obstacle course can be likened to the translation mission building block from Chapter 3. For this stage of the simulation, the astronaut was modeled as a rigid body, so the simulation did not incorporate astronaut limb movements. The full set of obstacle course tasks was comprised of a familiarity run (with either control system) and two actual runs (one with each attitude control system). The familiarity run offered the user a chance to get a “feel” for piloting the system, a sense of how the heads-up display (HUD) information would be used, and a look at how the attitude autopilot controlled the system. When each user was
comfortable enough with the sim (usually after about three minutes), the user moved on to the actual runs.

Each of the two actual runs was completed with a different control system (jets-only configuration and MAJIC’s jets-and-CMGs configuration). The order was counterbalanced between the users to account for bias. Only one course was used, consisting of four orange traffic cones emitting a blue beam above each for visibility. The course was run once in one direction and once in the reverse direction so as to create the illusion of two distinct courses. In the VR helmet, the user had a $360^\circ$ view on the surface of the asteroid. As seen in Fig. 4.2, the first traffic cone was always visible upon starting and pertinent information was shown on a HUD throughout the simulation runs. The users controlled their translation in the three axes with a hand-held gaming controller, while attitude was automatically controlled by the simulation controller.

![Figure 4.2: User’s initial view of the asteroid obstacle course](image)

The users were instructed to fly as quickly or as slowly as they felt comfortable, but to keep an eye on the fuel levels. They were also told that each course would contain four cones, which would mean three major autopilot attitude adjustments. Since the control response to these attitude adjustments would be the main distinction between the two control configurations, users were
asked to focus on the system's reaction to the attitude adjustments during each of these major turns.

After completing both runs of the obstacle course, users were given a set of questions that asked them to rate the level of difficulty associated with completing the course for each run, as well as locating and traversing to the next cone during each segment. The difficulty of each task was rated on a 10-point Likert scale. Additionally, several short questions asked the users to describe any differences they noted between the two control systems, their impression of the heads-up-display design, and any further comments. This obstacle course questionnaire can be found in Appendix A. Upon completion of the rating scales and questions, users proceeded to the second part of the evaluation.

4.2.2 Part 2 (Simulation Video) Description

Because the human-in-the-loop simulation did not include real-time disturbance torques from astronaut motion, the obstacle course only demonstrated system responses to navigation inputs and did not account for astronaut disturbances. In order to address motion disturbances, the second part of the evaluation consisted of a series of two simulation videos and corresponding questionnaires. The two videos were created using the EDGE graphics environment. These videos were based on the tool retrieval mission building block from the previous section. The view was of a portion of the ISS, and the two videos differed only in the attitude control system that was used to compensate for the disturbances.

For each control system, each user was shown a video of the actual motion to give them a mental picture of what their astronaut was enacting, and then shown the first video. After watching the first video, they were asked to complete a set of questions that asked them to transpose this motion response into hypothetical mission scenarios and rate the difficulty of the task and then provide any additional comments. The three scenarios were translation, reaching out and grasping something (rock sample, ISS handhold), and a precision task (insert a PIP pin into a designated hole, position a pistol grip tool for a drilling task). When
the first set of rating scales was completed, the second video was shown, and the same rating scale questions were asked for that video. Difficulty for each task was rated on a 10-point Likert scale. To account for bias, the order in which the videos were shown was counterbalanced. The ISS EVA questionnaires can be found in Appendix A.

4.2.3 Part 3 (Operational Functions and Interface) Description

Finally, each subject was given a questionnaire that asked for additional feedback on the design of the interface and operational aids for the jetpack regardless of the control system used. Five potential operational functions were presented, and the users were asked to rate the usefulness of each function on a 10 point scale that ranged from “Unnecessary” at 0 to “Imperative” at 10. Users were further asked to list any mission applications for which each operational function might be useful. The five operational functions rated are shown in Table 4.1.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attitude hold</td>
<td>Cancels out all force and torque disturbances to maintain rigid attitude and stabilize the astronaut.</td>
</tr>
<tr>
<td>Target tracking</td>
<td>Maintains a specified orientation with respect to a chosen point, surface, or object (either during translation or stationary at worksite).</td>
</tr>
<tr>
<td>Range hold</td>
<td>Maintains a specified distance from a chosen point, surface, or object (either during translation or stationary at worksite).</td>
</tr>
<tr>
<td>Discrete attitude inputs</td>
<td>User can command discrete attitude inputs for ± roll, pitch, and yaw (e.g. positive roll 15°; negative pitch 5°).</td>
</tr>
<tr>
<td>Discrete translation inputs</td>
<td>User can command discrete translational inputs (e.g. forward 4m; to the right 0.5 m).</td>
</tr>
</tbody>
</table>
They were also asked for ideas for additional operational functions or aids beyond the five presented, and to describe the associated mission applications. Further questions addressed the heads-up-display in the context of these navigational aids, the reality of the simulation, and any additional comments. This operational function and navigational aids questionnaire can be found in Appendix A.

4.3 Evaluation Results

4.3.1 Part 1 (Obstacle Course) Results

The results of the users' responses to the rating scales are shown in Fig. 4.3. As shown, the results do not conclusively show a user preference for the obstacle course simulation. More users felt that overall they completed the obstacle course better with the CMG configuration; however, when asked about specific tasks within the obstacle course, the results differed. For users who stated a preference, more reported they could locate the next cone better with jets than CMGs; however, the majority of users reported no difference. For the task of traversing to the next cone, half of the users were split evenly between jets and CMGs, and half of the twelve users reported no preference.

![Figure 4.3: User preference of control configuration from the obstacle course runs, based on 10-point difficulty ratings of: Question 1) obstacle course completion; Question 2) locating the next cone; Question 3) traversing to the next cone](image-url)
The free response question that addressed the users’ perceived differences in the control responses between the two runs can offer some insight into these results. In this obstacle course simulation, the jet configuration’s high gains “swing” the user around quickly towards the new target, while the CMG configuration, while smoother, is slower. Five of the twelve users were able to correctly perceive a difference in both the speed and smoothness of the control response. However, some users valued the speed over the smoothness, and thus preferred the jet configuration for this navigation task. Because no fine motor tasks were required in this part of the simulation, smoothness and stability did not seem to matter as much to the users.

The inconclusive results of the obstacle course user ratings are also likely due in part to the simulation setup and methodological considerations. In this first evaluation, translation took up the majority of the simulation time, and during translation the rotational control responses were minimal. The scenario was developed this way because the user could not control attitude in the simulation design at the time of evaluation. To counter this, the evaluation should have included runs that have more turns, bigger turns, and less traversing, allowing better comparisons of the differences surrounding the main proposed benefit of the CMG system: rotational stability. The user should also have had direct attitude control in order to better see the control response to known inputs. Finally, a full practice run using a different course should have been used for training to lessen the learning effects from the first to the second run. With these considerations incorporated into an enhanced evaluation task design, the users would be better able to perceive any differences between the two attitude control systems. The limitations identified here were addressed in a follow-up evaluation design detailed in Chapter 5.

Despite some uncertainty as to user preference in the obstacle course, fuel data show distinct benefits for the CMG system. There is a 47.5% difference in average fuel use between the two control systems, corresponding to 1.4 kg of fuel savings. A box plot of the data is shown in Fig. 4.4. The central red mark on each
box is the median, the edge of each box represents the 25th and 75th percentile, and the whiskers extend to the most extreme data points.

![Box plot of fuel consumption for the obstacle course run](image)

Figure 4.4: Box plot of fuel consumption for the obstacle course run

4.3.2 Part 2 (Video Simulation) Results

The results of the rating scales for the set of two simulation videos are shown in Fig. 4.5. A discussion of the results follows.

![User preference of control configuration from the videos](image)

Fig. 4.5: User preference of control configuration from the videos, based on 10-point difficulty ratings of: Question 1) translation; Question 2) reaching out and grasping something; Question 3) precision task
As seen in Fig. 4.5, all users preferred CMGs over Jets if they indicated a preference. Rather than rigid-body attitude changes during translation as in the obstacle course simulation, these evaluations were targeted to fine motor tasks and control responses to torque-inducing body motions. These were used to showcase each control system's response to rotational disturbances from a heavy tool retrieval motion. Using the jets-only configuration, the tool reach caused over-rotations that took several seconds longer to counteract than the CMG configuration's almost immediate response. The free responses from this part gave some additional perspective on the control systems. More than one evaluator said the system should be implemented for EVA as soon as possible, and many noted that the value is the hands-free stability it provides at the worksite. One user touched on another benefit of the system: eliminating disorientation during EVA tasks. Oftentimes, an astronaut will look at tools in his or her hands during a task rather than at a stationary reference point. If the astronaut later looks up and is in a different position relative to the stationary structure, there is a risk of disorientation. The ability of the CMG system to return to a consistent attitude after every motion without the risk of drift gives the astronaut more freedom to focus on tasks rather than staying oriented.

4.3.3 Part 3 (Operational Functions and Interface) Results

The results of the 10-point usefulness rating scale for the five operational functions in the final questionnaire are shown in Fig. 4.6. A discussion of the results and the additional free response answers follows.
As illustrated by Fig. 4.6, attitude hold was rated as the most imperative (9.1) for almost any task or mission scenario. Not many comments were included for this operational function; all users simply agreed it was necessary. The remaining four had more disparity in terms of comments. Target tracking was rated at 7.5, and useful particularly for translation tasks or any mission where a target exists, such as automatic self-rescue. One user pointed out that not all missions have targets, which limits the usefulness. This function was also deemed useful for complicated missions that require six degree-of-freedom control, by offsetting some of the pilot's workload. Range hold had an average rating of 6.2, with specific functionality for stationary worksite stability and any hands-free task during which the astronaut would like to maintain a fixed distance from a structure. Some users worried that this might have the potential to over-control or be sensitive to navigation noise. Discrete translation and attitude inputs were rated the lowest, at 5.5 and 5.8, respectively. Discrete attitude inputs were rated useful for getting into tight spaces or orientations, but users felt that it can be hard to judge angles and having to estimate attitude inputs could be difficult. Users had similar comments regarding discrete translation inputs: the function would be useful when one is close enough to the target to judge distance, and it would
be beneficial as a safety manual override if translation was fully automated. However, users again pointed out the necessity to “guesstimate” distances.

The users also suggested additional features. Attitude rate kill was suggested to allow the pilot to eliminate any attitude rate in order to maintain a desired orientation after turning, which is a functionality of the original SAFER system. It is therefore understandable that users familiar with SAFER would desire replication of current features, resulting in an augmented system, rather than a new system that lacks features with which users are already comfortable. It will be important in future design stages to keep current SAFER features in consideration. A similar function suggested by several users was attitude error kill, which would allow the pilot to set an initial “reference” attitude to which he or she could later return with one command rather than a series of control inputs.

Across the board, one of the most common suggestions for all the operation functions was to design an effective heads-up-display that incorporated these functions. Some users believed that a function like target tracking would be useless without an advanced, and likely interactive, HUD. Some HUD features users recommended were a feature similar to a cockpit flight director, a destination selection feature that would calculate a fully automated trajectory, a velocity vector, and improved display of the information already given.

Users offered further comments regarding the type of controller interface to be used. Most users desired having a choice of either discrete or continuous input modes for both rotational and translational control. Additionally, users wanted the ability to enable or disable stabilization features depending on the task to preserve energy, and the ability to switch between operational functions when switching tasks. In short, the user wanted to have control over different choices to tailor the functions of MAJIC for specific missions. Having these choices would provide greater flexibility across a wide range of mission types.
4.3.4 Evaluation Conclusions

For task completion (locating and traversing to the next cone), most participants did not feel that either control system offered a significant advantage; however, more participants preferred the CMG configuration for overall course completion. In the video simulation part of the evaluation, not a single user preferred the jets configuration, and an overwhelming majority preferred the CMG configuration. These results further emphasize that while the CMG configuration performs well in translation and navigation tasks, benefits are even more apparent during tasks that require enhanced rotational stabilization, which is in line with initial expectations.

4.4 Summary

This first user evaluation offered insight into users’ preferences between the two attitude control systems tested, and more importantly, into the underlying reasons for those preferences. However, a number of design deficiencies were discovered after analysis of the results and feedback from the users. These ‘lessons learned’ from this first evaluation, as well as user suggestions for improving the HUD and controller, were applied to the design of a second user evaluation, detailed in Chapter 5.
Chapter 5

Follow-up User Evaluation

Based on drawbacks from the preliminary user evaluation discussed in Chapter 4, a follow-up evaluation was designed to further investigate user preference and system performance. The two main portions of the previous evaluation (obstacle course and ISS EVA tasks) were enhanced to provide a more realistic piloting experience to allow users to more accurately assess the differences between the systems. Three control systems were tested instead of the prior two: the original jets-only configuration, one CMG system with a large sized array, and a second CMG system with a smaller sized array. These two arrays were selected using the CMG sizing platform developed in Chapter 3. The large array was sized for task performance, and the small array sized for mass. Direct rotational control was provided for the pilots, and real-time motion capture capabilities were integrated into the astronaut dynamics model. This chapter discusses the updates developed for the follow-up user evaluation, the improved evaluation protocol, and the results of this second user evaluation.

5.1 Real-time Motion Capture

Of the various updates to the evaluation design, the most significant change was incorporating real-time motion capture into the simulation. This allowed the user to observe the control response to direct inputs based on their own body movements, bridging the motion-response disconnect many users
noticed in the previous evaluation. Integrating motion capture involved sensor selection and integration, data filtering to enable real-time modeling of astronaut dynamics, and a size sensitivity analysis.

5.1.1 Sensor Selection and Integration

In order to incorporate motion capture capabilities into the MAJIC model environment, real-time body position tracking was necessary. A number of methods for body tracking exist, primarily in two categories: optical tracking and non-optical. Optical systems acquire data from one or more cameras, while non-optical systems utilize systems that do not require visual cues, such as inertial, mechanical, and magnetic sensors [28]. Optical systems tend to be the most expensive form of motion capture systems, are sensitive to light, and give position data only [29]. A less expensive alternative is to use inertial measurement units (IMUs), which are simple non-optical sensors that provide relative position, velocity, and orientation information. IMUs use a combination of accelerometers, gyroscopes, and magnetometers, and the small, lightweight units are ideal for positioning on the human body to track segment motions.

The VN-100 rugged IMU is a miniature IMU that was chosen for the follow-up user evaluation motion capture capabilities. It computes and outputs real-time attitude in quaternion format for continuous solution over a full 360-degree range of motion [30]. It also offers a number of customization options for optimal utilization, including error read-outs, baud rate and frequency settings, filtering customization, and output selection. In a study comparing the VN-100 to two other commercial IMUs based on noise density, bias stability, g-sensitivity, and dynamics range, the VN-100 outperformed the other two units, running for a full hour without drift in the sensor exceeding a 10-degree offset from true measurements [31]. For the shorter period motions desired for use in the follow-up evaluation, the VN-100 was deemed appropriate based on these findings.

For full-body motion capture, an IMU would be required on every body segment. Based on the astronaut body model in Fig. 2.3, the astronaut dynamics model would necessitate fourteen units to drive calculations for a full range of
motion. However, as discussed in Section 2.3, the most common types of motions that can be anticipated for an average EVA are arm motions in the immediate work envelope of the astronaut's chest. Focusing the motion analysis on the upper body reduces the required number of IMUs by half, from fourteen to seven—four if the task is a one-arm motion, which is done to further reduce cost. Finally, distinct hand motions are insignificant in terms of torque output due to the negligible mass of the hand relative to the rest of the body, eliminating the need for a separate hand IMU.¹

These three remaining IMUs would be positioned on the forearm, the upper arm, and the torso for inertial and relative motion. For cost purposes, the forearm and torso units were eliminated, leaving just the upper arm unit. To account for these losses in range of motion, users in the follow-up evaluation were instructed to keep their elbow rigid and torso motionless so the only movement comes from the upper arm trajectory. However, due to the likelihood of unintended motion, two comparative analyses were performed to determine the effects of eliminating the forearm and torso units.

The analysis for the forearm unit determined the difference between the results of an upper arm motion with a rigid elbow and with a free-moving elbow, using the MAJIC control system. The motion profile used is the hammer motion from Table 2.5, without the impact force. In the rigid elbow case, all the motion comes from the shoulder joint; there is no rotation in the elbow. In the free-moving elbow case, the shoulder motion is identical to the rigid case, but the elbow joint undergoes a constant-rate extension over the 4 seconds. The motion is slight, so as to represent a user's unintended elbow movement during a shoulder-only motion task.

¹ This may not be true for cases with a tool in the hand; however, little to no relative motion of the hand compared to the lower arm segment is expected in such scenarios.
Torque vs. Time (Hammer)

(a) Torque profile for rigid and free elbow

(b) Attitude Error vs. Time (Hammer)

(c) Attitude error profile for rigid and free elbow

Figure 5.1: Forearm unit comparison
Figures 5.1a-b shows the results of the forearm unit comparison. 5.1(a) depicts the three-axis torque profile for the hammer motion, with the rigid elbow case in the solid line and the free elbow case in the dashed line. 5.1(b) shows the three axis attitude error for the resulting torque profile, with the solid and dashed lines representing the same cases as in (a). The differences from the rigid case to the free case are slight, with the magnitude of the greatest difference being 0.99 Nm in the y-axis (from -11.27 to -12.26 Nm). This 8.1% increase in torque between the two cases propagates to a maximum difference in attitude error of 0.12 degrees of yaw (z-axis), corresponding to a 16.3% attitude error increase.

For low-torque motions such as these, and those to be executed in the follow-up user evaluation, approximate 1 Nm torque differences and 0.1 degree attitude error differences were deemed acceptable. The forearm IMU was therefore deemed not necessary for the evaluation.

The analysis for the torso unit determines the difference between the results of an upper arm (rigid elbow) motion with a fixed torso and with a free-moving torso. The arm motion used in this analysis is the side reach with tool motion from Table 2.4. In the fixed torso case, all the motion originates from the shoulder joint; in the free torso case the shoulder motion is the same, but the torso executes a constant 4-second rotation to the right about the z-axis (vertical).
Figure 5.2: Torso unit comparison

(a) Torque profile for rigid and free torso

(b) Attitude error profile for rigid and free torso
Figures 5.2a-b show the results of the torso unit analysis. 5.2(a) displays the three-axis torque profile for the side reach motion, with the rigid torso case in the solid line and the free torso case in the dashed line. 5.2(b) shows the three-axis attitude error for the resulting torque profile, with the solid and dashed lines representing the same cases as in (a). The magnitude of the greatest torque difference between the two cases is 3.37 Nm in the y-axis (from 1.79 to 5.17 Nm). This 189% increase in torque between the two cases seems rather large, but propagates to a maximum difference in attitude error of 0.22 degrees of yaw (z-axis), a mere 8.5% increase in attitude error.

Again, for relatively low-torque motions such as those completed in these analyses, approximate 3 Nm torque differences and 0.2-degree attitude error differences were deemed acceptable. The torso IMU was therefore also eliminated, leaving the one upper arm IMU as sufficient for the purposes of the follow-up evaluation.

5.1.2 Real-time Integration

This final IMU was integrated into the MATLAB/Simulink MAJIC model using a C-MEX S-function, which allows the execution of C/C++ code of the VN-100 within the simulation. The VN-100 setup was customized to output only angular rate and the quaternion attitude solution at a frequency of 50 Hz. The angular rate and orientation correspond to the shoulder joint (3b in Fig. 2.1b) based on the right upper arm attachment of the IMU. Sensor noise in the inputs was reduced using a real-time 5-point moving average, and the smoothed data was fed into the astronaut dynamics model. Smoothing data in real-time introduces a time delay into the system; however, the 100 millisecond lag introduced by the 5-point average is within the acceptable time range before which a human will perceive the delay, and is thus sufficient for this application [32]. The Simulink block diagram for this real-time integration is shown in Fig. 5.3.
The astronaut dynamics model portion of the MAJIC simulation is based on calculations discussed in Section 2.2. These calculations are executed in real-time based on the inputs from the IMU. A weighted average is taken for each input from the VN100 IMU block (quaternion solution on the top, angular rate on the bottom). The quaternion solution for the shoulder joint from the IMU has the scalar as $q_4$ rather than $q_1$, but with a simple reordering as shown in Fig. 5.3, corresponds directly to $q_{rot}$ in Eq. 2.2 from Section 2.2 ($q_1$, $q_2$, $q_3$, $q_4$ in Fig. 5.3). The angular rate from the IMU provides $\omega$ from Eq. 2.3 ($wx$, $wy$, $wz$ in Fig. 5.3), and $\alpha$ from Eq. 2.4 can be found by taking the time derivative of the angular rate input ($ax$, $ay$, $az$ in Fig. 5.3). These inputs are then used to calculate the torque, moment of inertia, and center of mass at every time-step (0.02 s; 50 Hz) for the new body parameters following the remaining calculations in Section 2.2.

5.1.3 Size Sensitivity Analysis

To allow for real-time customization of the astronaut body model, an initialization procedure was created to personalize astronaut gender, height, and weight using GEBOD, choose initial body position, and specify presence and type of tools in hands. The capability to personalize the astronaut body model for any given individual or EVA scenario offers a number of benefits for analysis and evaluation. However, due to privacy issues and experiment design concerns
for the follow-up evaluation, a sensitivity analysis was executed to determine what effects changing the astronaut’s size would have on the simulation outputs.

Female and male body parameters from the 2nd to the 99th percentile were computed using GEBOD. Each percentile body model was run through a one-way side reach motion using the astronaut dynamics model and the resulting attitude error profiles were compared using the CMG-augmented control system. Table 5.1 shows the sizes of each astronaut run through the analysis. Figure 5.4 shows the attitude error profiles for each astronaut size by gender. These graphs indicate an inverse relationship between astronaut size and attitude error; the larger the astronaut, the smaller the error. The attitude error accumulates more slowly with more inertia, so the error for a large astronaut does not reach the same magnitude as the error for a smaller astronaut.

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Female Mass (kg)</th>
<th>Male Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd</td>
<td>42.26</td>
<td>58.74</td>
</tr>
<tr>
<td>10th</td>
<td>48.06</td>
<td>66.24</td>
</tr>
<tr>
<td>20th</td>
<td>51.37</td>
<td>70.51</td>
</tr>
<tr>
<td>30th</td>
<td>53.75</td>
<td>73.60</td>
</tr>
<tr>
<td>40th</td>
<td>55.79</td>
<td>76.23</td>
</tr>
<tr>
<td>50th</td>
<td>57.70</td>
<td>78.69</td>
</tr>
<tr>
<td>60th</td>
<td>59.59</td>
<td>81.14</td>
</tr>
<tr>
<td>70th</td>
<td>61.63</td>
<td>83.77</td>
</tr>
<tr>
<td>80th</td>
<td>64.02</td>
<td>86.86</td>
</tr>
<tr>
<td>90th</td>
<td>67.32</td>
<td>91.13</td>
</tr>
<tr>
<td>99th</td>
<td>75.17</td>
<td>101.28</td>
</tr>
</tbody>
</table>
Comparing the change of the input (astronaut size) to the change of the output (attitude error), the system is remarkably resilient to changes in astronaut size. For females, a 77.9% increase in mass (32.91 kg) corresponds to only a 28.4% decrease in maximum attitude error (2.57 degrees of yaw). For males, a 72.4% increase in mass (42.55 kg) corresponds to only a 25.8% decrease in attitude error (1.88 degrees of yaw). Scatter plots of maximum attitude error vs. astronaut size for each gender are shown in Figure 5.5.

Figure 5.4: Attitude error over time

Figure 5.5: Maximum attitude error vs. astronaut size
For the follow-up user evaluation, the average astronaut (male, 81.6 kg, 1.83 m) was used for all subjects regardless of gender, height, and weight. Due to the resilience of the system to size variation, the expected differences in attitude error would be small enough that personalized body parameters would be unnecessary for the purposes of this study. The capability for size customization, however, remains a powerful tool for additional evaluations and analyses.

5.2 Protocol Updates

The follow-up user evaluation was designed to compare two versions of the MAJIC system and the JSC Jetpack system. The two MAJIC systems differed in CMG array size; one was oversized for task performance (112 kg system) and the other was sized based on mass savings from fuel (6 kg system). The revised protocol built upon the foundation developed for the first user evaluation. Like the first evaluation, it included an asteroid obstacle course portion and an ISS EVA portion. In the obstacle course runs, the astronaut was modeled as a rigid body, while in the ISS EVA runs the astronaut was modeled as a dynamic body using the real-time motion capture capability developed in Section 5.1. Ten subjects volunteered to take part in the evaluation, half of whom are astronauts with spaceflight experience. Design improvements to address limitations discussed in Section 4.3 and at the beginning of this chapter are detailed below.

5.2.1 Part 1 (Obstacle Course) Description

The obstacle course portion was set up similarly to the first evaluation; the scene was on the asteroid Itokawa with a series of cones to be traversed. In Section 4.3, it was noted that to offer better comparison of the rotational stability of each attitude control system, the follow-up evaluation should have more turns, less traversing, and direct attitude control. To address these concerns, five cones were used for the obstacle course instead of the previous four, and they were positioned closer to each other to minimize the time spent in pure translation. Human-in-the-loop control was transferred from translational
control to rotational control; translation was controlled automatically by the control system, while the user was responsible for any required rotation.

The user's task was altered to reflect these design changes. Each user was instructed to manually adjust roll, pitch, and yaw to keep each target cone upright and centered in the heads-up display. They were given a hand-held gaming controller to control their attitude in three axes. A number of additional features were incorporated into the heads-up display to aid in their task, as shown in Figure 5.6

A crosshair was added to the center of the display to aid in the main target attitude task, shown in Figure 5.6. Several other changes were made to the HUD as well. User inputs on the right were changed to show only attitude rate commands where it previously also displayed translational velocity commands. Since in this improved evaluation, users only controlled rotation, the translation inputs would always display zeros, and were thus eliminated. A desaturation\textsuperscript{2} indication was included in the bottom right-hand corner; if CMG desaturation was in process, the indicator would light up red to inform the user that they would have no control authority at the time. On the bottom of the HUD, attitude rates were shown in each axis. Finally, a secondary attitude indicator in addition to the crosshair was provided on the left-hand side of the screen. This 3D indicator shows the target cone's z-axis orientation relative to the astronaut's vertical z-axis.

\textsuperscript{2}CMGs saturate when they can no longer absorb any additional momentum; at this point some form of momentum management scheme is required to desaturate. In the simulation's desaturation mode, the pilot has no control authority until desaturation is complete. For more information on the desaturation methods, see [23].
The users completed the obstacle course four times: once for training and once with each control system (small CMGs, large CMGs, jets-only). The full training run was added to address learning effects experienced over the course of the first evaluation, and the cone setup remained the same for all four runs to eliminate any difficulty differences. Every user completed a training run first, but the order of the other three runs was counterbalanced to account for bias. After completing each of the runs with the three attitude control systems, users were asked to verbally rate how well they felt they completed the obstacle course and how difficult they felt it was to match their attitude to the target cone’s attitude. Upon completion of all three of the actual obstacle course runs, they were given a series of short-answer follow-up questions about differences they noticed between the control systems, which they preferred and why, and any additional comments. The rating scales and questionnaires can be found in Appendix B.

5.2.2 Part 2 (ISS EVA) Description

The second portion of the evaluation was designed to incorporate real-time motion capture. As discussed in Section 4.2.2, the original evaluation included videos that showed users the control systems’ stabilization responses to EVA task motions. Although the videos showed the responses accurately, users had difficulty matching the timing of the response to a mental timeline of the
motion that was being enacted by the astronaut. Real-time motion capture in the second evaluation allowed users to enact the sample EVA motion themselves and view the response directly as a result of their own movement. This bridged the motion disconnect encountered in the first evaluation.

Figure 5.7: User with VR helmet, chest plate, and VN-100 IMU on right armband

An armband was manufactured to secure the VN-100 unit to the right upper arm of the user, as shown in Figure 5.7. This configuration allowed tracking of the full range of motion of the right shoulder joint. Users were taught a simple motion profile that they would be asked to repeat multiple times. The motion profile starts with both arms straight down. The user then brings the right arm up to the front 90 degrees for the first motion, 90 degrees out to the right in a second motion, and 90 degrees back to straight down in a third motion. When the arm is back in the straight down starting position, the user brings it 180 degrees up frontwise to straight overhead, and finally, 180 degrees down sideways to straight down in the initial position in a fifth, and final, motion. Each 90 degrees was instructed to take 2-3 seconds, and users were requested to keep
the motion profile as consistent as possible between all the runs. There was individual variability between subjects, but reasonable consistency was demonstrated across trials for each subject. If a subject completed the scripted motion with time to spare in the 30 seconds allotted run, they were given the remaining time to complete any additional motions they desired to gain more information about the system. The statistical analysis in Section 5.2.2 excludes this free time from the data.

Each user completed the motion profile seven times: once as a familiarity run to see how the system would respond to their arm motions, and then six actual runs. The six runs were split into two three-run segments: once without a tool in their hand for each of the three control configurations (small CMGs, large CMGs, jets-only), and once with a tool in their hand for each configuration. The order of the control systems was counterbalanced to account for bias, but all subjects completed the three runs without the tool before the three with the tool. In those three cases with the tool in their hand, they were given a representative tool to hold and the 1.33 kg EVA Power Tool from Table 2.4 was incorporated into the astronaut body model. This would allow the users the opportunity to observe the control system responding not only to their own motions, but also responding to added mass and inertia.

In between each run, users were asked to verbally rate how well they thought each control configuration kept their initial position, how difficult they thought it would be to reach out and grasp something (rock sample, ISS handhold) with that control configuration, and how difficult they thought it would be to complete a precision task (insert a PIP pin into a designated hole, position a pistol grip tool for a drilling task). Upon completion of all six actual runs, each user was given a questionnaire that asked for any additional comments about the differences between the configurations. These rating scales and questionnaires can be found in Appendix B.
5.3 Evaluation Results

5.3.1 Part 1 (Obstacle Course) Results

Figure 5.8 summarizes the users' stated preferences based on responses to the post-session questionnaire. Preference was based on users' comparative ratings of the three systems, and is grouped in Fig. 5.8 by the two questionnaire rating scales and further distinguished by control system used for the training run.

As shown in Fig 5.8, none of the ten users preferred the small CMGs to either the jets or the larger CMG array configurations for any of the obstacle course runs, so the user preference results presented in Fig. 5.8 compare only the original jets control configuration and the larger CMG array configuration. The first rating scale asked users with which control system they felt they completed the obstacle course better. As shown, the results do not conclusively show a user preference based on overall obstacle course completion. Five of the ten users preferred jets, while four preferred CMGs. Of these nine who indicated a preference, the initial training run control system type did not seem to influence their decision.

The results from the second question, however, showed a more distinct preference. Users were asked with which control system they felt they could better manually match their attitude to the target cone's attitude. Only two users preferred jets in this case, while seven preferred CMGs. These results are even more intriguing when noting which control system was used for the training run for each user. Of the two users who preferred the jets-only configuration for attitude control, both had the jets-only case as their training run, meaning they learned how to pilot the simulation with the system they ultimately preferred.
It should be noted that the jets-only configuration has a more sensitive response to user inputs, a consequence of the gain calculations in the MAJIC simulation. In other words, the jets-only control system response to one discrete yaw rate command is equivalent to two or three discrete yaw rate commands with the large CMG array system. While this difference is not extreme and neither gain setting is decisively better than the other, it is certainly a factor in how each user learns the system. Indeed, the free response question that addressed users' perceived differences in the control responses support this idea. Seven of the nine people who indicated a preference in the attitude control and stability rating scale cited the response time and input sensitivity as reasons for their preference. The two who chose jets preferred the system because the jets responded more quickly to input commands. However, the five remaining people who cited the gain as their reasons for preference chose CMGs because the jets actually reacted too quickly and did not allow enough time for steady control. Because the only two users who preferred jets learned to fly the
simulation with the jets system, it suggests the training run had a significant impact on their ultimate preference.

The gain was not the only perceived difference between the two systems; however, it was the only one that some users viewed as a benefit to the jets-only system. A second common difference mentioned in the free responses was cross-coupling in the jets and small CMGs cases. Four users noticed a slight cross-coupling between axes, and all four of these users preferred the large CMGs over the other two. A final common difference cited as a reason for indicated preference was that the jets-only case required constant control input to keep at a desired attitude, while the CMGs would hold a desired attitude once reached. This is expected because of the "bang-bang" nature of the jets' control response, and five users noticed it and saw this as a distinct negative of the jets system.

Besides subjective user preference garnered from questionnaires, objective data comparing the three systems was also analyzed, specifically fuel consumption. The mass of fuel used for each of the three control systems for all ten users was measured and recorded. Figure 5.9 compares the fuel data for each of the three control systems. The central red mark on each box is the median, the edges of each box represent the 25th and 75th percentile, and the whiskers extend to the most extreme data points not considered outliers. Outliers are plotted individually.

![Box plot for fuel consumption](image)

Fig. 5.9: Box plot for fuel consumption
A repeated measures analysis of variance (ANOVA) test is used to analyze the differences between the control systems. The three treatment groups in this repeated measures ANOVA test correspond to the three attitude control systems used in the obstacle course evaluation: one representing the fuel consumption of the jets-only configuration, one the fuel consumption of the large CMG array configuration, and the final group the fuel consumption of the small CMG array configuration. The statistical threshold used for this test is $p = 0.05$. The three control system trials ($k = 3$) and ten subjects ($n = 10$) provide 30 observations; however, one trial was compromised and the data was discarded, leaving 29 observations. There were no statistically significant difference in fuel consumption between the three groups, $F(2, 17) = 2.25$, $p = 0.136$ (for full ANOVA table, see Appendix C). This demonstrates that when translation was controlled automatically and pilots only had to manually control rotation, there is no significant fuel savings between the different systems. This is different from the previous evaluation when translation was commanded manually, because in that case, translation is the more fuel-heavy task and variations between piloting techniques have much larger effects.

5.3.2 Part 2 (ISS EVA) Results

Figure 5.10 summarizes the users' stated preferences based on their answers to the post-trial questionnaire. Like in the obstacle course portion, preference was based on users' comparative ratings of the three systems and is grouped in Fig. 5.10 by question, and further distinguished based on which run had the greatest attitude error in response to the motions enacted. As in the results from Section 5.3.1, the small CMG array system was eliminated from user preference results in Fig. 5.10 because every user rated them lowest for all cases. Figure 5.10a shows the results for the runs without the tool in the user's hand; figure 5.10b shows the results for the runs with the tool. For all but one rating scale (system attitude stability without a tool), more users rated the systems equally rather than preferring either.
Figure 5.10: User preference of control configuration from the motion capture runs, based on ratings of: Question 1) system attitude stability with reference to initial position; Question 2) difficulty to reach out and grasp something; Question 3) difficulty to complete a precision task. Color indicates which control system reached the maximum attitude error between the two runs for each user.

As illustrated in Fig. 5.10, there were only two users who experienced a larger maximum attitude error with the CMG system than with the jets system. This is likely a result of slight differences in their motion profile for each run, but serves as an explanation for why one of the subjects rated the jets-only case higher for stability—based on experienced attitude error for that user, it actually was more stable. The attitude error data for each scripted profile portion of the motion capture run is presented in Table 5.2 and in Figure 5.11.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Without Tool</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jets Only</td>
<td>5.06</td>
<td>1.92</td>
</tr>
<tr>
<td>Small CMGs</td>
<td>84.81</td>
<td>67.82</td>
</tr>
<tr>
<td>Large CMGs</td>
<td>3.48</td>
<td>1.56</td>
</tr>
<tr>
<td><strong>With Tool</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jets Only</td>
<td>7.40</td>
<td>1.90</td>
</tr>
<tr>
<td>Small CMGs</td>
<td>38.12</td>
<td>52.20</td>
</tr>
<tr>
<td>Large CMGs</td>
<td>5.28</td>
<td>2.44</td>
</tr>
</tbody>
</table>

Table 5.2: Maximum Attitude Error (degrees)
From Table 5.2 and Fig. 5.11, it is clear why all subjects rated the small CMG array system lowest on every run. Most users saturated the small CMGs at least once and if the system continued to accumulate angular momentum without being able to successfully desaturate, it lost control and accelerated into a spin. The control system response depended heavily on the speed and magnitude of the enacted motions, so variation between users' motion profiles resulted in the large variation in attitude error in the small CMGs case reflected in the data. Because of the stark difference in attitude error for the small CMG array, those data were eliminated. Box plots comparing attitude error and fuel use for just the jets and large CMGs are shown in Figs. 5.12-13.
Repeated measures ANOVA tests were run for the two remaining control systems (jets-only and large CMGs), offering analysis of the motion capture runs both with and without the tool. One subject’s large CMG trial was not recorded, decreasing the denominator degree of freedom by one. Based on a statistical threshold of $p = 0.05$, the difference in maximum attitude error without a tool in the hand is not statistically significant, $F(1,8) = 4.14$, $p = 0.076$. However, with a tool the difference becomes significant, $F(1,9) = 13.03$, $p = 0.0057$. Fuel use
followed the same pattern, with no statistically significant difference between consumption without a tool in the hand, $F(1,9) = 4.06, p = 0.079$. With a tool, however, fuel consumption was significantly less with the large CMGs case, $F(1,8) = 6.21, p = 0.034$ (full ANOVA tables included in Appendix C). This suggests that CMG augmentation of the jetpack specifically benefits tasks that increase body mass properties—such as using tools or moving larger objects. Despite the significant difference in the with-tool case, the questionnaires show that user perception of attitude error and system stability was not enough to decisively settle on a user favorite for either with- or without-tool case.

5.3.3 Human Interface and Application Feedback

While not a primary goal of this evaluation, several questions about the HUD, hand controller, and potential EVA applications were included in the free response portions of the questionnaires. Much of the HUD feedback was mission-specific; for example, users did not feel they needed the translational velocity indication or surface distance indication during the obstacle course portion because neither was necessary, or even related, to the primary attitude-control task. These comments, however, suggest that an ideal HUD may be customizable based on mission type and even within each phase of the mission. One feature that could be implemented immediately for any mission is a better desaturation mode indication. Users sometimes missed the desaturation indication, and voiced a desire to have the indication flash up in the center of the display. Since the pilot has no control authority when in desaturation mode, the more central indication would be helpful in understanding the change in system response.

Some users had some difficulty with the mapping of the controller buttons to roll, pitch, and yaw. Several users, specifically those who are SAFER trained, expressed a desire for a joystick hand controller design. The joystick design is better suited for attitude commands, and has the added benefit of being familiar for current astronauts.
Finally, users suggested various mission scenarios both on and off the ISS that they could envision MAJIC being used for. The majority of the scenarios suggested fell under one of the broad concept of operations mission categories, and supported the conclusions from the analysis in Chapter 3. Users specified solar array inspection, surveying damage for repairs, taking photographs, and translation to and from worksites, especially those in hard-to-reach places, as applications for MAJIC on the ISS. Suggestions for off-ISS applications mostly included asteroid scenarios, likely because it was the mission setting for the first evaluation portion. As mentioned multiple times in this thesis, however, one of the primary benefits of MAJIC will be its flexibility and applicability to multiple mission types.

5.3.4 Evaluation Conclusions

For the primary attitude task completion in the obstacle course, more users preferred large CMGs to the jets-only system. The two users who indicated a preference for the jets system had jets as their training run, and this system familiarity could explain their preference. Fuel use for the obstacle course run was not significantly different between the three control systems, despite stark differences in fuel results presented in the obstacle course results in Chapter 4. This is likely due to the primary task required for each; in the preliminary evaluation, users controlled translation which is a much more fuel-consumptive task. In this follow-up evaluation, users controlled fine rotation, which required much smaller control inputs and ultimately left less variation in fuel.

For the motion capture trials, there was no clear indication of preference, except that the small CMGs case was the least preferred. When looking at fuel use and attitude error data between the jets and large CMGs, however, some patterns emerge. While there were no statistically significant differences in fuel use or attitude error without a tool in the hand, in cases with a tool, both attitude error and fuel use were significantly lower with the large CMGs.

As with any evaluation, there are some drawbacks to the design that can be addressed in future studies or evaluations. In the obstacle course portion,
gains for both the jets and CMGs should be set so the controller requires the same number of inputs for each since this seemed to be a factor in user preference. The motion capture portion of the evaluation could be improved to include more realistic motions with a wider range of tools and incorporated masses, specifically since the runs with tools had significant differences between the control systems.

5.4 Summary

This follow-up user evaluation addressed design deficiencies from the first evaluation by incorporating a third control system to the comparison, updating the obstacle course primary task to focus on attitude control, and integrating real-time motion capture into the VR graphics environment. The added capabilities offered more specific insight into user preferences and underlying reasons. While results varied between the two portions of the evaluation and also between users, patterns and statistically significant differences in certain cases presented in this chapter offer motivation for continued investigation of the MAJIC system.
Chapter 6

Summary and Conclusions

With an array of possibilities for the future of human space exploration, including crewed asteroid missions, exploration of Martian moons, as well as maintaining current ISS EVA operations, astronauts will require a unique form of mobility unit. In order to be a feasible and worthwhile investment for the future of manned spaceflight, this mobility system must be robust and flexible enough to support a variety of mission architectures and EVA objectives, while offering substantial benefits over current designs. This research investigates the performance of the proposed Mobility Augmenting Jetpack with Integrated CMGs (MAJIC) towards this aim.

6.1 Thesis Review

This thesis addresses a number of research objectives to support an investigation of the proposed CMG augmentation of a jets-only mobility unit:

Objective 1: Assess EVA task motions, astronaut dynamics, and mission concepts to support the objective comparison of the original jets-only Jetpack system and MAJIC

Objective 2: Analyze the performance of both systems based on user evaluations of the two control configurations
A comprehensive simulation that includes the Jetpack and MAJIC control models as well as an astronaut dynamics model was developed to accomplish the first objective. Chapter 2 discusses the investigation of a range of EVA tasks and tools and the development of an astronaut dynamics model that was used to analyze the dynamics of those tasks. Chapter 3 delves deeper into EVA tasks and develops a concept of operations for MAJIC. The mission scenarios explored in the concept of operations are analyzed using the comprehensive simulation to compare performance of MAJIC and the Jetpack system based on fuel consumption and attitude error, the two main parameters of interest. MAJIC substantially decreased fuel consumption and increased attitude stability across all mission scenarios. Chapter 3 also discusses the foundation for a CMG sizing study based on the concept of operations and utilizing the astronaut dynamics and controls simulation.

The second objective was accomplished by integrating the MAJIC simulation into Johnson Space Center’s Virtual Reality Laboratory graphics environment to develop a real-time human-in-the-loop evaluation of the two systems. Chapter 4 describes the preliminary evaluation design and discusses results of the three-part experiment. Users in the preliminary evaluation preferred MAJIC for EVA task attitude stability, but no conclusion could be made about user preference for translation- and navigation-based tasks. Drawbacks in the preliminary evaluation setup and design were addressed in Chapter 5, which details the improvements made for a second user evaluation and discusses the results. For this evaluation, fuel differences during the obstacle course portion were not significant, nor were differences in attitude error for a representative EVA motion profile. However, MAJIC significantly decreased attitude error and fuel use while holding a tool. This suggests that mission scenarios that increase mass properties of dynamic body segments, such as crewmember rescue, equipment deployment, or tool handling tasks, can significantly benefit from the addition of CMGs into the mobility unit control system.
6.2 Limitations and Future Work

The discrepancies between the very positive results from the simulation-based analysis in Chapter 3 and the more uncertain results from the user evaluations in Chapters 4 and 5 introduce some ambiguity into the extent of MAJIC's benefits. In some cases, the addition of CMGs showed drastic improvement, whereas in other cases, differences were slight. A number of areas could benefit from further investigation to eliminate this uncertainty:

- The parameters of interest for this research were limited to fuel consumption and attitude error. For translation- and navigation-based tasks, fuel consumption is far more important than for simple EVA repair or sampling motions that tend to last for a shorter amount of time and cover less distance. Likewise, for those EVA tasks that require substantial astronaut body movement, attitude error is a more telling parameter than fuel consumption. Future work could further explore the benefits of MAJIC by expanding the range of parameters of interest and analyzing different mission scenarios based on the most appropriate ones.

- As discussed in Chapter 5, user preference for the obstacle course runs was influenced heavily by the difference in control gains. Future evaluations should attempt to eliminate undesired differences between the piloting of the systems in order to strengthen the focus on system performance.

- The motion capture capability introduced in Chapter 5 can be improved by adding more IMUs to expand the range of motion allowed by users in future evaluations.

- The current MAJIC-EDGE simulation described in Chapters 4 and 5 does not include contact models. Future evaluations and analyses could benefit from incorporating contact models in order to demonstrate system
responses to bumping into objects, pushing off of structures, and any other impact motions.

- The piloted portions of each of the two HITL evaluations were limited to either translation (preliminary evaluation) or rotation (follow-up evaluation). A future HITL evaluation should allow users to command both translation and rotation simultaneously, as practical applications of MAJIC will entail both.

- In the two user evaluations completed in this research, the controller used was chosen based on ease of simulation integration and availability. Future HITL simulations should incorporate a specific hand controller design based on a thorough investigation of current controllers, consideration of proposed mission applications, and attention to human interface concerns.
THIS PAGE INTENTIONALLY LEFT BLANK
Appendix A

Preliminary Evaluation Questionnaires
Worksheet: Obstacle Course

1. How well do you feel you completed the obstacle course?
   
   1st: Perfectly 0 1 2 3 4 5 6 7 8 9 10 Failure
   
   2nd: Perfectly 0 1 2 3 4 5 6 7 8 9 10 Failure

2. How difficult was it for you to locate the next cone?
   
   1st: Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible
   
   2nd: Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible

3. How difficult was it for you to traverse to the next cone?
   
   1st: Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible
   
   2nd: Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible

4. How did the attitude control response affect your ability to locate and traverse to the next cone during your 1st and 2nd runs?

   __________________________________________________________
   __________________________________________________________
   __________________________________________________________

5. Some of the HUD features in the obstacle course simulation include distance from asteroid surface, fuel remaining, attitude error, etc. Which of the features currently included in the HUD do you think are significantly enhancing, and which aren't necessary? Can you think of any other HUD features that might be beneficial?

   __________________________________________________________
   __________________________________________________________
   __________________________________________________________
   __________________________________________________________

6. Do you have any additional comments?

   __________________________________________________________
   __________________________________________________________
   __________________________________________________________
Worksheet: ISS EVA

1. How difficult do you think it would be to translate towards a specific point with this system configuration?
   
   Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible

2. How difficult do you think it would be to have to reach out and grasp something fixed (rock sample; ISS handhold) with this system configuration?
   
   Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible

3. How difficult do you think it would be to have to complete a precision task (insert a PIP pin into a designated hole, position a pistol grip tool for a drilling task) at any time during this system configuration?
   
   Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible

4. Do you have any additional comments?

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

99
Subject Number: __________

**Post-Session Questionnaire**

This section describes a number of functions designed to assist EVA operations. How useful or important would it be to incorporate each of the following functions into the jetpack system for effective EVA operations?

1. **Attitude Hold**: cancels out all force and torque disturbances to maintain rigid attitude and stabilize the astronaut.

   Unnecessary 0 1 2 3 4 5 6 7 8 9 10 Imperative

   For what tasks and missions might this function be useful? Include any additional comments.
   ________________________________________________________________
   ________________________________________________________________

2. **Target Tracking**: maintains a fixed orientation with respect to a chosen point, surface, or object (either during translation or stationary at worksite).

   Unnecessary 0 1 2 3 4 5 6 7 8 9 10 Imperative

   For what tasks and missions might this function be useful? Include any additional comments.
   ________________________________________________________________
   ________________________________________________________________

3. **Range Hold**: maintains a fixed distance from a chosen point, surface, or object (either during translation or stationary at worksite).

   Unnecessary 0 1 2 3 4 5 6 7 8 9 10 Imperative

   For what tasks and missions might this function be useful? Include any additional comments.
   ________________________________________________________________
   ________________________________________________________________
4. **Discrete Attitude Inputs:** user can command discrete attitude inputs for ± roll, pitch, and yaw (e.g. positive roll 15°, negative pitch 5°).

Unnecessary 0 1 2 3 4 5 6 7 8 9 10 Imperative

For what tasks and missions might this function be useful? Include any additional comments.

5. **Discrete Translational Inputs:** user can command discrete translational inputs (e.g. forward 4m, to the right 0.5 m).

Unnecessary 0 1 2 3 4 5 6 7 8 9 10 Imperative

For what tasks and missions might this function be useful? Include any additional comments.

4. Do you have any suggestions for additional operational functions that are not included above?

5. Now that you've seen some videos and discussed potential operational functions, do you have any new suggestions for HUD features (apart from what you may have already discussed in the first worksheet)? Is there other information that would be useful during the mission?
Subject Number: ________

6. How realistic is the simulation? What aspects in the graphics environment are good or bad?

________________________________________________________________________________________
________________________________________________________________________________________
________________________________________________________________________________________
________________________________________________________________________________________
________________________________________________________________________________________

7. Do you have any additional comments?

________________________________________________________________________________________
________________________________________________________________________________________
________________________________________________________________________________________
________________________________________________________________________________________
________________________________________________________________________________________
Appendix B

Follow-Up Evaluation Questionnaires
**Worksheet: Obstacle Course**

1. How well do you feel you completed the obstacle course?

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1st:</td>
<td>Perfectly</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>2nd:</td>
<td>Perfectly</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>3rd:</td>
<td>Perfectly</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

2. How difficult was it for you to locate the next cone?

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1st:</td>
<td>Very Easy</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>2nd:</td>
<td>Very Easy</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>3rd:</td>
<td>Very Easy</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

3. How difficult was it for you to match your attitude to the target cone's attitude?

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1st:</td>
<td>Very Easy</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>2nd:</td>
<td>Very Easy</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>3rd:</td>
<td>Very Easy</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

4. How did the attitude control response affect your ability to complete the task in each run? Please comment on any noticeable differences.

5. Which system did you prefer? Why?

6. Were the hand controller command inputs intuitive? What, if anything, would you improve about the hand controller?

7. Do you have any additional comments?
Worksheet: Motion Profile

1. How difficult do you think it would be to translate towards a specific point with this system configuration?

   1st: Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible
   2nd: Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible
   3rd: Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible

2. How difficult do you think it would be to have to reach out and ISS handhold) with this system configuration?

   1st: Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible
   2nd: Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible
   3rd: Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible

3. How difficult do you think it would be to have to complete a precision task (insert a PIP pin into a designated hole, position a pistol grip tool for a drilling task) at any time with this system configuration?

   1st: Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible
   2nd: Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible
   3rd: Very Easy 0 1 2 3 4 5 6 7 8 9 10 Impossible

4. Based on the motion profile you enacted, how did the magnitude of the attitude error compare to what you expected your attitude error to be?

   ______________________________________________________
   ______________________________________________________
   ______________________________________________________

5. Which control system did you prefer? Why? Please comment on any noticeable differences between the attitude control responses of each run.

   ______________________________________________________
   ______________________________________________________
   ______________________________________________________

6. Do you have any additional comments?

   ______________________________________________________
   ______________________________________________________
   ______________________________________________________
Post-Session Questionnaire

1. Overall, which system configuration did you prefer? Why? Did this vary by task?

2. For what specific ISS applications can you envision this system being used?

3. For what non-ISS applications can you envision this system being used?

4. Some of the HUD features in the obstacle course simulation include distance from asteroid surface, fuel remaining, an attitude indicator, etc. Which of these did you use most/least? Which of the features currently included in the HUD do you think are significantly enhancing, and which aren’t necessary? Can you think of any other HUD features that might be beneficial?

5. How realistic is the simulation? What aspects in the graphics environment are good or bad?

6. Do you have any additional comments?
Appendix C

Repeated Measures ANOVA Tables

Full ANOVA tables for statistics discussed in Chapter 5 are included here.

Table C.1: Obstacle Course Fuel Consumption

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditions</td>
<td>0.00379</td>
<td>2</td>
<td>0.00189</td>
<td>2.25</td>
<td>0.136</td>
</tr>
<tr>
<td>Subjects</td>
<td>0.00443</td>
<td>9</td>
<td>0.00049</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>0.01432</td>
<td>17</td>
<td>0.00084</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table C.2: ISS EVA Attitude Error Without Tool

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditions</td>
<td>14.163</td>
<td>1</td>
<td>14.164</td>
<td>4.14</td>
<td>0.076</td>
</tr>
<tr>
<td>Subjects</td>
<td>21.585</td>
<td>8</td>
<td>2.698</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>27.339</td>
<td>8</td>
<td>3.417</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table C.3: ISS EVA Attitude Error With Tool

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditions</td>
<td>22.526</td>
<td>1</td>
<td>22.526</td>
<td>13.03</td>
<td>0.0057</td>
</tr>
<tr>
<td>Subjects</td>
<td>70.467</td>
<td>9</td>
<td>7.830</td>
<td>4.53</td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>15.556</td>
<td>9</td>
<td>1.728</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table C.4: ISS EVA Fuel Consumption Without Tool

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditions</td>
<td>8.994e-05</td>
<td>1</td>
<td>8.994e-05</td>
<td>4.06</td>
<td>0.079</td>
</tr>
<tr>
<td>Subjects</td>
<td>0.000359</td>
<td>8</td>
<td>4.492e-05</td>
<td>2.03</td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>0.000177</td>
<td>8</td>
<td>2.21e-05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table C.5: ISS EVA Fuel Consumption With Tool

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditions</td>
<td>0.000405</td>
<td>1</td>
<td>0.000405</td>
<td>6.21</td>
<td>0.034</td>
</tr>
<tr>
<td>Subjects</td>
<td>0.000724</td>
<td>9</td>
<td>8.046e-05</td>
<td>1.23</td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>0.000588</td>
<td>9</td>
<td>6.529e-05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Reference


