Investigation of Customized Refresher Training for Telerobotic Operations in Long-duration Spaceflight.

by

Lynn Marie Geiger

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 2016

Signature redacted

Author .....
Department of Aeronautics and Astronautics
May 19, 2016

Signature redacted

Certified by .....
Charles M. Oman
Senior Research Engineer
Thesis Supervisor

Signature redacted

Accepted by .....
Paulo C. Lozano
Associate Professor in Aeronautics and Astronautics
Chairman, Department Committee on Graduate Theses

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Abstract

As humanity prepares to break the bonds of Earth's orbit and send explorers deeper into the solar system, mission duration will drastically increase; forcing crewmembers to retain skills and knowledge from prior training on Earth for unprecedented lengths of time. Since performance generally diminishes when a skill is unused, the development of efficient and effective refresher training is essential. The effectiveness of training presumably can be increased by taking into account the learning style of the student and customizing training or retraining material. To understand the effect of customized retraining material on skill reacquisition, we compared space telerobotics performance post training and six months later using two refresher training regimens: written refresher material and personally customized refresher videos. Videos were created by the subjects after training was completed. We used a simulator of the ISS Robotic Arm as a complex task, which requires intricate bi-manual control as well as adherence to complex procedures. We compared performance change between the two retraining styles using subjective instructor evaluation as well as quantitative performance metrics. We assessed each subject's Felder-Silverman Index of Learning Style (ILS), and developed an analogous rubric to assess the teaching style of the refresher videos. We found weak correlations between learning and teaching metrics in 2/4 dimensions. We also found metrics of a subject's spatial abilities (MRT and PTA, with p-values <0.005) predicted performance and retention in procedurally complex tasks. Spatial ability had more effect on the control group's retention than those who received customized retraining. Results of this study will be used to inform NASA on the appropriate refresher materials for long-duration spaceflight crews.

Thesis Supervisor: Charles M. Oman
Title: Senior Research Engineer

Acknowledgments

I would like to thank Dr. Chuck Oman and Dr. Andy Liu for being wonderful advisors and taking me on as a student. Without their support, I would not have made it through grad school. Because of them, I was able to work on a great, interesting project that I would never have thought about. I was able to see the experiment through from beginning to end and "learn how sausage is made" as Chuck would say.

I would also like to thank my UC Davis collaborators, Dr. Steve Robinson, Chris Stevens, and Kim Jenks, for letting me fly out to see the other half of the project and let me lend a hand in their experiment.

Thank you to the rest of the Team, Jennifer Mindock, Vicky Byrne, and Liz Warren, for letting me bounce ideas off you. Thank you for all of your help and feedback along the way. Best of luck with the JIT Training!

To all of my subjects, who had to bear with me through 16 hours of training and evaluation, I sincerely thank you! I litterally could not have done this project without you.

I would also like to thank Alan Natapoff for patiently sitting through long stats meeting and helping me to get results out of my messy data.

Thank you to all the MVLers who have made these past three years enjoyable. From chatting about fish, to playing boardgames, Lab Lunch every Friday, writing in the Muddy, to even having Nerf gun wars, the MVL is definitely the Most Valuable Lab to me.

Also, thanks to my patient wife, who had to read my first drafts and wince at my lack of Oxford Commas. And all of my family, thank you for supporting me in every aspect of my life.

Thanks to the folks at Roshankish, for keeping me sane and giving me an outlet for all the stress of writing a thesis! Thanks to JM for keeping me on task during study parties.

This work was supported by the National Space Biomedical Research Institute through NASA NCC 9-58 Project HFP03801.

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Chapter 1

Introduction

Human spaceflight is beginning to increase in mission duration, which poses a challenge to ground-based training. Longer missions often lead to a greater length of time between ground-based task training and completing the actual task, introducing the probability of performance degradation.

There are two potential solutions to this training challenge: ground based task training with refresher training prior to starting the task, or a deep level of skill training on the ground followed by Just in Time Training for specific tasks. In this context, skill training refers to becoming proficient in an ability, learning to control a robotic arm for example, while task training refers to learning to use that ability in a specific scenario. A team of researchers from MIT and UC Davis is conducting experiments that incorporate customized training materials into both of these possibilities to make on-board training more time efficient. Veteran NASA astronaut, Dr. Steve Robinson, and colleagues created short training videos of tasks they were to perform on-board Shuttle and ISS missions, utilizing them as refresher training during flight. The retraining proved successful, and Dr. Robinson initiated a NASA/NSBRI funded research project as a UC Davis faculty member years later. The goal of the project was to examine the technique in detail, to learn about any pedagogical issues, and to understand the generality of the method.

This thesis describes the refresher training portion of the investigation, applied to space telerobotics. The experimental training materials we evaluated were customized

refresher videos (CRVs), which were made by subjects at the conclusion of their initial training when they had high proficiency. Because the CRVs are personally created by the subjects, they can include specific tips for themselves and explain their own mental model of the task, theoretically increasing the efficiency of retraining by getting them up to speed more quickly.

We utilized space telerobotics as our complex task, training subjects on a computer simulator and retesting proficiency after 6 months, the average duration for an International Space Station mission. Half of the subjects receiving the customized refresher training, while the other half received generic training documents. Theoretically, presenting information in a way that corresponds to how a trainee prefers to learn, their learning style, can make training more effective [5]. If subjects create customized training videos that correspond to their own learning style, the matched learning style could increase retraining efficiency. We hypothesized that subjects who study with customized videos will have better performance retention than the control group, and the performance reacquisition will be faster. In addition, we hypothesized that the videos will match their creator's learning style preferences. Finally, we hypothesized subjects with strong spatial abilities, as described below, will learn and retain the demanding telerobotics skills better than those without.

1.1 Learning Styles

There are many models that attempt to decipher the different ways people learn. In conceiving this experiment, we utilized the Index of Learning Style (ILS) created by educators Felder and Silverman (1988), depicted in Figure 1-1 [5]. The ILS characterizes learning preferences in four dimensions (Processing, Perception, Input, and Understanding), based on answers to a set of 44 questions[1]. A person's learning style preference is scored along a spectrum with adjectives describing the extremes of each dimensions. The ILS was designed to assess the learning styles of college level engineering students, making it very applicable in this experiment, as many astronauts

[1] https://www.engr.ncsu.edu/learningstyles/ilsweb.html

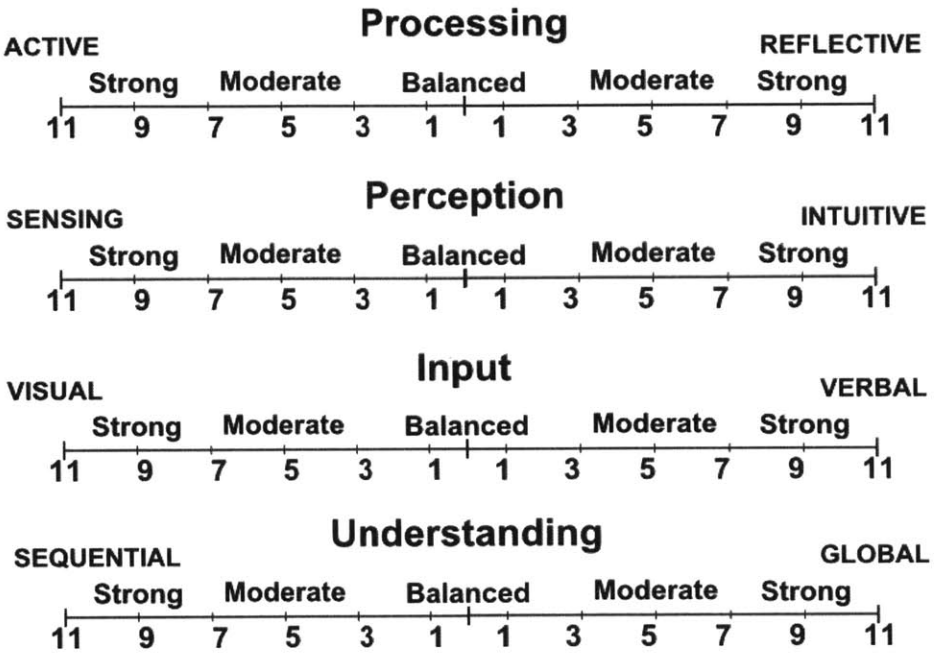


Figure 1-1: Felder-Silverman Index of Learning Styles

have high level engineering or science education.

The first dimension, Processing, describes how a student encapsulates information; how they manipulate ideas to comprehend them. Do they actively experiment with an idea, or do they reflect on the idea, internally thinking about it? This dimension is characterized by Active Learners and Reflective Learners.

The second dimension, Perception, is how one interprets information. It is split into Sensing and Intuitive Learners. Sensors gather information through observation and prefer concrete facts and rote learning, while the Intuitors prefer abstract concepts and theories, drawing conclusions indirectly and inventively. This distinction in behavior first appears in the psychological types described by Carl Jung (1971), and is also appears in the Myers-Briggs Type Indicator which is used to describe personality types [16] [25].

The third dimension, Input, describes what type of stimulus a person prefers: Visual or Verbal. Visual input includes picture, graphics, or videos while Verbal input includes spoken word or text.

The final learning style dimension, Understanding, explains how a student comprehends information. In this case, the distinction lies within the context of which

information is being taught. A Sequential Learner requires information to be presented in a step-by-step manner. A Global Learner needs to be able to connect the information to the greater context, to see how it fits within the big picture. Global learning tends to be non-linear and sporadic, learning in "fits and starts" [5].

Though the dimensions were hypothesized to be independent, there is some cross over in the definitions given by in the original 1988 paper. For example, both Sensing and Active Learners prefer problem-solving over fundamental understanding. Moderate correlations between the Sequential / Global and Sensing / Intuitive dimensions have been shown in a few studies, with p-values <0.001 [6] [30] [35]. The stability of an individual's ILS score depends on the dimension and time between testing, from correlation coefficients of 0.73 to 0.87 over four weeks to 0.60 to 0.78 over 7 months [6] [20] [29], with the Input (Visual / Verbal) and Understanding (Sequential / Global) dimensions being least stable over long periods.

Felder and Silverman (1988) hypothesized that if teaching materials are aligned with a student's learning style preference, then the student should be able to learn better [5]. This is also referred to as "the Matching Hypothesis". Carver et. al (1999) demonstrated that students who were allowed to choose how teaching material was presented, through hypermedia that provided different tools catering to all ILS types, displayed a greater depth of understanding at the end of the course than students who were taught traditionally [1]. The Matching Hypothesis has been tested directly, on the Understanding (Sequential / Global) dimension specifically, and has been shown to promote better learning and motivation in 5th grade students [15].

There has been very little literature published on grading teaching styles. Felder and Silverman report specific teaching strategies or activities that could benefit certain learning style types, but they do not provide a method for estimating the level style bias in an example of teaching [5]. Wieman and Gilbert (2014) created a Teaching Practices Inventory (TPI) that will characterize the effectiveness of an instructor's teaching in science and mathematics, based on what kinds of activities are incorporated into the lecture [33]. The TPI does not take into account any information on learning styles, ILS or otherwise, or if the style of teaching is balanced, but simply

assesses the variety of teaching activities used.

1.2 Refresher Training and Forgetting

When skills go unused, they presumably degrade. The rate of forgetting procedural tasks increases as the time off lengthens [2] [14]. In addition, training procedures, optimized for quick mastery of a subject, are detrimental to long term retention [12] [10]. There are two main ways to minimize abatement: by preemptively protecting against memory loss, through specific training techniques, or through post-training refresher sessions. Training techniques to increase retention include: over-learning tasks, engaging and active training sessions, spacing training over several sessions, practicing a wider range of scenarios than required, randomizing trial order if multiple skills are being learned, and laying groundwork for deeper understanding of the task [28] [2] [10]. Many of these techniques integrate learning styles often overlooked in a standard lecture format, such as Global or Active learning, by incorporating teaching materials that fall along the whole range of ILS types, making the learning more accessible to a wider range of people.

Mengelkoch, Adams, and Gainer (1971) conducted an experiment training ROTC students, with no flying experience, on a flight simulator to investigate retention four months after training [24]. They found that flight controls, the manual ability to fly the plane, were remembered better than procedural responses. Automatic skills are more likely to be retained over lay-off periods [2], and complex tasks are more susceptible to forgetting [14]. To keep performance at an optimal level, Anders Ericsson suggests that the skill be practiced continually and deliberately [3]. Deliberate practice is not simply running through a task, but concentrating fully and striving for improvement through self-analysis and reflection. Ericsson (2003) described the effect of continual practice on doctors ability to effectively diagnose and treat disease [4]. A study by Hollister et al. (1973) evaluating performance of airplane pilots found that the pilots scored the best on skills they use frequently and score poorly on rarely used skills (ex. stalls), concluding that recency is more important than experience

[13]. Rigg (1981,1983) and Rose et al. (1984) created algorithms to estimate information loss and performance decreases over time, as a function of training performance and task cohesion respectively, in order to approximate when refresher courses are necessary [26] [27] [28]. Many times, these refresher sessions include lower fidelity simulations of the task [2], and it takes less training to relearn a task than the initial training [24].

Could we create a refresher training regimen that brings a student up to speed quickly without needing time intensive simulator retraining? Anecdotal reports by Astronauts Robinson (STS-130) and Burbank (ISS-30) suggest that self-made customized refresher videos (CRV) are an effective and time efficient method for retraining. This has not been tested experimentally for refresher training. A similar concept, videotape self-modeling (VSM), was investigated by Linnerooth et al (2014) [18]. VSM involves splicing footage of an individual into a video that demonstrates optimal task performance. The video is then shown to the individual during initial training, with the notion that seeing yourself perform the task perfectly will bolster performance. The experiment proved VSM ineffective for enhancing training [18] [34]. One key difference between VSM and CRV is the person in control of video content. VSM is used during initial training to increase performance and therefore has to be created by instructors, but CRVs are created by the individual who will be using it, allowing them to include tips or hints to themselves and present the information in a style they prefer. CRVs allow for inclusion of personal Learning Style, instead of a standardized format.

1.3 Space Telerobotics as a Complex Task

Space telerobotics is an inherently complex task, requiring mental visualization skills, fine motor control, and adhering to procedure and flight rules. Often space telerobotics is accomplished only using video views of the work area, so the robotic arm operator must interpret two dimensional images to create a 3D mental model of the environment and their position inside it, all the while being aware of arm kinematics

and limitations, avoiding collisions, and following procedural flight rules. To add to the workload, they also control the arm in six degrees of freedom, using separate rotational and translational hand controls, where the movement axes are frequently not aligned with camera views (e.g. the operator views the scene backwards or upside down). Space telerobotics has been used in other research at MIT to understand human performance under adverse conditions and to test countermeasures, as well as understanding the effect of spatial visualization skills on robotics performance [9] [7] [21] [22] [32].

1.3.1 MIT Robotic Workstation Simulator

The MIT Robotic Work-Station Simulator (MIT-RWSS) is a computer based simulation of the robotic arm on the outside of the International Space Station (ISS), and resembles the "Dynamic Skills Trainer" used by NASA for training astronauts. The simulator was created in Vizard, a virtual reality program that uses Python coding language. Figure 1-2 shows the configured simulator with three monitors, two joysticks, and a keyboard for controlling system states. There are eleven camera views that can be used in the environment, nine mounted on the ISS (Figure 1-3), one on the arm elbow, and one on the end of the arm, selected via keyboard control. Three different camera views can be displayed at one time. The cameras mounted on the ISS can be slewed in pitch and yaw using a knob on the joystick. In this experiment, the subjects had to memorize the locations of the cameras.

The simulator uses bimanual control, where the left hand controls translations and the right hand controls arm rotations. The motions can be controlled in two frames of reference selected on the keyboard: an internal control frame that is aligned with the view of a camera mounted on the end of the arm (Figure 1-4.a), and an external frame of reference that is aligned with the cardinal directions of the ISS virtual environment (Figure 1-4.b). The system also had a "Vernier" rate setting, where the arm speed was reduced by a factor of ten to allow for fine motion control. The operator used the keyboard to control the brake and indicate whether the arm had an attached payload. The grapple trigger for picking up objects, was located on the Rotational Joystick.

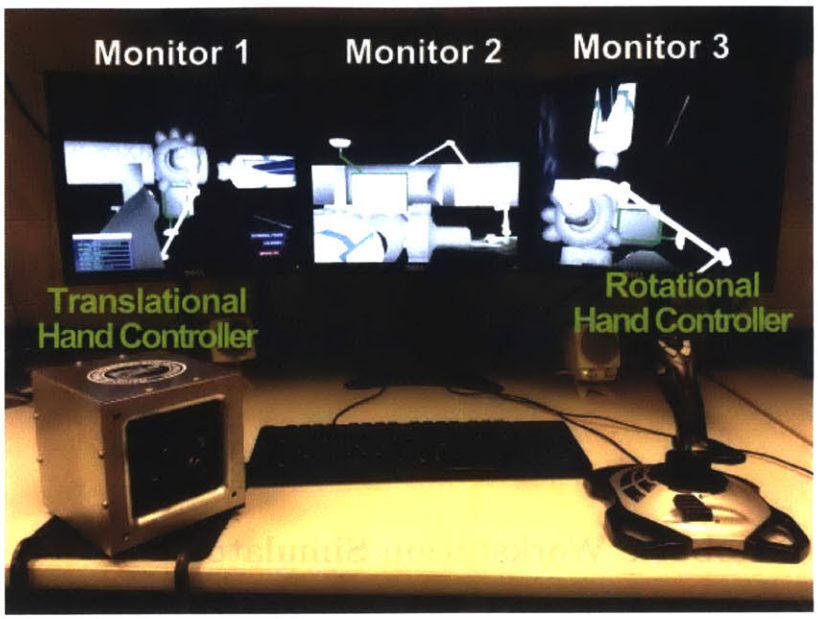


Figure 1-2: MIT-RWSS Simulator set-up

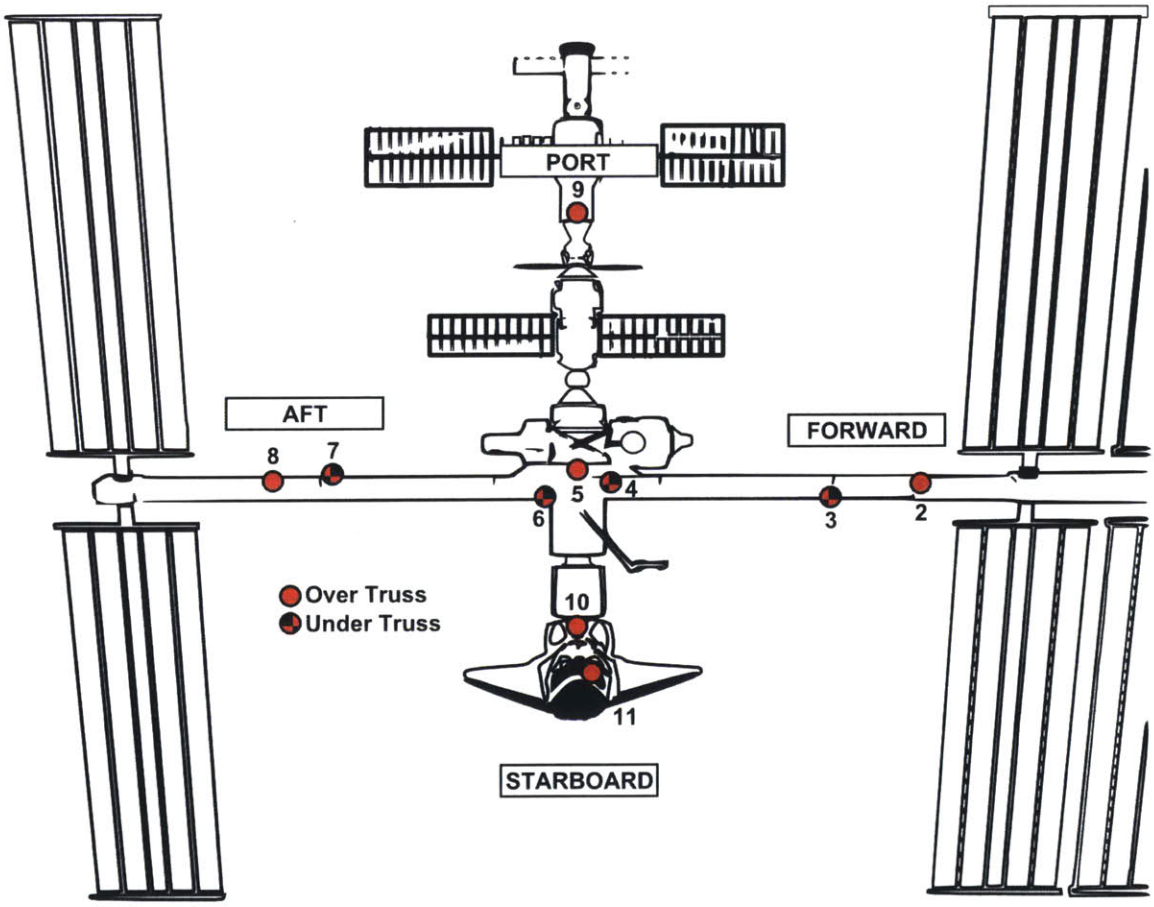


Figure 1-3: Map of the virtual environment in MIT-RWSS. Cameras are marked by circles.

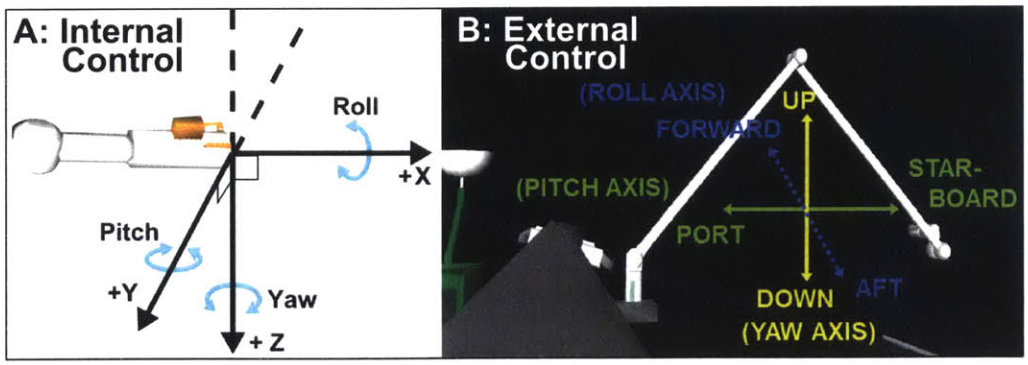


Figure 1-4: Control frames of the robotics simulator. A) Internal Control is aligned with the end of the arm. B) External Control is aligned with the ISS.

Figure 1-5: Joint Angle display. Note the Wrist Pitch joint is nearing a hardstop and the display bar turned yellow

The simulated arm has kinematic limitations similar to the real robotic arm, though the MIT-RWSS arm has only 6 degrees of freedom and the ISS arm has seven. The six joints in the arm cannot rotate indefinitely, but have rotation limits called hard stops. Each joint has a different range, similar to the ISS arm. There is a joint angle display on the first monitor that indicates the angle of all six joints and where the joint is within its range with a green bar (Figure 1-5). In addition to joint hard stops, there are kinematic singularities, arm configurations where the arm controller loses a degree of freedom, and the robot becomes unresponsive. The MIT simulator has 3 singularities that the subjects were trained to be aware of and avoid.

Operators are asked to follow three flight rules: regulate speed when operating within 1 meter of structure, keep the arm at least 0.6 meters from structure unless

grappling, and apply the brake when not actively flying the arm.

1.3.2 Robotics Tasks

Subjects were trained and evaluated using three types of telerobotics tasks: Track and Capture (TC), Payload Positioning (PP), and Astronaut Assist (AA). Being able to effectively perform these tasks relied on two main things: 1. procedural memory - defined as task related information, such as flight rules and step-by-step procedures or checklists, and 2. muscle memory - defined as the proficiency in manually controlling the arm in a coordinated and automatic manor, without having to consciously think about the required input. Ideally, the subject should be trained to the point where these things are done automatically.

In addition to the main tasks the subjects were asked to respond to a side task, acknowledging a message that would appear randomly every 2-10 seconds in the bottom of first monitor. The subject had 10 seconds to respond to the message before it was counted as a miss. The length of time taken to respond to the side task can be used to estimate the cognitive workload and spare attention of the subject, increasing when a subject fixates on the primary task [22]. In this thesis, secondary task response time is referred to as "reaction time". The reader should be aware that it is typically quantitatively longer than the psychomotor response time measured if the same task were presented as the sole primary task. The same side task has been used in previous MIT telerobotics experiments and was found to be a sensitive measure of workload [9] [21].

Track and Capture Task

The Track and Capture task (TC) involved capturing a resupply vehicle within 90 seconds (Figure 1-6). The resupply vehicle could be translating, rotating, or both. The task was completed in the internal command frame aligned with end effector camera, which is preselected for the task. This removed the complexities of having visual cues misaligned with the coordinate frame of the hand controllers.

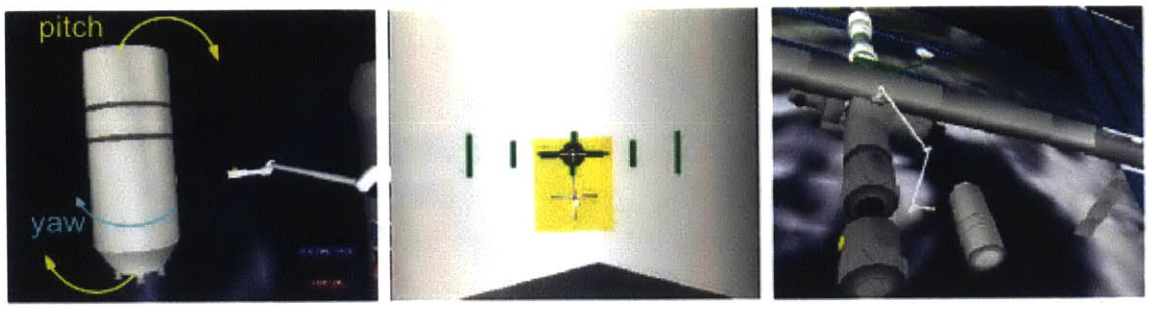


Figure 1-6: Starting positions of a Track and Capture Trial. The first monitor shows an overhead view of the resupply vehicle and arm starting location. The second monitor shows the initial view from the end effector camera, pre-aligned with the grapple target. The third monitor is a global view.

A trial begins with all of the simulator states preset for grappling: the arm is two meters away and aligned with grapple target, seen in Figure 1-7. Once the subject disengaged the brake, the resupply vehicle began to move. The subject had to compensate for the motion while approaching the target and maintain alignment with the grapple target. When the camera's cross hairs were properly aligned with the target, the end effector would be in position to grapple and the subject would pull the grapple trigger, capturing the vehicle. Once the vehicle was captured or the 90 second time limit was up, the trial would end automatically.

The task was relatively straightforward because there were no joint limitations in the path to the vehicle, and the subjects did not have to do any path planning. The TC required very little procedural memory, but because the time limit was very short, the task depended heavily on proficiency with the hand controllers (muscle memory).

Payload Positioning Task

The Payload Positioning task (PP) involved moving the robotic arm to a specified object, grappling the object, and then relocating it to a designated position indicated in the written procedures. The training objects ranged from simple boxes to large space station modules. In a PP task, the subject was in charge of selecting all of the settings for the simulator as well as choosing which camera views to use for the task.

The PP task is more complex than the TC task. It consists of six phases, shown

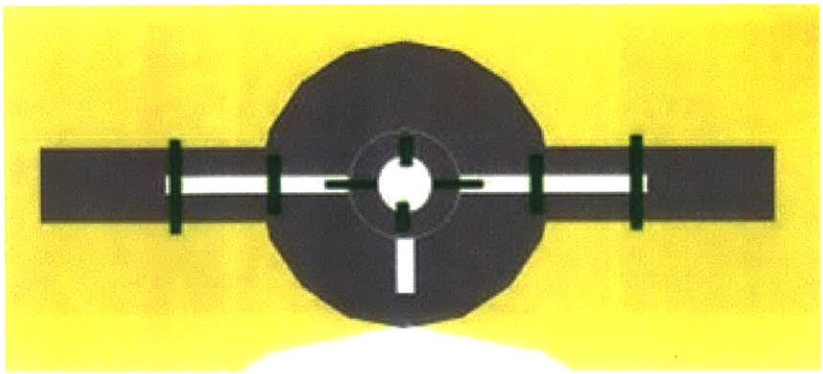


Figure 1-7: Image of the standardized grapple fixture. The green lines are overlain on the end effector camera, and are used to align the arm with the target. The cross-hairs must be centered on the central circle and the white bar must be within the vertical green lines.

in Figure 1-8 and listed in Table 1.1. During phase 1, the plan phase, the subject sets up the simulator: choosing the proper frame of reference, selecting and trimming cameras, and mentally acquainting themselves with the specific task. When the subject begins to move the arm, they enter phase 2, the fly-to phase, where they pilot the arm to the object they wish to pick up. This phase involves path planning and is conducted in the external control frame. Subjects are instructed to fly to 1 meter above the grapple fixture (Figure 1-7), and then begin phase 3, the grapple phase. During grapple alignment, the subjects are operating in the internal control frame and the Vernier, slow, rate of motion. After the object is grappled, there is another brief planning phase, phase 4, in which the subject must change the arm settings and plan the next flight-path. When the arm begins to move again, the subject enters phase 5, loaded flight. Loaded flight is slightly more difficult as the subject must rotate the payload to the final orientation while moving to the final position in the external control frame, remaining aware of the size of the payload to avoid collisions. When the payload is within one meter of its final location, the final alignment, phase 6, begins. When the subject is satisfied with the position, they indicate with the keyboard that they are finished, and the trial ends.

The goal was to complete a PP in ten minutes or less. The subjects are given paper procedures during the trial that indicate the object they are retrieving and

Table 1.1: Robotic Task Phases

Phase	Track & Capture	Payload Positioning	Astronaut Assist
1	Plan	Plan	Plan
2	Grapple	Fly-to	Loaded Flight
3	- - -	Grapple	Alignment
4	- - -	Plan	Repair
5	- - -	Loaded Flight	Plan
6	- - -	Alignment	Loaded Flight
7	- - -	- - -	Alignment

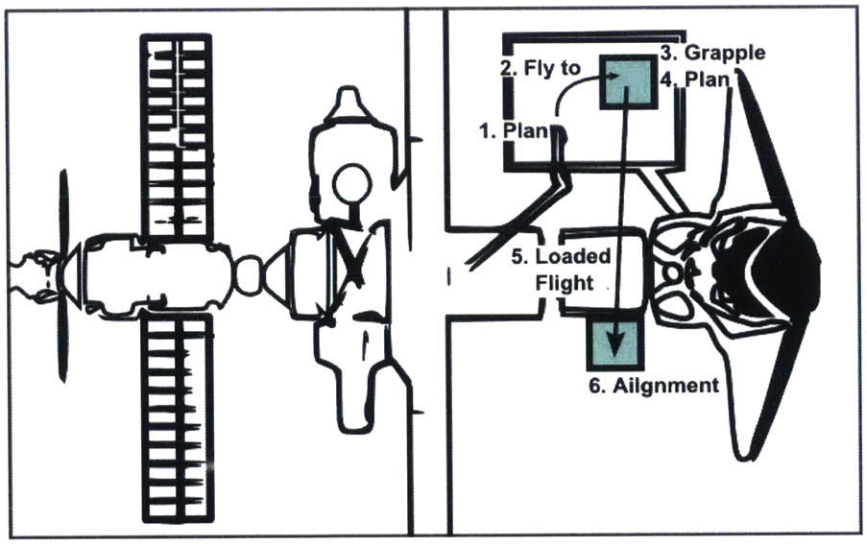


Figure 1-8: Diagram of the Payload Positioning Task, and the corresponding flight phases.

where the final position is. The PP trials are much more procedurally challenging than the Track and Capture trials because subjects have to adhere to flight rules, be cognizant of joint limits, and mentally plan flight paths.

Astronaut Assist Task

In the third type of task, the Astronaut Assist task (AA), a subject must move an astronaut to a specified location, assist with a repair, and then move them to another location (Figure 1-9). Because the first and second half of the trial are essentially the same, the trial is broken down into phase type: plan, fly-to, align and

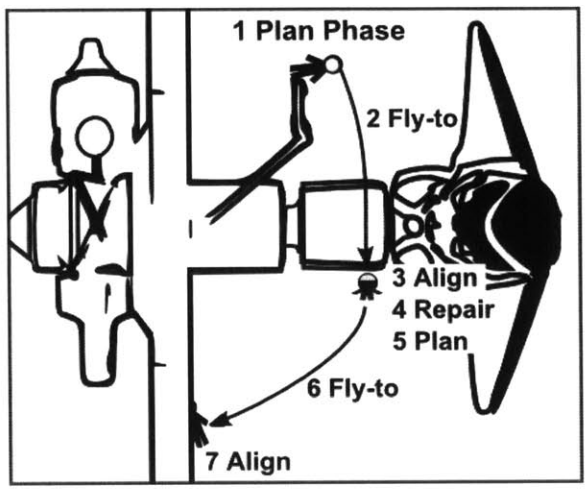


Figure 1-9: Diagram of the Astronaut Assist Task, and the corresponding phases

repair. The plan, fly-to, and align phases are similar to the second half PP task; the subject in is charge of the various simulator settings and cameras, and they must be aware of the added clearance difficulty of loaded flight. During the repair phase, a message from the astronaut will pop up on the screen directing the subject to adjust the astronaut's position by a certain amount. The directions are given in terms of the external coordinate frame, for example "Move me 0.5 meters Port", to test the subject's memory and ability to estimate distances.

The AA task should have taken 15 minutes or less and was accompanied by a set of written procedures outlining the task and the locations to place the astronaut. Though procedurally similar to the PP task, the AA task was more even cognitively challenging because singularities and joint hard stops were purposefully placed along the shortest flight path to intentionally test the subject's awareness.

1.4 Spatial Abilities

Because there is such a heavy reliance on mental visualization, innate spatial abilities may assist in learning and retention of telerobotic proficiency. Previous studies have found that subjects with poor spatial abilities (SpA) had a higher failure rate at the mid-training screening [9], and links between subject performance and SpA [23]. Correlations between certain measures of SpA and telerobotics performance were

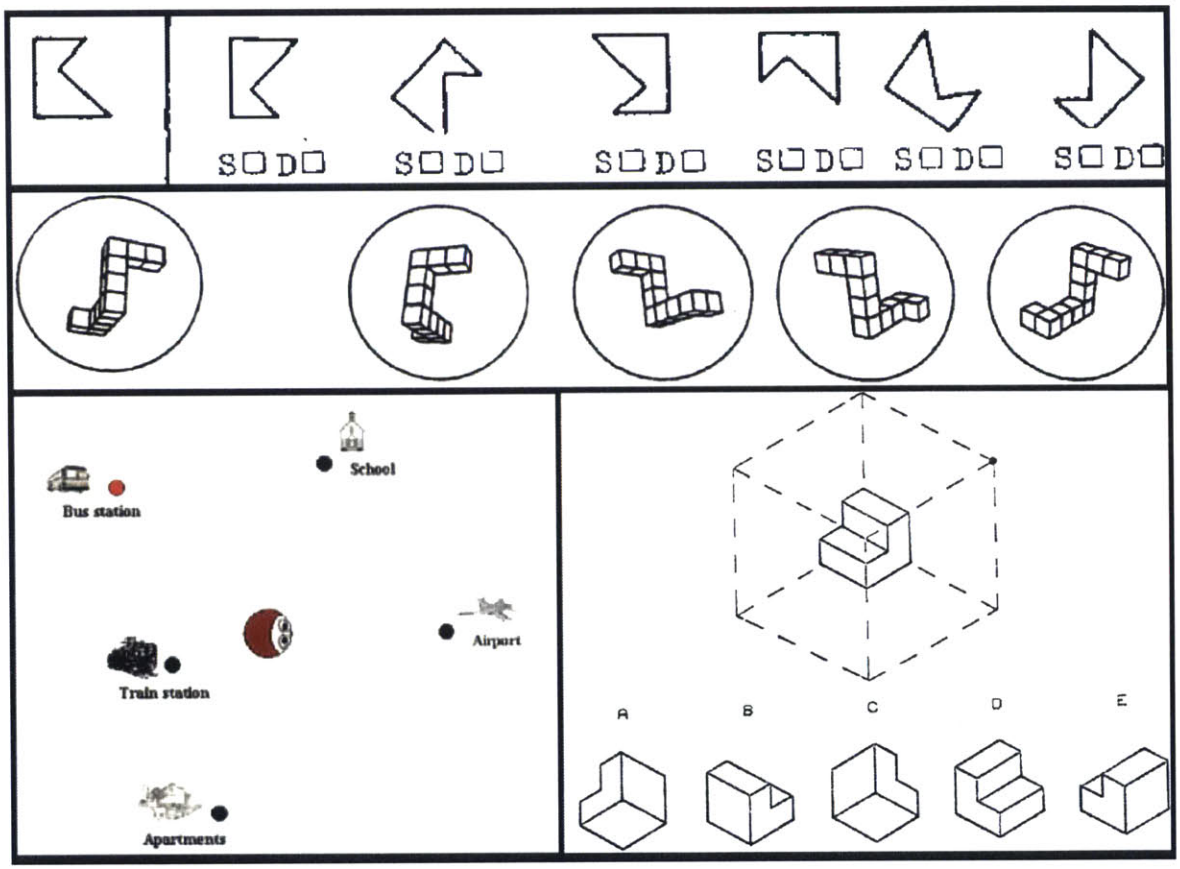


Figure 1-10: Example trials from each Spatial Ability Test. A) Card Rotation Test[8], B) Mental Rotation Test[31], C) Perspective Taking Ability Test[17], D) Purdue Spatial Visualization Test[11]

found in NASA astronauts as well [19]. SpA appears to affect performance at all levels of proficiency. Our experiment investigates these spatial abilities and retention of telerobotic skills using four metrics of spatial ability: the ability to mentally rotate an object in two and three dimensions, and the ability to visualize a different perspective in two and three dimensions. These SpA metrics are assessed using the Card Rotation test [8], the Vandenberg Mental Rotation Test (MRT) [31], the Perspective Taking Ability Test (PTA) [17], and the Purdue Spatial Visualization Test (PSVT) [11], respectively. Example questions from each test are shown in Figure 1-10.

1.5 Thesis Outline

In Chapter 2, I step through the experimental method that we used, explaining the telerobotics training and evaluation. Then I describe the performance metrics used and the data collected. In Chapter 3, subjective and quantitative results of the change in performance over the 6 month break and differences in treatment retention are presented, along with a comparison of subject's ILS and video teaching style, and the effects of spatial ability on performance and retention. The results are discussed in Chapter 4, in relation to our hypotheses and previous work. Lastly I conclude the lessons of the experiment and discuss future work.

This thesis aims to test the following hypotheses:

H1: What is the effect of a 6 month lay-off on telerobotic performance?

H2: Customized Refresher Videos will aid in retraining by ameliorating performance decrements and increasing the rate of reacquisition.

H3: Customized Refresher Videos will contain teaching style features parallel to the creator's learning style.

H4: Subjects with better spatial abilities will relearn the telerobotic tasks more quickly.

Chapter 2

Methods

In this chapter, we explain the refresher training experiment, beginning with a description of the subjects, then stepping through the experiment flow, and finish with an overview of the data collection.

2.1 Recruitment

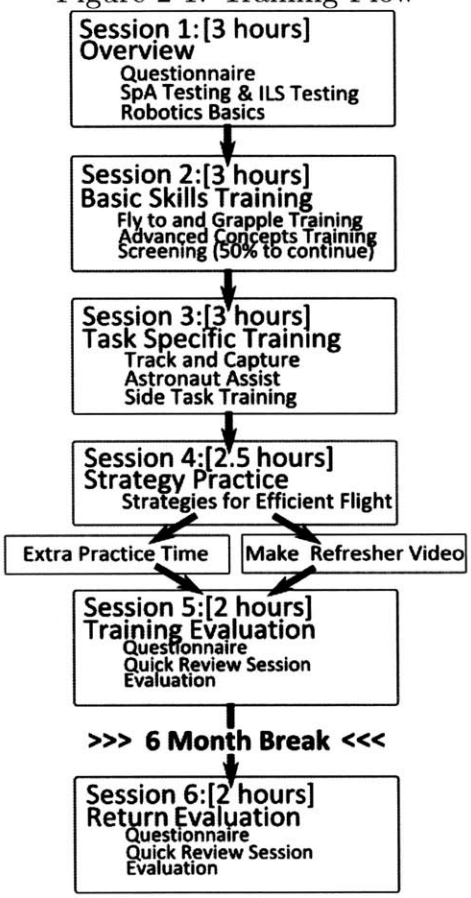
18 subjects (8 male and 10 female) were recruited from the MIT graduate and undergraduate student population, ages 18-34. All subjects were right handed. The subjects were randomly assigned to a treatment: either the control group, who were provided generic refresher-training materials; or the experimental treatment, where they created their own custom refresher-training material. Since subjects were randomly assigned during recruitment, the groups were not balanced on the basis of spatial ability or ILS test results.

A between subject experimental design was chosen because naiveté of the subjects before training was paramount to the investigation; previous exposure to space telerobotics could have affected their retention and performance.

2.2 Robotics Training

All subjects were trained on the MIT Robotic WorkStation Simulator (MIT-RWSS) over the course of 12 hours, split into four three hour sessions. All training and the first evaluation were completed within one week to minimize potential issues with forgetting material during the training process. The training sessions were split into Robotics Overview, Basic Skills, Task Specific Skills, and Strategy Practice, Figure 2-1. All training sessions included reading through an instructional PowerPoint and hands-on training with the simulator. All training slides are included in Appendix C.2. Both the treatment and control groups were trained in identical fashion until the final stage of the fourth training session. Below I describe in detail each session and the methodology used.

Figure 2-1: Training Flow



2.2.1 Session 1

The first session began with a questionnaire on their background and a Spatial Abilities (SpA) test battery that lasted one hour. The SpA battery included tests assessing the ability to mentally rotate a shape in 2D (Card Test) and 3D (Mental Rotation Test (MRT)), and the ability to visualize another perspective in 2D (Perspective Taking Ability Test (PTA)) and 3D (Purdue Spatial Visualization Test (PSVT)). After the SpA tests were finished, the subjects completed a paper version of the Index of Learning Style (ILS) assessment[1], which took 15 minutes. Next, the subjects were given a brief break to refresh themselves before the robotics training began.

The Robotics Basics focused on robotics terminology and familiarization with the simulator. Subjects worked through training slides at their own pace and were

[1]https://www.engr.ncsu.edu/learningstyles/ilsweb.html

encouraged to ask questions. At key points in the training, they were asked to try out a skill in the simulator. After reading the PowerPoint, the subjects completed 6 target practice trials, where they were required to fly the robotic arm through hoops or hit ball targets.

2.2.2 Session 2

At the beginning of the second session, subjects were asked questions about the content from the first session, to ensure they had retained the salient information. In the second session, subjects learned general skills, such as grappling (picking up) and positioning objects, controlling the camera views, and changing the various simulator settings. The training content was delivered through a slide show. The subjects completed eight unique practice trials to familiarize themselves with the new concepts and material. In order to remain in the experiment, the subjects had to complete a preliminary screening at the end of the session, within the allotted time and error limits. The screening tested their basic telerobotic skills through grappling a target and positioning two payloads. All subjects passed this screening.

2.2.3 Session 3

The third session focused on learning complex skills specific to the harder tasks that subjects would be tested on during the evaluation; capturing a moving object and assisting an astronaut in repairs. Again, the session began with questions testing retention of information in the previous session. Then, subjects stepped through training slides and practice trials one task at a time, beginning with the Track and Capture task (TC), described in Section 1.3.2. The subject had 90 seconds to capture a moving resupply vehicle. The task demanded high competency in bimanual control of the robot, as the vehicle could be rotating as it translated. For practice, they completed 10 unique trials and were provided scripted feedback from the instructor (see Appendix C.1 for the feedback provided).

Subjects then learned the Astronaut Assist task, where they were required to fly

an astronaut standing on the end of the arm to a repair location, assist with a repair, and then fly to a drop-off location. Training included four unique trials.

After the task specific trials were completed, the subjects were given a secondary task, in which the subjects were told to respond as quickly as possible to a pop-up message with a button click. The secondary task was used as a proxy for spare attention, and subjects were told not to respond if it would compromise primary task performance. They were given five Track and Capture, one Astronaut Assist and one Payload Positioning trials to practice responding to the secondary task.

2.2.4 Session 4

The final training session involved 1.5 hours of strategy practice. The subjects worked through slides detailing five key strategies for flying the robotic arm: understanding arm motion, predicting joint limitations, watching clearances, reducing task time, and recognizing camera parallax. Each strategy was accompanied by a target practice trial in which the subject would have to explicitly use that strategy.

At the end of the directed practice, the control group was given an extra hour to practice whichever skills they wished. The experimental group took this time to create their customized refresher video.

2.2.5 Customized Refresher Video Creation

At the end of the final training session, the experimental group created their own customized refresher materials. We chose to create the videos before the evaluation so that the evaluation performance measured their final level of skill before the break, in case learning occurs during video creation. We were also able to counter balance the extra exposure to the simulator and materials by having a free practice period for the control group. Time was limited to one hour for both activities.

The subjects were told the video should be 15-20 minutes long, and that they could use any materials in the video. They were also provided paper to sketch out or organize their thoughts. They were given one hour to both film then edit their

video in the Windows MovieMaker computer program. In case the subjects were unfamiliar with the software, the instructor provided a brief tutorial for all subjects and was available for questions. The instructor did not contribute content to the videos, other than loading requested simulator trials, informing the subject when they made a mistake in while explaining, and controlling the camera if asked.

2.2.6 Evaluation

After training was completed, the subjects returned for an evaluation within 3 days[2]. The evaluation session lasted 2 hours. The session began with a questionnaire on the training process and confidence in the evaluation, see Appendix A.1. Then, the subject was given refresher materials, generic and/or customized. The evaluation itself consisted of 12 Track and Capture tasks, 2 Astronaut Assist tasks, and 2 Payload Positioning tasks. The evaluation itself took roughly an hour and a half. The evaluations were videotaped. In addition to quantitative performance metrics calculated from the simulator output, the subject's performance was evaluated using a 100 point grading rubric, see Appendix A.2. To promote consistency, the author scored the subjective rubric for all subjects and both sets of evaluations. After the evaluation, the subjects filled out a questionnaire on their performance.

2.2.7 Retraining

After the six month layoff period (180 $\pm$ 5 days), the subjects returned for a single session that included refresher training and a repeat of the performance evaluation. The session began with retaking the ILS test, to evaluate the stability of learning styles, and a questionnaire on their activities during the layoff period, as well as confidence in being able to perform the robotics tasks. Next, the subjects were given 20 minutes to review the refresher materials, which included basic review slides and, if they were in the experimental group, their personal video. After reviewing, the subjects completed the exact same evaluation they did 6 months previous. This

[2]Subject 14 had to reschedule testing and returned 5 days from training

was so that trial performance could be directly compared for analysis. After the evaluation, the subjects were given a final questionnaire to see how they felt about their performance.

2.3 Data Collection

2.3.1 Subjective Questionnaires

Three questionnaires were given during the experiment to look at the subject's background and self-reported performance (Appendix A.1). The first questionnaire was taken at the beginning of the first training session. The questionnaire focused on understanding the subject's background and experience pertaining to complex spatial tasks. Subjects rated their current and previous experience with video games and their spatial visualization skills on a scale of 1-5. Subjects were also asked to write in what types of video games they play, which were categorized post hoc by the complexity of the game's visual perspective. The subjects were asked if they had any training in spatial skills, such as being taught to visualize atomic structures of molecules. Demographic information, including age, gender, dominant hand, average sleep, and education level, were collected with open questions.

The second questionnaire was taken during the first evaluation session. This questionnaire had two parts, taken before and after the evaluation. The subjects were asked to rate how helpful the various components of training were in learning to operate the simulator. They were also asked how confident they were in their ability and what was most worrying for the evaluation. After the evaluation, subjects were asked how well they did and what they found difficult during the evaluation.

The final questionnaire was taken during the return session six months later. It was comprised of three parts. Initially, the subjects were asked about their time during the six month break: how often they thought about the robotics skills, how frequently they played video games, and how much they remember about and their confidence in operating the robotic tasks. They were given the refresher training and

then filled out the second portion of the questionnaire, reporting their confidence and what they were concerned about for the evaluation. After the evaluation, they completed the final section of the questionnaire. Subjects were asked to rate their performance, the most difficult part of the evaluation, and the most helpful part of the refresher training. They were also asked if there was anything they wished they had studied more.

2.3.2 Spatial Ability Score

The subjects completed a suite of four Spatial Ability tests, administered during the first session, beginning with the Card Rotation test. The Card test is a paper test comprised of a series of questions, in which the subject must indicate whether a 2-dimensional shape is the same as a reference shape. The questions are broken into two parts each with a three minute time limit; most people cannot complete all of the questions in time. The second test is the Vandenberg Mental Rotation Test (MRT), a similar test in which the subjects must mentally rotate 3-dimensional shapes. The third is a computer based test, the Perspective Taking Ability Test (PTA), where the subject must indicate as quickly as possible the direction to a landmark from the perspective of a character on the screen. The PTA takes into account accuracy as well as reaction time in the score. The final test is the Purdue Spatial Visualization Test (PSVT). In the PVST, the subject must indicate what a complex, three-dimensional shape would look like from an indicated perspective. The PSVT is a paper based test with a 20 minute time limit, though many people complete it in less time.

All of the paper based tests are scored as the number of correct answers minus the number of incorrect answers, penalizing guessing. Subjects were all read a standardized description of the tests and given practice questions for the paper based tests. In the Card and MRT tests, there was a one minute remaining warning. The PSVT had a halfway, five minute, and one minute time warning. In addition to the individual scores, a composite score was created for each subject by averaging all of their SpA scores.

2.3.3 Robotics Performance

At the end of training and six months later, subjects completed the robotics performance evaluation. The evaluation included three types of robotics tasks (Track and Capture, Astronaut Assist, Payload Positioning) and was assessed using a qualitative grading rubric as well quantitative data extracted from the simulator output files. The subjective and quantitative performance data was analyzed in the SYSTAT_13 statistical analysis software program to look for differences in performance across the rest period and between experimental groups, as well as to model performance change.

Qualitative Performance Evaluation

The qualitative evaluation rubric was based on the final exam grading scale for NASA's General Robotics Training (GRT) at Johnson Space Center. The rubric incorporated the same performance standards as the GRT grading scale, but was written in a finer resolution to remove as much subjective variability as possible (Appendix A.3). The rubric is split into three performance categories: situational awareness, task performance, and technique (pulled from the GRT scale). Each category had two to five elements, depending on the trial type, graded on a three tier scale (0, 1, or 2 points). The elements were scored individually for every trial and tallied up for a total performance score. Because there were so many track and capture trials (12), they were weighted 0.5 to balance the total. The score was multiplied by 0.63 to make a perfect score 100. The rubric can be split by either task type or by performance category; both divisions were analyzed here.

Quantitative Robotics Performance Metrics

The SSRMS simulator records the hand controller position, simulator state, target position, secondary task response, and keystroke inputs at 20Hz. The data files are then processed in MATLAB to create 27 variables, listed in Table 2.1. The complete definitions and equations for each metric is located in Appendix B.1. These variables comprise five aspects describing subject performance, listed as 'Skill Type' in Table

2.1: 1.procedural memory (remembering task related information), 2.muscle memory (The ability to manually control the arm reflexively, without having to think about the required input), 3.familiarity with the simulator, 4.situational awareness, and 5.cognitive workload. The metrics were assigned to a skill type based on how they relate to the skills and what skills are required to better the metric score.

2.3.4 Subject Learning Style and Video Teaching Style

The Felder Index of Learning Style (ILS) was chosen as the learning style measurement because it was created to describe learning preferences in high-level engineering students. The ILS covers four elements of learning: Processing, Perception, Input, and Understanding. Each element has two end points with the ILS score describing where on the spectrum a person falls for each element. To look at the stability of the ILS score, we collected scores twice for each subject: at the first training session after completing the SpA tests and at the return evaluation session before the retraining. The ILS was collected using a paper form and the scores were calculated only after the completion of the experiment to avoid unintentional investigator bias in training or in grading the teaching style of the refresher videos.

Each refresher video was individually evaluated by a single experimenter to ascertain the teaching style. The teaching style was graded using a rubric, created to parallel the Felder ILS test, with scores ranging from -11 to 11 in each of the four learning style dimensions (Details of the teaching style rubric used are provided in Appendix A.2). We based the teaching style rubric on descriptions of the ILS dimension and recommendations for teaching to different ILS types found in the original Felder-Silverman paper [5]. We expanded the concepts to describe elements of video instructional materials, and evaluated the rubric on refresher videos made by pilot subjects. Correlations between subject ILS and refresher video scores were analyzed in SYSTAT_13.

Table 2.1: List of Quantitative Variables. *Type depends on phase

Variable Name	Abbr.	Description	Skill Type
Phase Time	$Time$	Time to complete a trial subphase	1, 2, 3*
Translational Error	$ErrT$	Offset error in position in final alignment or grappling	1, 3
Rotational Error	$ErrR$	Error in orientation in final alignment or grappling	1, 3
Failed Grapples	$FlGr$	Number of times the trigger was pulled and failed to grapple	1, 3
Travel Efficiency (Tran)	TE_T	Efficiency of the translational path taken, net / total	2, 3
Travel Efficiency (Rot.)	TE_R	Efficiency in rotational control, net rotation / total rotation	2, 3
%Bimanual Control	$\%Bi$	Percentage of flight time both hand controllers were used simultaneously	2, 3
%Multi-Axis Control	$\%MAx$	Percentage of flight time moving in more than one direction at once	2
Time Efficiency	$\%TMv$	Percentage of phase time spent moving	3, 5
THC Reversals	Rev_T	Number of times the subject reversed direction	2, 3, 4
RHC Reversals	Rev_R	Number of reversals in rotation	2, 3, 4
Collisions	Col	Number of times the arm or payload collided with an object	4
Clearance Violations	Clr	Number of times that the clearance limit flight rule was broken	3, 4
Camera Switches	$CamSw$	Number of times the camera selection was switched	1, 3
Double Cameras	$DblCam$	Number of times the same camera was assigned to multiple monitors	1,3,4
Max Switch Rate	$MxSwR$	Highest rate of camera switches per minute	3, 4
Reaction Time	RT_{avg}	Average side task reaction time	4, 5
Responses	RT_{Resp}	Number of side task responses	4, 5
Misses	RT_{Miss}	Number of side task stimuli missed	4, 5
The following metrics are adapted from Rohrer 2002, to describe smoothness			
Jerk Metric (Tran/Rot)	$SmthT_J$ $SmthR_J$	Average jerk magnitude normalized by maximum speed	2
Speed Metric (Tran/Rot)	$SmthT_S$ $SmthR_S$	Average Speed normalized by maximum speed	2, 3
Peaks Metric (Tran/Rot)	$SmthT_P$ $SmthR_P$	Number of speed peaks	2
MAPR Metric (Tran/Rot)	$SmthT_M$ $SmthR_M$	Ratio of time speed was higher than 10% maximum speed	?

Chapter 3

Results

In this chapter, I first present the results of the spatial abilities tests. Next, I review the results from the Robotic Performance Evaluations. Starting with the qualitative rubric data (explained in Section 2.3.3), I compare the difference in performance before and after the 6 month break and between the refresher video and control groups, as well as the effects of spatial ability on performance, and hierarchical regression models of subjective performance. Next, I discuss findings from the quantitative metrics: differences between evaluations and between groups, different rates of skill reacquisition, and models of the change in performance. Finally, I discuss the results from the Index of Learning Styles and the Video Teaching Style Rubric.

3.1 Spatial Abilities

There was a range in spatial ability scores across the subjects (Table 3.1). To look at how the two treatment groups were balanced in Spatial Ability, we used a two sample t-test to compare the means of the four SpA metrics, and found no difference in ability present. Comparing between genders, we noted a statistically significant difference in ability in only the PSVT score, with males performing slightly better (mean difference 8.5, p=0.024).

Table 3.1: Spatial Ability scores by group and gender

	Mean	Std D	Range	Treatment			Gender		
				Cont	Exp	p	F	M	p
Card	112.1	22.5	75	104	120.2	0.131	115.0	108.5	0.550
MRT	20.5	9.3	32	16.4	24.6	0.063	17.1	24.8	0.066
PTA	20.4	3.1	9.3	19.6	21.2	0.302	19.6	21.4	0.197
PSVT	20.9	8.6	30	20.7	21.1	0.916	17.1	25.6	0.024

3.2 Subjective Robotics Performance Data

3.2.1 Differences in Performance

The mean subjective performance results for Evaluation 1 and Evaluation 2 are broken down by category and trial type in Table 3.2. Using a two sample t-test, we found a small but significant decrease in the mean total performance across all subjects (p=0.044), as well as decreases in subcategory performance for the Astronaut Assist task (p= 0.032), the Payload Positioning task (p=0.002), and the hand controller technique (p=0.038). Performance in the Payload Positioning task also decreased within the treatment groups (control group: p=0.043; experimental group: p=0.011), and total performance decreased in the experimental group (p=0.046). Mean performance between the treatments was similar.

When comparing median performance and subcategory performance between the two treatments, using the nonparametric Mann-Whitney U test, we saw no consistent difference between groups in Evaluation 1, Evaluation 2, or in the percent change in performance between the evaluations (Figure 3-1). There was also no difference in the variance of performance between the two groups.

Looking at differences in subjective performance by gender, we saw a discrepancy in performance scores favoring males, shown in Table 3.3. However, there is no difference in the percent change in performance between genders. The 6 month layoff had a similar effect on performance for both genders.

Table 3.2: Mean subjective performance by evaluation. P-values are from two sample t-test.

		All Subjects			Control			Experimental		
Variable	Eval	Mean	Std D	p-val.	Mean	Std D	p-val.	Mean	Std D	p-val.
Total	1	82.311	8.112	0.044*	82.611	9.301	0.305	82.011	7.290	0.046*
Perf.	2	76.056	9.752		77.033	12.703		75.078	6.211	
Track &	1	59.139	8.967	0.859	60.667	9.836	0.808	57.611	8.298	0.522
Capture	2	58.611	8.715		61.833	10.177		55.389	5.872	
Astro.	1	33.444	3.552	0.032*	33.333	4.528	0.148	33.556	2.506	0.127
Assist	2	29.444	6.591		28.778	7.645		30.111	5.732	
Payload	1	37.778	3.098	0.002*	37.444	3.432	0.043*	38.111	2.892	0.011*
Position	2	32.667	5.402		31.667	6.837		33.667	3.606	
Sit.	1	71.111	3.833	0.112	70.556	4.157	0.222	71.667	3.640	0.336
Aware	2	67.944	7.215		66.444	8.604		69.444	5.615	
Task	1	66.611	12.001	0.646	68.444	11.631	0.894	64.778	12.775	0.429
Perf.	2	64.722	12.475		69.222	12.824		60.222	10.986	
Control	1	52.833	8.494	0.038*	53.222	10.244	0.270	52.444	6.930	0.053
Tech.	2	46.333	9.518		47.333	11.565		45.333	7.517	

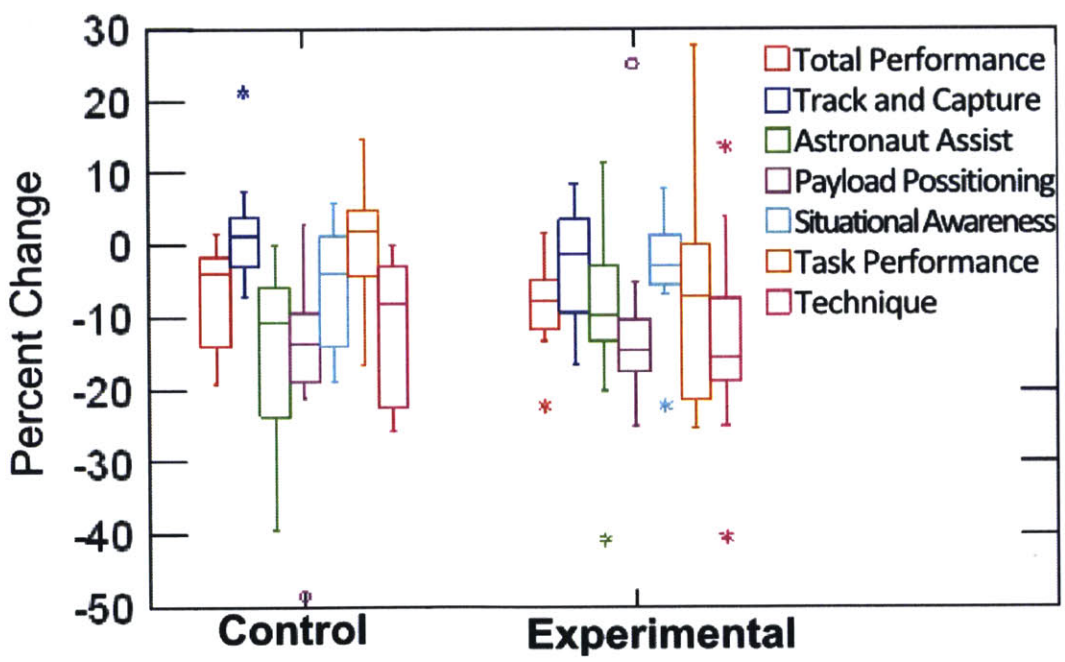


Figure 3-1: Box plots of the percent change in subjective performance split by group.

Table 3.3: Differences in subjective performance by gender. P-values are from Man-Whitney U

	Overall [p-value]	Evaluation 1	Evaluation2
Total Performance	M > F [0.002]	.	M > F [0.013]
Track and Capture	M > F [0.009]	.	.
Payload Positioning	M > F [0.046]	.	M > F [0.018]
Astronaut Assist	M > F [0.027]	M > F [0.043]	.
Situational Awareness	.	.	.
Task Performance	M > F [0.001]	.	M > F [0.009]
Controller Technique	.	.	.

3.2.2 Spatial Ability and Subjective Performance

To see if the individual components of Spatial Ability affected subjects' performance across the subcategories differently, a linear regression was fit to each subset to look at each SpA vs. Performance Type and SpA vs. Task Type (Table 3.4).

A subject's situational awareness is highly correlated to their spatial abilities, specifically the ability to mentally rotate shapes in three dimensions and the ability to change perspective (the PTA is in 2D but it is thought to be a more sensitive test than the 3D PSVT). Task specific performance is correlated with ability to mentally rotate and change perspectives, but controller technique is only affected by the ability to mentally rotate shapes in 3D. Being able to mentally plan an optimal rotation path seems to promote efficient hand controller technique.

Based on the number of correlations between SpA metrics and task performance, the more cognitively challenging a task is (TC < PP < AA) the more spatial abilities are required to achieve better performance. The AA task is correlated with MRT ($p=<0.0005$), PTA ($p=0.004$), and PSVT ($p=0.27$), but the TC task is only correlated with MRT ($p=0.034$), Table 3.4). This could indicate that subjects with higher SpA skills have a lower spatial workload and more mental faculties available to focus on good performance during these complex tasks.

To look at the effect of spatial ability on performance retention, we used simple correlations between the SpA metrics and the percent change in subjective performance

Table 3.4: Linear Regression Results Subjective Performance versus Spatial Ability. Values listed are slopes and p-values

	Total		Sit. Aw		Tsk Perf.		Tech.	
	slope	p-value	slope	p-value	slope	p-value	slope	p-value
Card	0.049	0.503	0.002	0.97	-0.013	0.89	0.135	0.060
MRT	0.637	**<0.0005**	0.289	**0.006**	0.644	**0.003**	0.412	**0.016**
PTA	1.606	**0.001**	0.956	**0.003**	1.643	**0.013**	0.785	0.14
PSVT	0.445	**0.015**	0.190	0.11	0.608	**0.01**	0.116	0.55

	TC		PP		AA	
	slope	p-value	slope	p-value	slope	p-value
Card	0.047	0.491	0.018	0.651	-005	0.918
MRT	0.336	**0.034**	0.280	**0.002**	0.347	**<0.0005**
PTA	0.746	0.127	0.851	**0.002**	0.870	**0.004**
PSVT	0.288	0.099	0.173	0.086	0.244	**0.027**

and all of the subcategories. Table 3.5.A shows the Pearson correlation coefficients for all of the subjects; there was a significant correlation between MRT and retention of AA task performance ($p<0.05$). Breaking the retention data into the treatment groups, we see there is an effect of spatial abilities (PTA and PSVT) on the control group's retention in the AA task as well ($p<0.05$) (Table3.5.B). The experimental group's task performance retention is correlated PSVT ($p<0.05$) (Table3.5.C).

3.2.3 Modeling Subjective Performance

Two mixed hierarchical regression models were fit to the subjective performance scores. Because the MRT score was highly correlated with all the facets of performance, it was chosen as an initial variable for modeling performance. Model 1 incorporates evaluation and treatment as categorical variables and MRT score as continuous and is shown in Table 3.6. In Model 1, the effect of MRT score is significant with a slope of 0.837, ($p <0.0005$). The range in MRT scores was 2-34 points, which would correspond to a difference of 28 performance points. The effect of Evaluation number is also significant ($p <0.0005$), with Eval 1 having approximately 6 point better score than Eval 2. The Control Group had an estimate of 8 points higher

Table 3.5: Correlations between spatial ability metrics and retention in subjective performance. For all subjects, N=18, a correlation coefficient of 0.40 corresponds to $\alpha < 0.05$ (A). For the control (B) and experimental groups (C), N=9, and a r of 0.582 corresponds to $\alpha < 0.05$.

A)	Δ%Tot.	Δ%TC	Δ%AA	Δ%PP	Δ%Sit.Aw	Δ%Tsk Perf.	Δ%Tech
Card	-0.178	-0.352	0.020	0.097	0.103	-0.289	-0.048
MRT	0.104	-0.380	**0.440**	0.347	0.208	-0.139	0.004
PTA	0.343	0.030	0.346	0.397	0.363	0.236	-0.029
PSVT	0.326	0.043	0.281	0.317	0.318	0.336	-0.180

B)	Δ%Tot.	Δ%TC	Δ%AA	Δ%PP	Δ%Sit.Aw	Δ%Tsk Perf.	Δ%Tech
Card	-0.387	-0.572	-0.324	-0.036	-0.133	-0.547	-0.229
MRT	0.322	-0.322	0.550	0.494	0.166	0.046	0.054
PTA	0.514	0.130	**0.608**	0.356	0.467	0.309	0.233
PSVT	0.432	-0.040	**0.604**	0.354	0.553	-0.198	0.074

C)	Δ%Tot.	Δ%TC	Δ%AA	Δ%PP	Δ%Sit.Aw	Δ%Tsk Perf.	Δ%Tech
Card	0.025	-0.048	0.167	0.083	0.176	-0.083	0.068
MRT	-0.051	-0.255	0.263	0.084	0.116	-0.090	0.005
PTA	0.173	0.105	-0.090	0.408	0.141	0.404	-0.275
PSVT	0.232	0.134	-0.002	0.287	0.105	**0.641**	-0.333

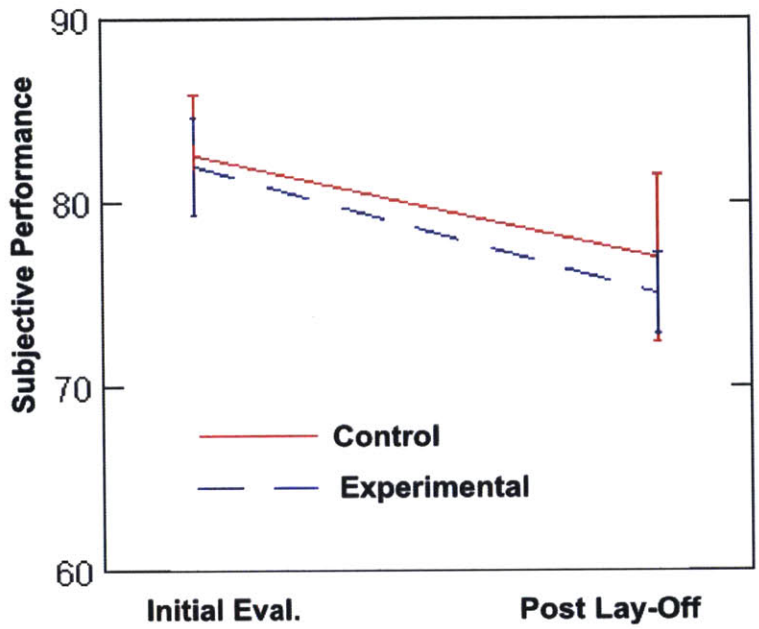


Figure 3-2: Treatment group subjective performance change over the layoff

Table 3.6: Subjective Performance Model 1

Variable	Estimate	Std Error	Z	p-Value
Intercept	62.021	3.015	20.574	0.000
MRT Score	0.837	0.137	6.121	0.000
Evaluation	3.128	0.655	4.778	0.000
Treatment	4.034	1.238	3.259	0.001

than the Experimental group ($p = 0.001$).

The second model calculated the effect of the PTA instead of the MRT (Table 3.7). The effect of PTA has a slope of 1.781 and PTA scores range from 15.6 to 24.9, which corresponds to an additional 28 to 44 performance points ($p = 0.001$). The effect of evaluation is the same as in the first model, but the effect of treatment group was lost in this model. Spatial abilities (MRT and PTA) had a large correlation with performance, whereas the treatment group did not.

The residuals for both models were normal and homoscedastic. I was not able to find a reliable model that included a significant cross effect of Group and Evaluation (Figure 3-2).

Table 3.7: Subjective Performance Model 2

Variable	Estimate	Std Error	Z	p-Value
Intercept	42.866	10.867	3.944	0.000
Treatment	2.014	1.573	1.280	0.201
Evaluation	3.128	0.655	4.778	0.000
PTA Score	1.781	0.528	3.375	0.001

3.3 Quantitative Robotics Performance Data

Twenty-seven metrics were analyzed across the separate trial types. A list and description of the metrics, as well as to which skill type they belong, can be seen in Table 2.1. Each trial type had several different subsets. Track and Capture trials rotated in one of three directions, Astronaut Assist had 4 distinct phases of flight, and Payload Positioning had 6 distinct phases of flight. The different phases can be seen in Table 1.1.

The only metric that can be used across task type is the side task reaction time. In order to see how the cognitive workload varied across task type, we compared average reaction times of the three task types during the first evaluation, see Figure 3-3. Theoretically, the subjects should be at their highest performance level during Eval 1, therefore differences in workload between task types would be due to the cognitive of the tasks type, and not by potential forgetting. Two sample KS tests show that there is a statistical difference between TC and PP ($p<0.005$) and between TC and AA ($p<0.005$), but there is no statistical difference between AA and PP ($p=0.818$). This shows that the TC task theoretically requires less mental workload than the PP and AA tasks.

We were interested in how treatment group and layoff affected the metrics across the different task types. Because the data set is so highly dimensioned, regression analysis or ANOVAs were impractical. For purposes of exploratory data analysis, we adopted the following strategies to assess which quantitative metrics were most strongly affected: comparing pre- and post-layoff to see the direction of change, comparing difference in retention between treatments and genders, and comparing speed

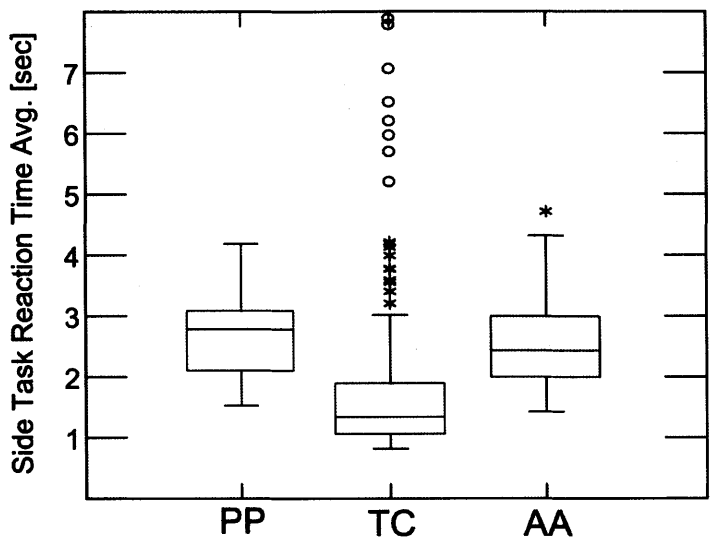


Figure 3-3: Box plot shows the distribution of reaction times for the different task types. A lower reaction time is indicative of a lower mental workload.

of reacquisition between treatments. To analyze all metrics in the same manner, non-parametric tests were used, as some of the metrics were non-normally distributed. Only statistically significant results will be shown here. Results for all of the metrics can be found in Appendix B.

3.3.1 Changes in Quantitative Performance

Track and Capture Task

The direction of change from pre- to post-layoff performance for the Track and Captures broken down by spin type can be seen in Table 3.8, as calculated using a Wilcoxon Signed-Rank test. Overall, there is a decrease in percent bimanual control after the break, and an increase in translational smoothness (Jerk Metric). There is no clear differences between the metric changes seen in the two treatment groups.

To make the directional results more understandable, the number of performance changes in all the rotation types were pooled by the skill type they describe, see Table 2.1 for assignments. The net direction of performance change for the skill types is shown in Figure 3-4. A negative result means more metrics showed a decrease in performance than an increase. There are more familiarity metrics that decreased

Table 3.8: Change in metric performance from Evaluation 1 to Evaluation 2 in the Track and Capture Task (Wilcoxon Signed-Rank test). Metrics are ordered by ascending p-value, italics denote p <0.0005.

		Overall	Control Group	Experimental Group
All	↑	*$SmthT_J$*, *$SmthR_{S,P}$*, Rev_T	*$SmthR_{S,P}$*, $SmthT_J$, Rev_T	*$SmthT_J$*, $SmthR_P$
	↓	*Time, %Bi, $SmthR_M$*, ErrR	*%MAx, Time, %Bi, $SmthR_M$*, RT_{avg}, RT_{Miss}	*%Biman*, %MAx, $SmthR_M$, ErrR
No Spin	↑	$SmthT_J$, FlGr	$SmthT_J$	FlGr, $SmthT_J$, $SmthR_P$
	↓	%Bi, $SmthR_{M,P}$ Time	Time, %Bi	$SmthR_M$, %Bi
Yaw	↑	*$SmthT_J$*, Rev_T	$SmthT_J$, Rev_T	$SmthT_J$
	↓	*%Bi, $SmthR_M$*, Time	*$SmthR_M$*,%Bi, Time, RT_{avg}	$SmthR_M$, %Bi
Pitch	↑	- - -	$SmthT_P$, $SmthR_{S,P}$	$SmthT_J$
	↓	*%Bi*, $SmthR_P$, Time, RT_{avg}	*Time*, %Bi, RT_{Miss}, $SmthR_M$,RT_{avg}	- - -

over the break than increased across all subjects and within both treatment groups. The muscle memory[1] metrics showed an opposite effect; more increasing metrics over the break than decreasing metrics across both treatment groups. The situational awareness and cognitive workload metrics do not have a clear trend; neither of them changed in the experimental group, but there was a net increase in the control group. It seems that the muscle memory is better retained than familiarity with the simulator for the TC trials.

Astronaut Assist Task

Few quantitative metrics had a significant trend in performance change over the break (Table 3.9), which is intriguing given the decrease seen in the subjective AA scores. Of note, we saw an overall increase in the number of double camera selections when initializing the simulator p=0.027), as well as a decrease in time efficiency and increase in rotational smoothness in the fly-to phase (p=0.025 in the Speed metric and 0.038

[1]In this thesis muscle memory describes the ability to manually control the robotic arm automatically, in a coordinated manor, without needing to think through the motions.

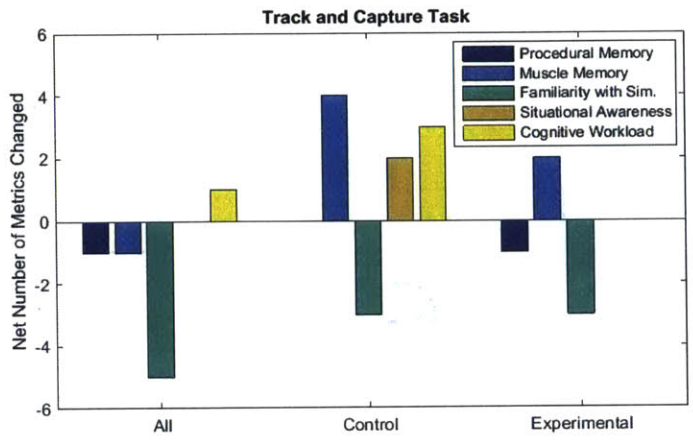


Figure 3-4: Net number of performance metrics that changed in TC trials, broken down by performance type

Table 3.9: Direction of change in performance from Evaluation 1 to Evaluation2 in the Astronaut Assist Task split by the phase type. The numbers listed are p-values

		Overall	Control Group	Experimental Group
Plan	↑	Double Cam.: 0.027	- - -	- - -
Fly-to	↑	SmthR$_S$:0.025, SmthR$_P$:0.038	SmthR$_S$:0.010	SmthR$_P$:0.042
Phase	↓	%TMv:0.040	- - -	%MAx:0.031, %Bi:0.050
Align	↑	- - -	- - -	- - -
Phase	↓	- - -	- - -	- - -
Repair	↑	- - -	- - -	- - -
Pase	↓	SmthR$_P$:0.014	- - -	SmthR$_P$:0.044)

in the Peak metric). Rotational smoothness decreased in the repair phase, which is odd, as all repairs were translational only. The correlation of the smoothness metrics and performance is not well understood yet.

The experimental treatment group shows additional changes in the percent of multi-axis movement and percent of bimanual control that is not present in the control group or in the overall data (p = 0.031 and 0.050 respectively).

Figure 3-5 shows the net directional results of all phases pooled by skill type, see Table 2.1. In the AA task, the familiarity and cognitive workload categories have more metrics with decreasing performance overall, there is no net change in

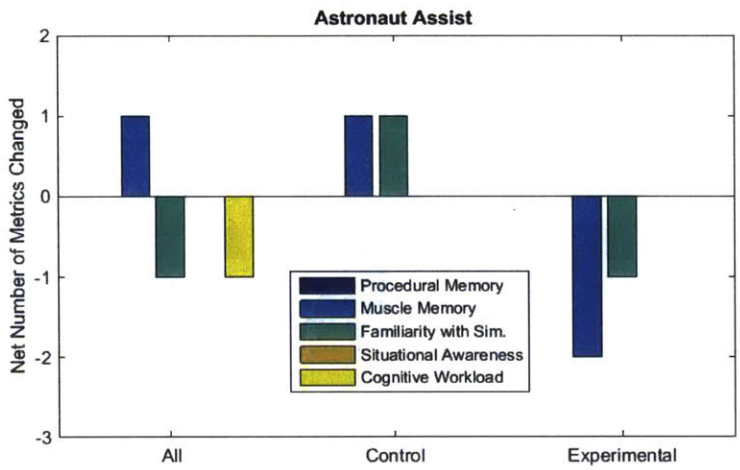


Figure 3-5: Net number of performance metrics that changed in AA trials, broken down by skill type

procedural memory metrics, and muscle memory metrics had a net increase overall and in the control group, but a net decrease in the experimental group. In this task type, the net directional results were very small: ± 1 metric for all skill types except experimental muscle memory (-2 metrics).

Payload Positioning Task

The Payload Positioning task had an overall decrease in movement performance during the fly-to phase, seen in the increase in translational reversals (p=0.002), and decrease in both rotational and translational travel efficiency (p=0.040 and 0.009 respectively), Table 3.10. Movement decrements were also seen in both treatment groups, though the translational efficiency was only significant in the experimental treatment (p=0.028), and the rotational efficiency was only significant in the control treatment (p=0.036).

The grapple phase saw an overall decrease in translational smoothness, depicted by an increase in speed peaks (p=0.019), and a decrease in the time efficiency (p=0.046). The control group did not have any significant trend, but the experimental group had an increase in side task misses (p=0.027) and an increase in speed peaks (p=0.020).

In the final alignment phase, there was an overall increase in the rotational place-

Table 3.10: Direction of metric change from Evaluation 1 to Evaluation 2 in the Payload Positioning Task split by phase. The numbers displayed are p-values

		Overall	Control	Experimental
Plan		- - -	- - -	- - -
Fly-to Phase	↑	Rev_T:0.002	Rev_T:0.046	Rev_T:0.019
	↓	TE_T:0.009 TE_R:0.040	TE_R:0.036	TE_T:0.028
Grapple Phase	↑	- - -	- - -	RT_{Miss}:0.027
	↓	$SmthT_P$:0.019, TMv:0.046	- - -	$SmthT_P$:0.020
Plan		- - -	- - -	- - -
Loaded Fly-to	↑	$SmthT_J$:0.042	- - -	- - -
	↓	- - -	- - -	- - -
Align Phase	↑	ErrR:0.018, $SmthT_J$:0.017, RT_{Miss}0.025	$SmthT_J$:0.001	ErrorR:0.031, RT_{Miss}:0.044
	↓	- - -	- - -	$SmthR_M$:0.015

ment error (p=0.018), missed side tasks (p=0.025), and translational smoothness (Jerk metric p=0.017). The increase in translational smoothness was also significant in the control group (p=0.001). The increase in rotational error and side task misses was significant in the experimental group (p=0.031 and p=0.044 respectively).

In the Payload Positioning task, the experimental treatment group had significant performance decrements that were not present in the control group. Figure 3-6 displays the net direction of change of the quantitative metrics split by performance type. There is a net decrease in all performance types overall, with familiarity metrics having the largest net decrease.

3.3.2 Difference in Retention between Treatments

Using the nonparametric Mann-Whitney U test, the change and percent change across the lay off period for each metric were compared between the two treatments groups to see if there was a significant difference in the performance retention cause by treatment. The Mann-Whitney U test evaluates whether or not two samples come from the same population. Table 3.11 shows a summary of the statistically significant

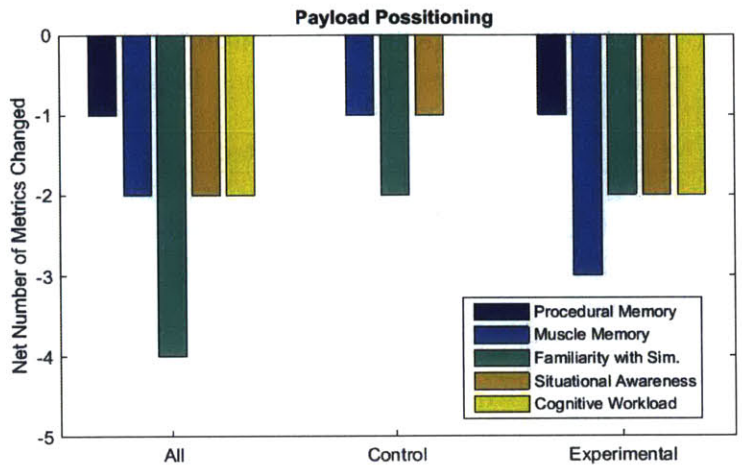


Figure 3-6: Net number of performance metrics that changed in PP trials, by skill type

differences in performance change between the control and experimental treatment groups, broken down by task type. The control group had better retention than the experimental group in the Track and Capture tasks for three of the metrics. In the Astronaut Assist task, the control group had a better retention of manual control skills (percent multiaxis movement and rotational smoothness) than the experimental group during the fly-to phase of the trials. The experimental treatment group had better retention of the side task reaction time throughout the Astronaut Assist task, which indicates retaining a low cognitive workload. In the grapple phase of the Payload Positioning task, the control group had a lower increase in missed side-tasks. During loaded flight, two rotational smoothness metrics showed the control group having better retention. Finally, during the alignment phase, the experimental group exhibited better retention of translation smoothness (jerk metric) and better retention in side task reaction time.

Although the control group had better control skill retention during the Astronaut Assist fly-to phase, the experimental group showed a higher level of cognitive retention, denoted by the better change in reaction time, during the entire Astronaut Assist test. Figure 3-7 shows the side task reaction times for every subject by evaluation. The mean change in reaction time for the experimental group was -0.353

Table 3.11: Differences in skill retention between treatment groups split by trial type

Metric Name	Mean Percent Change		p-value	Better Retention
	Cont	Exp		
Track and Capture				
$SmthT_P$	+3.0%	+12.7%	0.016	Control
RT_{Miss}	-6.5%	+26%	<0.0005	Control
Time	-10.5%	+0.8%	0.021	Control
AA: Fly-to				
%MAx	+1.3%	-0.2%	0.018	Control
$SmthR_S$	+22.1%	-5.5%	0.008	Control
$SmthR_J$	+5.9%	-17.2%	0.031	Control
AA: Entire Task				
RT_{avg}	+52.6%	+4.3%	0.025	Experimental
PP: Grapple				
RT_{Miss}	+7.6%	+85.2%	0.015	Control
PP: Loaded Flight				
$SmthR_S$	+106.1%	+74.4%	0.021	Control
$SmthR_J$	+158.3%	+113.5%	0.025	Control
PP :Align				
$SmthT_J$	+70.9%	+129.0%	0.002	Experimental
RT_{avg}	+57.9%	-22.1%	0.037	Experimental

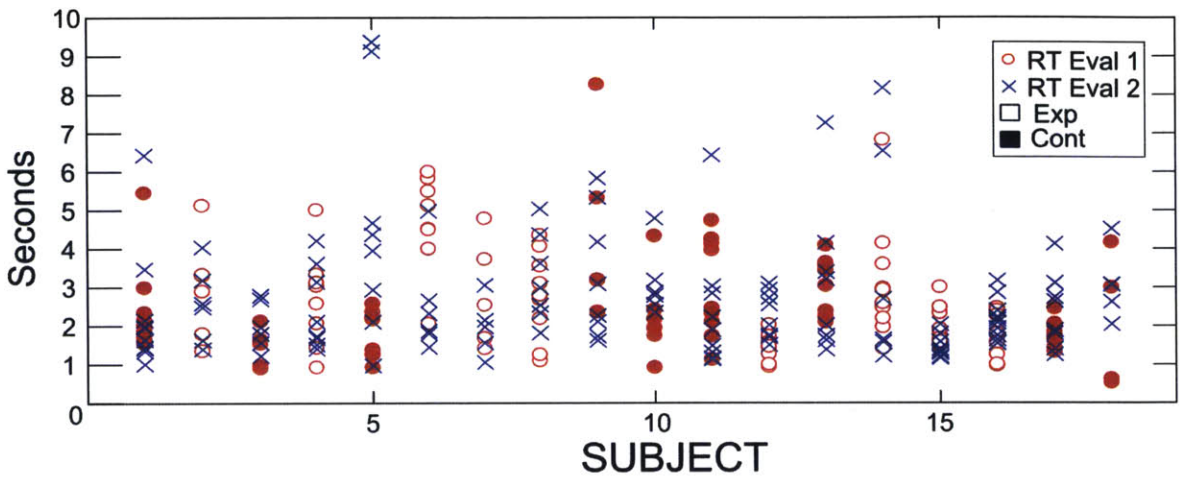


Figure 3-7: Average side task reaction time for each AA phase in Evaluation 1 (○) and Evaluation 2 (×). The subjects with filled circles were in the control group, and open circles had the experimental treatment

seconds and the control was +0.245 seconds. Figure 3-8 shows the distribution of the change in reaction time by group. A lower reaction time is indicative of lower workload. A Kolmogorov-Smirnov test shows that the changes in reaction time in the control and experimental group are derived from separate populations ($p = 0.032$). This suggests that the customized refresher videos did assist in AA task retention.

3.3.3 Differences in Skill Reacquisition Rate

We hypothesized that customized refresher training might enable the experimental subjects to return to their previous performance level more quickly than the control. To test this, we looked at the difference in the quantitative performance metrics between the groups broken down by trial and phase to get finer time resolution (using a nonparametric Mann-Whitney U test to test for significant differences). The evaluation order was 6 Track and Capture tasks, then 1 Astronaut Assist task, 1 Payload Positioning task with 2 targets, 6 more Track and Capture tasks, and 1 final Astronaut Assist task.

During the first Track and Capture task, the control group had a significantly larger decrease in rotational travel efficiency ($p=0.026$). In the first quarter of Track and Capture tasks, the control group had a significantly higher percent change in

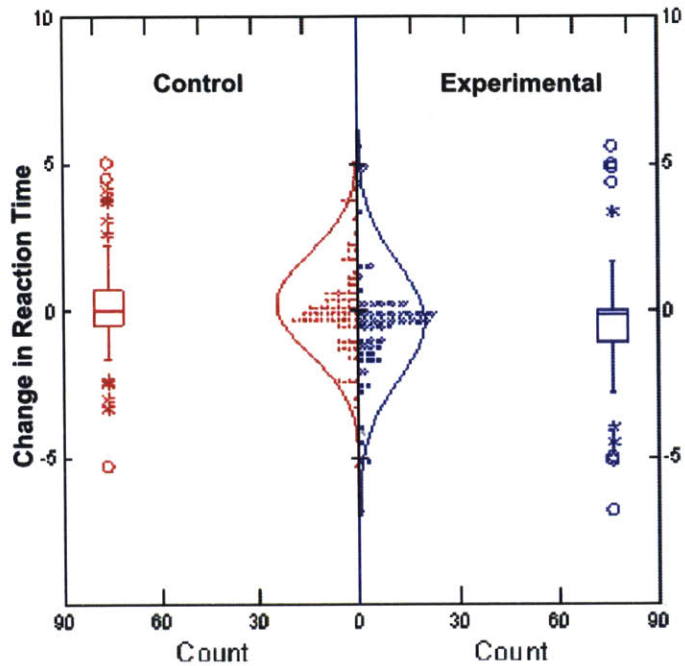


Figure 3-8: Distribution of changes in side task reaction time over the 6 month break. The left side is the control group and the right side is the experimental group. A positive change in reaction time shows worsened performance.

plan time (p=0.034). Both of these results point to marginally better performance by the experimental group. However, in the first half of Track and Capture tasks, the experimental group had a worse percent change in task time (p=0.022). Given the low number of significant variables or a consistent trend, it seems there was no difference in reacquisition speed in the TC task.

In the Astronaut Assist task, multiple performance metrics show the experimental group retained better arm control in the first trial than the control group (Table 3.12). The experimental group also retained alignment accuracy better than the control. During the second trial, there was no significant difference between the two groups, implying that the control group's performance may have caught up to the experimental group by the second trial.

The Payload Positioning task had no clear trend in the differences between the groups (Table 3.13). The control group seems to have better retention during the first trial: having less speed peaks (Rot) in the fly-to, less side task lapses during grapple, and greater travel efficiency (Rot) in the alignment phase. In the second trial, the

Table 3.12: Change between groups in the Astronaut Assist task split by phase and trial to see differences in skill reacquisition. P-values are listed for either the difference (d) or percent change (p). Bold indicate metrics where retention is better in the experimental treatment than the control. Experimental retention is higher in the earlier phases. Plan phases showed no differences. *Smoothness metrics may indicate differences in strategies rather than performance

Trial	Phase	Control No Change	Experimental ↓ Avg RT	Difference
T1	P2 Fly-to	- - -	- - -	ΔRev_T **Cnt>Exp** [d:0.047]
T1	P3 Align	- - -	- - -	$\Delta\%MAx$ **Exp>Cnt** [d:0.039]
T1	P4 Repair	↑ RT_{Avg} [0.028]	- - -	ΔTE_R **Exp>Cnt** [d:0.010;p:0.010]
T1	P6 Fly-to	- - -	- - -	Δ $SmthR_M$ Cnt>Exp* [d:0.039; p:0.005] $\Delta SmthR_P$ **Cnt>Exp** [d:0.045;p:0.020]
T1	P7 Align	- - -	↓ RT_{Resp} [0.027]	$\Delta ErrT$ **Cnt>Exp** [d:0.040] Δ $SmthT_M$ Exp>Cnt* [d:0.019]
T2	P2 Fly-to	- - -	- - -	ΔTE_T **Exp>Cnt** [d:0.031; p:0.031]
T2	P3 Align	- - -	- - -	- - -
T2	P4 Repair	- - -	↑ RT_{Miss} [0.041]	$\Delta SmthR_J$ Cnt>Exp [d:0.048]
T2	P6 Fly-to	↓ RT_{Miss} [0.034]	- - -	- - -
T2	P7 Align	- - -	- - -	- - -

Table 3.13: Change between groups in the Payload Positioning task split by phase and trial to investigate differences in skill reacquisition. P-values are listed for either the difference (d) or percent change (p) in the metric. Italics indicate metrics where retention is better in the experimental treatment than the control. * Smoothness metrics may indicate differences in strategies rather than performance

Trial	Phase	Control No Change	Experimental ↓ Avg RT	Difference
T1	P2 Fly-to	- - -	- - -	$\Delta SmthR_P$ Exp>Cnt [d:0.050; p:0.041]
T1	P3 Grapple	- - -	- - -	ΔRT_{Miss} Exp>Cnt [d:0.020; p:0.020] ΔRT_{Resp} Cnt>Exp [p:0.024]
T1	P5	- - -	- - -	- - -
T1	P6 Align	- - -	- - -	ΔTE_R Cnt>Exp [p:0.037] $\Delta SmthT_J$ Cnt>Exp* [d:0.047; p:0.047]
T2	P2 Fly-to	- - -	- - -	$\Delta SmthR_S$ Cnt>Exp* [d:0.021; p:0.021] ΔRev_R **Cnt>Exp** [d:0.025; p:0.039]
T2	P3 Grapple	- - -	- - -	$\Delta SmthR_M$Cnt>Exp* [p:0.007]
T2	P5	- -	- - -	- - -
T2	P6 Align	- - -	- - -	ΔRT_{Avg} **Cnt>Exp** [d:0.034; p:0.014] $\Delta SmthT_J$ Cnt>Exp* [d:0.043; p:0.027]

experimental group had a lower change in rotational reversals during the fly-to phase and a better side task response time retention during the align phase. This does not support the idea of faster reacquisition. Since the Payload Positioning tasks were located in the middle of the evaluation, any performance boost from the customized refresher training probably occurred earlier and the control group's performance may have caught up by this point in the evaluation.

Table 3.14: Model 1 - Change in Rotational Travel Efficiency, PP task

Variable	Estimate	Standard Error	Z	p-value
Intercept	-0.727	0.264	-2.753	0.006
PTA	0.031	0.013	2.424	0.015

3.3.4 Modeling Quantitative Performance

We were able to successfully fit mixed hierarchical regression models in two trial types: the Payload Positioning task, and the Astronaut Assist task, but not for the Track and Capture task. The models presented had normal, homoscedastic residuals. Models were attempted for all metrics, but few had significance (see Appendix B for failed models).

Payload Positioning Task Models

We created models for four of metrics for the PP task: change in rotational travel efficiency, change in percent of bimanual control, change in percent multi-axis movement, and change in time efficiency. Other models were created, but the residuals were either non-normal or heteroscedastic.

The first model estimates the effect of Perspective Taking Ability score on the change in Rotational Travel Efficiency (TE_{rot}) Table 3.14. The model predicts that higher a PTA score leads to higher retention or even increase in PP task Travel Efficiency, by 3% per point, Equation 3.1. It is logical that Rotational Travel Efficiency be dependent on Spatial Ability, as being able to mentally visualize the rotation axes is much more efficient than guessing then reversing direction, though interesting that it did not show dependency on any other SpA metrics.

$$\Delta TE_{rot} = -0.727 + 0.031 * PTA \tag{3.1}$$

We were able to fit two models to the change in the percentage of time subjects used bimanual control ($\%Bi$). The first $\%Bi$ model looks at the type of video game subjects identified playing and how often they have played games during the lay-off

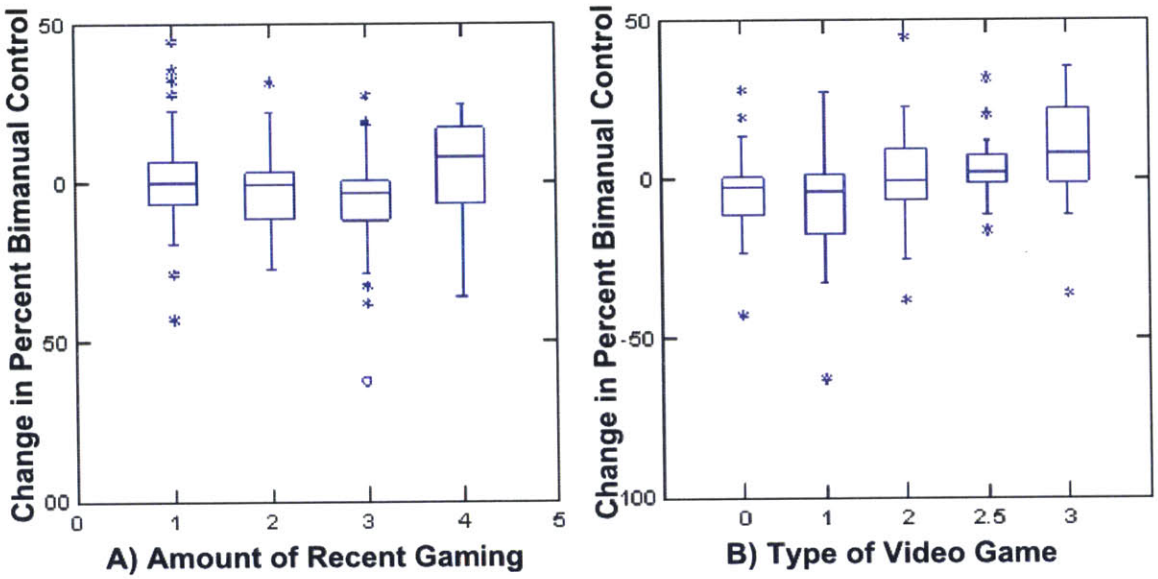


Figure 3-9: Change in Percent Bimanual Control as a function of A) Self-reported Gaming Frequency, B) Type of video game played. It is interesting to note that no subject reported a 5 in gaming frequency (playing all the time), and the effect looks non-linear.

period (Table 3.15. The experimenter classified the game types based on the spatial visualization and point of view characteristics of the game (0-No PoV or Characterless; 1-First Person PoV; 2-Third person 2D; 3-Third person 3D, subjects assigned 2.5 reported playing both type 2 and 3 games). Results of the first model indicated subjects who played video games that require little to no spatial visualization had a greater decrease in the amount of bimanual control, about 7 percentage points less than the mean change, whereas the subjects who played video games that required the most spatial skills had almost 10 $\Delta\%Bi$ points more than the mean. The model also takes into account the amount of video games played recently (self-reported on a scale of 1-5), but the effect is smaller, only about -3 percentage points, and could be non-linear (see Figure 3-9). Applying the Bonferroni post hoc correction, Game Type 1 becomes insignificant, but type 0 and 3 are still significant ($p < 0.01$ is significant).

The second $\Delta\%Bi$ model includes MRT score as a predictor instead of recent gaming, but shows the same trend in game type as the previous model, though game type 0 is no longer statistically different (Table 3.16). There is an inverse relationship with MRT score and $\%Bi$ retention. Though the effect is only half a percentage point

Table 3.15: Model 2 - Change in Percent Bimanual Control

Variable	Estimate	Standard Error	Z	p-Value
Intercept	7.360	3.303	2.229	0.026
GameType 0	-7.271	2.545	-2.858	0.004
GameType 1	-5.973	2.411	-2.478	0.013
GameType 2	2.263	2.478	0.913	0.361
GameType 2.5	1.338	3.247	0.412	0.680
GameType 3	9.644	3.275	2.945	0.003
Recent Gaming	-3.649	1.539	-2.370	0.018

Table 3.16: Model 3 - Change in Percent Bimanual Control

Variable	Estimate	Standard Error	Z	p-Value
INTERCEPT	8.821	3.457	2.552	0.011
MRT Score	-0.419	0.155	-2.699	0.007
Game Type 0	-3.475	2.270	-1.531	0.126
Game Type 1	-6.357	2.344	-2.712	0.007
Game Type 2	-2.276	2.732	-0.833	0.405
Game Type 2.5	3.202	3.136	1.021	0.307
Game Type 3	8.906	3.169	2.810	0.005

per MRT point, the MRT scores range from 2-34, which would correspond to a 15 percentage point decrease.

The fourth model predicts change in percent of multi-axis movement (Table 3.17). This model did not have a significant effect of game type, but it did have a significant effect of recent gaming (p=0.045). The more gaming, the more decrement to multi-axis movement, with a slope estimate of approximately 5. This variable only proved significant when modeled with another, insignificant variable.

The final model is the change in time efficiency, or the percent of trial time spent moving (Table 3.18). In this model we see that the games with a third person point of view in two dimensions (Type 2) had a significantly larger decrease in time efficiency than the mean, by about 7 percentage points. The mechanism for this is unclear, but it could lie in the game play mechanics. Applying a Bonferroni correction, the model becomes insignificant ($p < 0.01$ is significant).

Table 3.17: Model 4 - Change in Percent Multi-Axis Movement

Variable	Estimate	Standard Error	Z	p-Value
Intercept	8.719	5.598	1.557	0.119
Game Type 0	-6.567	4.314	-1.522	0.128
Game Type 1	-0.613	4.082	-0.150	0.881
Game Type 2	1.756	4.201	0.418	0.676
Game Type 2.5	-1.207	5.504	-0.219	0.826
Game Type 3	6.631	5.554	1.194	0.232
Recent Gaming	-5.221	2.609	-2.001	0.045

Table 3.18: Model 5 - Change in Percent Time Moving

Variable	Estimate	Standard Error	Z	p-Value
Intercept	3.185	3.778	0.843	0.399
MRT	-0.185	0.170	-1.089	0.276
Game Type 0	-2.622	2.481	-1.057	0.291
Game Type 1	-2.896	2.562	-1.130	0.258
Game Type 2	-7.290	2.986	-2.441	0.015
Game Type 2.5	6.347	3.428	1.852	0.064
Game Type 3	6.461	3.464	1.865	0.062

Table 3.19: AA Model 1 - Change in Translational Travel Efficiency

Variable	Estimate	Std Error	Z	p-value
Intercept	-0.290	0.108	-2.679	0.007
Sleep	0.072	0.030	2.438	0.015

Table 3.20: AA Model 2 - Change in Percent MultiAxis Movment

Variable	Estimate	Std Error	Z	p-value
Intercept	23.540	10.353	2.274	0.023
Sleep	-3.730	1.588	-2.349	0.019

Astronaut Assist Task Models

For the Astronaut Assist task, we were able to create models which predicted the change in two metrics: Translational Travel Efficiency and Percent MultiAxis Movement. No other metrics could be successfully fit to a model with normal and homoscedastic residuals.

The first AA performance change model predicts the retention of the translational travel efficiency, Table 3.19. This model is based on the amount of sleep that the subject received the night before the return evaluation. The more sleep, the better they performed, with an estimated benefit of 0.07 per hour of sleep (p=0.015). In this experiment, subjects reported sleep ranging from 2 to 8 hours, which would correspond to a ΔTE_T of -0.146 to +0.286.

The second AA model predicts the change in percent multiaxis control, Table 3.20. Here additional sleep is detrimental to retention (p=0.019), though the effect size is smaller than in the previous model, -3.7 percentage points. The range in hours of sleep would equate to a range of -22.2 percentage points.

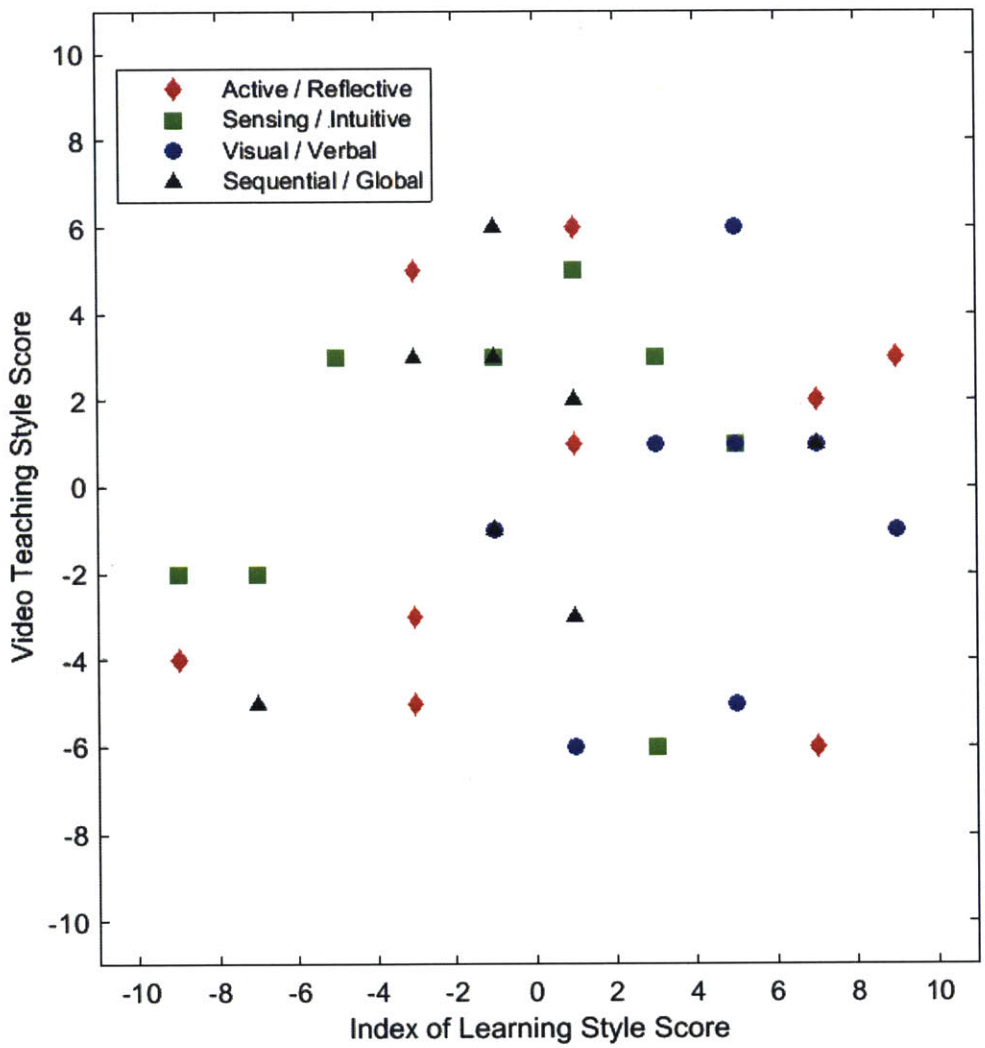


Figure 3-10: Experimental subject's ILS component scores versus the corresponding teaching style components assessed in their customized refresher video.

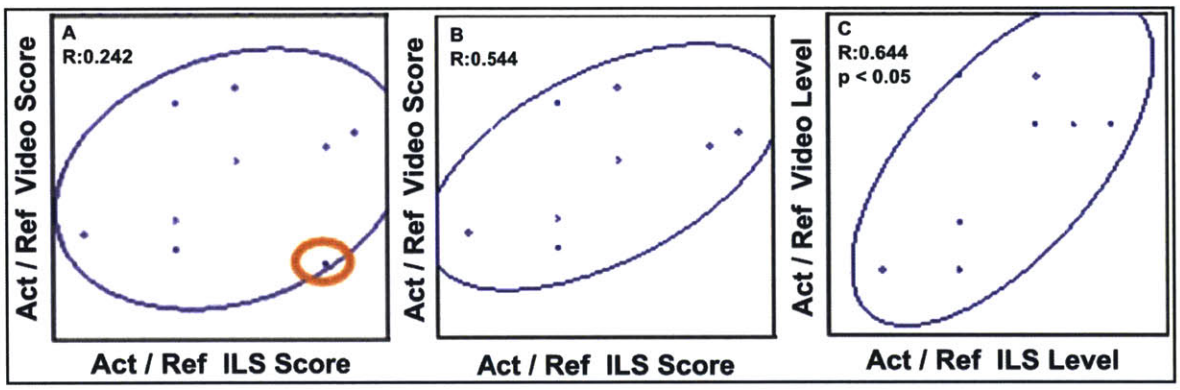


Figure 3-11: Correlation between the Processing (Active (+) / Reflective (-)) dimension video score and the ILS score. A) Raw correlation. B) Correlation with outlier removed. C) Correlation of coarse dimension scores.

3.4 Matching Hypothesis: Video Teaching Style and Index of Learning Style

The Index of Learning Style and the evaluated Teaching Style of the refresher training videos for the 9 subjects in the experimental group is shown in Figure 3-10. To look for correlations between the teaching style and learning style, we tested for positive correlations (H0: Correlation =0, H1: Correlation >0). In the Processing dimension of the ILS (Active - Reflective), there is no correlation in the data (Figure 3-11.a). However, one data point can be considered a significant outlier: the subject was very uncomfortable being filmed and, therefore, created a video which scored as reflective on the teaching style rubric even though the subject was an active learner. Removing that point from the data-set, (Figure 3-11.b) there is still no significant correlation. The Felder-Silverman ILS is often reported on a coarse, 6-level scale of balanced, moderate, or strong for either learning preference. Applying the coarse scale to the Act/Ref video scores (Figure 3-11.c), there is a significant correlation (Correlation Coefficient:0.644; $p = 0.042$).

The Perception dimension (Sensing / Intuitive), is shown in Figure 3-12. Again, there was no correlation between the video teaching style and ILS score. There were 2 obvious outliers: one was the same outlier from before and the other was first one to create a video, potentially before the experiment procedure was settled. By removing

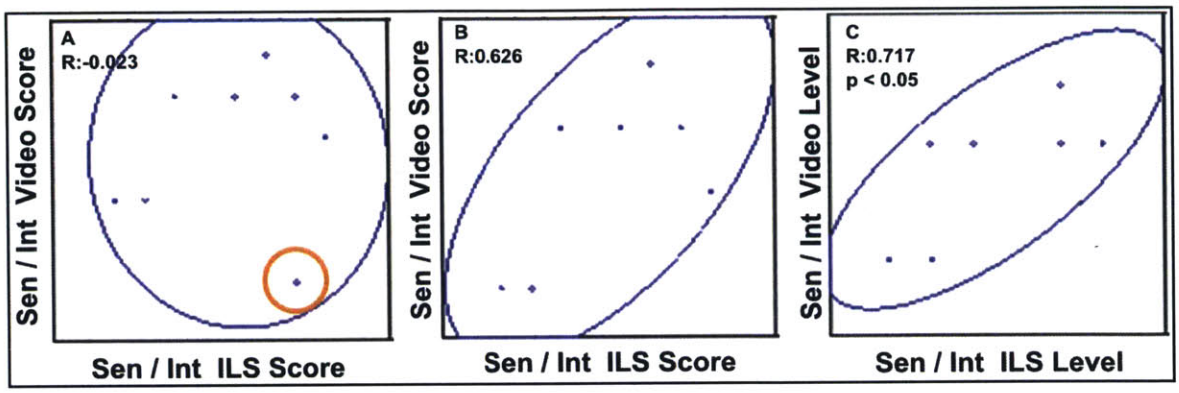


Figure 3-12: Correlation between the Perception (Sensing (+) / Intuitive(-)) dimension video score and the ILS score. A) Raw correlation, orange circle shows the two outliers (had the same data). B) Correlation with outliers removed. C) Correlation of coarse dimension scores.

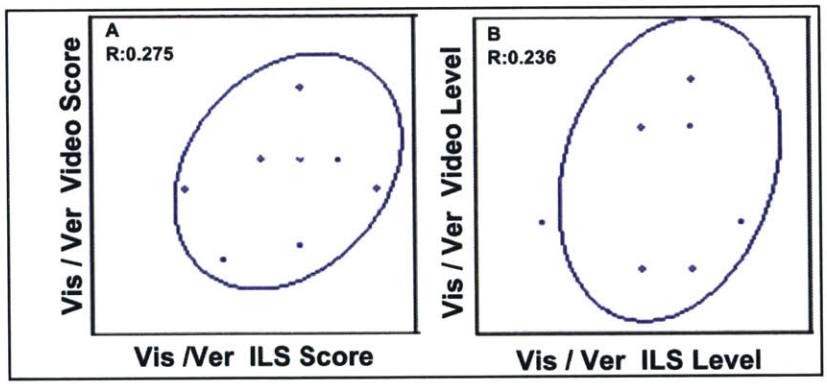


Figure 3-13: Correlation between the Input (Visual (+) / Verbal(-)) dimension video score and the ILS score. A) Raw correlation. B) Correlation of coarse dimension scores.

the outliers and looking at the coarse grading scale, we saw a significant correlation in the Sensing / Intuitive dimension (Correlation Coefficient: 0.717; p=0.035).

The Input and Understanding dimensions (Visual / Verbal, and Sequential / Global, respectively) are shown in Figure 3-13 and Figure 3-14. In these dimensions, there is no obvious correlation present in the fine or coarse grading scales.

Comparing the video teaching style dimensions to each other on the fine scale, we noted a significant correlation between the Input and the Perception dimensions (Pearson R:0.704; $p<0.025$) and an inverse correlation with the Processing and Understanding dimensions (Pearson R:-0.729; $p<0.025$), Figure 3-15. Neither of these correlations are present in the ILS survey data of the subjects (Figure 3-16).

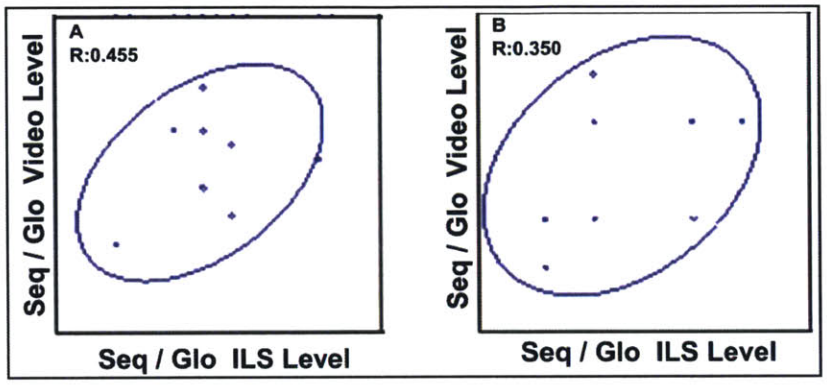


Figure 3-14: Correlation between the Understanding (Sequential (+) / Global (-)) dimension video score and the ILS score. A) Raw correlation. B) Correlation of coarse dimension scores.

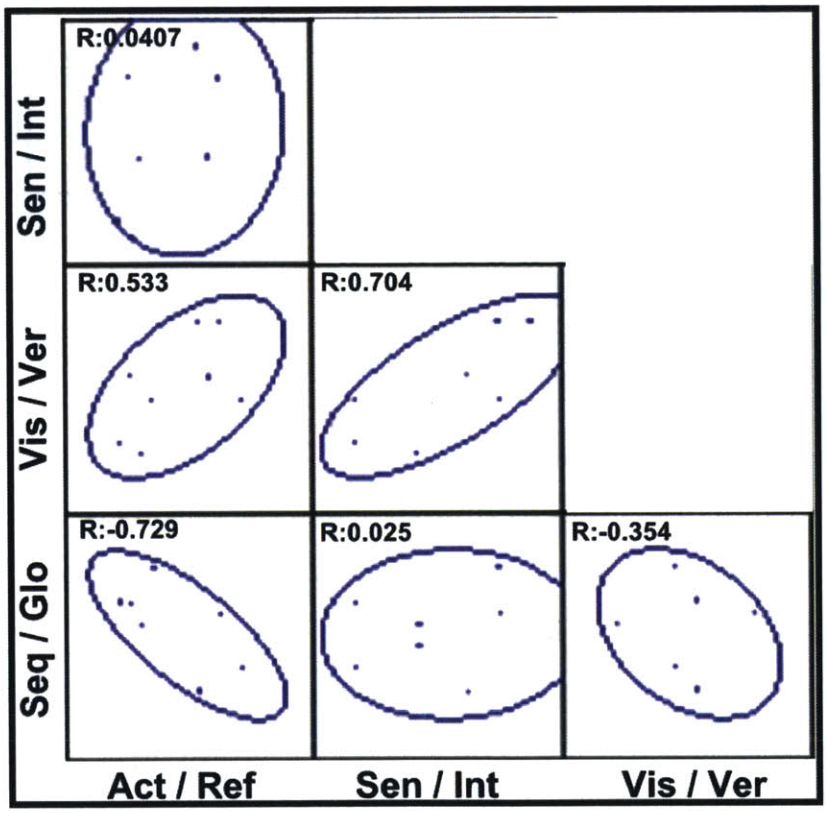


Figure 3-15: Correlations between dimensions of the video teaching style scores (Fine Scale).

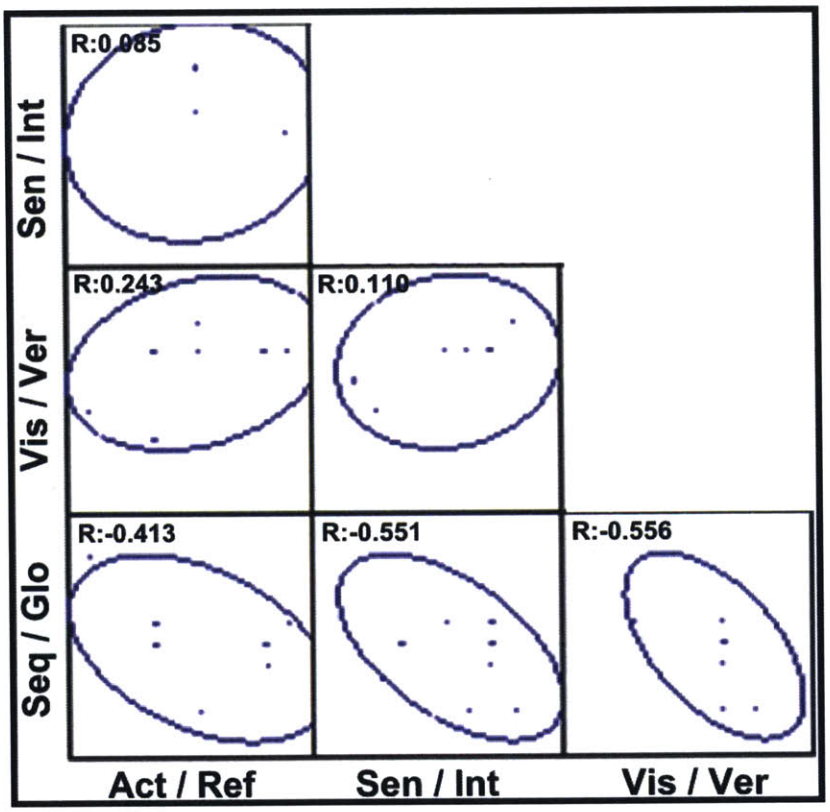


Figure 3-16: Correlations between dimensions of the ILS scores (Fine Scale).

There was no correlation between the teaching score estimation errors and the order in which the videos were graded. The ILS scores at the beginning of the experiment were correlated to the scores obtained 6 months later in all dimensions (Pearson R: Processing: 0.735*; Perception: 0.837*; Input: 0.788*; Understanding: 0.614. N=18 *p<0.0005). Looking at only the subjects in the experimental group, not all of the ILS dimensions correlated after the 6 month break. The Input dimension scores from training had no correlation with the ILS tests scores from the return visit (Pearson's Correlation = 0.452, α>0.05), which implies the dimension was not stable for those subjects. The Understanding (Sequential / Global) dimension had a weakly significant retest correlation (Pearson = 0.618, α<0.05), and both the Processing and Perception dimensions had very strong retest correlations, 0.758 and 0.879 respectively, $\alpha < 0.005$.

Chapter 4

Discussion

This experiment focused on performance retention in space telerobotic operations in two subject groups, which used different refresher training materials, generic written materials and customized videos. The telerobotics experiment used three types of tasks: Track and Capture (TC) - a manually challenging task that required fine motor control and drew upon muscle memory[1], Payload Positioning (PP), and Astronaut Assist (AA) - the latter two tasks were much more cognitively difficult (Figure 3-3), requiring procedural memory and spatial visualization skills. Results from subjective performance evaluations and 27 quantitative performance metrics (regarding procedural memory, muscle memory, familiarity with the simulator, situational awareness, and cognitive workload) were compared before and after a six month break. We also investigated the correlation of spatial abilities on robotics performance, and we tested the Matching Hypothesis for learning and teaching styles.

4.1 Hypothesis 1

What is the effect of the 6 month layoff period on performance?

Data from the subjective evaluation rubric showed overall decreases in performance and technique (Table 3.2), as well as decreases in the AA and PP task sub-

[1]In this thesis muscle memory describes the ability to manually control the robotic arm automatically, in a coordinated manor, without needing to think through the motions.

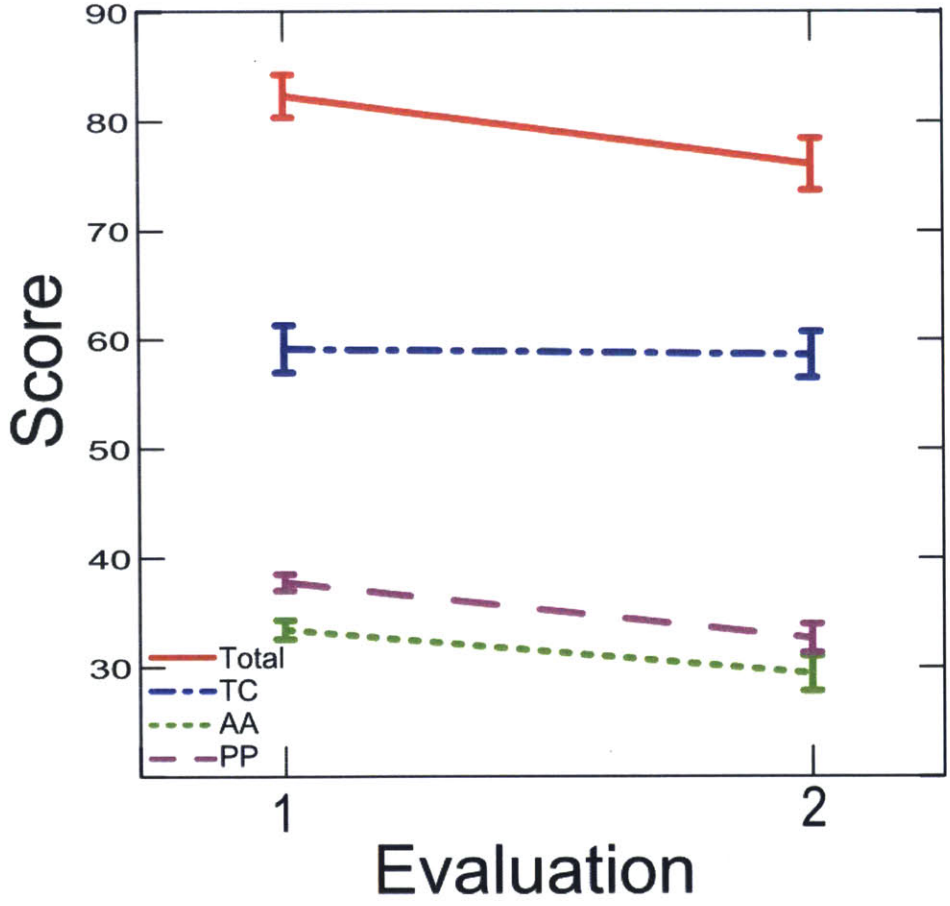


Figure 4-1: Subjective performance for the different task type subscores

scores (Figure 4-1). Since the TC scores did not see a decrement after the break, one concludes that although muscle memory seems to remain intact, procedural memory may be hindered as a result of the 6 month break. Looking at quantitative metrics in the TC task, more familiarity metrics decreased over the break, overall and within each treatment group (Figure 3-4). The muscle memory metrics showed an opposite effect; there were more metrics showing increased performance over the lay-off period. This implies that the muscle memory is better retained than familiarity with the simulator for the TC trials. In the PP task, there are more decreasing metrics overall in all metric type, with familiarity skill having the most decreasing metrics (Figure 3-6). In the AA task, the familiarity and cognitive workload categories have more metrics with decreased performance across all subjects, and muscle memory skills had more increasing metrics (Figure 3-5). This argues that muscle memory is less susceptible to temporal degradation than procedural and cognitive memory, which corroborates the conclusions of Mengelkoch et al (1971) [24].

When looking across gender, males had higher subjective performance scores overall, but there was no difference in the percent change in any performance metrics over the break, either subjectively or quantitatively. There is no clear difference in ability to retain information between men and women, over a six month lay-off period.

H1 SUMMARY Cognitive and procedural memory appear to deteriorate without use, more so than muscle memory, which did not seem to be affected in some cases.

4.2 Hypothesis 2

H2: Customized Refresher Videos will aid in retraining by ameliorating performance decrements and increasing the rate of reacquisition.

Comparing retention between the treatments, there was no significant difference in retention based on the qualitative analysis. Quantitative results did, however, show some differences between the groups (Table 3.11). In the Track and Capture tasks, the control group had better retention than the experimental group in three

metrics: speed peaks, side task lapses, and task time, which show a better retention of flight controls and situational awareness, see Table 2.1 category assignments. In the Astronaut Assist task, the control group retained better flight control in the fly-to phase, but the experimental group had better situational awareness and cognitive workload over the entire task. In the Payload Positioning task, the control group retained better muscle control in the loaded flight phase, but the experimental group had better retention of flight control and situational awareness during the align phase. In summary, the experimental group had better situational awareness and a lower cognitive workload than the control group during the cognitively challenging tasks in the second evaluation, though the effect is small and was not seen in all of the metrics (Section 3.3.2. Because safety is imperative in space telerobotics, the increase in situational awareness is very important and this finding argues customized refresher training could be a useful tool to increasing safety for space flight crews.

The second part of Hypothesis 2 was regarding the speed with which performance was regained. In the TC task, there was no appreciable difference in retention between treatments the early trials. Because the TC is reliant on muscle memory, this is consistent with Mengelkoch, Adams, and Gainer (1971) finding that manual control skills are less affected by layoff time [24]. Therefore, it follows that the different refresher training regimens should not affect relearning the TC task.

In the more cognitively demanding AA task, the experimental group had better retention for the first trial than the control group for procedural memory, muscle memory, familiarity, and situational awareness (Table 3.12). After the first AA task, the subjects conducted two PP tasks. In the PP tasks the trend of enhanced performance in the experimental group does not continue (Table 3.13). The trend is absent in the final AA task as well. Therefore, after a six month lay-off, the control group apparently catches up to the experimental group after approximately 15 minutes of cognitively challenging exertion (25 min if the TC trials are included as well).

H2 SUMMARY Customized refresher training videos helped subjects retain slightly better performance than the standard retraining materials during the most cognitively challenging task: the Astronaut Assist. This benefit is more apparent in

the performance metrics that describe situational awareness and cognitive workload. The customized refresher training appears to help subjects reacquire procedural skills faster than the control group; it takes 15 minutes or so for the control group to catch up. The customized refresher training did not appear to help the subjects in less cognitively challenging tasks, as the Track and Capture performance was not affected by treatment.

4.3 Hypothesis 3

H3: Customized Refresher Videos will contain teaching style features parallel to the creator's learning style.

Felder and Silverman (1988) suggest that people teach in accordance to their own learning style preferences [5]. We tested this by creating a teaching style rubric to evaluate the customized refresher training videos that the subjects created and compared the rubric results to the ILS scores of the subjects. The Matching Hypothesis held for the Processing (Active / Reflective) dimension (Figure 3-11), and the Perception (Sensing / Intuitive) dimension (Figure 3-12), showing moderate correlation in the coarse 6-point scale, with outliers removed. The Matching Hypothesis did not hold for the Input (Visual / Verbal) (Figure 3-13) and Understanding (Sequential / Global) dimensions (Figure 3-14). There were two significant correlations between video dimensions: Processing and Understanding, and Perception and Input (Figure 3-15). This implies some interdependence between dimensions in the rubric, and perhaps the rubric needs to be rewritten for the last two dimensions.

Note, the experimental subjects' Input dimension scores from training had no correlation with the scores from the return visit, and the Understanding dimension scores only had a weakly significant retest correlation. This could imply the dimensions are not very stable, since both the Processing and Perception dimensions had very strong retest correlations, with $\alpha < 0.005$. Felder and Spurlin (2005) discuss the test-retest stability of the ILS over 4 to 6 months and also found weaker correlations in the Input and Understanding dimensions than the Processing and Perception dimensions [6]. If

the Input and Understanding dimensions are unstable, it may possibly explain why the video rubric scores did not match the ILS scores in those dimensions. Our results lend support to the Matching Hypothesis for the more stable Index of Learning Style dimensions. However we were limited in our sample size (9 videos), and the small N may have effected our results.

H3 Summary The Matching Hypothesis held for two of the four dimensions. The failure of the hypothesis in the Input and Understanding dimensions could be related to either an instability in the learning style preference over time, or faults in the video teaching style rubric.

4.4 Hypothesis 4

H4: Subjects with better spatial abilities will relearn the telerobotic tasks more quickly.

A subject's spatial ability has been shown to affect whether or not they can quickly learn telerobotics; subject with poor spatial ability in Galvan's (2012) study had a higher probability of being released from the study [9]. We looked at the final evaluation performance and its dependence on spatial ability as well as the effect of spatial ability on retention.

Subjective performance was linearly correlated with performance on the MRT, PTA, and PSVT tests. The MRT and PTA were shown to help subjective task performance in models that take into account the evaluation and refresher training treatment as well (Models 1 & 2 in Section 3.2.3). The ability to mentally rotate shapes appeared to be helpful across all subsections of performance, Table 3.4. As the telerobotics tasks became more cognitively difficult, more SpA tests correlated with performance, meaning the more complex the task, the more skills are drawn upon to maintain task performance. If a person has innate spatial abilities, then utilizing those skills requires less mental effort, allowing more mental workload to be allocated to performing the task at hand.

The effect of spatial ability on skill retention is also apparent in the subjective

data, Table 3.5. The Astronaut Assist task performance retention correlated with the MRT SpA test across all of the subjects, and the control group percent change in performance on the AA task was correlated with the PTA and PSVT tests. The experimental group did not show any SpA correlations with performance change in any of the tasks types ($r<0.26$ for all tasks). Perhaps the experimental group does not show a benefit from SpA skills because they are retrained to a higher performance level from the refresher training materials, to the point were the SpA effects are washed out. Conversely, the control group's retention may have benefited from SpA skills because their retraining was poor, supporting H1.

Quantitative models also exhibited dependence on Spatial Ability in performance change. Model 2 showed that PTA skill increases retention of Rotational Travel Efficiency, a metric that describes muscle memory and familiarity with the simulator. Rotational control should be especially sensitive to Spatial Ability. In application, this means a subject who can quickly visualize the 3D work area from the different camera perspectives will have a better understanding of which way to turn the arm, increasing their rotational travel efficiency.

Model 4, on the other hand, showed that the MRT scores negatively correlate with bimanual control in the PP task. The model also showed subjects who play video games that require mental visualization skills performed better than subjects who play games that don't require practicing spatial skills. Model 3 also shows this retention trend with choice of video game. This implies that if a subject has poor spatial skills, they can retain bimanual control performance in visually demanding tasks, if they practice SpA skills in video games.

H4 Summary Having good spatial abilities seems to increase performance in telerobotics, especially during cognitively demanding tasks. Spatial skills also appear to increase performance retention in the cognitively demanding Astronaut Assist task when custom refresher training is absent. Playing visually demanding video games during the lay-off period correlated with telerobotics skill retention in the Payload Positioning task.

Chapter 5

Conclusion and Future Work

We trained 18 MIT students in 3 difference Space Telerobotics tasks and evaluated their level of proficiency immediately after training. Six months after training, the subjects returned and were reevaluated after a brief retraining session. Half of the subjects viewed a custom retraining video they had made at the conclusion of the initial training, while the other half of the subjects were given generic, written training materials. The performance post break was compared to performance at the end of initial training. Both subjective performance and quantitative performance were evaluated.

We attempted to answer the following questions: What is the effect of a 6 month lay-off on telerobotic performance? Will Customized Refresher Videos improve retraining? Would these Customized Refresher Videos contain teaching style features that are parallel to the creator's learning style? And, do subjects with better spatial abilities relearn the telerobotic tasks more quickly?

The muscle memory of flying the robotic arm was less affected by the 6 month lay-off period than the procedural and task related memory. Subjective performance decrements seen in cognitively and procedurally challenging tasks were not seen in the task requiring mainly good hand control. Across all trial types, quantitative metrics describing familiarity and procedural memory generally decreased over the break, more so than metrics describing muscle memory.

The customized refresher material appears to cause slightly increased retention

of procedural memory and decreased the cognitive workload during complex tasks: the experimental group had better retention of their initial side task reaction time six months later than the control group during the Astronaut Assist task. The customized training also boosted the subject's performance on early complex trials: during the first Astronaut Assist trial, five metrics showed better retention by the experimental group, but during the second trial only one did. Customized training did not help in the performance or reacquisition of the Track and Capture task, which relied most heavily on muscle memory and had very few procedural guidelines to remember. The effect of refresher training was not as large as we were expecting. It is important to note, because we wanted to test the Matching Hypothesis for video learning style, we deliberately chose not provide any guidelines for what the subject should include in their refresher videos. Our subjects were naïve learning the robotics tasks, and had no prior experience in regimented refresher training after a layoff. In retrospect, not providing content guidelines for the customized refresher videos may have decreased the effectiveness of the videos. By contrast, our astronaut collaborators had made multiple refresher videos before their flights, in addition to being trained to a much higher proficiency. Perhaps their experience making videos, and better understanding of what they may forget, allowed them to make videos that were effective retraining tools.

The customized refresher videos appear to match their creator's Index of Learning Style (ILS, Felder and Silverman 1988) preferences in two of the four learning style dimensions when using the coarse grading scale and removing outliers. The video evaluation rubric needs to be tuned to remove cross coupling of dimensions before a final assessment of the matching hypothesis is possible. Since it seems that there is at least some correlation, it could be that matching ILS and teaching scores may cause the benefit in procedural memory recall that was seen from the customized refresher training.

Finally, we confirmed with several earlier studies that spatial ability affects final performance. Higher spatial ability appears to increase performance and performance retention, especially in cognitively challenging tasks. Playing visually challenging

video games during the lay-off also correlated with performance retention.

Customized refresher materials may prove effective for the retraining of space flight crews. Most tasks conducted by the crews will be cognitively challenging, which benefit more from customized materials than simple tasks. The customized training also steepens the learning curve after a break. Therefore, an astronaut given custom retraining would require less simulator time to reach their peak performance, or they may be able to skip simulator practice entirely. This would cut down the amount of crew time spent on refreshing skills and allow for more time to be spent conducting science or other crucial tasks. In emergency scenarios, astronauts may not have time to run through simulator training, or have one chance to do the task, in which case customized retraining may be beneficial for raising performance quickly. For visual demanding tasks like space telerobotics, people with innate spatial skills may not experience as much benefit from customized training as those with very little spatial ability.

5.1 Future Work

A partner study is currently being run at the University of California Davis, where a customized refresher training experiment is being run using a manual repair task instead of telerobotics. They are following similar experimental procedures; initial task training, followed by self-directed video creation, and a six month break, before refresher training and a final evaluation. A repair task was chosen because repairs are a common skill that astronauts must train for but use infrequently. Results from that experiment will be used as confirmation of this experiment. Because subjects will have a previous background with the medium they are being trained on, the interfering effects from the depth of initial skill training will be minimized, allowing for more sensitive analysis.

Future experiments with the MIT telerobotics simulator include a Just-in-Time training experiment, which seeks to address the rest of the Human Research Program's knowledge gap. This experiment will involve in-depth telerobotics skill training, but task specific training will not occur until late in the experiment, as a Just-in-Time training scenario.

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Appendix A

Materials

This appendix contains the written materials and handouts used in this experiment.

A.1 Questionnaires

Three questionnaires were given during the experiment to look at the subject's background and self-reported performance. The first questionnaire was taken at the beginning of the first training session, and focused on understanding the subject's background and experience pertaining to complex spatial tasks. The second questionnaire was taken during the first evaluation session. This questionnaire had two parts, taken before and after the evaluation. The final questionnaire was taken during the return session six months later. It was comprised of three parts: at the begining of the session, after retraining and after the evaluation.

All three questionnaires used in this experiment are presented below

Subject Number: _____
Date: _____

Refresher Training Experiment Initial Questionnaire

General Information:

What is your age: _____ Gender: _____ Dominate Hand: _____

Highest Degree Attained: _____ Current Level of Education (Year): _____

Over the last week, how much sleep have you gotten on average per night: _____

Is this Below Average / Above Average / Normal for you? (Circle One)

How much Sleep did you get last night? _____

Experience:

How much experience do you have with videogames?

How often did you play videogames *Growing Up*:

Never Played - 1 2 3 4 5 - Played All the Time

How often do you play videogames *Currently (over the past few years)*:

Don't Play - 1 2 3 4 5 - Play All the Time

What types of videogames are your favorites? (First Person, Arcade, etc.)

What videogame have you played the most?

Do you consider yourself to have good spatial abilities and visualization skills?

I'm Horrible - 1 2 3 4 5 - The Best

Have you had any educational classes that have taught you spatial skills? (Chemistry, Mineralogy, etc.)

Please Hand Questionnaire back to Experimenter

Subject Number: _____
Date: _____

Post Training Questionnaire 2

What parts of training did you find the helpful in learning to control the arm?

	Not at all				Very Much
Reading PowerPoint:	1	2	3	4	5
Asking Questions:	1	2	3	4	5
There was an "Ah-Ha" moment:	1	2	3	4	5
Learning hands on:	1	2	3	4	5
Learning from mistakes:	1	2	3	4	5
Other: _____	1	2	3	4	5

What was the *most* helpful in learning to control the arm?

After the training, how would you rate your knowledge of the Robotics Simulator?

Nothing- 1 2 3 4 5 - Every Detail

How confident are you in your ability to operate the Simulator?

Total Failure - 1 2 3 4 5 - I'm going to ace it!

What is the one thing you are most worried about for the evaluation?

Wait Before Continuing

Post-Evaluation

How well were you able to operate the Simulator?

Total Failure - 1 2 3 4 5 - I'm going to ace it!

Was one of the following harder for you than the others?

- ○ Clearance Violations (why? _____)
- ○ Unexpected Motions (why? _____)
- ○ Singularities / Hardstops (why? _____)
- ○ Procedures / Flight Rules (why? _____)
- ○ All were equally difficult / easy

Was one Type of Task harder for you than the others?

- ○ 90s. HVT Capture (why? _____)
- ○ Astronaut on the Arm (why?_____)
- ○ Moving Payloads (why? _____)
- ○ All were equally difficult / easy

What is the one thing you felt the worst about in the evaluation?

Please Hand Questionnaire back to Experimenter

Subject Number: _____
Date: _____

Return Visit Questionnaire 3

Welcome Back:

Since your last visit, how often did you think about using the Robotic Simulator?
1. Never 2. Once or Twice 3. Occasionally 4. Frequently 5. All the Time

If you have been thinking about it, in what ways? (talking with friends, mentally practicing, etc.)

Since your last visit, how often have you played video games?
1. Never 2. Once or Twice 3. Occasionally 4. Frequently 5. All the Time

What types of game?

Have you had any experiences that may have altered your views on learning?

How much do you remember about the Robotics Simulator?
Nothing- 1 2 3 4 5 - Every Detail

How confident are you in your ability to operate the Simulator?
Total Failure - 1 2 3 4 5 - I'm going to ace it!

What is the one thing you are most worried about for the evaluation?

Wait Before Continuing

Post Refresher Training

After the refresher training, how much do you remember about the Robotics Simulator?
Nothing- 1 2 3 4 5 - Every Detail

How confident are you in your ability to operate the Simulator?
Total Failure - 1 2 3 4 5 - I'm going to ace it!

What is the one thing you are most worried about for the evaluation?

Please Hand Questionnaire back to Experimenter

Subject Number: _____
Date: _____

Post-Evaluation

How much did you remember about the Robotics Simulator?

Nothing- 1 2 3 4 5 - Every Detail

Is there anything you wish you had reviewed or studied more before the evaluation?

What would you have changed in your video? (Addition, edits, deletions...)

How well were you able to operate the Simulator?

Total Failure - 1 2 3 4 5 - I Aced It!

Was one of the following harder for you than the others?

- ○ Clearance Violations (why? _____)
- ○ Unexpected Motions (why? _____)
- ○ Singularities / Hardstops (why? _____)
- ○ Procedures / Flight Rules (why? _____)
- ○ All were equally difficult / easy

Was one Type of Task harder for you than the others?

- ○ 90s. HVT Capture (why? _____)
- ○ Astronaut on the Arm (why?_____)
- ○ Moving Payloads (why? _____)
- ○ All were equally difficult / easy

What is the one thing you felt the worst about in the evaluation?

What contributed to refreshing your memory?

	Not at all				Most Helpful
Recap PowerPoint:	1	2	3	4	5
Refresher Training Video:	1	2	3	4	5
Muscle memory / "Ah-Ha" moment:	1	2	3	4	5
Learning on the Fly / from mistakes:	1	2	3	4	5
Other:_____	1	2	3	4	5

Why did these help? What about it was helpful?

Anything else to share?

Thank You for Being a Part of Our Experiment

Please Hand Questionnaire back to Experimenter

A.2 Video Teaching Style Rubric

Each refresher video was evaluated using the following rubric, created to parallel the Felder ILS test. Scores ranging from -11 to 11 in each of the four learning style dimensions. The teaching style rubric is based on descriptions of the ILS dimensions and the recommendations for teaching to different ILS types found in the original Felder-Silverman paper. We expanded the concepts to describe possible elements from an instructional video, and evaluated the rubric on refresher videos made by pilot subjects.

When grading the videos, only one was graded at a time with at least 30 minutes between video evaluation. Only up to 4 videos were graded each day, in order to avoid biasing. The order of grading was randomized.

Subject Number: _____
Evaluator Name: _____

Refresher Training Experiment
Video Eval Version 3.5

Video Evaluation for ILS Components

There are four dimensions to the Index of Learning Style. Each dimension corresponds to an element of learning: Processing, Perception, Input, and Understanding. When teaching, these dimensions are Participation, Content, Presentation, and Perspective, respectively[1]. This rubric creates a scale, by which a video can be evaluated and mapped to the ILS. The rubric is based off of information from the original Felder paper and expanded to possible video elements.

When using the rubric, it is recommended that you view the video once all the way through to get an overall view of stylistic components, grading as much as you are able. Then, you may rewatch the video, pausing and replaying sections to help you answer the rest of the questions. Do not over-watch the video. There is space underneath each element for note taking. An extreme value for an element describes a video without any characteristics belonging to the opposite dimension. A zero denotes an evenly balanced video, and a moderate value is used on a video that contains characteristics from both dimension but tends towards one side.

Total ILS Score:

Act/Ref: Sen/Int:

Vis/Ver: Glo/Seq:

[1] Felder, Silverman. Learning and Teaching Styles in Engineering Education. Engr. Education, 1988; 78(7), 647-681.

Processing / Participation

Considering the participation level of the subject and the style of the video, Circle a score for each subcategory. Did the video support **active engagement** or more **passive processing?** When finished, total up the two columns, then subtract column B from A. Scores range from 11 (Strongly Active) to -11 (Strongly Reflective).

	A) Active Experimentation				**B) Reflective Observation**
PP1	Video was a "Discussion", "Stream of Consciousness", or disorganized "oh yeah.."	3 - 2 - 1	0	1 - 2 - 3	Video was organized and thoughtful or reflective
PP2	Very Active Video, Tools are used in an active manner	3 - 2 - 1	0	1 - 2 - 3	Video was passive, subject off screen.
PP3	The Informational Flux had Almost No Downtime	3 - 2 - 1	0	1 - 2 - 3	Many Pauses for Thinking, or Quiet time in video
PP4	Video Focuses on Problem Solving tools. Ex. How to run through a task	2 - 1	0	1 - 2	Focus on Fundamental Understanding

Totals: _____ – _____ =

Perception / Content

Think about the perception and content of the video, was the focus on the **concrete** or **abstract**. Circle a score for each subcategory. When finished, total up the two columns, then subtract column B from A. Scores range from 11 (Strongly Sensing) to -11 (Strongly Intuitive).

	A) Sensing, Concrete Facts				**B) Intuitive, Abstract Theories**
PC1	States Specific Observations of the Simulator	3 - 2 - 1	0	1 - 2 - 3	Includes Patterns or Inferences they have discovered
PC2	Uses "Concrete" Examples of a Task, the Facts	2 - 1	0	1 - 2	Discusses Abstract Concepts, theories, and principles
PC3[2]	Problem Solving / Procedural Information	2 - 1	0	1 - 2	Fundamentals of the Simulator or tasks
PC4	Very High Attention to Detail.	2 - 1	0	1 - 2	Generalizations of concepts
PC5	Repeats Information, Shows multiple Tasks	2 - 1	0	1 - 2	Only displays or discusses one type of task
	Totals:	_____	_	_____	=

[2] For problem solving, you would do multiple algebra problems step by step, showing your work so that later you can view the problems to learn. For fundamentals, you would describe how you need to solve for one variable, plug back into the original equation, and solve for the final variable. But NOT actually doing it.

Input / Presentation

Think about the presentation of information in the video and the **sensory input** involved. Grading is different for this dimension. Answer the verbal question, and evaluate the visual input frequencies. When finished, total up the two types, then subtract VER from VIS. Scores range from 11 (Strongly Visual) to -11 (Strongly Verbal).

IP1: What percentage of the information was **verbal**: % x 0.1 = VER
(Talking to Camera, Using text heavy slides)
Does not include descriptions of a visual

	Visual Characteristics		N/A
IP2	Subject used demonstrations (Simulator, Plastic Model, ...)	4 – 3 – 2 – 1 Constantly, Frequently, Occasionally, Rarely	-1
IP3	Subject points out something on the screen (with finger or pen, "notice in upper-left...)	4 – 3 – 2 – 1 Constantly, Frequently, Occasionally, Rarely	0
IP4	Subject included pictures, sketches or diagrams	>3 – 2 – 1 (number of visual aids)	0

Total VIS: _____ - Total VER: _____ = _____

Understanding / Perspective

Consider the perspective of the video and the type or **level of understanding** behind it. Circle a score for each subcategory. When finished, total up the two columns, then subtract column B from A. Scores range from 11 (Strongly Global) to -11 (Strongly Sequential).

	A) Global Perspective				**B) Sequential Understanding**
UP1	Has an introduction to the video or subsections, potential goals for video	2 - 1	0	1 - 2	Jumps straight into the details
UP2	Video **jumps around**, or has interjections	2 - 1	0	1 - 2	Step by step, regimented
UP3	Summarizes key concepts	2 - 1	0	1 - 2	Very detail oriented video
UP4	Real world applications, **Motivations** or context	2 - 1	0	1 - 2	Subject never deviates from the experiment, no background information
UP5	Relationships or connections between tasks or skills	3 - 2 - 1	0	1 - 2 - 3	All task very separated, only talks about one task at a time, focused

Totals: _____ – _____ =

A.3 Subjective Evaluation Rubric

The Subjective Evaluation Rubric is shown below. The rubric is used in both evaluation sessions to grade the ability and performance of the subject. The scores from the two evaluations could be compared to see how performance changed.

The rubric is based on the final exam grading scale for NASA's General Robotics Training at Johnson Space Center. The GRT grades are extreamely subjective and based on a 0-5 scale. This rubric breaks the GRT grades into smaller components to remove as much subjective variability as possible. The rubric was split into three main performance categories: situational awareness, task performance, and technique. Each category had two to five elements, depending on the trial type, graded on a three tier scale (+, check, -). Important elements were identified in the GRT rubric and pulled out to be scored individually in our rubric. Following the rubric is are guidelines for how to grade each element.

Each element was scored for every trial and tallied up for a total performance score. Because there were so many track and capture trials (12), they were weighted 0.5 to balance the total. The score was multiplied by 0.63 to make a perfect score 100. The rubric can be split by either task type or by category, for analysis.

FINAL EVALUATION RUBRIC

Subject Number: _____
Date: _____ Time: _____

Three Tier Grading Scale for each task [+, ✓, -]

Track and Capture Tasks	T1	T2	T3	T4	T5	T6	T9	T10	T11	T12	T13	T14
Situational Awareness	/4	/4	/4	/4	/4	/4	/4	/4	/4	/4	/4	/4
Scan Pattern												
Recognize HTV Motion												
Task Performance	/4	/4	/4	/4	/4	/4	/4	/4	/4	/4	/4	/4
Movement Strategy												
Time (t<50 = 2, t>80 = 0, Fail = -2)												
Controller Technique	/4	/4	/4	/4	/4	/4	/4	/4	/4	/4	/4	/4
Excessive Motion												
Smoothness / Jerk												
TRIAL TOTALS												
TRACK AND CAPTURE TOTAL					/144	x0.5						

EVA Support Tasks	T7	T15
Situational Awareness	/8	/8
Camera Usage		
Scan Pattern		
Unexpected Motion		
Clearance Awareness		
Task Performance	/10	/10
Positioning Errors		
Movement Strategy		
Time to Completion (25m max)		
Repair Performance		
Proper Modes		
Hand Controller Technique	/4	/4
Bimanual Control		
Smoothness / Jerk		
TRIAL TOTALS		
EVA SUPPORT TOTAL		/44

Advanced Task: T8	OBJ 1	OBJ 2
Situational Awareness	/8	/8
Camera Usage		
Scan Pattern		
Unexpected Motion		
Clearance Awareness		
Task Performance	/10	/10
Final Placement		
Movement Strategy		
Time to Completion		
Grapple Performance		
Proper Modes		
Hand Controller Technique	/4	/4
Bimanual Control		
Smoothness / Jerk		
TRIAL TOTALS		
ADV. TASK TOTAL		/44

TOTAL TASK SCORE _____ x 0.63 = _____ / 100

Tally Number of Violations:

FLIGHT RULES		Multiply	Total
Vernier at 1m		x1	
Clearance at 0.6m		x1	
Forgot Brakes		x1	
OTHER			
Collisions (1/T&C)		x3	
Singularities		x2	
Hard Stops		x1	
SHIFT + R		x3	
Failed Grapple		x0.5	

FINAL SCORE: Task Total ( ) - Violations ( ) = _____ / 100

RUBRIC Explanation: Skill Categories
Three Point Scale [+, ✓, -] = [2,1,0]

SITUATIONAL AWARENESS

Camera Usage: Poor Setup: Arm is consistently (>30% of trial) outside of view (1+ monitor)
Acceptable: May start moving without arm in all monitors but realizes, occasionally looses arm from 1 or 2 monitors
Excellent: Arm is always in view

Scan Pattern: Poor Scan Pattern: Dwells on ONE monitor for entirety of a task, or phase of a task
Acceptable Scan Pattern: Uses 2+ monitors, only scans all during certain phases.
Excellent Scan Pattern: Continues to check all three monitors through all task phases

Unexpected Motion: Poor: Guess and check arm movements, repeatedly uses the wrong motion
Acceptable: Uses the wrong axis occasionally, but recognizes eventually
Excellent: Rarely (<3) moves the arm in the wrong direction, and if they do, they immediately recognize it.

Recognizes HTV Motion: Poor: Doesn't recognize motion, simply chasing HTV around
Acceptable: Eventually recognizes, playing catch-up
Excellent: Recognizes motion in 1st 15 seconds, able to compensate / predict

Clearance Awareness: Poor: Does not acknowledge a Clearance Violation. Has multiple (3+) violations, barely misses 2+ collisions
Acceptable: Hits 2 or less clearances, poor awareness from camera choices, or barely misses a collision, recognizes clr violation once they happen
Excellent: Is aware of clearance violations before they get to them

TASK PERFORMANCE

Positioning /Placement: Poor: Is widely off in both position and orientation
Acceptable: Is only off in either orientation or position
Excellent: Within the threshold for both orientation and position

Movement Strategy: Poor: Moves in an illogical path: Has to double back. Many H.Stop/ Sing
Acceptable: Less then optimal path: large arc to movement, 2-3 HStop/Sing
Excellent: Optimal Path, minimal Hardstop/Singularities (<2).

T&C Movem. Strat.: Poor: Moves in all rotation Axes, repeatedly overshoots pin.
Acceptable: Minimal overshooting (≤3), grapple within 10s of entering envelope
Excellent: Optimal path, straight line, very few alignment corrections, grapples as soon as in envelope.

Time to Completion: FAILURE: DNC = -2 points, 10min overtime on EVA & AdT, time up for T&C
Poor: Finishes 5-10minutes Over time allotted (or >80s in T&C)
Acceptable: Finishes within 5min of allotted time
Excellent: Finishes task below allotted time

Grapple Performance: Poor: Multiple failed grapples, bad final alignment, repetitive corrections
Acceptable: One failed grapple, moderate final error, some corrections over pin
Excellent: No failed grapples, Corrections finished before over pin. Smooth approach

Repair Performance: Poor: Moves wrong direction on repairs, or off by more than 1.0m on any
Acceptable: Right Directions, but bad estimation, off by more than 0.5m on any
Excellent: Good repair.

Proper Modes: Poor: Misses 3+ mode changes, either during CFRM or alignment phases
Acceptable: Misses 1-2 modes (CFRM, alignment phases)
Excellent: All modes are correct. (Not considering Flight Rule #1)

HAND CONTROLLER TECHNIQUES

Bimanual Control: Poor: Positions Arm completely, then orients arm.
Acceptable: Stops while positioning to orient. Or only orients 1 axes while moving
Excellent: Orient arm while moving into position (2+ axes are correct by end of motion)

Smoothness/Jerk: Poor: Slamming Controllers, Bang-Bang Control all the time, any hazardous force
Acceptable: Only jerks controls a few times, i.e. if agitated. Pulsing only one hand
Excellent: <2 jerky motions, ramping in an out of motions.

RUBRIC Explanation: Violations
Tally System

FLIGHT RULES

Vernier At 1.0 m: Talley if they haven't realized they should be in Vernier by 0.75 m
Only Tally once per infraction / per item they get close to
If they notice within 10 seconds and apply V or pull away, don't tally
No minus points for using Vernier outside of 1.0m
Maximum of 3 tallies per Trial

Clearance Violation: Tally if they haven't realized within 5 seconds
Tally if they do realize but don't pull away or apply V
Only Tally once per infraction / per item they get close to
Maximum of 3 tallies per Trial

Forget to Use Brake: Talley if they have nose buried in procedures (>5sec)
Only Tally once per infraction / per phase of flight
Talley if they are fiddling with cameras for >10 sec
If they notice at all and apply, don't tally
Maximum of 2 tallies per Trial

OTHER VIOLATIONS

Collisions: Talley for collisions of any kind
Only Tally once per infraction / per item they get close to
If they move away (1m) then back in and collide again, tally again.
For self-Collisions; tally if they are spaced by more than 1 minute
No Maximum per Trial (except T&C, tally once)

Singularities: Talley for any singularity
Only Tally once per infraction / per cluster
If they move thoroughly away (>2m) then back in again, tally again.
Maximum 3 per Trial

Joint Hardstop: Only Tally once per infraction / per cluster of hardstops
If they are hitting Wrist Yaw and Wrist Pitch at the same time, count as 1 tally
If they move away (JA goes back to green / 10 degrees) then back in again, tally again.
Maximum 5 per Trial

SHIFT + R: If pressed because of JA glitch, it was triggered by the WY singularity. Tally singularity
Otherwise, tally.
No Maximum per Trial

Failed Grapple: Talley for trigger press, if in grapple phase
Do Not tally if accident / attempt to answer sidetask (unless it happens 3times)
Maximum 5 per Object

Appendix B

Data

This Appendix will list more thorough descriptions of the 27 quantitative metrics and how they were calculated. To see results of all the statistical tests and the raw data, consult the accompanying CD.

B.1 Metric Calculations

Metrics were calculated from simulator output files, which supplied information on Hand Controller input (THC & RHC), simulator state information, Target / Payload Position, Keystrokes, arm joint angles, and side task response data. Metrics are calculated in MatLab scripts 1.CalcDist.m, 2.CalcStat.m, 3.PullSessionData.m, and 4.cleanSecondary.m present in the accompanying CD.

Because the End Effector (EE) position was not collected, the metrics associated with travel were calculated from the Hand Controller Input information, which recorded the speed of the EE in the X,Y,Z (THC) and Roll,Pitch,Yaw (RHC). In the equations below, this speed data will be presented as X,Y,Z,r,p,y.

1. **Phase Time**[3] *Time*: Time to complete a trail subphase. Phases are split in script SplitTrials.m

   (a) "Plan Phase" timing began when the trial loaded and ended at the first arm movement. Some subjects would take off the brake early then plan,

other subjects would forget to take off the brake before trying to move, then sit and think about what they were doing. Therefore, neither 'Brake Off' nor'First Controller Input' could be used to flag the end of the plan phase. Secondary Plan Phases would begin at the end of the Grapple or Repair Phase.

(b) "Fly-to Phase" timing started at the end of Plan Phase and ended when the subject entered Alignment or Grapple Phase, which either corresponded to switching to 'Internal Frame', or approaching within 1 meter of the final position

(c) "Grapple Phase" began directly after the Plan Phase in the Track and Capture Tasks, and began after the Fly-to in the other task types. The Phase ended with the successful grapple of the target.

(d) "Alignment Phase" timing began at the end of the Fly-to and ended with either ungrappling the payload or identifying the arm was in position with the keyboard, 'm' or 'Shift+D' depending on the trial type

(e) "Repair Phase" begins when the subject presses the 'm' key, while braked, in the Astronaut Assist Task, and ended at the last repair placement.

2. **Translational Error**[3] Err_T: Offset error in position in final alignment or grappling. Calculated as the translational offset in X,Y,and Z axes between the goal position and the payload's final position, or the offset between the center of the grapple target and the end effector position at the final trigger pull (had to be less than 0.28 m to grapple).

3. **Rotational Error**[3] Err_R: Error in orientation in final alignment or grappling. Calculated as the Rotational offset between the goal orientation and the payload's final orientation, or the offset between the center of the grapple target and the end effector orientation at the final trigger pull (had to be less than 5 degrees to grapple).

4. **Translational Travel Efficiency**[1] TE_T: Efficiency of the translational path

taken.

$$TE_T = \frac{\sqrt{(\sum X)^2 + (\sum Y)^2 + (\sum Z)^2}}{\sqrt{(\sum |X|)^2 + (\sum |Y|)^2 + (\sum |Z|)^2}} \tag{B.1}$$

5. **Rotational Travel Efficiency**[1] TE_R: Efficiency in rotational control.

$$TE_R = \frac{\sqrt{(\sum r)^2 + (\sum p)^2 + (\sum y)^2}}{\sqrt{(\sum |r|)^2 + (\sum |p|)^2 + (\sum |y|)^2}} \tag{B.2}$$

6. **Percent of Bimanual Control**[1] $\%Bi$: Percentage of flight time both hand controllers were used simultaneously.

$$\begin{aligned} THC &= (X \neq 0) \vee (Y \neq 0) \vee (Z \neq 0) \Rightarrow 1 \\ RHC &= (r \neq 0) \vee (p \neq 0) \vee (y \neq 0) \Rightarrow 1 \\ \%Bi &= \frac{\sum(THC * RHC)}{\sum((THC + RHC \geq 1) \Rightarrow 1)} * 100\% \end{aligned} \tag{B.3}$$

7. **Percent of Multi-Axis Movement**[1] $\%MA$: Percentage of flight time moving in more than one direction at once

$$\begin{aligned} N_{Ax} &= (X \neq 0) \Rightarrow 1 + (Y \neq 0) \Rightarrow 1 + (Z \neq 0) \Rightarrow 1 \\ &+ (r \neq 0) \Rightarrow 1 + (p \neq 0) \Rightarrow 1 + (y \neq 0) \Rightarrow 1 \\ \%MA &= \frac{\sum(N_{Ax} \geq 2 \Rightarrow 1)}{\sum(N_{Ax} \geq 1 \Rightarrow 1)} * 100\% \end{aligned} \tag{B.4}$$

8. **Time Efficiency**[1] $\%TMv$: Percentage of time spent moving

$$\begin{aligned} N_{Ax} &= (X \neq 0) \Rightarrow 1 + (Y \neq 0) \Rightarrow 1 + (Z \neq 0) \Rightarrow 1 \\ &+ (r \neq 0) \Rightarrow 1 + (p \neq 0) \Rightarrow 1 + (y \neq 0) \Rightarrow 1 \\ \%TM_v &= \frac{\sum(N_{Ax} \geq 1 \Rightarrow 1)}{N} * 100\% \end{aligned} \tag{B.5}$$

9. **THC Reversals**[1] Rev_T: Number of times the subject reversed direction with the Translational Hand Controller. The X, Y, and Z speed input at each frame of THC use is compared to the proceeding X,Y, Z input. Each time signs are

different, it is counted as a reversal, i.e. there could be up to three reversals in one frame. This method counts reversals across down-time with no input, as well.

10. **RHC Reversals**[1] Rev_T: Number of rotational reversals with the Rotational Hand Controller. The calculation is the same as the THC Reversal calculation. The input at each frame of RHC use is compared to the proceeding RHC input, with each axis evaluated individually.

11. **Collisions**[2] Col: The number of times the arm or payload collided with an object. Simply calculated as a tally of collisions.

12. **Clearance Violations**[2] Clr: Number of times that the clearance limit flight rule was broken.

13. **Camera Switches**[2] $CamSw$: Number of times a selected camera was switched. Calculated from the system state output. Every time a monitor state switched, a tally was added.

14. **Double Cameras**[2] $DblCam$: Number of times the same camera was assigned to multiple monitors. Calculated from state output. Every time a monitor swithced, the new camera number was compared to the other two and if they matched, a tally was added.

15. **Max Switch Rate**[2] $MxSwR$: Highest rate of camera switches per minute. The number of camera switches was calculated every minute, and the highest rate was selected.

16. **Side Task Reaction Time**[4] RT_{avg}: Average side task reaction time. All successful side task responses were averaged to calculate this metric.

17. **Side Task Responses**[4] RT_{Resp}: Number of side task stimuli successfully responded to

18. **Side Task Misses**[4] RT_{Miss}: Number of side task stimuli missed. After the stimuli is displayed for 10 seconds, it is counted as a miss and removed.

19. **Jerk Metric**[1] $SmthT_J$ or $SmthR_J$: Smoothness of control, described by jerk. Calculated as negative average jerk magnitude normalized by maximum speed. (Making the metric negative means that a positive increase is smoother).

20. **Speed Metric**[1] $SmthT_S$ or $SmthR_S$: Smoothness, described by speed. Calculated as average speed normalized by maximum speed

21. **Peaks Metric**[1] $SmthT_P$ or $SmthR_P$: Smoothness described by the number of speed peaks. To smooth output noise, local were only counted if they were the higher than all speeds within 40 frames (2 seconds)

22. **MAPR Metric**[1] $SmthT_M$ or $SmthR_M$: Ratio of total time that speed was higher than 10% of the maximum speed recorded.

Appendix C

Experiment Flow and Training Materials

This appendix includes materials used for guiding the instructor through conducting the experiment and the training materials provided for the subject. The instructions for the experimenter includes maps for each training and evaluation trial.

C.1 Instructions for Experimenter

Below is the script that was used by the experimenter to guide them step-by-step through running the experiment. It was created to remove any instructor bias or variation in the subject training.

MIT Robotics Refresher Training Experiment

Experimenter's Guide

Version 1.2 April 2015

This document will outline how the experiment is to be run. It includes schedules and notes for carrying out each day's training, as well as the standard teaching practices that the experimenter shall adopt. At the end of the document there is a list of helpful tips for quick reference for use during an experiment.

Outline

I. Experiment Schedule (V3.0)

The refresher training experiment is spread across 6 sessions. Ideally, the first half of the experiment takes place over 3 days, with Sessions 1 & 2 and 3 & 4 and Session 5 is the next day. Then six months later, subject come in for a single 2 hour session. The whole experiment will be roughly 16 hours.

Session 1: Consent, Questionnaires & Initial Training [3 hours]

- Consent & Experimental Overview Forms
- SpA Testing
- ILS Testing
- Robotics Basic Training

Session 2: Basic Skills Robotics Training [3 hours]

- Fly to and Grapple Training
- Advanced Concepts Training
- Preliminary Screening (50% success to continue)

Session 3: Task Specific Training [3 hours]

- Track and Capture Task
- EVA Support Task
- Side Task Training

Session 4: Strategy Practice & Training Video [3 hours]

- Strategy for Flight
- Make Refresher Video OR Extra Practice Time

Session 5: Training Evaluation [2 hours]

- Quick Review Session
- Evaluation

>>> 6 Month Break <<<

Session 6: Return Evaluation [2 hours]

- Quick Review Session
- Evaluation

II. Guidelines for Instructor

The goal of these guidelines is to standardize the training that all subjects receive. It will be impossible to give the exact same experience to each subject, especially between instructors. Adhering to guidelines can minimize variation.

II.A Guidelines for General Training

Training is based on PowerPoint slides. Subjects are to go through the slides at their own place. You, as the instructor, should:

- Follow along and point out the few comments that are listed in the notes section of the PowerPoint, and to answer the questions of the trainee.
- Don't lecture them using the PowerPoints, by minimizing the presentation that instructors give, we minimize the potential to forget or embellish on ideas from subject to subject.
- Let the subject have a chance to figure out for themselves before supplying answers. Use phrases such as "Good question, what do you think?" If they get flustered or annoyed, it is better to tell them the answer at this point then to make them struggle and waste time.
- Don't withhold information. Many people learn through asking questions and fitting concepts into a big picture.
- At the end of each PowerPoint, be sure to ask if there are any questions. We want to facilitate an atmosphere where the subject feels comfortable asking questions, so that they may master the robotics skill set in a short period of time.

During hands on training, subjects will go through a variety of different tasks that range in difficulty. As the instructor, you should:

- Give positive feedback for the subjects, especially in the beginning. This can be during or after a trial.
- Give constructive feedback, i.e. things to work on or think about, in between trials. For example: "Good job completing the trial, next time focus on scanning all of your views and using smoother controller inputs"
- Acknowledge the subjects' verbalizations, simple nodding of the head, or 'yup', 'ok' responses will encourage subjects to talk more. Let them know they will see you do a trial to get an idea of what to verbalize when you get to the Adv. Task training.
- Follow along with the procedures for that day, many times there are hints for specific trials.
- During the first few trials of each type, it is ok to say things like "Are you forgetting something?" or "Where is your elbow?" when a subject is doing something incorrect (flight rules, cameras, CFRM). Don't correct them outright. Acknowledge when they identify what is wrong.
    - ★ Exception: If subjects are being unsafe with the equipment (i.e. Jerking the controllers): Call them out on it outright and immediately. We only have two working THCs.
- If a subject is consistently forgetting or messing up some task, encourage them to come up with a memory aid, like a pneumonic.

Skills to focus on during Training:

- Taught in Generic Robotics:
    - Scan Pattern
    - Number of Joint Hardstops and Singularities hit

- Percentage of multi-axis movement, and bimanual Control
- Smoothness of controller input

- Taught in Grapple Training:
  - Number of Clearance Violations and Collisions
  - Grapple Attempts (pulling the trigger out of envelope)
  - Adherence to flight rules
- Taught in Advanced Control:
  - Flight Strategy
  - Camera Management
  - CFRM
  - Time to task completion

II.B Guidelines for Evaluations

All evaluations should be completely hands-off. Because the subjects are used to feedback during training trials, it may make them nervous if you suddenly stop talking, so give them a heads up before they start.

1) During the evaluation, you must be actively following the rubric. Evaluate each trial individually, and then average the score in each category. This will keep a record of performance for each trial. If in doubt, round down.

2) Leave the camera running during the entire evaluation: Pushing stop and start after each trial will draw attention to the fact they are being recorded, and may psyche out the subject.

3) Because the evaluation may take roughly 1.5hrs, there will be a 3 minute break halfway through. At this point, tell the subject "Good work, you are halfway there." This provides encouragement and can keep up performance.

4) Try not to frown during an evaluation. Do Not Laugh.

At the end of each evaluation, smile and congratulate the subject on finishing. Tell them it will take a while to score the evaluation, but that you think they did well.

- ★ Exception: If it is the preliminary evaluation, you must score it right away to see if they qualify to continue.

III. Procedures for Sessions

Session 1: Consent, Questionnaires & Initial Training [up to 3 hours]

This session goes over the very basics of robotics and information about the rest of the experiment. Before the subject arrives, calibrate the joysticks, have printouts for all tests, consent forms, payment forms, have at least 2 working writing instruments and a stop watch, and set up the PTA on a computer.

Outline:

- Consent & Experimental Overview Forms [20 minutes]
- SpA Testing [60 minutes]
  - Card
  - MRT
  - PTA
  - PSVT
- ILS Testing [15 minutes]
- Break [10 minutes]
- Robotics Basic Training [60 minutes]
  - General Robotics and Simulator Info
  - Fly – To Controls
  - Hands on Flying Practice

Total Predicted Time: 2hrs 45min

Begin the session by greeting the subject and welcoming them to the lab.
"Welcome to the MVL and thank you for participating in our study... First off, let me explain why we are doing this experiment. We want to know how and what humans forget, and the best ways to "refresh" their memory. In this experiment you will be a stand in for real astronauts, missions to Mars / ISS. You will learn a complex skill, telerobotics control, over these next few days. Then after 6 months (the standard ISS mission time) we will bring you back in and see how you preform after the hiatus. When you come back, we are going to "jog" your memory with a video clip. You may be randomly chosen to make your own clip at the end of your training. Keep that in mind as you go through the training, and think about what aspects you want to incorporate into your movie."

You will need to have them read and sign the consent forms before continuing. Step them through the consent form, especially the schedule and what will be expected of them. They need a copy of the entire consent form, and you need a copy of signature page, so print two. At this point you should also get their information for contacting them next semester and for sending the compensation check.

Once you have their consent, begin administering the SpA tests. The order and script, to control for learning effects, is as follows:

1. The Card Test – 2D rotation.
   a. The Card test is located in the ***BLUE*** folder. Have the subjects write directly on the test sheet.
   b. "This is the Card test: the objective is to test your ability to mentally rotate a shape. You are to identify if each shape is the same, 's', or different, 'd', as the shape on the left but rotated. There is no penalty for leaving a question blank, but there is a penalty for an incorrect answer. There are two parts: I will tell you when to start. Each part has a 3

minute time limit, at the end of 3 minutes you will have to stop writing. I will give you a one minute warning."

c. Give the subject time to read through the instructions if they wish. Be sure they understand what to do before you begin.
d. Give the subject a 1 minute warning during the test.

2. The MRT – 3D rotation
   a. The MRT is in the ***GREEN*** Folder. Have subjects write directly on the test sheet.
   b. "This is the Mental Rotation Test. It is similar to the Card test but you are now rotating in 3 dimensions. In this test, you will check the box under a shape if it is the same as the shape on the left. There are two and only two correct answers in each question. Again there will be 2 parts, each with a 3 minute time limit. The first part is both sides of this paper, so don't forget to flip it over. I will give you a one minute warning."
   c. Again, give the subject time to read if they wish, and make sure they understand.
   d. Give the subject a 1 minute warning.

3. The PTA – 2D Perspective Test
   a. Before the subject is at the computer, have this test ready and cued up, with the volume on. Also be sure that you have a mouse for the subjects to use, as it is difficult with a trackpad. Make sure all subjects use the mouse. There is a print out with an image of the test, show this to subjects as you explain
   b. "This test is the Perspective Taking Ability test. It will be on the computer. In this test, you will pretend that you are the guy with the red hat in the center of the screen. One of the locations on the screen will flash and the computer will beep. As quickly as you can, identify with the arrow buttons on the screen which direction the dot is from the person. You will be tested on speed and accuracy. This test will take approximately 8 minutes."
   c. Have the subject press the Enter button when they are ready to begin.

4. PSVT – 3D Perspective
   a. The PSVT is in the ***RED*** folder. Have subjects write on the answer sheet and Not in the test booklet (Easier to grade and it is a lot of paper to print out).
   b. "The last Spatial Ability test is the Perdue Spatial Visualization Test. This is a 3D perspective taking test. On each page, there will be a shape in the middle of the cube, made of the dashed lines, and a dot in one of the eight corners. Pretend that you are sitting on the corner with the dot looking at the shape. Identify on your answer sheet the letter that corresponds to the image of what the shape would look like from that viewpoint. In one question, there will be a dashed circle that looks like it is in the middle of the shape. This represents looking at the shape from *behind*. There are 30 questions, and a 20 minute time limit."
   c. Allow subjects to read the instructions and do the practice questions before you begin.
   d. Give the subject a ten minute warning. Most will complete in time, write down the completion time on their answer sheet.

Next, move on to the ILS test located in the ***YELLOW*** folder:

"Now we are going to test your learning style with the 'Index of Learning Styles' Test. This is a 44 question test to identify how you learn best. There are no right answers here. Pick the statement that best describes how you feel at the moment. Please don't leave any questions blank."
If the subject asks for clarifications on a question, deflect it. "What describes you *now*."

Once the subject has finished all of the testing, offer them a quick ~10 minute break for the restroom or coffee. While they are out:

1. Place all testing documents in a manila folder, *Do Not* grade them until the end of training, and after their refresher video has been scored for ILS components. This is to avoid any bias in teaching them or evaluating their video.
2. Prep the training slides on a laptop.
3. If the simulator computer has logged out, recalibrate the THC
4. Boot up the simulator, up to the dialog box that says "Synchronize Experiment Time".

When the subject returns, have them begin training by working their way through the power point slides. Encourage them to ask you questions, and answer them fully in a friendly manner (there is no such thing as a dumb question). Remember to smile even if you are tired, if you are grumpy they may get nervous and speed through the slides without fully learning. Follow along in with the training slide binder, and make points and ask them questions where noted. Have subjects identify the links and joints of the 3D printed model arm. When they get to singularities, have them try to hit them on the model arm. At the end of the PowerPoint, there is a 4 minute free time for the subjects to play with the simulator, be sure to interrupt and have them continue. When they reach the target practice trials, explain the objective:

"Now we are going to do some fun target practice. In the trials that follow, there will be a series of targets for you to hit. We'll start with ball targets: move the end effector to hit the ball. When you get it, a new ball will appear. There is a counter on the top of the screen that tells you how many targets are in each trial. Go ahead and try it out"

Give subjects feedback and encouragement. For example "Nice use of both hands at once", "Good, smooth inputs" or "Try and be a little more gentle on the THC".

When the subject reaches the Ring targets:

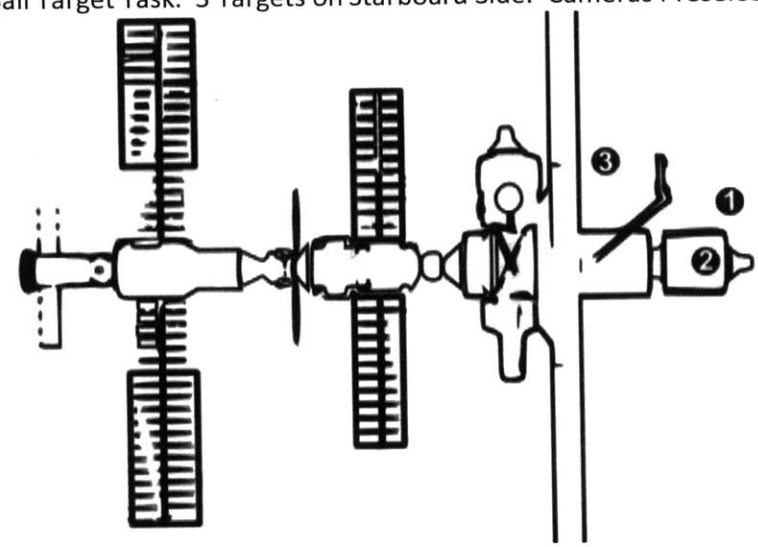
"You're doing great, now it's going to get a little harder. The ring targets require you to line up the end effecter so that you are going through the ring perpendicularly. There is a little wiggle room, so it doesn't have to be perfect. After this trial, we will mix the balls and rings together"

Have the subject keep practicing until they feel comfortable flying the arm, or until the session time hits 2 hours and 50 minutes. Then you must stop the subject and have them fill out and sign the monetary compensation form before leaving. Also remind them when the next session will be.

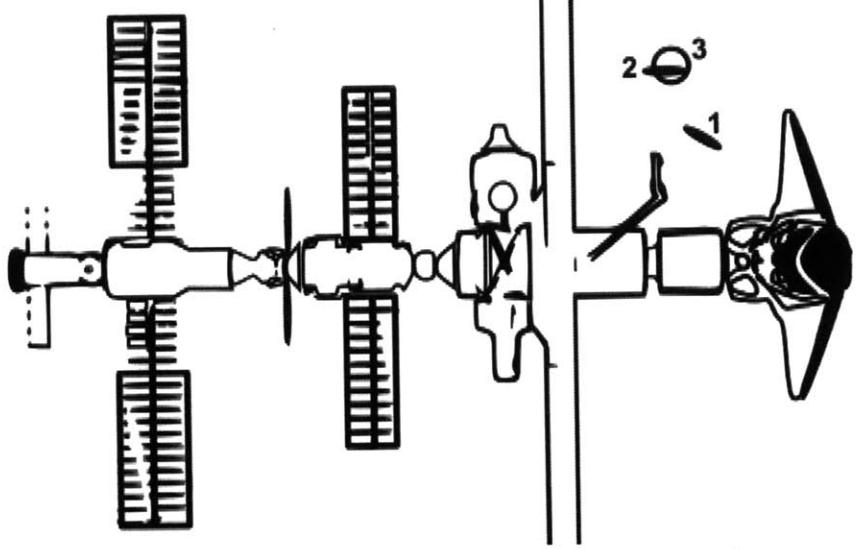
After the subject leaves, move all of the simulator data to the subject's folder, in a sub-folder labeled S1-DDMMYYYY. Back up the data.

>>>>>> TRAINING TRIALS <<<<<<

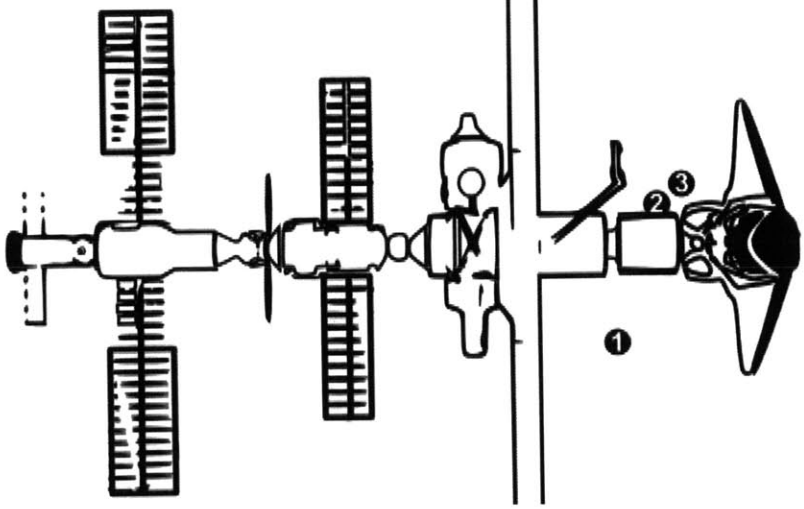
Trial 1: Simple Ball Target Task. 3 Targets on Starboard Side. Cameras Preselected



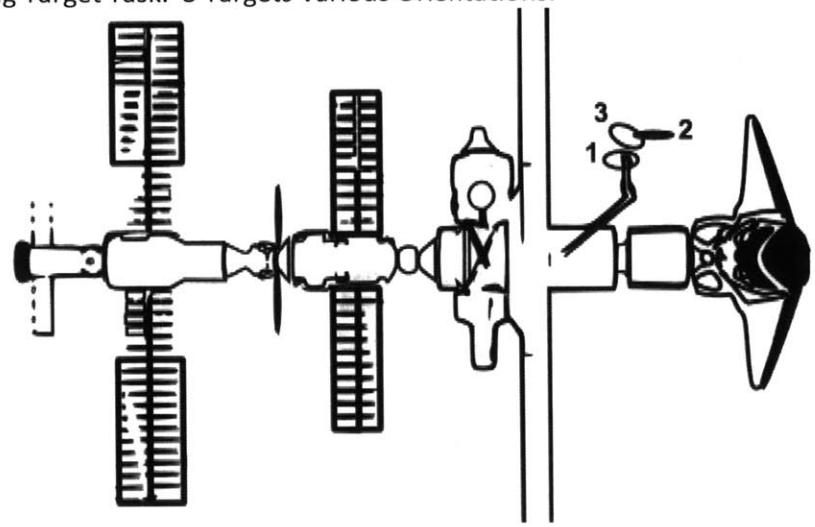
Trial 2: Simple Ring Target Task. 3 Targets on Starboard Side of Truss with varying orientations.



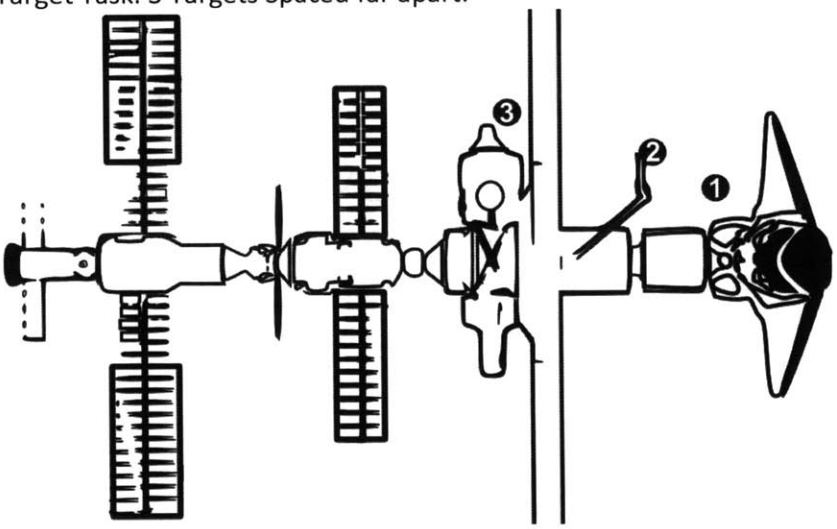
Trial 3: Simple Ball Target Task. 3 Targets at varying heights, clearance practice.



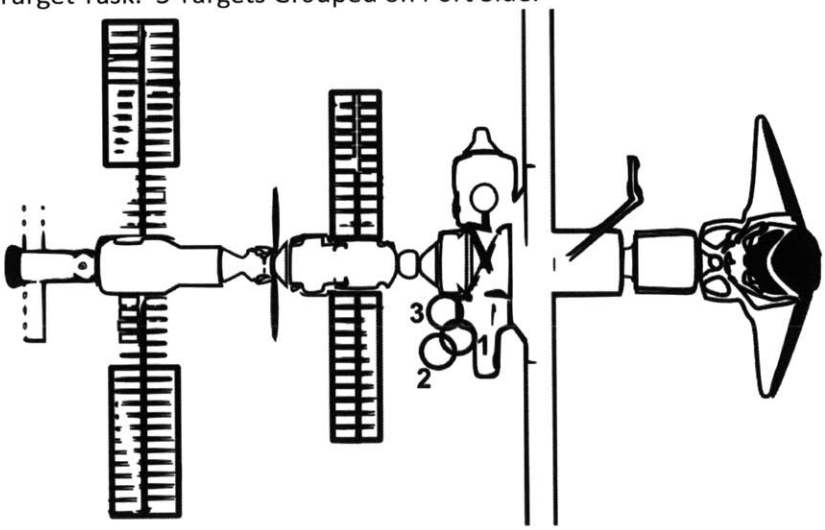
Trial 4: Simple Ring Target Task. 3 Targets Various Orientations.



Trial 5: Basic Ball Target Task. 3 Targets Spaced far apart.



Trial 6: Basic Ring Target Task. 3 Targets Grouped on Port Side.



Session 2: Basic Skills Robotics Training [3 hours]

In this session, the subject will be learning basic task skills, such as grappling and loaded flying. At the end of the session there is a preliminary evaluation. This session is the most content heavy, keep an eye on the time, it is easy to run over. Before the subject arrives, calibrate the arm, cue up the training slides and simulator, have the evaluation rubric printed out and a working pen. Have the back-up station running as well for the Instructor Example.

- Fly to and Grapple Training [1 hr]
  - Fly-to Review
  - Grappling Introduction
  - Hands on Training, Grappling [~40 min]
- Break [5min]
- Advanced Concepts Training [1 hr 20min]
  - C.F.R.M.
  - Camera Controls
  - Loaded Flight
  - Instructor Example [~8 min]
  - Hands on Training [~45 min]
- Break [5min]
- Preliminary Evaluation [30 Min]

Predicted Time: 3 Hours

When the subject arrives, welcome them back and ask them if they are ready for more training. Quiz the subjects on last session's topics. Jot down a quick grade for each question, A+, Check, Minus.

"I'm going to quiz you on some of the things you learned yesterday, don't feel pressured if you can't remember them, there will be review in the training slides. This is just for your benefit and to see what you remembered.

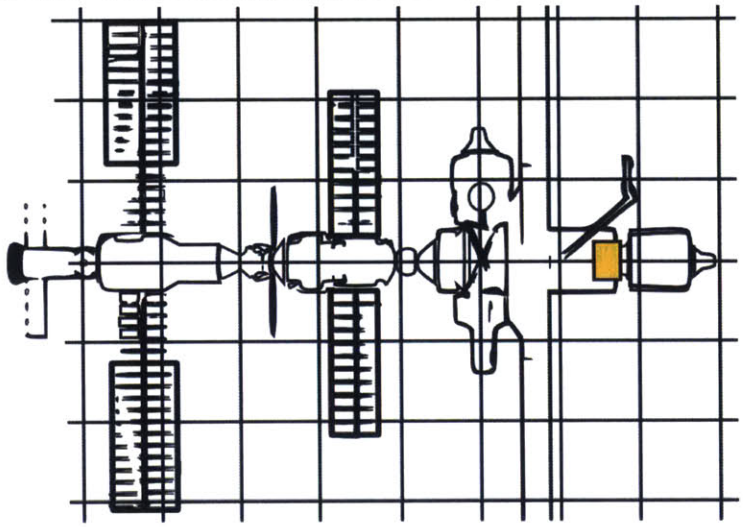
- In your own words, what is the difference between Internal and External Command Frames and when you use them?
- What is the name of the piece on the end of the arm?
- Can you tell me the directions of the ISS?" (Show subjects a map)
- "How much did you sleep last night?" (<, =, > 7-8 hours)

Have the subjects run through the PowerPoint slides for the day. Let the subject know that this is the most content heavy session; it will take the full 3 hours.

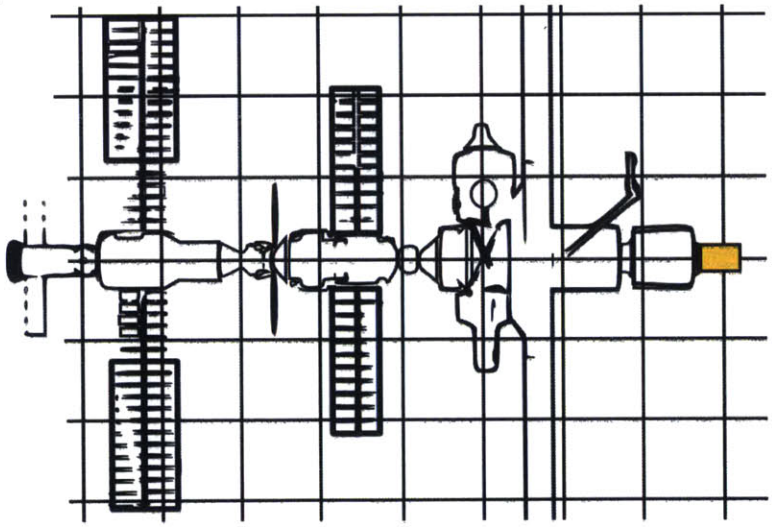
At the end of the "Fly-to and grapple" there are 6 training trials. Have the subject run through all of them. Make a note of how long the first trial lasts. When their performance improves, point out how much faster they have become.

>>>>>> GRAPPLE TRAINING TRIALS [Goal: 5 min / trial] <<<<<<

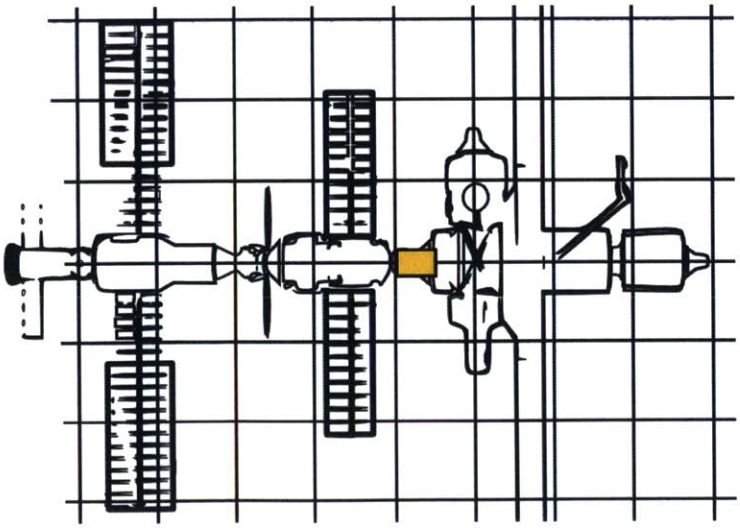
Trial 1: Simple Grapple Task. Target on Starboard Side on Node 1. Cameras Preselected



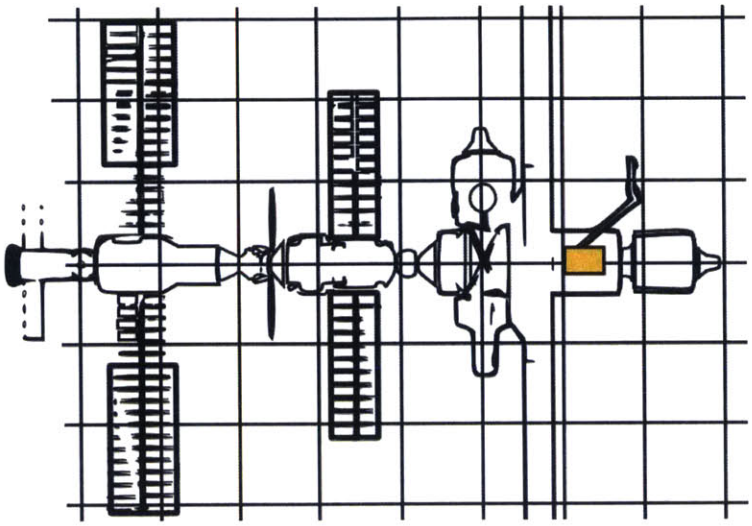
Trial 2: Simple Grapple Task. Target on Starboard Side on top of Shuttle Dock. Cameras Preselected



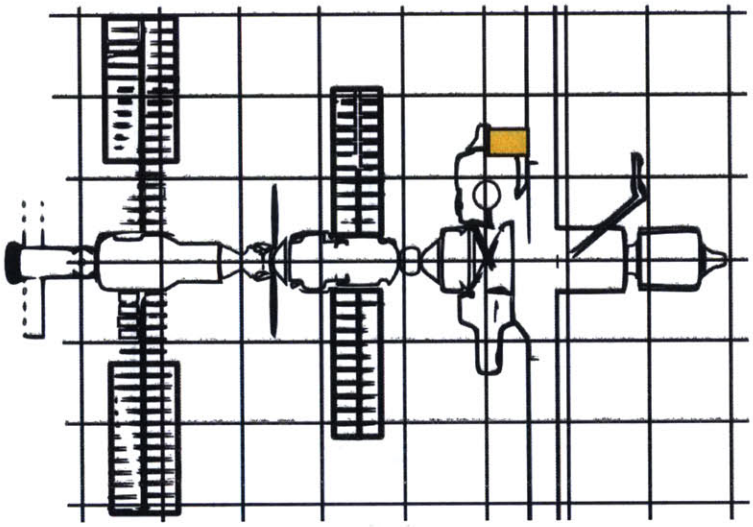
Trial 3: Simple Grapple Task. Target on Port Side on Connection to Russian Node. Cameras Preselected



Trial 4: Simple Grapple Task. Target on Starboard Side Node 1. Cameras Preselected



Trial 5: Simple Grapple Task. Target on Port Side of Truss. Cameras Preselected

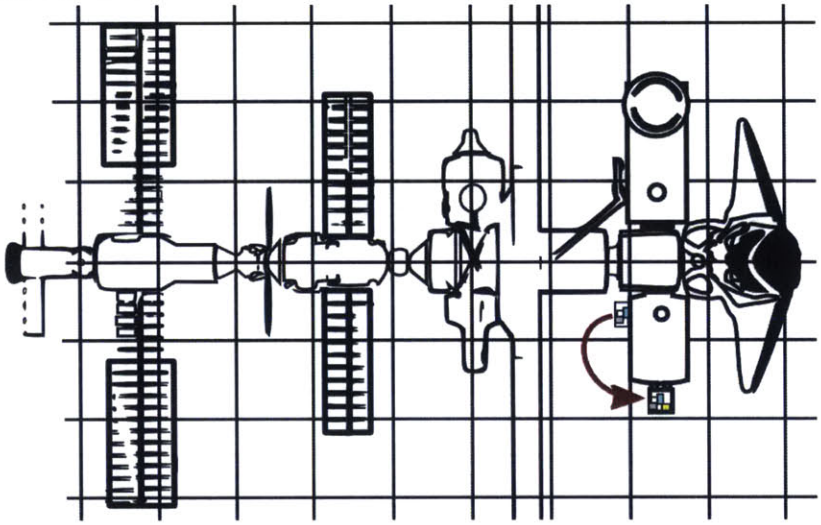


When they have completed all of the Grapple Tasks, offer the subjects a very short ~5 minute break (unless quite ahead of schedule). While they are gone, load the MIT-RfT_AdvTaskTraining.exp in the simulator. When the subject returns, have them begin the Advanced Concepts Slides.

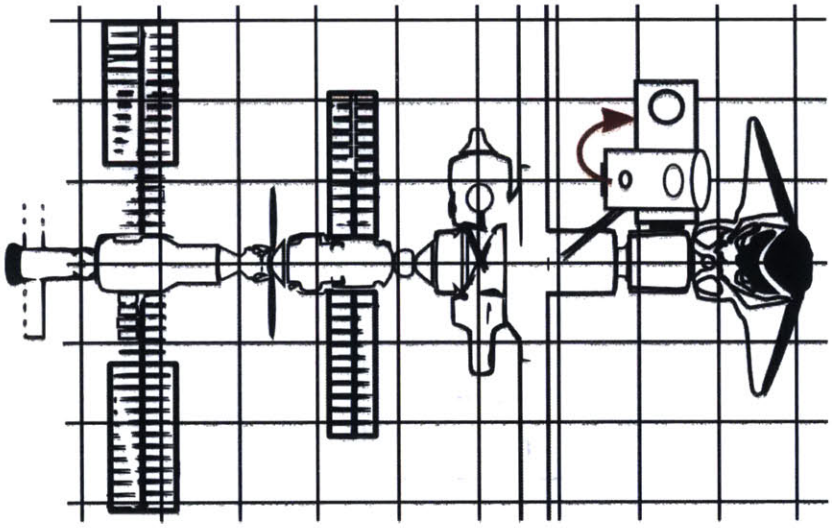
At the end of the Advanced Concepts Slides, there is an Instructor Example trial. Show the subject the "Best Technique" be overly verbal while you are flying so that they can get an understanding of "mutter mode" since this is how we will evaluate if they are doing "CFRM" and monitoring Singularities and Clearances. Then, have the subject complete their trials. Put on a stopwatch and warn the subject every five minutes. They should spend 5 minutes grappling and 5 minutes positioning the payload. It is ok to be over the time limits at the beginning, but at the end of the trials they should be close.

>>>>>> ADVANCED TRAINING TRIALS <<<<<<

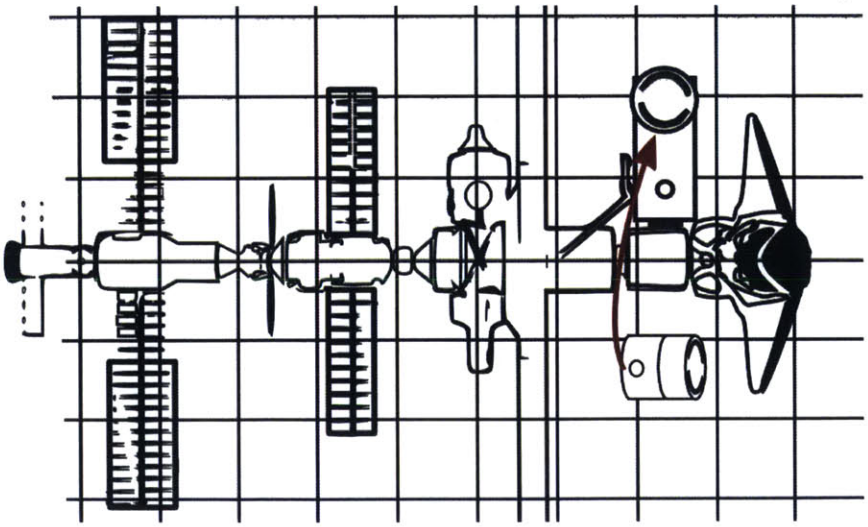
Example Trial: Moderate Advanced Task. Relocate EuTEF. Choose Cameras.



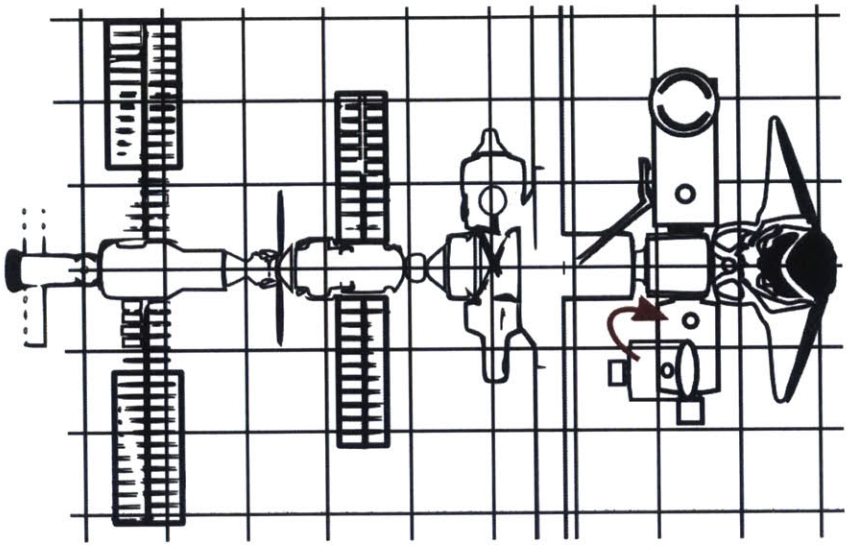
Trial 1: Advanced Task. Attach Columbus Module to ISS. Cameras Preselected - Subject must update



Trial 2: Basic Advanced Task. Attach Kibo node to ISS. Two Cameras Preselected - Subject must update



Trial 3: Moderate Advanced Task. Attach JEM to Kibo. Choose Cameras. Major Parallax on grapple.



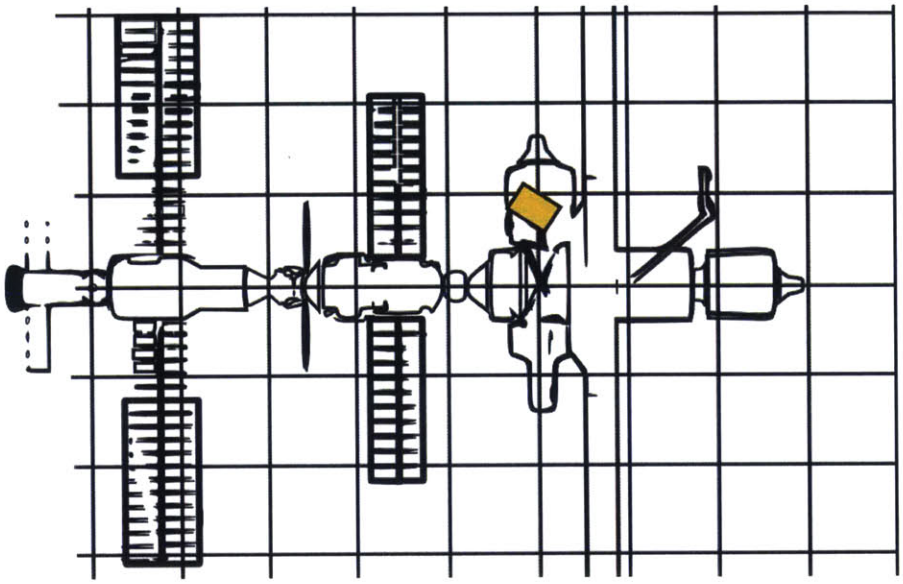
After they finish the trials, offer them a break ~10 minutes (if running behind, shorten). Let them know they will have a preliminary evaluation when they get back, so they can cogitate during the break.

Before the Evaluation begins, tell the subject what you are testing them on in the rubric. Let the subject know that you will be calling out every 5 minutes so that they can keep pace accordingly. Keep track of their time. Also tell them that, though you won't respond, they need to continue verbalizing. After the evaluation score the rubric while the subject fills out the monetary compensation form. The rubric is formatted so that it will be quick to score. If the subject has at least 50% performance, they can continue with the experiment. Let them know if they are welcome back before they leave.

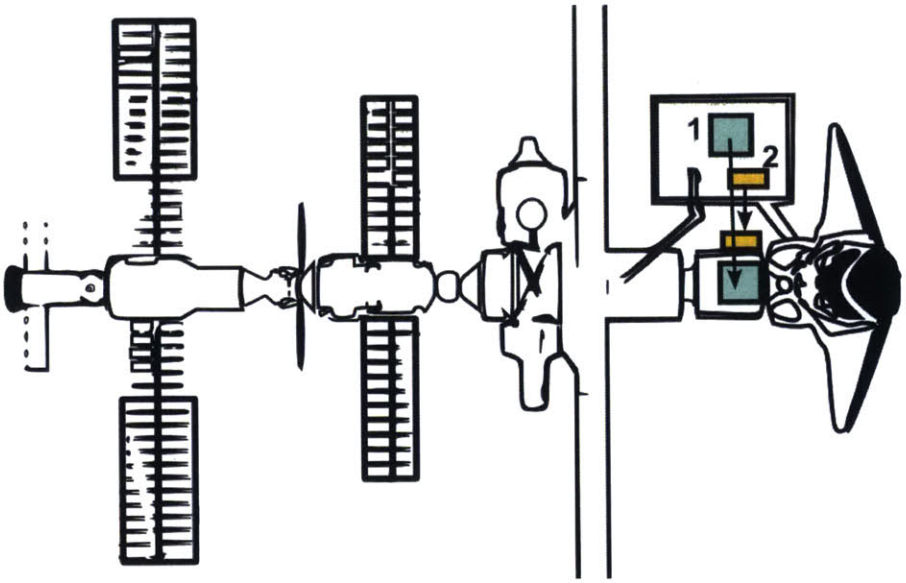
After the subject leaves, move all of the simulator data to the subject's folder, in a sub-folder labeled S2-DDMMYYYY. Back up the data.

>>>>>> PRELIMINARY SCREENING <<<<<<

Trial 1: Moderate Grapple Task. Target Located on P1 Truss. Cameras Preselected.



Trial 2: Basic Advanced Task. Relocate Two Payloads to Node 2 positions 1 & 2. Choose Cameras



Session 3: Task Specific Training [3 hours]

This session is also content heavy; the subject will be learning all of the task specific skills and procedures. Before subjects arrive, calibrate the arm, cue up the training slides and simulator (RfT_TrackCap-Training.exp). Also, be ready with the GCA scripts.

- Track and Capture Task [35 Min]
  - Grapple Review
  - Task Requirements
  - Hands on Training (10 Trials)
- EVA Support Task [1.5hr]
  - Fly to and Repair Task
  - Hands on Training
- Break 10 Min
- Side Task Training [30 Min]

Predicted Time: 2hr 45min

When the subject arrives, welcome them back and ask them if they are ready for more training. Quiz the subjects on last session's topics.

"I'm going to give you another small quiz. Remember, you're performance is not graded; we just want to get an idea of how much you remember.

- What are the 3 flight rules?
- Before you begin moving the arm, what are the four settings you need to check (CFRM)?
- What are the three types of camera views that you should have?
- How much did you sleep last night?"

The first task the subject will learn is the Track and Capture. This task can be very difficult the first time around, let the subject know it's OK if they miss some trials, there will be more practice time later.

- Before the third trial, Tell subjects to look at monitor 1 & 3 to get a better sense of which direction the HTV is rotating.
- On the forth trial, if they have been coming up short, tell them to push the THC all the way in and correct on the fly while they are moving. Complement subjects on Bi-manual control and smooth inputs.
- On the fifth trial, if the timer runs out and they are perfectly aligned, tell subject there is a bit of wiggle room and they don't have to be perfect to grapple.
- If they still haven't gotten one by trial eight, coach them through the trial.

>>>>>> TRACK AND CAPTURE TRAINING TRIALS <<<<<<

Trial 1: Target has No Drift : No Spin	Trial 2: Up Left Drift : Pitch
Trial 3: Up Left Drift : Yaw	Trial 4: Up Left Drift : No Spin
Trial 5: Up Right Drift : Pitch	Trial 6: Down Left Drift : Yaw
Trial 7: Down Left Drift : Pitch	Trial 8: Up Right Drift : Yaw
Trial 9: Down Right Drift : Pitch	Trial 10: Up Right Drift : No Spin

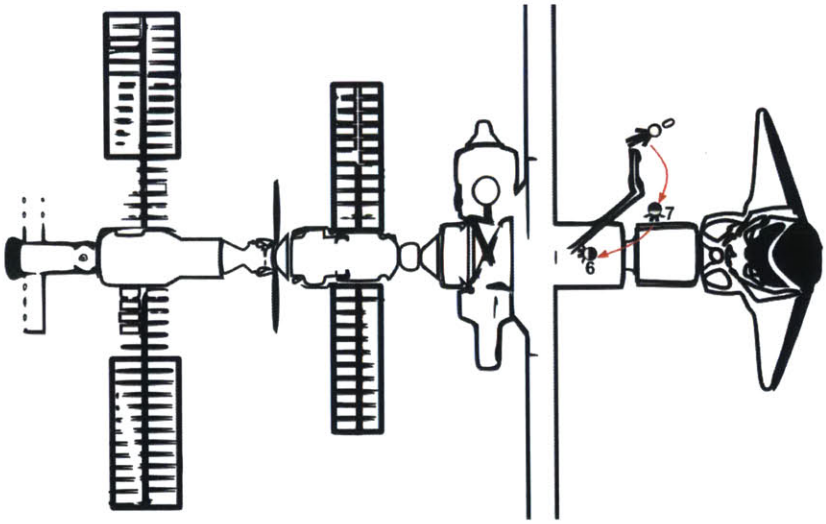
They may take a 10 minute break either before or after the EVA training.

EVA support is less time critical. Inform the subject that time is still important to their final score, and they should be aim for less than 15 minutes for each EVA trial (supply 5 minute time cues during the trials). You will be in charge of issuing the GCA commands for the subject; there are scripts for each trial. Try to keep to the script, but if that would cause a collision, you may improvise, but write down what you said in the EVA GCA sheet. An appropriate change would be translating forward 0.5m instead of 1m to avoid collisions. Do not skip a direction: you may reverse the command if required, i.e. you move 0.5m aft instead of 1m forward.

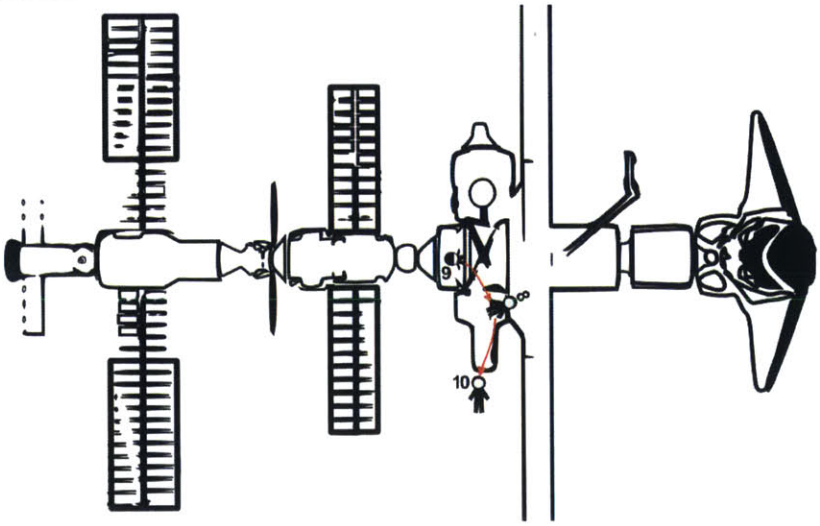
The Power Point steps through the first trial. Have the simulator up and running, and be sure the subject is going through the trial. (If they really want, they may read through the section and return)

>>>>>> EVA SUPPORT TRAINING TRIALS <<<<<<

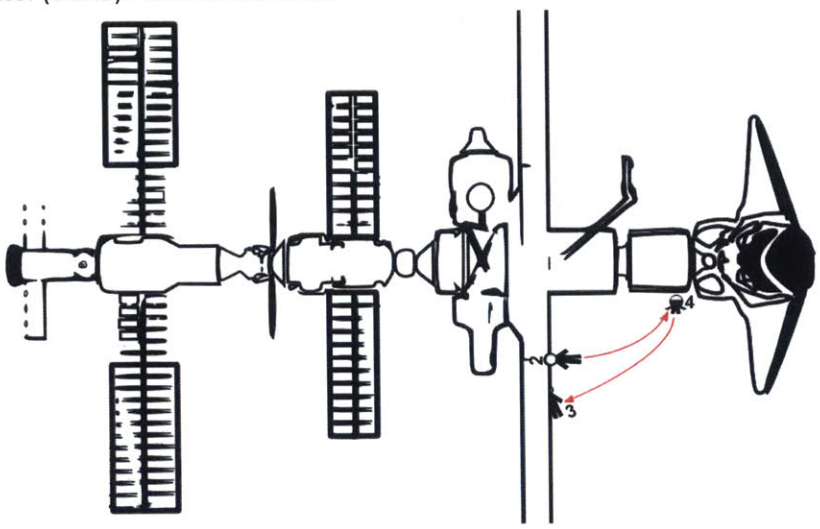
Trial 1: Example EVA Trial. Move Astronaut to Poster Placement (EVA7), then to SSRMS Base (EVA6). Choose Cameras



Trial 2: Basic EVA Trial. Help astronaut to repair S1 Truss (EVA8), then to Lower Airlock (EVA10). Choose Cameras



Trial 3: Basic EVA Trial. Help astronaut to repair Node 2 Aft Berthing Fixture (EVA4), then to Airlock Under Truss. (EVA3). Choose Cameras



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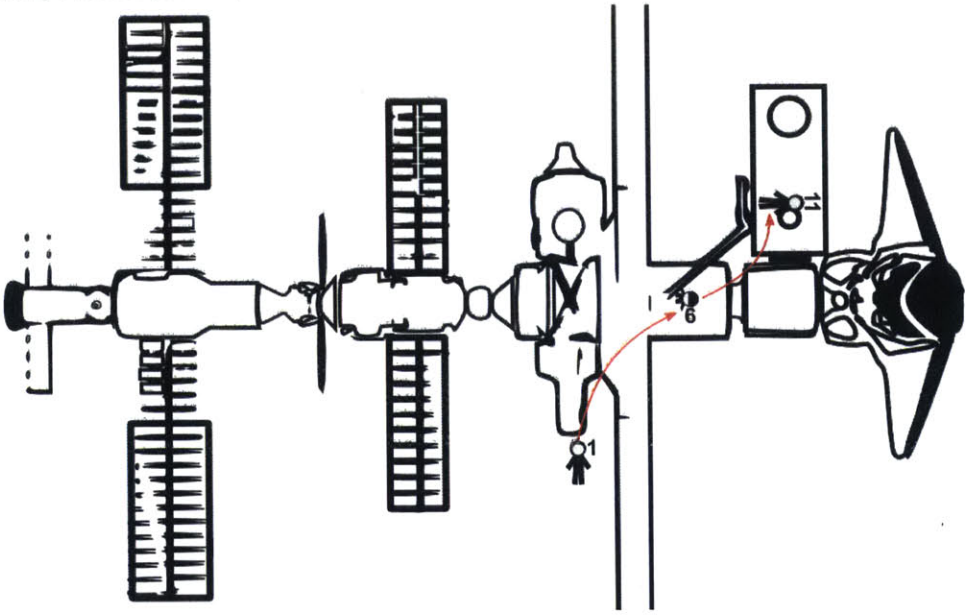
Trial 4: Moderate EVA Trial. Assist astronaut in maintenance of SSRMS Base (EVA6), then to Kibo Zenith Berthing Fixture (EVA11). Choose Cameras



After the EVA support training, the subject will learn the side task. If the experiment is running long, it is OK to cut short the side task practice trials. The subject must complete at least three T&C and one EVA trial before leaving. Have subject sign the monetary compensation form.

After the subject leaves, move all of the simulator data to the subject's folder, in a sub-folder labeled S3-DDMMYYYY. Back up the data.

>>>>>> SIDE TASK TRAINING TRIALS <<<<<<

Trials 1 – 5: Track and Capture Training (Half of original T&C trials)

Trial 1: Target has No Drift : No Spin

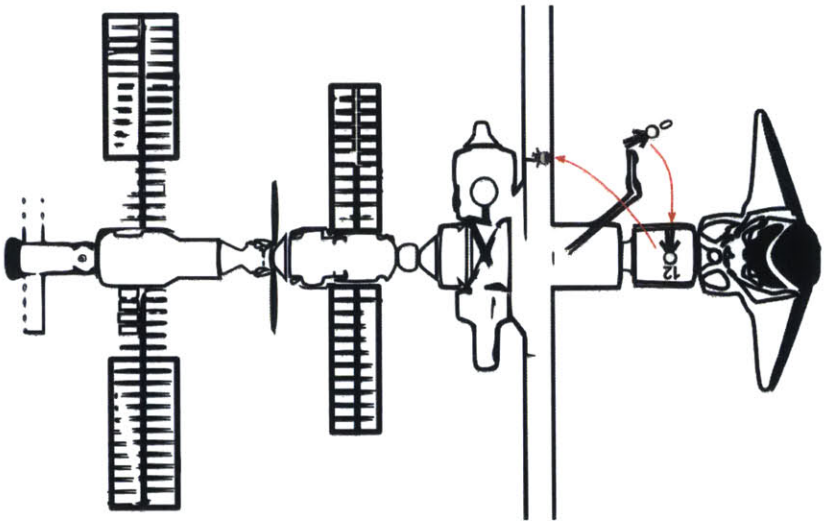
Trial 2: Down Right Drift : Pitch

Trial 3: Down Right Drift : Yaw

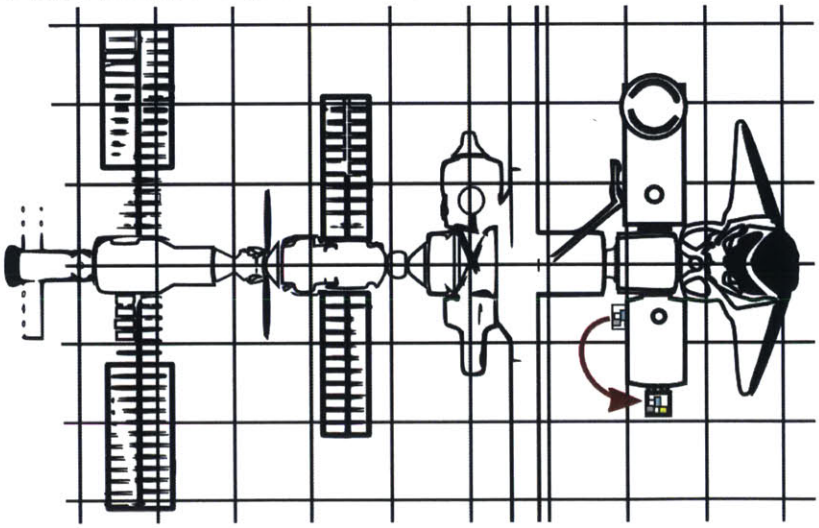
Trial 4: Left Up Drift : Pitch

Trial 5: Right Up Drift : Yaw

Trial 6: EVA Support Trial: Move Astronaut to Node 2 Zenith Berthing Fixture (EVA12), then to S1 Truss (EVA15). Choose Cameras



Example Trial: Moderate Advanced Task. Relocate EuTEF. Choose Cameras.



Session 4: Strategy Practice & Training Video [3 hours]

This is the final training session. We focus here on flying strategies: there are 5 strategies outlined in the PPT for the day (<20min on each). If the subject will be recording a refresher video, they will make it after the strategy training. Before the subject arrives, calibrate the THC, cue up the training slides and simulator. If applicable, have the video camera charged and the SD card empty, have Windows Movie maker up and running.

- Strategy for Flight [1hr 30min]
  - Singularity & Clearance Tips
  - Reducing Task Time
  - Practice on "Difficult" Trials
- Break 15 min
- Make Refresher Video OR Extra Practice Time [1hr]
  - Record 3rd P. Perspective video, subjects choose trials
  - 30 min on laptop to edit in Movie Maker

Predicted Time: 2hr 45 min

When the subject arrives, greet them as always, and then give them a small quiz on the Task specific training.

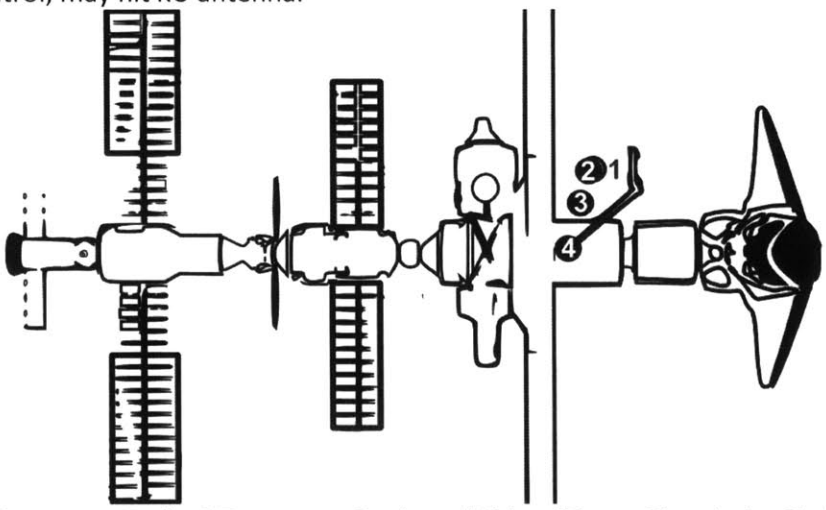
"Welcome to the final training session. I'm just going to ask you two questions this time, again don't worry about your performance, it is just to see what you remember.

- How long do you have to grapple the HTV in a Track and Capture trial?
- What frame of reference does the Astronaut use in the repair commands?
- What is the point of the Side Task?" (reiterate that if they shouldn't respond if it will compromise primary task performance)
- "How much did you sleep last night?"

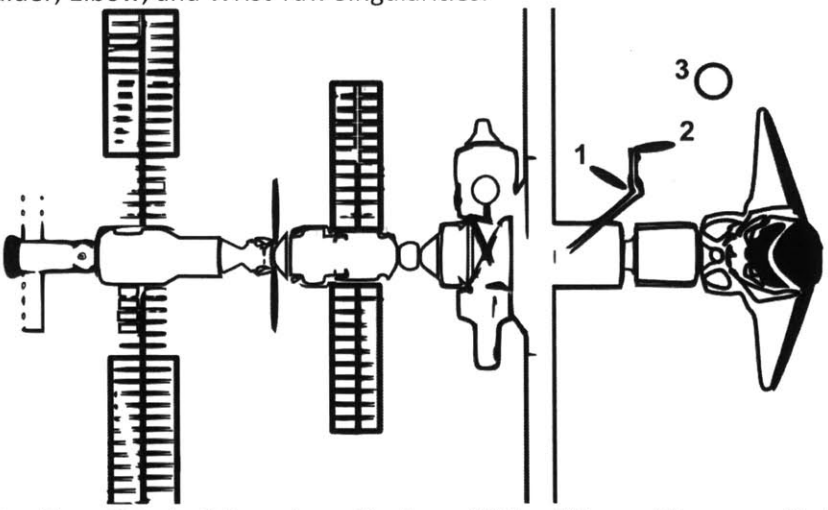
As the subject runs through the strategy training, answer any questions that come up. Make sure they are completing the trials that are associated with each strategy, and not just reading the whole PPT at once. There are 6 trials in the training file, one for each strategy and a final very difficult trial. The strategy trials are more complicated "target practice" trials with the same format as the basic training trials. If the subject cannot find the next target, have them use the overhead camera, number 12, to locate the target. Once they locate it, the subject must switch back to the regular camera views.

>>>>>> TRAINING TRIALS <<<<<<

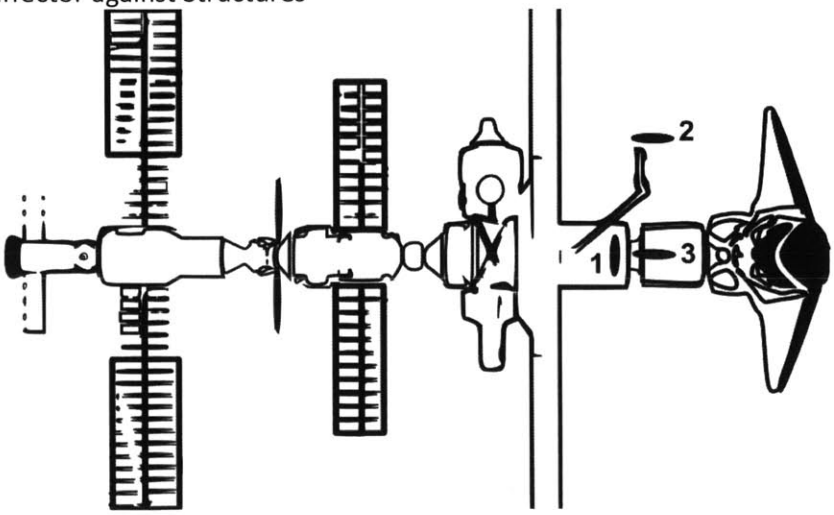
Trial 1: Difficult Ball Target Task. 3 Targets on Starboard Side of Truss. Movement Challenge: Difficult Elbow control, may hit KU antenna.



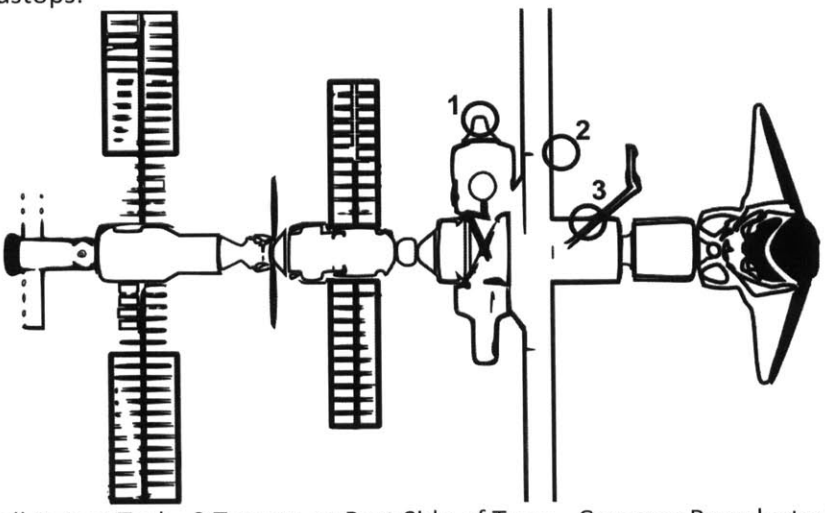
Trial 2: Difficult Ring Target Task. 3 Targets on Starboard Side of Truss. Singularity Challenge: Wrist Over Shoulder, Elbow, and Wrist Yaw Singularities.



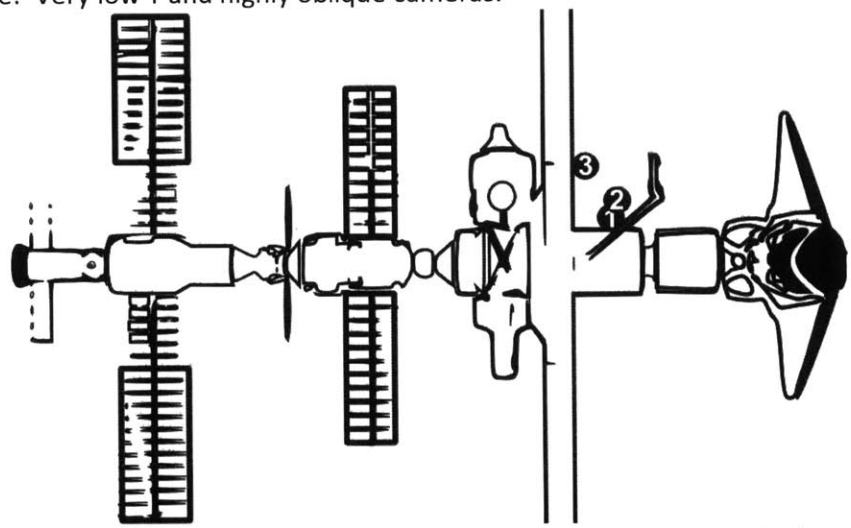
Trial 3: Difficult Ring Target Task. 3 Targets on Starboard Side of Truss. Clearance Challenge: Booms and End Effector against Structures



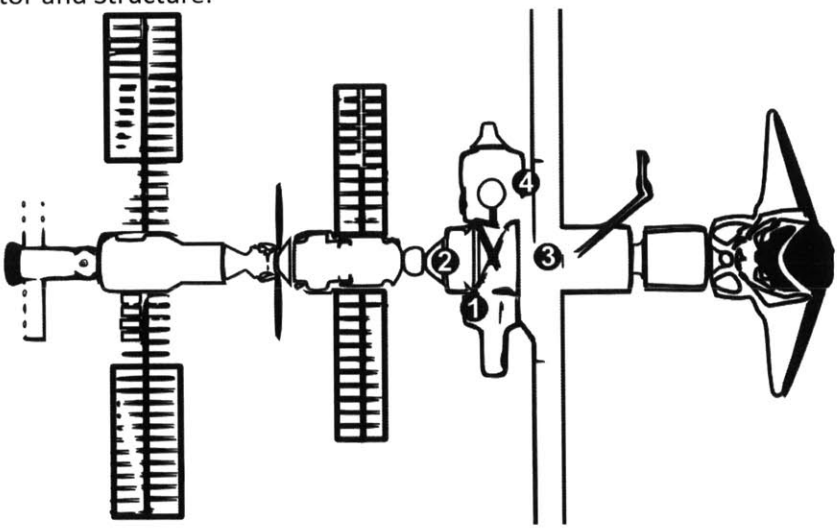
Trial 4: Difficult Ring Target Task, 3 Targets. Quick Movement Challenge: Very difficult Wrist Yaw Joint Angle Hardstops.



Trial 5: Difficult Ball Target Task. 3 Targets on Port Side of Truss. Cameras Preselected. Parallax Challenge: Very low Y and highly oblique cameras.



Trial 4: Difficult Ring Target Task. 3 Targets along Node 2. Cameras Preselected. Clearance Challenge: End Effector and Structure.



After the strategy training, offer the subject a 10 minute break. While they are gone, set up the video camera (if applicable).

If the subject is making a video, ask them what they would like to record. It may be trials, playing with the arm model, snapshots of PPT slides. Assist in recording, but do not tell them what to say or do. Don't talk during recording; it will be very loud on playback. You may ask if they want a close up on something. Once they have all of the footage they need, plug the SD card into a laptop and have them edit the movie in Windows Movie maker. If the subject is not comfortable using the software, you may assist, have them direct you as to the order of the video. Keep them on track time wise, the video should be no more than 10-15 minutes long. They may also not continue editing past the session time limit. Before they leave, have them fill out the monetary compensation form. Save the video and export it. Move the video to the subject's folder and the data to a subfolder named S4-DDMMYYYY. Back up the data. Clear the SD card.

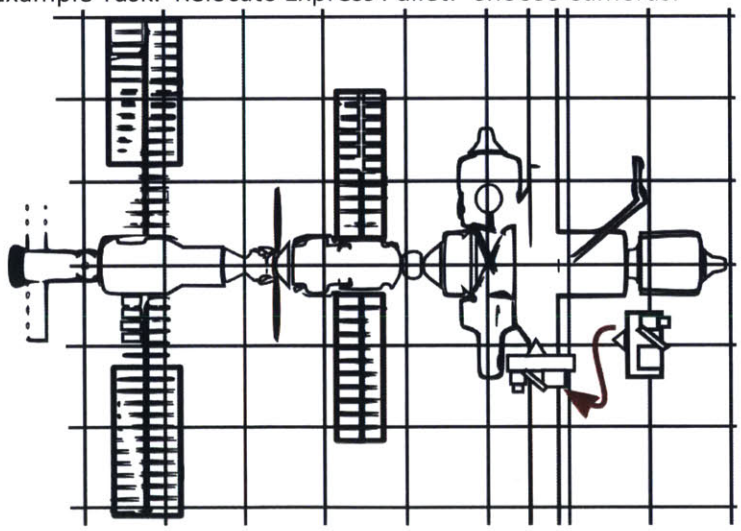
If the subject is not making a video, have them tell you which type of trials they would like to practice, or if there are any PowerPoints they would like to study. Because we are trying to keep the amount of exposure to the material constant over the two groups, remind them that they will be paid for staying and practicing. If they wish to leave, they may leave after the 2hr mark (the last half hour is video editing for the other group and not necessarily helping them train). Have the subject fill out the compensation form. Move the data to a subfolder S4-DDMMYYYY, back up the data.

>>>>>> ADDITIONAL TRAINING TRIALS <<<<<<

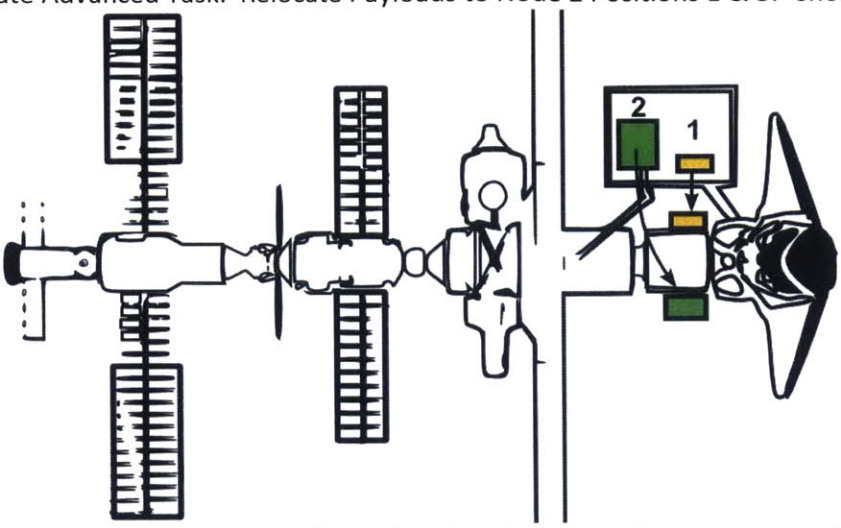
Track and Capture: Use Original T&C File

Trial 1: Target has No Drift : No Spin	Trial 2: Up Left Drift : Pitch
Trial 3: Up Left Drift : Yaw	Trial 4: Up Left Drift : No Spin
Trial 5: Up Right Drift : Pitch	Trial 6: Down Left Drift : Yaw
Trial 7: Down Left Drift : Pitch	Trial 8: Up Right Drift : Yaw
Trial 9: Down Right Drift : Pitch	Trial 10: Up Right Drift : No Spin

Advanced Task Training: There are 2 more unique trials that the subject hasn't completed:
Option 1: Instructor Example Task. Relocate Express Pallet. Choose Cameras.

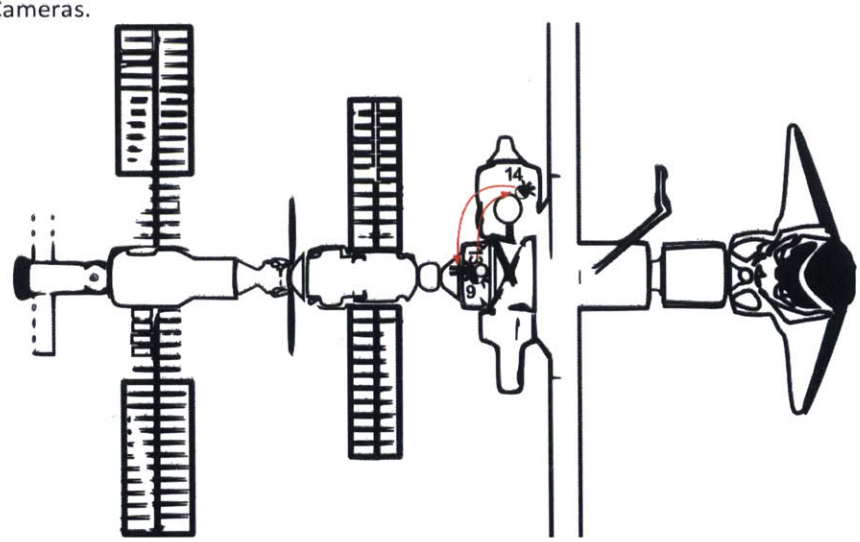


Option 2: Moderate Advanced Task. Relocate Payloads to Node 2 Positions 1 & 3. Choose Cameras.

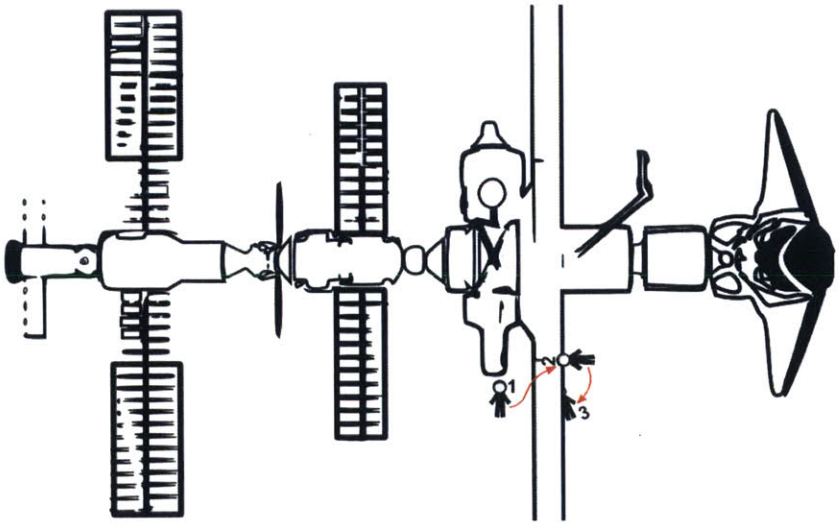


EVA Support Training: There are 2 more unique trials that the subject has yet to complete:

Option 1: Moderate EVA Support Task. Move astronaut to repair KU antenna (EVA14) then back to CMG (EVA13). Choose Cameras.



Option 2: Basic EVA Support Task. Move astronaut to repair S1 Truss (EVA2) then to Airlock(EVA3). Choose Cameras.



Session 5: Training Evaluation [2 hours]

This is the final evaluation of the Subject's peak performance after training. There will be a very brief review and the evaluation. Before the subject arrives, cue up the simulator, review slides and refresher video. Set up the video camera and make sure the SD card is blank. Have the questionnaires and evaluation form printed out, along with two working pens.

- Quick Review Session [30 min]
  - Questionnaire
  - Review PPT
  - Refresher Video
- Break [5 min]
- Evaluation [1 hr]

Predicted Time: 1 hour 35 minutes

When the subject arrives, greet them and have them fill out the post training questionnaire. After they finish, have them read through the brief review PowerPoint, then the refresher training video. After the retraining, give them the pre-Evaluation questionnaire. Then have them sit down for the evaluation. Explain to the subject that the video camera is present so a secondary instructor will be able to evaluate their performance independently, and the scores will be averaged. Warn the subject that you will not be able to respond to questions during the evaluation, but they should still verbalize during the trials.

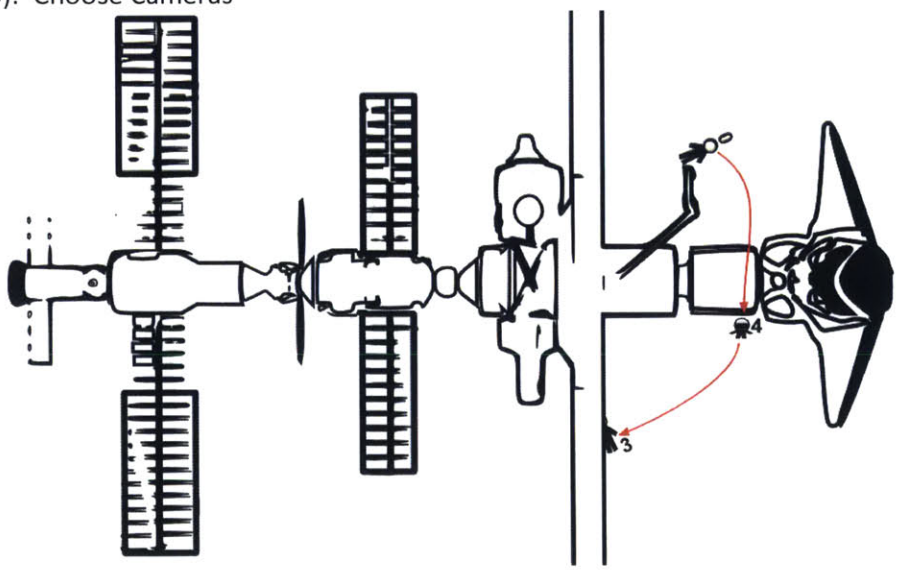
During the evaluation, fill out the rubric. Don't give feedback to the subject but don't make it seem like you are disapproving either (my GRT evaluator was grumpy; it made me super nervous that I was messing up and hurt my performance). Do not score the evaluation until later.

>>>>>> EVALUATION <<<<<<

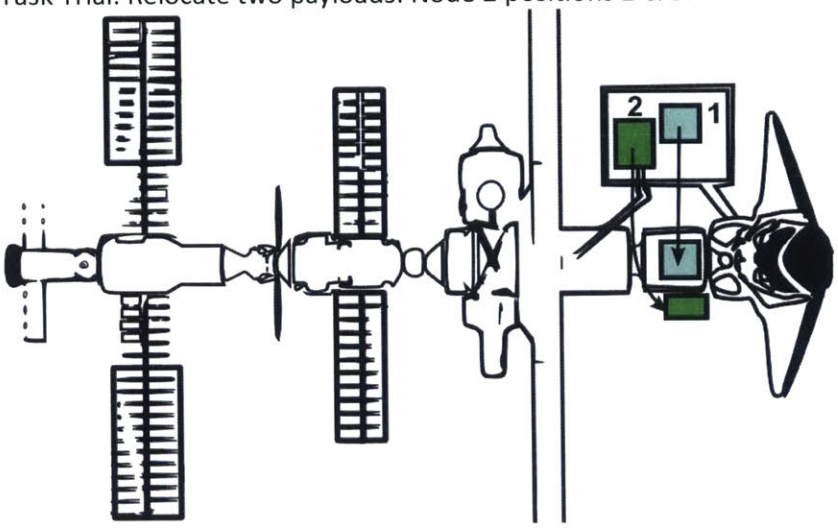
Trials 1 – 6: Track and Capture Training. Cameras Preselected

Trial 1: Up Left Drift : No Spin
Trial 2: Up Right Drift : Yaw
Trial 3: Up Right Drift : Pitch
Trial 4: Down Left Drift : No Spin
Trial 5: Up Left Drift : Yaw
Trial 6: Down Left Drift : Pitch

Trial 7: EVA Support Trial: Move Astronaut to Node 2 Port Berthing Fixture (EVA4), then to Airlock (EVA13). Choose Cameras



Trial 8: Advanced Task Trial: Relocate two payloads: Node 2 positions 2 & 3. Choose Cameras



Trials 9 – 14: Track and Capture Training. Cameras Preselected

Trial 9: Up Right Drift : No Spin

Trial 10: Down Right Drift : Yaw

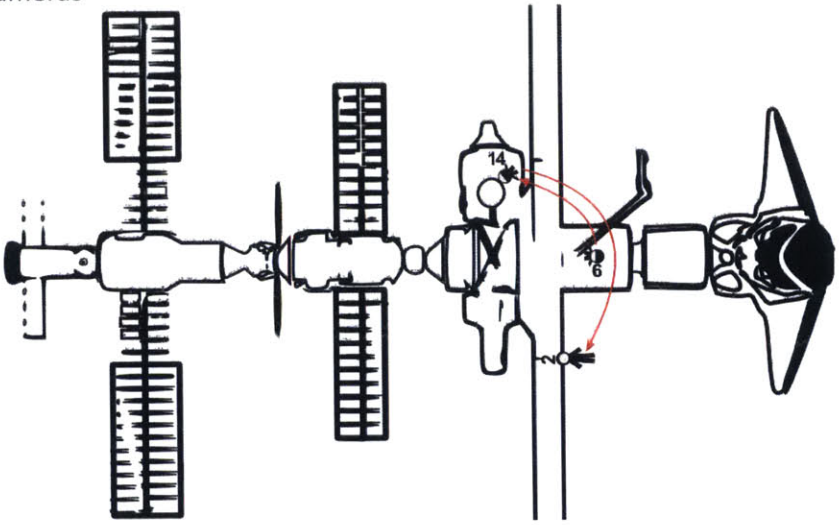
Trial 11: Down Right Drift : Pitch

Trial 12: Down Left Drift : Yaw

Trial 13: Up Left Drift : No Spin

Trial 14: Up Left Drift : Pitch

Trial 15: EVA Support Trial: Move Astronaut to KU Antenna (EVA14), then to SSRMS Base (EVA6). Choose Cameras



When the subject finishes, have them check the contact information is correct so that we may schedule part two in six months. Remind them they will get a retroactive $3 more per hour spent when they come back (14x3 = $42 + $18 = $60 for the final visit). Have them fill out the compensation form and post evaluation questionnaire before leaving.

After they have left, move all data and the evaluation video to the subject's folder in a subfolder named TE-MMDDYYYY. Back up the data. Place the evaluation rubric in the subject's manila folder. Wipe the SD card.

Session 6: Return Evaluation [2 hours]

After six months (±9 days), the subject will return for a final evaluation. It is set up to almost exactly parallel the previous Evaluation session. Before the subject arrives, cue up the simulator, review slides or refresher video. Set up the video camera and make sure the SD card is blank. Have the return questionnaire, ILS and evaluation form printed out, along with two working pens. Also have the subject's ILS information sheet ready.

- Quick Review Session
  - Questionnaires [5min]
  - ILS Retest [15min]
  - Review PPT OR Refresher Video [20min]
- Evaluation

When the subject arrives, welcome them back. First have them fill out part one of the return questionnaire, then have them retake the ILS test. When they are finished, they get 20minutes of review time. If they are a control subject give them the review PowerPoint, cue cards, and procedures. If they are an experimental subject, they get to review their refresher training video and the procedures. As they are doing this, grade their new ILS results and add them to the ILS information sheet. After the retraining, give them the pre-Evaluation section of the questionnaire. Offer a bathroom break (they won't be able to leave during the evaluation). Then, have the subject sit down for the evaluation. Again, explain that the video camera is so that a secondary Instructor can evaluate their performance independently, and the scores will be averaged. Warn the subject that you will not be able to respond to questions during the evaluation, but they should still verbalize during the trials.

During the evaluation, fill out the rubric. Don't give feedback to the subject.
Don't score the evaluation until later.

When the subject finishes, have them fill out the post evaluation questionnaire. Then congratulate them on completing the experiment, and give them their ILS information sheet. Have them fill out the compensation form before leaving.

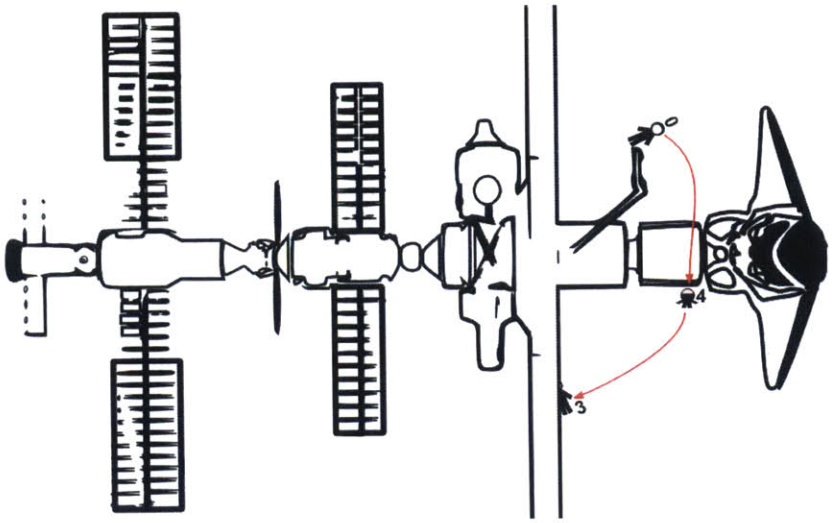
After they have left, move all data and the evaluation video to the subject's folder in a subfolder named RE-MMDDYYYY. Back up the data. Place the evaluation rubric in the subject's manila folder. Wipe the SD card.

>>>>>> EVALUATION <<<<<<

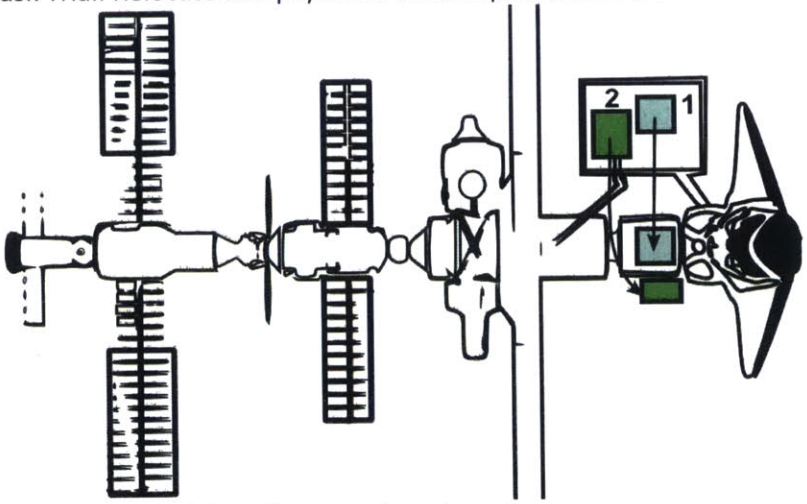
Trials 1 – 3: Track and Capture Training. Cameras Preselected

Trial 1: Up Left Drift : No Spin	Trial 2: Up Right Drift : Yaw
Trial 3: Up Right Drift : Pitch	Trial 4: Down Left Drift : No Spin
Trial 5: Up Left Drift : Yaw	Trial 6: Down Left Drift : Pitch

Trial 4: EVA Support Trial: Move Astronaut to Node 2 Port Berthing Fixture (EVA4), then to Airlock (EVA13). Choose Cameras



Trial 5: Advanced Task Trial: Relocate two payloads: Node 2 positions 2 & 3. Choose Cameras



Trials 6 – 8: Track and Capture Training. Cameras Preselected

Trial 9: Up Right Drift : No Spin

Trial 10: Down Right Drift : Yaw

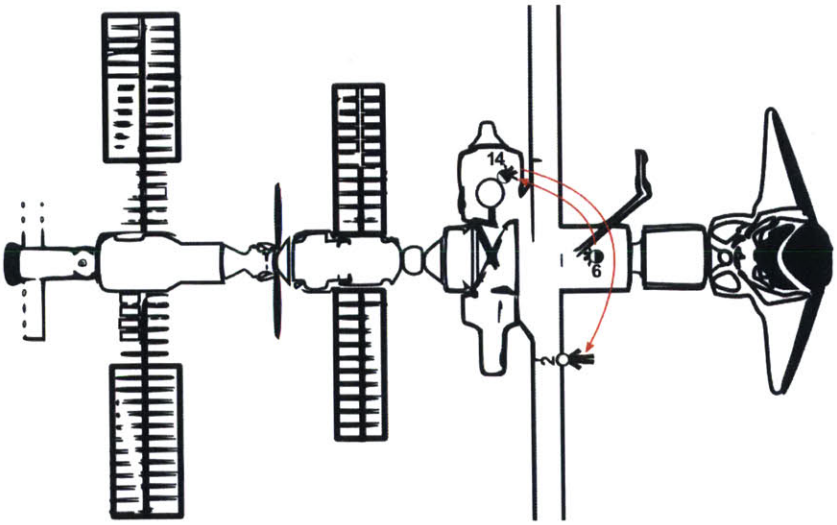
Trial 11: Down Right Drift : Pitch

Trial 12: Down Left Drift : Yaw

Trial 13: Up Left Drift : No Spin

Trial 14: Up Left Drift : Pitch

Trial 9: EVA Support Trial: Move Astronaut to KU Antenna (EVA14), then to SSRMS Base (EVA6). Choose Cameras



IV. Simulator Cheat Sheet

IV.A Debugging Simulator

If the simulator is not loading correctly:

1) Check that there are no blank lines in the Camera, Object, Joint Angle, or Experiment Files
2) Check that you have not accidentally hit 'Enter' somewhere in the simulator source code

If there is a window that says "Writing Data File" that last more than 30 seconds.

The sim has hit an error. In the command line you will need to pickle all data variables. Then reopen them once the subject has left to resave in the correct format.

IV.B Restarting Simulator

If you have restarted the simulator you have THREE options:

1) If you want to continue starting with the next trial:
   You should enter the same "Subject Name" when prompted. Select "Continue Next Trial" when asked (Second to last dialog box).
2) If you need to repeat the trial that you quit out of (i.e. the subject hadn't finished):
   You must enter a NEW "Subject Name" (ex. Sub1-Take2). Then use 'q' key to skip through to the trial you wish to start on. You will have to do post processing of the data files once finished.
3) If you need to restart all of the trials (or you are doing option 2 on the 1st trial):
   You should enter the same "Subject Name" when prompted and Select "No" when asked to Continue with Next Trial (Second to last Dialog box)

IV.C Simulator HotKeys

Key	Description	Trial Types
ESC	Escape from simulation. Will wrap up session and then quit	All
Shift + A	Open Autosequence menu	NA
b	Toggle **Brake**	All
Shift + D	End Trial "**Done**"	Adv Tsk
e	Enter **External** Command Frame	All
f	Change Frame rate in Debug Mode	Debug Mode Only
Shift + F	Change Frame rate in Debug Mode	Debug Mode Only
g	Grapple while in "Keyboard Controller" Mode	NA
i	Enter **Internal** Command Frame	All
l	Enter **Loaded** Mode, Follow with Weight ID	All but T&C
m	Send Message to Ground	EVA
q	Quit Trial - Skip to next	Only Training Trials
Shift + R	Reset the Arm	All
Shift + S	Sync Experiment Time	NA (For BWH Exp)
Shift + T	Turn off Side Task	Only Training Trials
u	Enter **Unloaded** Mode	All but T&C
v	Toggle **Veriner** Mode	All
Shift + X	Restart the Current Trial	Only Training Trials
0	Grapple while in "Keyboard Controller" Mode	NA
1	Change control to **Monitor 1**	All
2	Change control to **Monitor 2**	All
3	Change control to **Monitor 3**	All
F1	Change camera in **Monitor 1**	All
F2	Change camera in **Monitor 2**	All
F3	Change camera in **Monitor 3**	All
F4	Display Current Target Position	
F5	Display Monitor 1 Camera View Position	
F6	Check Distance to Grapple Pin	
F7	Toggle Full Screen	Debug Mode Only
F8	Take a Screen Shot	
F9	Pause HTV movement	
F11	Display Joint Angles	
F12	Display EE tip Position	

IV.D Acronyms

CFRM	Cameras, Frame of Reference, Rate of Motion, Mode (Un/Loaded)
Eu-TEF	European _____ Exposed Facility
EVA	Extra-Vehicular Activity
GCA	Ground Control Approach
HTV	H-II Transfer Vehicle
ILS	Index of Learning Styles
ISS	International Space Station
JEM-ELM	Japanese Experimental Module – Experimental Logistics Module
MRT	Mental Rotation Test
PPT	Power Point
PSVT	Perdue Spatial Visualization Test
PTA	Perspective Taking Ability
RfT	Refresher Training
RHC	Rotational Hand Controller
SpA	Spatial Ability
SSRMS	Space Station Remote Manipulator System
THC	Translational Hand Controller
T&C	Track and Capture

C.2 Training Slides

C.2.1 Session 1

Slide Notes:

S07: Point out the end effector view in the monitor

S09: Have subject identify links/joint on the screen. "Think of it like your own arm"

S12: Have subject identify what 1m is on monitor 3.

S17: Point out the Z1 truss on the first monitor

S18: If they ask, clarify port is left and starboard is right

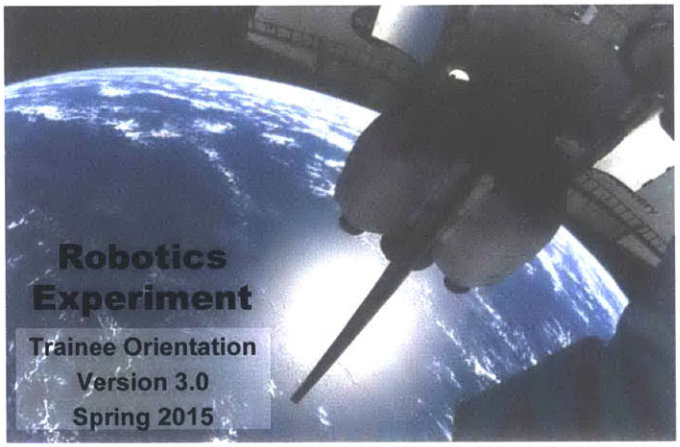
S19: Make sure they try pushing the controller in/out not just up/down

S20: Make sure they rotate all 3 axes

S21: Encourage multiaxis movement

S45: Use the plastic arm model to demonstrate the singularities and have them try it out.

S50: Compliment subject on control, keep an eye on the timer



Training Schedule

- Session 1: Overview
- Session 2: Basic Skills
- Session 3: Task Training
- Session 4: Strategy Practice
- Session 5: Final Evaluation

< 6 month break >

- Session 6: Return Evaluation

Session 1:
Overview and Initial Training

- Introduction to Simulator
- Arm Motion Concepts
- Hands on practice

Objective: You will learn how to move the robotic arm

Version 3.0 Spring 2015
MVL Robotics Experiment

The Simulator

The MVL SSRMS simulator was created to mimic the robotics training simulator used by astronauts at NASA. Our simulator has two main components:

The Virtual Environment

The International Space Station:

The Robotic Arm

The Space Station Remote Manipulator System (SSRMS):

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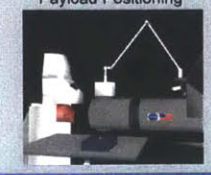
MVL Robotics Experiment

Your Role

You will have the role of an astronaut controlling the robotic arm for a series of tasks, which you will learn over the next few session.

The tasks include moving payloads and suited astronauts, and catching moving objects

Payload Positioning



Astronaut Support

Track and Capture

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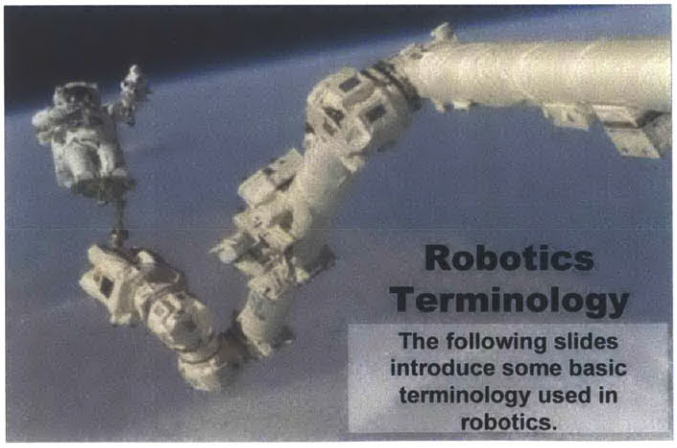
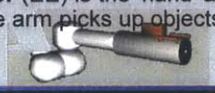


Robotics Terminology (1 of 5)

- **Links** are the rigid bars that form the robotic arm.

- **Joints** allow two links to rotate with respect to one another.

- The **End-Effector** (EE) is the 'hand' at the end of the arm. It is how the arm picks up objects.



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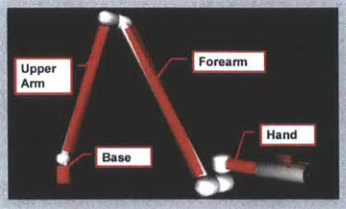
MVL Robotics Experiment

Robotics Terminology (2 of 5)

- The arm has:
  - 4 Links



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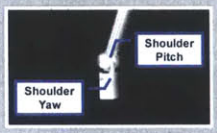
Version 3.0 Spring 2015
MVL Robotics Experiment

Robotics Terminology (3 of 5)

- The arm has:
  - 4 Links
  - 6 Joints



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Version 3.0 Spring 2015
MVL Robotics Experiment

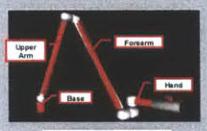
Robotics Terminology (4 of 5)

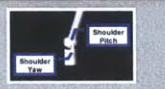
- The arm has:
  - 4 Links
  - 6 Joints
  - and a BREAK that may be toggled on/off by pressing '**b**'.

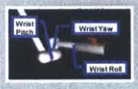
BRAKE ON

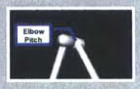
Brake indicator in lower right corner of screen disappears when brake is off.

The brake must be off in order for the arm to move.









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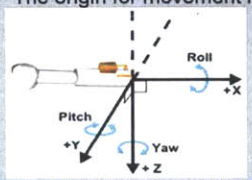
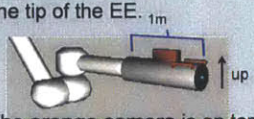
Robotics Terminology (5 of 5)

- The Space Station Remote Manipulator System (SSRMS) Simulator is a 6-degree of freedom robotic arm. This means it can move in 6 directions: x, y, z & pitch, yaw, roll.
- All arm movement is based off of the End-Effector.
- The origin for movement is at the tip of the EE.





- The **orange camera** is on top.
- The arm is 17m long when fully extended, and the end-effector is 1m long.

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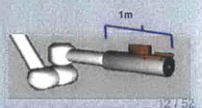
Terminology Recap

- The arm is made up of 4 **Links** and 6 **Joints**.
- The brake should be applied whenever the arm is not in motion.
  - Press '**b**' to toggle the brake on/off.

BRAKE ON

- The end-effector may move left/right, up/down, forward/backward or may pitch, yaw, or roll.
- The arm is 17m long when fully extended, and the end-effector is 1m long.



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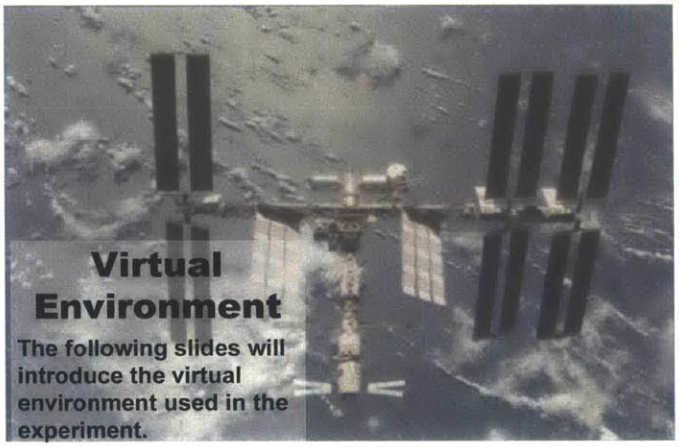

Virtual Environment

The following slides will introduce the virtual environment used in the experiment.

Virtual Environment:
The International Space Station

The ISS, has 3 types of components:

- Modules
- Truss & Solar Arrays
- Robotic Arm

Because there is no "Up" in space, we must define the coordinates of ISS.

The directions used in the simulation are the same as on a ship

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International Space Station Components

- **Modules**
  - The habitable space of the station.
  - Located on the port/starboard axis of the ISS in this simulation.

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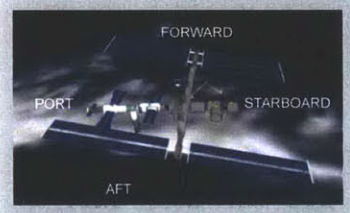
International Space Station Components



- **Truss and Solar Arrays**
  - The truss is mounted at the starboard end of the modules in this simulation, oriented along the forward/ aft axis of the ISS.
  - The large solar arrays are mounted on the truss.

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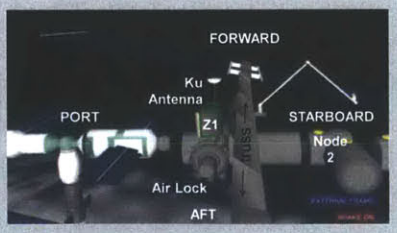
International Space Station

Anatomy of the Truss



- A useful cue for determining which side of the truss you are looking at is the Z1 truss (green box) with the Ku-band antenna (white dish).
- Note that the Z1 is located on the port side of the truss in this simulation.

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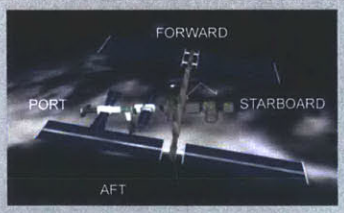
Virtual Environment Recap



- ISS components include modules, the truss and solar arrays, and the robotic arm.
- In this simulation:
  - -The modules are located on the port/starboard axis of the ISS.
  - -The truss is oriented along the forward/aft axis.
  - -The Z1 truss with the Ku-band antenna is located on the port side of the truss.

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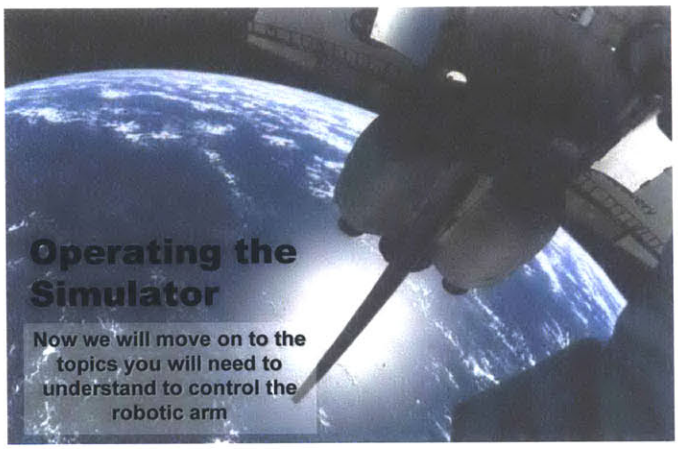

Operating the Arm

To control the arm you will need to understand:

- The Hand Controllers
  - What is bimanual control, how do I move the arm with two joysticks?
- Reference Frames for Movement
  - How does the joystick input map to the arm movement?
- View Points
  - Why do we have three monitors?
- Arm Limitations
  - Every mechanical system has it's limits.
- Flight Rules
  - What are the safety precautions and rules we must follow?

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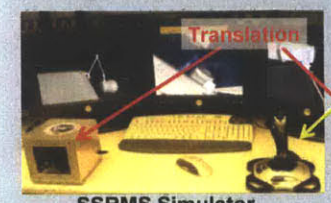
The Hand Controllers

- Telerobotics use Bimanual Control, one hand controls Translations and the other controls rotations. This is the same way the Lunar Module was landed on the moon.



SSRMS Simulator

Apollo Lunar Lander

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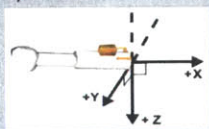
Translational Hand Controller (THC)

Using your **left hand,** you will control the THC.

This ***moves*** the end-effector in X, Y, and Z.



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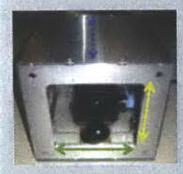
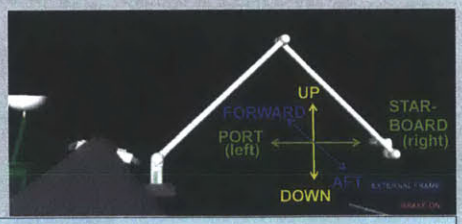
Try It Out - Translation





- Press '**b**' to disengage the brake.
- Move the controller left/right, up/down, and in/out.
  - Notice that the orientation of the end-effector does not change when you use the translational hand controller.
  - Watch all of the joints to ensure they do not collide with other objects.
- When done, press '**b**' to engage the brake.
  - Remember to always use the brake when not actively moving the arm.

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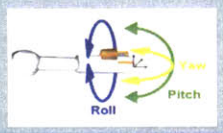
Rotational Hand Controller (RHC)

Using your **right hand,** you will control the RHC.

This ***rotates*** the arm about the tip of end-effector in Pitch, Yaw, and Roll.



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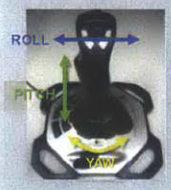
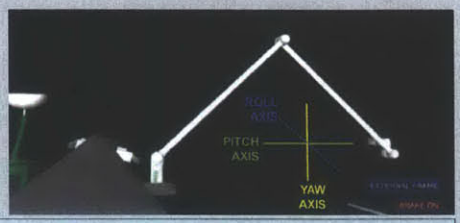
Try It Out - Rotation





- Type 'Shift+r' to reset the arm's position. Press '**b**' to disengage the brake.
- Push right to roll around the end-effector tip; push left to return to the starting position.
- Twist to input yaw and push forward and backward to input pitch.
- Engage the brake when finished.

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Evaluating Hand Controller Use

- It is important to make **smooth** movements with the hand controllers. Quick motions could damage a robotic arm, wearing out the motors. Ramp In and Out slowly.
  - ➢ **You will be judged poorly for jerky movements**
- It is often desirable to move in more than one axis at once. This is called **multi-axis control** and increases the efficiency of the movement.
  - ➢ **Your percentage of multi-axis control will be recorded**

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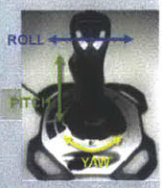
Hand Controllers Recap

- Left hand controls translation, moving the tip of the end-effector.
- Right hand controls rotation, rotating the arm about the tip of the end-effector.
- Make smooth movements with the hand controllers.



- Move in more than one axis at a time.
- Always use the brake when not paying attention to or actively controlling the arm.
- Monitor all views while controlling the arm; do not focus solely on the end-effector.

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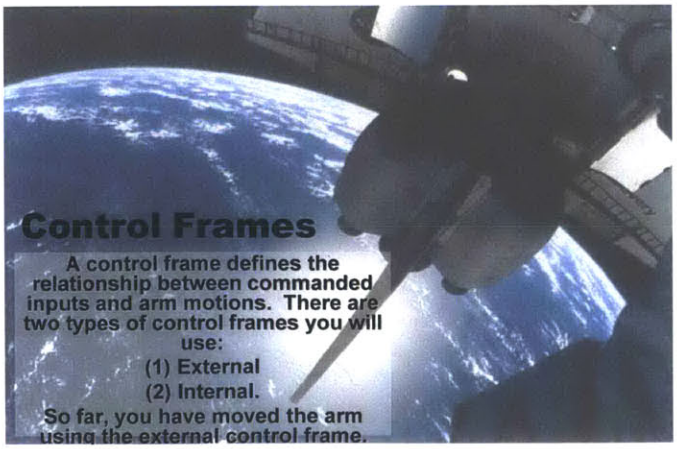


Control Frames

A control frame defines the relationship between commanded inputs and arm motions. There are two types of control frames you will use:

(1) External

(2) Internal.

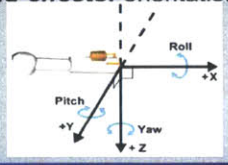
So far, you have moved the arm using the external control frame.

Control Frame

The selected control frame tells the arm software how to map your hand controller input to the arm movement.

In ***External Frame***, arm movement is aligned to ***ISS*** coordinates.

In ***Internal Frame***, arm movement is aligned to ***end-effector*** orientation



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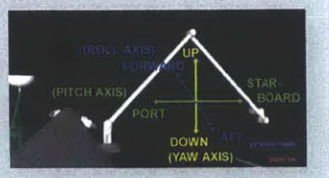
External Control Frame

- An ***external*** frame is fixed with respect to the environment.
  - Directions are permanently aligned with the ISS.
  - Forward and aft are along the truss.
  - Port and starboard are along the core modules.
  - Zenith (Up) and Nadir (down) are above and below the station.



- Generally, you will use an external frame when making large arm movements
- Rotations are still about the EE, but the rotation axes are aligned to the ISS.
- Recall:
  - The Z1 truss with the Ku-band antenna is located on the port side of the truss. When attempting to orient yourself in the external frame, it may be useful to imagine yourself in the environment, facing forward along the forward/aft axis.

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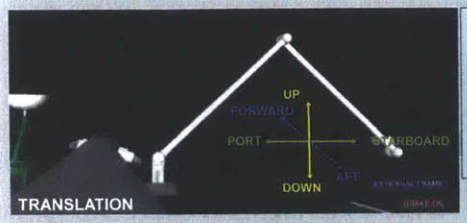
Try it Out – Translation, External Control Frame



- Press 'Shift+r' to reset the arm.
- Make left/right, up/down, and forward/aft movements with the translational hand controller.
- Did you remember to engage the brake?

Motion may not be intuitive, depending on the camera view.

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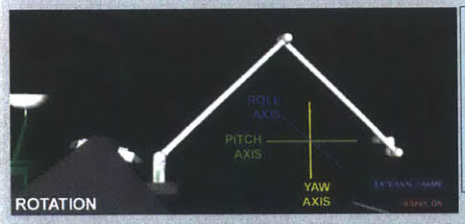
Try it Out – Rotation, External Control Frame



- Press 'Shift+r'.
- Make positive and negative pitch, yaw, and roll movements with the rotational controller.

- Remember that the controller causes rotation about a single axis – rotations are linked to axes, not specific joints.

Did you press 'b' when done?

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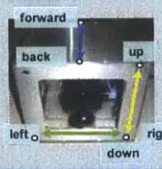
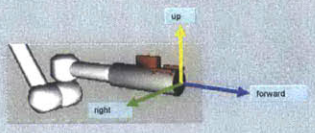
Internal Control Frame

- *Internal* frame is fixed to the tip of the end-effector.
- Generally you use an internal frame for small movements when aligning to grab objects.
- Use the orange Camera to help you remember which side is up on the EE





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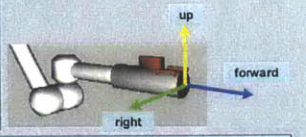
Try it Out - Translation Internal Control Frame

- Press 'Shift+r' to reset the arm.
- Press 'i' to switch to the internal control frame.
  - ➢ Note that the frame indicator in the lower right corner of the left monitor has changed to "internal".



- Make left/right, up/down, and forward/backward movements with the translational hand controller.
  - ➢ Motion is intuitive through the end-effector camera view.

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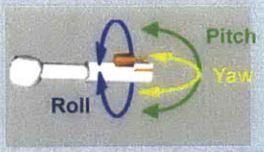
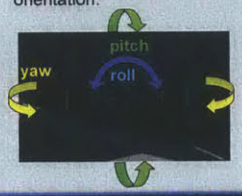
Try it Out - Rotation Internal Control Frame

- In the internal control frame, hand controller inputs produce the same end effector motion regardless of end effector orientation.





Use the rotational controller to become familiar with pitch, yaw and roll in the internal control frame.

- ➢ Motion is intuitive through the end-effector view.

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Control Frame Recap

External frame is fixed with respect to the ISS.

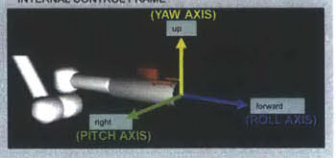
- Use the external frame when making large arm movements.

Internal frame is fixed to the tip of the end-effector.

- Use the internal frame for small movements and alignment.

EXTERNAL CONTROL FRAME

INTERNAL CONTROL FRAME



- Press '**e**' to switch into the
- Press '**i**' to switch into the internal

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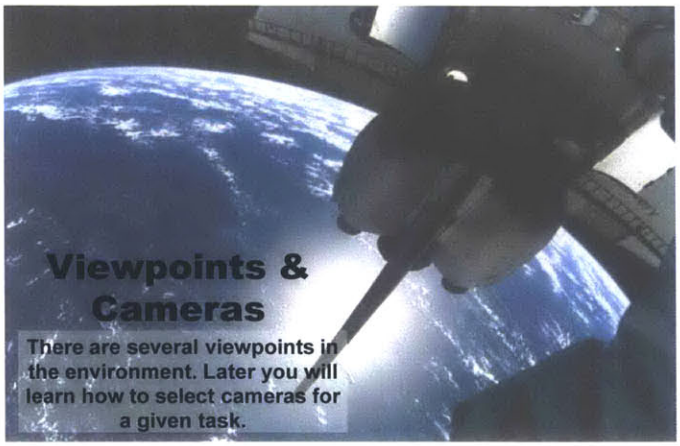

Views

There are 3 types of camera views:

1) **Big Picture** – whole arm and work area
2) **Clearance** – view to avoid collisions, showing structures that may be in the way of the arm or payload. Keep an eye on the elbow joint
3) **Task** – end-effector or intuitive view, used to provide a more detailed image of the current task. The end-effector view includes cross-hairs centered on the screen for alignment over objects.

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Views

- As you fly the simulator, scan all of the monitors and make sure the arm is moving in the way you want. And keep an eye out that you won't hit anything
- End-effector motion may appear different depending on the camera orientation.
- It is important to monitor all three views in order to fly safely and accurately.
- In the next session, you will learn how to switch your cameras to different views.
- **Never** let any part of the arm out of view.

Watch the Elbow!

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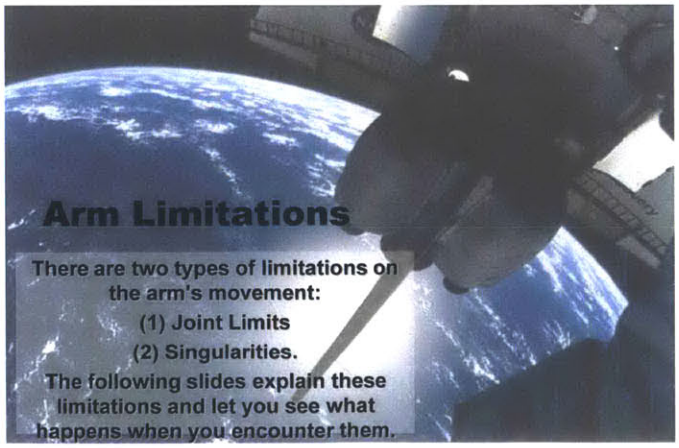

Joint Limits

The arm joints have a finite range of motion:

- A **hard-stop** is the limit on how far a joint can rotate.
- If you hit a hardstop, the following message will be displayed:

HARDSTOP

- If you hit a hardstop; move in the reverse direction to free the arm.

- Hardstops count against you during evaluations

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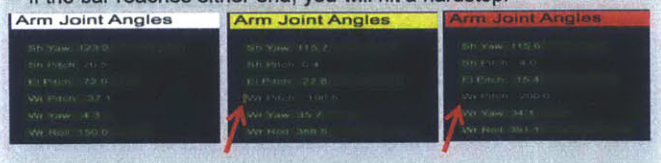
Joint Angle Display

- In the bottom left corner, you will see a slide bar for each joint on the arm. As you move the arm, these bars will change.
- If the bar reaches either end, you will hit a hardstop.



- During training, when you get close to a hardstop, the bars will turn yellow to help you get used to watching for hardstops
  - During Evaluations, they will not turn yellow

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Try It Out – Hardstops

- Press 'Shift+r' to reset the arm.
- Roll the rotational hand controller to the right and hold it there.
  - Watch the arm rotate around the end-effector until it hits the hardstop.
  - Notice the warning displayed on the screen.
  - Notice how the sliders change color as you approach the hardstop.
- Rotate in the opposite direction to recover the arm.
- Engage the brake.

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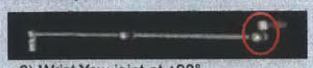
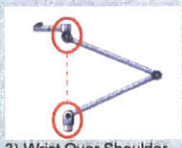
Singularities

The arm also has kinematic limitations, known as **singularities**. At a singularity, some directions of motion are not possible.

1) Elbow Pitch joint at 0° or ±180°



2) Wrist Yaw joint at ±90°



3) Wrist Over Shoulder

Play with the plastic arm model, and see how each singularity works

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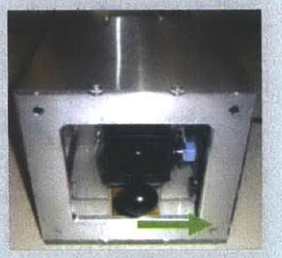
Try It Out – Singularities

- These steps will let you see what happens when you reach the elbow pitch singularity:
  - Press 'Shift+r' to reset the arm.
  - Disengage the brake.
  - Push the translational hand controller to the right and hold it there.
- Watch the arm move until it reaches the singularity.

Singularity

  - Push the controller to the left to recover the arm
  - Engage the brake.



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Arm Limitations Recap

- Joints have a finite range of motion; a **hard-stop** is the limit on how far a joint can rotate.

HARDSTOP

- The arm has three kinematic limitations, known as **singularities**:
  1) Elbow Pitch joint at 0° or ±180°
  2) Wrist Yaw joint at ±90°
  3) Wrist over Shoulder

SINGULARITY

- Monitor all three views and pay attention to what each of the arm's joints is doing, not just to where the end-effector is going.
- If you encounter a hardstop or singularity, reverse direction to free the arm.
  - ➢ Pressing 'Shift+r' will reset the arm, but be aware that during the evaluation, resetting the arm will hurt your score.

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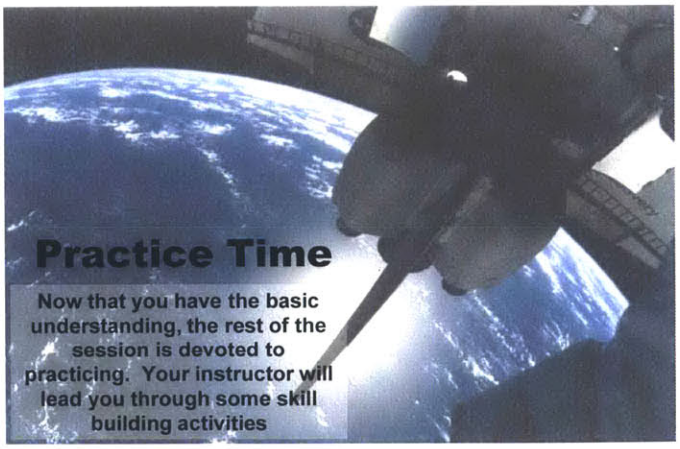

Review of Important Concepts

- Camera Viewpoints
  - The ISS environment has **multiple viewpoints**.
  - It is important to monitor big picture, clearance, and task views.
- Hand Controllers
  - ➢ **Translational** (box)
  - ➢ **Rotational** (joystick)
  - Use both at the same time, and move in multiple axes simultaneously whenever possible.
- Arm Limitations
  - **Hardstops** are the limit on how far a joint can rotate.
  - The arm's configuration includes three types of **Singularities**.
- Control Frames
  - **External** control frame axes are fixed to the ISS.
  - **Internal** control frame axes are fixed to the tip of the end-effector.

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Practice

Now that you have a basic understanding of the arm, you will have up to 4 minutes to gain some hands-on experience.

Try it out:

- Use both hand controllers at once, move the arm intentionally
- Discover how the arm responds to various controller inputs.
- Focus on making **smooth** motions.
- Practice **multi-axis** movement.
- Remember to **monitor all three views**.
- If you encounter a hardstop or singularity, reverse direction to free the arm.

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Training Schedule

- ✓ **Session 1: Overview**
- **Session 2: Basic Skill**
  - **Fly-to and Grapple**
  - **Advanced Concepts**
- **Session 3: Task Training**
  - **HVT Track and Capture**
  - **EVA Astronaut Support**
- **Session 4: Strategy Practice**
  - **Singularity & Clearance Tips**
  - **Reducing Task Time**
- **Session 5: Final Evaluation**

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HANDS ON PRACTICE

The Training PowerPoint is now complete. Feel free to look back through the material and ask questions.

Let your instructor know when you are ready to move on.

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C.2.2 Session 2

Slide Notes: S14: Make sure to point out that the end effector camera is on the top of the end effector so they don't try to grapple upside-down. Point out that the little pin is no the TOP and the big pin is on the BOTTOM of the grapple fixture.

S19: Point out that sometimes to correct for error they have to translate and rotate.

S28: When the subject completes the first fly-to phase, ask them to estimate how far they are from the pin. Then, press F6 to display distance to target.

S38: Show the subject the camera cheat sheet for use during the training

S51: Give the subject a few minutes to go to the restroom or study before starting the screening

Training Schedule

- ✓ Session 1: Overview
- ➢ Session 2: Basic Skills
- Session 3: Task Training
- Session 4: Strategy Practice
- Session 5: Final Evaluation

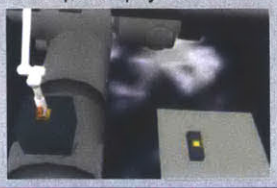
< 6 month break >

- Session 6: Return Evaluation

Session 2:
Basic Skills Training

- Recap Session 1
- Fly-to and Grapple Concepts
- Advanced Control & Loaded Flight

Objective: You will learn how to grapple and manipulate payloads



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Virtual Environment Recap

- ISS components include modules, the truss and solar arrays, and the robotic arm.
- The modules form the port/starboard axis of the ISS
- The truss is oriented along the forward/ aft axis.
  - The Z1 truss with the Ku-band antenna is located on the port side of the truss.
  - The grey US modules are on the starboard side of the truss.

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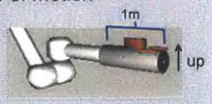
Robotics Recap

- The arm has 4 **links**, 6 **joints**, a brake, and the end-effector.
- The **end-effector** is 1m long with an orange camera on top.
- The **brake** should always be on when you are not moving the arm (toggle the brake with '**b**')
- **Hardstops** mark the end of a joint's range of motion
- The arm has three **singularities**:
  - 1) Elbow Pitch joint at 0° or ±180°
  - 2) Wrist Yaw joint at ±90°
  - 3) Wrist Over Shoulder



- Reverse direction to free the arm from a hardstop / singularity
- Pressing 'Shift+r' will reset the arm, but be aware that during the experiment, resetting the arm will hurt your score.

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Movement Recap

- Make **smooth** movements with the hand controllers.
- Move in more than one axis at a time.
- Always use the brake when not actively controlling the arm.
- Monitor all views while controlling the arm; do not focus solely on the end-effector.

The THC (Translation) is on the Left and **moves** the EE

The RHC (Rotation) is on the Right, and **rotates** the arm around EE

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Control Frame Recap

External frame is fixed with respect to the ISS.

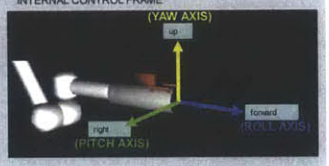
- Use the external frame when making large arm movements.

Internal frame is fixed to the tip of the end-effector.

- Use the internal frame for small movements and alignment.

EXTERNAL CONTROL FRAME

INTERNAL CONTROL FRAME



- Press '**e**' to switch into the external control frame.
- Press '**i**' to switch into the internal control frame.

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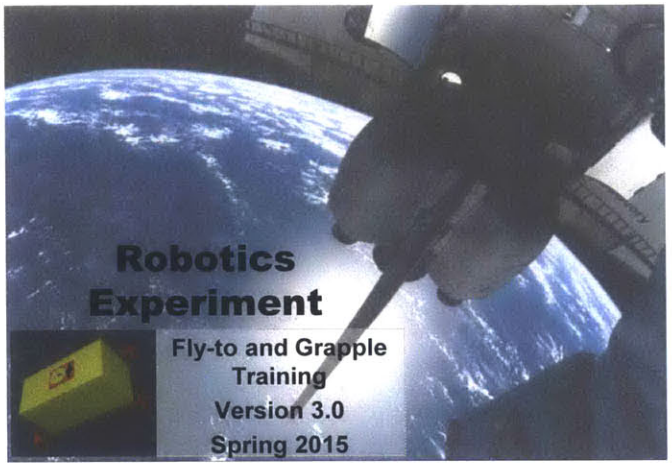

Objectives

Training Objectives:

- You will learn how to move the arm from one location to another near a target, called a fly-to.
- You will maneuver the arm into pre-grapple position.
- You will learn how to grapple (grab onto) the target.

The Fly-to and Grapple Task:

- Fly-to and grapple maneuvers are used to pick up objects, nodes, and cargo.
- The operator moves the arm from the starting position to the pre-grapple position, then grapples the target.
- The operator monitors the arm while flying to ensure there are no clearance violations or collisions.

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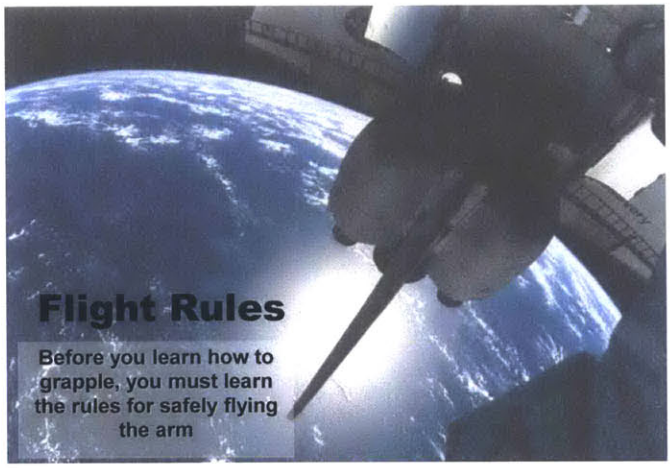

Flight Rules

In order to insure there are no accidental collisions with the arm, the following flight rules are in place:

1. When you are within 1 meters of any structure, you must operate in the slower "Vernier" rate, by pressing 'v'
2. There is a clearance limit of 0.6m between any part of the arm and ISS structure. Do not go break this limit unless grappling.
   - This warning will be shown when any part of the arm breaks clearance

     Clearance Violation

   - Look for the cause of the clearance violation and move away
   - If a collision occurs, this warning will be displayed on the screen:

     COLLISION

   - Remember that the arm can hit itself! Watch out for self-collisions
3. Apply the break when you are not operating the arm

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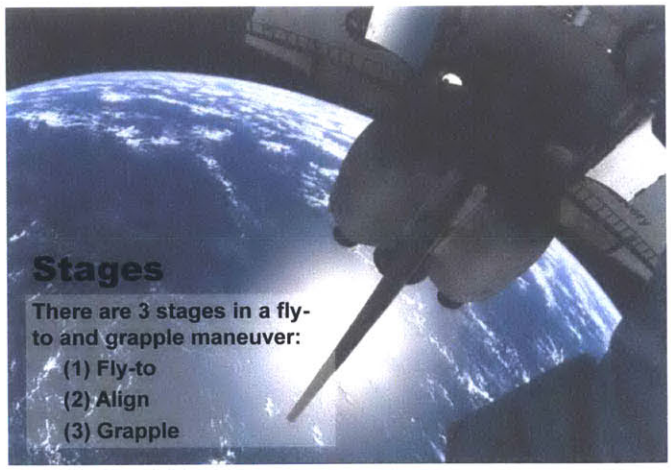
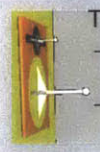


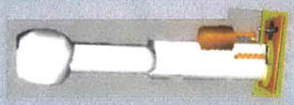
The Grapple

Every object that you grab will have the orange **grapple fixture**



The grapple fixture has 2 pins

- The large pin goes inside the EE to the grappling mechanism
- The smaller pin is used for aligning the camera



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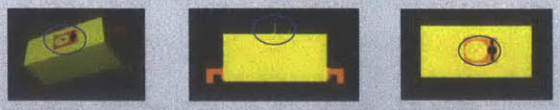
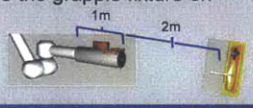
Stage 1: Fly-to

For your practice trials, the targets in the environment are yellow boxes with the same **grapple fixture** that will be used on nodes in the experiment.



During a fly-to, you will use both hand controllers to position the end-effector roughly 2 meters above the grapple fixture on the target.



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Stage 2: Pre-grapple Alignment

- Once you are above the target, you need to align the end-effector into pre-grapple position. This is often easiest in the ***internal*** control frame.
- In pre-grapple position, the end-effector is 1.5 meters above the target and perpendicular to the target, as shown:

Big picture

Task

Clearance

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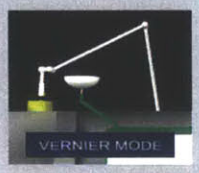
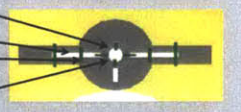
Stage 3: Grapple

Once you have the pre-grapple alignment, turn on Vernier ('v'). This slows the arm so you can carefully move the end-effector until it is in the grapple envelope.



- You are in the **grapple envelope** when the following conditions are met:
  - The white dot is in the white circle.
  - The long white line is within 5 degrees of horizontal.
  - The inner green lines are just inside the edge of the large gray circle.
  - The crosshairs are centered in the gray circle.



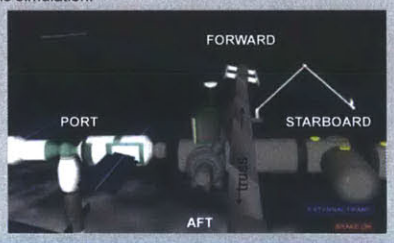
When in the envelope, pull the trigger on the joystick to grapple.

Strategies

The following slides introduce techniques that may help improve your performance in fly-to and grapple tasks.

Fly-to Techniques

- Large arm motions should be made in the external command frame.
- Monitor all views to fly safely and efficiently.
- Recall: The Z1 with the Ku-band antenna is located on the port side of the truss in this simulation.



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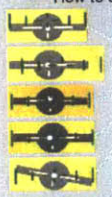
Alignment Techniques

small
above
large

VERNIER MODE

- Work in the Internal Command Frame.
- To significantly slow the rate of motion of the arm, press "v" to apply vernier rate when within 2m of a target. You will have finer control of translation and rotation, allowing for easier (and safer) alignment and grappling.
- How to correct alignment errors:



Error	*Technique 1*	*Technique 2*
Center of crosshairs above center of gray circle	Translate down	Pitch down
Center of crosshairs right of center of gray circle	Translate left	Yaw left
Dot high in white ring	Pitch down	Translate up
Dot left in white ring	Yaw right	Translate left
Roll error	Crosshair lines centered in white bar (make sure vertical line on white bar is pointing down)	

Keep in Mind

- Cameras
  - Use all of your viewpoints, observe clearances, monitor the task.
- Frames
  - Think carefully about how to move the arm in the external or internal control frame.
- Joints
  - Be aware of joint angle limits and arm singularities.

Strategies (Slide 1 of 3)

- Collision/Clearance Limit Avoidance
  - Monitor both the elbow and the end-effector's position and clearance.
  - Check all of the camera views for potential clearance concerns.
- Reducing Task-Time
  - Move in more than one direction at once and perform both rotational and translational movements together in order to finish the task more quickly.
  - Look for the shortest workable path between the start position and the target and follow that line as best you can.

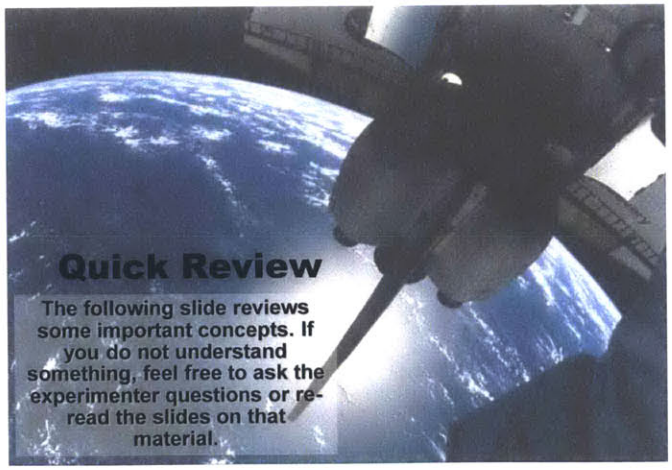
Strategies (Slide 2 of 3)

- Moving the Arm
  - Plan ahead. Before you start working, think about the movements required for the best route and how to avoid obstacles.
    - i.e. Where will the elbow be if you move the end-effector toward the port side? Will it be too close to a nearby object?
    - When you begin moving the arm, make sure it is doing what you expected. If not, think about what happened and why before moving again.
  - **Verbalize** what you are doing or planning to do while you are working.
    - e.g. "I'm pulling the translational hand controller back; I expect the arm to move away from the base. The elbow is going to get closer to the truss, but it won't violate the clearance limit."
    - If what you are planning to do does not make sense, you may be able to realize it in advance through hearing yourself say it out loud.

Strategies (Slide 3 of 3)

- Arm Alignment
  - Use the edges of fixed objects such as the targets or the trusses to determine when the end effector is vertical or horizontal with respect to a feature.
  - Look at all of your views when you are trying to align the arm with a grapple fixture. In most situations, you CANNOT get all of the information you need from a single view.
- Distance Estimation
  - Remember that the last component of the end-effector is 1m long. Use it as a guide to ensure that you do not violate the clearance limit and to position the end-effector correctly.

- Maneuvering
  - If you reach a hard-stop or singularity or collide with another object, try to move in the opposite direction. If you cannot escape, reset the arm to its original position by pressing 'Shift+r'. Be aware that resets will count against your overall performance score.



Review of Important Concepts

- Objective
  - Fly-to and grapple maneuvers are used to pick up objects, including nodes, cargo, and astronauts, and to move them from one location to another.
- Grapple Tolerance
  - White dot in white circle
  - White line level within 5 deg
  - Inner green lines on edge of large gray circle
  - Crosshairs centered in circle

- Stages
  - 1: Fly-to
    EXTERNAL COMMAND FRAME
    End-effector goal is 2m the target.
  - 2: Align
    INTERNAL COMMAND FRAME
    End-effector goal is 1.5m and perpendicular to target.
  - 3: Grapple
    INTERNAL COMMAND FRAME
    VERNIER RATE
    Enter grapple envelope, touching the grapple pin, and pull the trigger.

Performance Metrics

Your performance will be evaluated by:

- Time to task completion
- Number of Clearance Violations and Collision
- Number of Joint Hardstops and Singularities hit
- Grapple Attempts (pulling the trigger out of envelope)
- Percentage of multi-axis movement, and bimanual Control
- Number of resets of the arm position ('Shift+r')
- Smoothness of controller input
- Adherence to flight rules
- Flight Strategy
- Camera Management (Learn in next segment)

During training, you will receive feedback on these metrics

Hands-on Training

There are 5 unique scenarios in which targets will be placed. Your cameras will be selected for you.

Please review the previous slides as needed and proceed with the training simulation when ready.

Training

Try it out;

- Now complete your 5 trials.

10 Minutes

COFFEE BREAK

Deepening your Robotics Skills

ADVANCED CONTROLS

Advanced Controls

- Now you will be in charge of all the SSRMS settings
  - **C**amera Views
  - Reference **F**rame
  - **R**ate (Arm Speed)
  - Load **M**ode
- We use the Acronym CFRM

The next few slides will go over what will be expected of you for each setting

Switching Command Frames

- Scenarios will begin in the External Command Frame, with axes fixed to the ISS.
- Final alignment and grappling should be performed in the Internal Command Frame.

Recall:

- Press 'i' to switch to the Internal Command Frame.
- Press 'e' to switch to the External Command Frame.

- Loaded fly-tos, carrying a payload grappled to the end-effector, should be made in the External Command Frame.

Applying Vernier Rate

To slow the rate of motion of the arm, apply vernier rate.

Recall:

Press 'v' to toggle between course rates and vernier rates.

VERNIER MODE

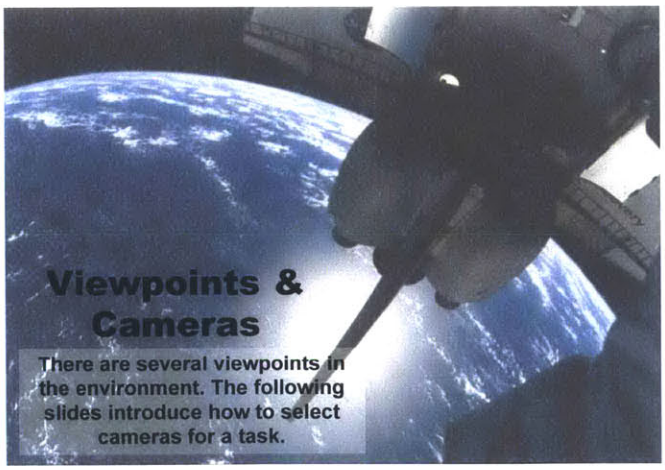
Vernier rate should be used during the grapple stage and for fine alignment, as well as when operating within 1.5m of structure or payloads.

Loaded Fly To

- When a payload is grappled, you need to change the loaded mode.
- Press 'l', then enter the object's name I.D.

Loaded Kibo

- This informs the arm software that there is a weight on the arm, and the software will automatically adjust joint torques accordingly.
- Ungrapple with the trigger, then press 'u' to enter unloaded mode.



Views

There are 3 types of camera views:

1) **Big Picture** – whole arm and work area

2) **Clearance** – view to avoid collisions, showing structures that may be in the way of the arm or payload. Keep an eye on the elbow joint

3) **Task** – end-effector or intuitive view, used to provide a more detailed image of the current task. The end-effector view includes cross-hairs centered on the screen for alignment over objects.

Views

Big picture | Clearance | Task

- When you select your camera views, make sure you have every category covered. One view can count as multiple types as well.
- It is important to monitor all three views in order to fly safely and accurately.
- End-effector motion may appear different depending on the camera orientation.
- **Never** let any part of the arm out of view.

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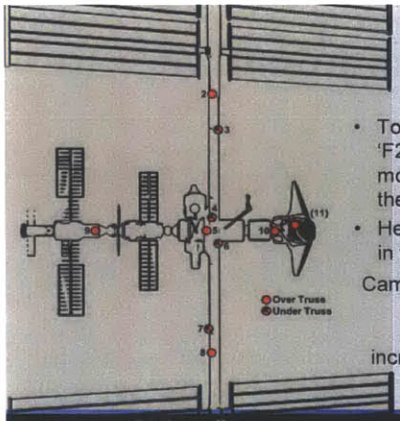
Selecting Cameras



- To switch views press 'F1', 'F2', or 'F3', to change monitor 1,2,or 3. Then type in the new camera number.
- Here are the camera locations in the simulation:

Camera 0 is the EE Cam, and 1 is the Elbow Camera
Note: Camera numbers increase going down the truss then Port - Starboard

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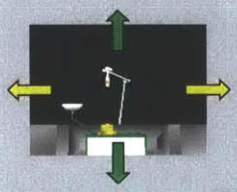
Moving Cameras

- Using the joystick hat, you can pan and tilt the camera view.
- Press '1', '2', or '3' to switch the control to monitor 1, 2, or 3



Try it now.
Make sure you try switching monitor control, too.

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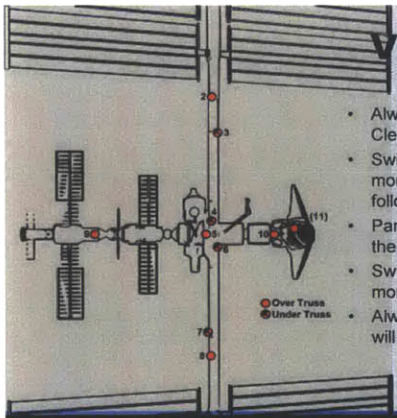
Views Recap



- Always have a Big Picture, Clearance, and Task view.
- Switch the camera displayed in a monitor with 'F1', 'F2', or 'F3', followed by the camera number.
- Pan or Tilt the active camera using the joystick hat.
- Switch pan & tilt control to a different monitor with the '1', '2', or '3' key.
- Always think about which camera will give you the best view

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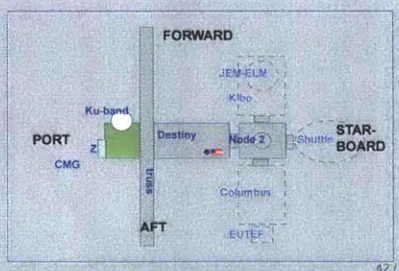
Quick Review

The following slide reviews some important concepts. If you do not understand something, feel free to ask the experimenter questions or re-read the slides on that material.

Helpful Hints

- The grapple fixture will have a consistent appearance.

- The following schematic may be useful to help determine final placements:



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Review of Important Concepts

- Cameras
  - Maintain Big picture, Task, and Clearance views by changing and panning the cameras
- Frames
  - Use the internal frame for final alignment and grappling. ('i')
  - Use the external frame for large arm motions. ('e')
- Rate of Motion
  - Apply vernier rate during grapple and for fine alignment, as well as when operating within 1.5m of structure or payloads. ('v')
- Mode
  - Verify arm is in the proper Loaded / Unloaded Mode.
  - The payload ID will be in the task procedure

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Task Procedure

- For each task you will be given scenario sheets that include:
  1) Task Description – a statement of your objective
  2) Final Placement – images of the final position and orientation of the payload as viewed with the appropriate cameras
- When referring to the scenario sheet, be sure to engage the brake.

BRAKE ON

- When you are satisfied with your final placement, engage the brake and press 'Shift+d' to indicate that you are done.
- You will now be judged on how quickly you can perform a task:
  - ➢ You should be able to complete advanced tasks in under 10 minutes per object to move.

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Training Schedule

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  - **Singularity & Clearance Tips**
  - **Reducing Task Time**
- **Session 5: Final Evaluation**

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HANDS ON PRACTICE

The Training PowerPoint is now complete. Feel free to look back through the material and ask questions.

Let your instructor know when you are ready to move on.

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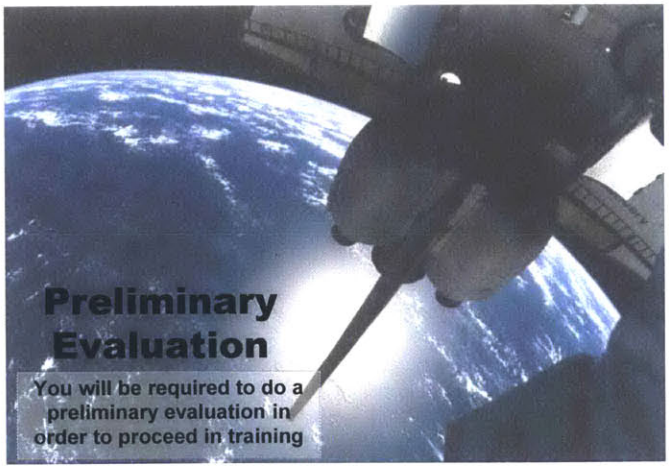


Performance Metrics

Your performance will be evaluated by:

- Time to task completion
- Number of Clearance Violations and Collision
- Number of Joint Hardstops and Singularities hit
- Grapple Attempts (pulling the trigger out of envelope)
- Percentage of multi-axis movement, and bimanual Control
- Number of resets of the arm position ('Shift+r')
- Smoothness of controller input
- Adherence to flight rules
- Flight Strategy
- Camera Management

Evaluation

- The evaluation is comprised of:
  - Fly-to and Grapple Trials
  - Advanced Fly-to
- If you are successful in 50% of the trails, you are welcome to continue training.

SCREENING

The Training PowerPoint is now complete. Feel free to look back through the material and ask questions.

Let your instructor know when you are ready to move on.

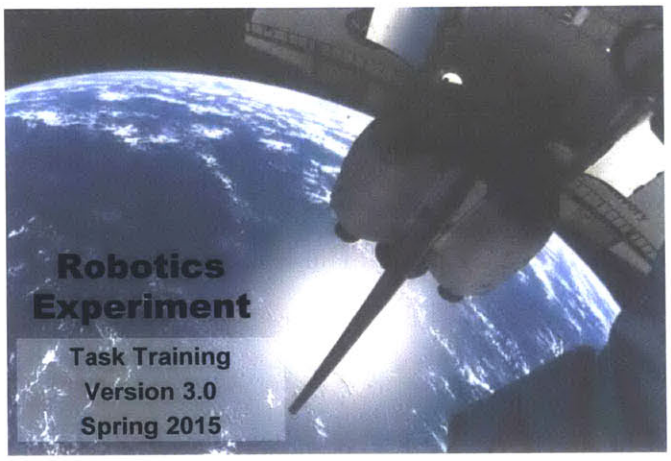
C.2.3 Session 3

Slide Notes:

S22: Have Subject stop reading at this point and run through the TC trials. Provide the feedback listed in the experimenter's procedures.

S26: Have Subject step through the first trial as they go through the PowerPoint.

S36: Emphasize that the side task is secondary, and should not get in the way of their performance



Training Schedule

- ✓ Session 1: Overview
- ✓ Session 2: Basic Skills
- ➢ Session 3: Task Training
- Session 4: Strategy Practice
- Session 5: Final Evaluation

< 6 month break >

- Session 6: Return Evaluation

Session 3:
Task Specific Training

- Recap Sessions 1& 2
- Track and Capture Task Training
- EVA Support Task Training

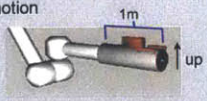
Objective: You will be able to complete each type of task

Virtual Environment Recap

- ISS components include modules, the truss and solar arrays, and the robotic arm.
- The modules form the port/starboard axis of the ISS
- The truss is oriented along the forward/ aft axis.
- The Z1 truss with the Ku-band antenna is located on the port side of the truss.
- The grey US modules are on the starboard side of the truss.

Robotics Recap

- The **end-effector** is 1m long with an orange camera on top.
- **Hardstops** mark the end of a joint's range of motion
- The arm has three **singularities**:
  - 1) Elbow Pitch joint at 0° or ±180°
  - 2) Wrist Yaw joint at ±90°
  - 3) Wrist Over Shoulder
- Make **smooth** movements with the hand controllers.
- Try to move in more than one axis at a time.
- Monitor all views while controlling the arm; do not focus solely on the end effector.

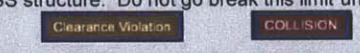


The THC (Translation) is on the Left and **moves** the EE

The RHC (Rotation) is on the Right, and **rotates** the arm around EE

Flight Rules

1. When you are within 1 meters of any structure, you must operate in "Vernier" rate, by pressing 'v'
2. There is a clearance limit of 0.6m between any part of the arm and ISS structure. Do not go break this limit unless grappling.

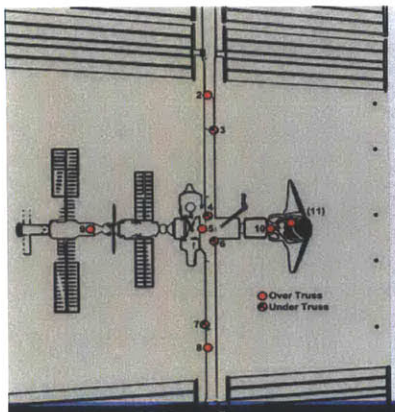


Remember that the arm can hit itself! Watch out for self-collisions

3. Apply the break when you are not operating the arm

Unofficial Flight Rules:

1. Use the Acronym CFRM to remember to check all settings
   - Verbalize as you do the checklist, so the instructor knows you did it!
2. Never let any part of the arm leave you views.



C: Cameras

- Always have a Big Picture, Clearance, and Task view.
- Switch the camera displayed in a monitor with 'F1', 'F2', or 'F3', followed by the camera number.
- Pan or Tilt the active camera using the joystick hat.
- Switch pan & tilt control to a different monitor with the '1', '2', or '3' key.
- Always think about which camera will give you the best view for your task

F: Control Frame Recap

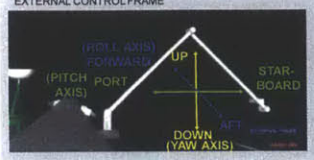
External frame is fixed with respect to the ISS.

➢ Use the external frame when making large arm movements.

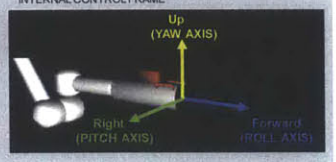
Internal frame is fixed to the tip of the end-effector.

➢ Use the internal frame for small movements and alignment.

EXTERNAL CONTROL FRAME



INTERNAL CONTROL FRAME



➢ Press '**e**' to switch into the external control frame.

➢ Press '**i**' to switch into the internal control frame.

R: Rate of Motion

- Switch to slower Vernier Mode using 'v'
- Operate in Vernier when near structure

M: (Un)Loaded Mode

- Press 'l' to enter Loaded mode, and enter the object I.D.
- Unload with 'u'

Strategies Recap (Slide 1 of 2)

- Moving the Arm
  - Plan ahead. Before you start working, think about the movements required for the best route and how to avoid obstacles.
  - *Verbalize* what you are doing or planning to do while you are working.
- Collision/Clearance Limit Avoidance
  - Monitor both the elbow and the end-effector's position and clearance.
  - Check all of the camera views for potential clearance concerns.
- Reducing Task-Time
  - Move in more than one direction at once and perform both rotational and translational movements together in order to finish the task more quickly.
  - Look for the shortest workable path between the start position and the target and follow that line as best you can.

Strategies Recap (Slide 2 of 2)

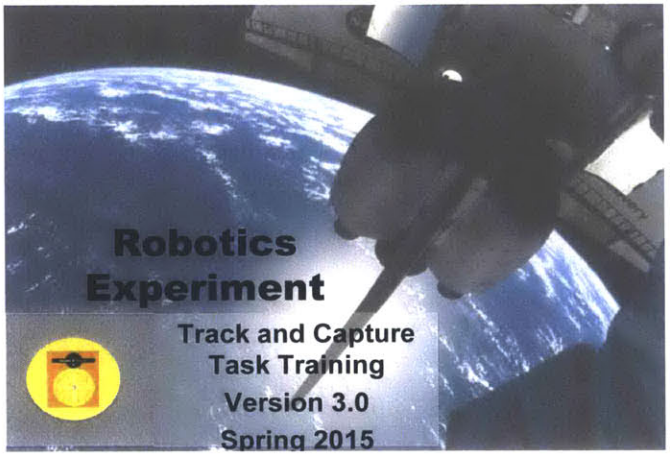
- Arm Alignment
  - Use the edges of fixed objects such as the targets or the trusses to determine when the end effector is vertical or horizontal with respect to a feature.
  - Look at all of your views when you are trying to align the arm with a grapple fixture. In most situations, you CANNOT get all of the information you need from a single view.
- Distance Estimation
  - Remember that the last component of the end-effector is 1m long. Use it as a guide to ensure that you do not violate the clearance limit and to position the end-effector correctly.

- Maneuvering
  - If you reach a hard-stop or singularity or collide with another object, try to move in the opposite direction. If you cannot escape, reset the arm to its original position by pressing 'Shift+r'. Be aware that resets will count against your overall performance score.

Review of Fly-to Concepts

- Objective
  - Fly-to and grapple maneuvers are used to pick up objects, including nodes, cargo, and astronauts, and to move them from one location to another.
- Grapple Tolerance
  - White dot in white circle
  - White line level within 5 deg
  - Inner green lines on edge of large gray circle
  - Crosshairs centered in circle

- Stages
  - 1: Fly-to
    External Command Frame
    End-effector goal is 2m to the target.
  - 2: Align
    Internal Command Frame
    End-effector goal is 1.5m and perpendicular to target.
  - 3: Grapple
    Internal Command Frame
    Vernier Rate
    Enter grapple envelope, touching the grapple pin, and pull the trigger.



Description

- Training:
  - You will learn how to grapple a moving target, the H-II Transfer Vehicle (HTV), an unmanned resupply vehicle.
  - You will start approximately in pre-grapple position and will have **90 seconds** in each scenario in which to approach, maintain alignment with, and latch onto the pin.
- Track and Capture Task:
  - Track and capture is used when a robotics operator aboard the ISS must grapple a free-flying vehicle.
  - The free-flying vehicle may be drifting or spinning in relation to the ISS

3

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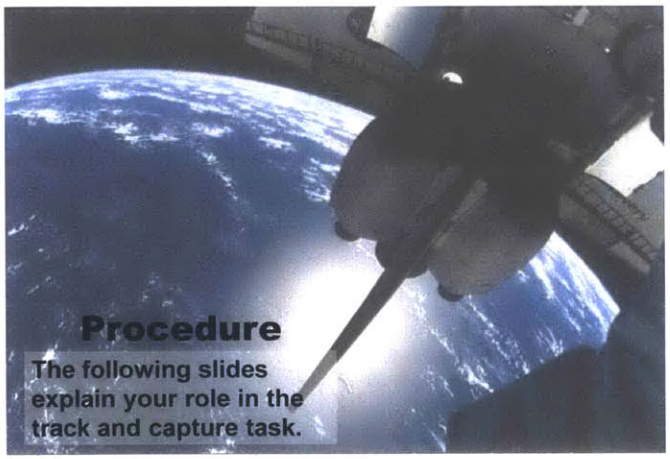

The Start

Scenarios will load with the proper camera views selected:

Clearance | Task | Big Picture

- The brake will be engaged.
- The arm will be in position roughly perpendicular and approximately 2m from the grapple fixture on the HTV.
- The initial command frame will be internal.
- The initial rate will be Vernier.

5

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Task Procedure

- You will have 90 seconds in which to grapple the HTV.
- Using the techniques that you learned for fly-to and grapple, coordinate translation and rotation such that you maintain proper alignment over the grapple fixture as you approach.

- When in the grapple envelope, pull the trigger to latch onto the HTV.

6

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Alignment Techniques

small
above
large

Correcting Alignment Errors:

Error	Technique 1	Technique 2
Center of crosshairs above center of black circle	Translate down	Pitch down
Center of crosshairs right of center of black circle	Translate left	Yaw left
Dot high in white ring	Pitch down	Translate up
Dot left in white ring	Yaw right	Translate left
Roll error	Crosshair lines centered	

Remember: If you input a translation, you may need a rotation to align the target, as the translational and rotational cues are coupled (e.g. pitch down and translate up)

8

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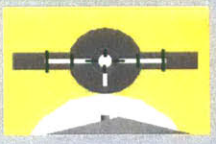
The Grapple Envelope

You are in the grapple envelope when the following conditions are met:



- The white dot is in the white circle.
- The long white line is within 5 degrees of level.
- The inner green lines are just inside the edge of the large gray circle.
- The crosshairs are centered in the gray circle

9

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HTV Training

Try it out:

- Now complete your 6 trials.

11

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Description

- EVA Assist Task:
  - On occasion the SSRMS is used to assist astronauts during EVA. The Robotics operator works together with the EV astronaut to complete various task.
  - All EVA tasks are accompanied by written procedures documenting all steps in the mission.
- Training:
  - You will learn how to fly the arm with an astronaut attached, and how to support them in repairs.
  - You will be following written procedures for each EVA support mission

3

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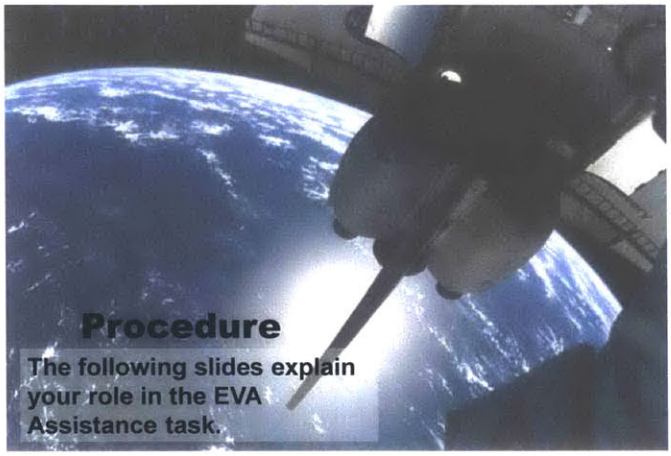
MVL Robotics Experiment

Task Overview

- The scenario will begin with the astronaut on the arm.
  - You will need to input the astronaut's load ID.
- Once you have configured the SSRMS, you will move the astronaut to the first fly-to position.
- The procedures will describe the details of each mission specifically. First we will go through a simple Fly-to and Repair like task.



Step 1: Configuring SSRMS

- The procedures will list all parameters that will be needed for the first fly-to on the arm.
- Since the arm begins loaded, make sure you update the load parameter before releasing the brake. Press 'l' and enter the Astronaut's weight ID.

(CFRM)

Step 2: Fly to and Repair

- Fly the astronaut to the repair location, specified in the procedures.
- Once you are there, apply the Brake ('b').
- Message the astronaut you are ready by pressing 'm'; Now the astronaut will give you a series of verbal commands to help her reach different areas for the repair.
- After each leg, apply the Brake so the astronaut can work.
- When the astronaut is finished, fly her to the final location. (Also listed in the procedures)
- Apply the brake when finished

Try it Out:
Fly to and Repair

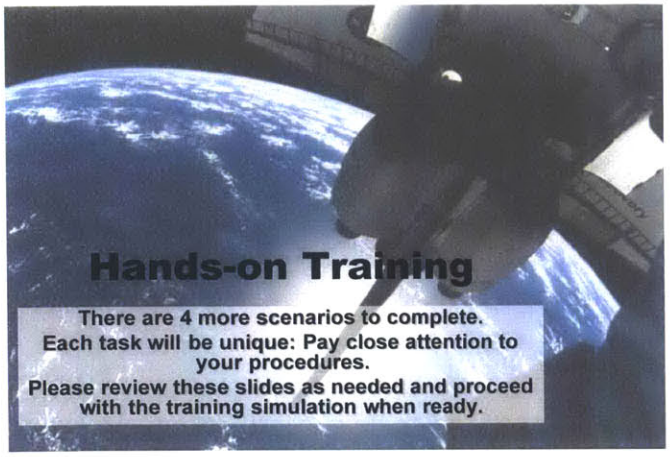
There's been a little friendly competition amongst the space agencies. Help put a poster on the side of Node 2

- Fly Astronaut Forward of Node 2, and apply the brake:

Try it Out: Fly to and Repair

- The astronaut needs to tape down the sides of the poster. Follow their commands, braking after each one.
- Enough fun, now back to the real EVA.
- Backoff from the module (Go Forward 1meter)
- Fly the astronaut to the Truss, and she'll continue her EVA.

- Remember: Apply the brake when finished with each leg



EVA Training

Try it out:

- Now complete 4 more trials.
- Procedures for each trail are in the binder

11

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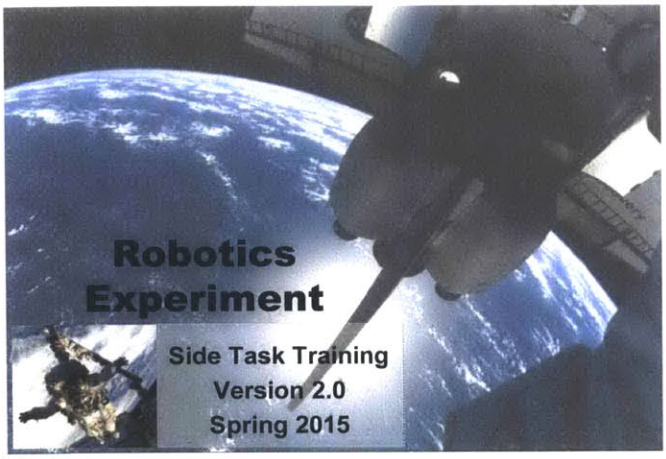
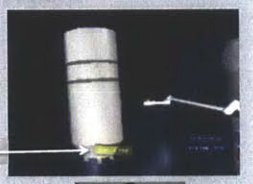


The Side Task

- At varying intervals, a notification will pop up on the left monitor (Monitor 1), indicating a communication from the ground. The notification will flash between yellow and green.



- When you see this notification, you should indicate that you have seen it by pressing the side button on the left side of the Rotational Hand Controller.

2

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Side Task Strategies

- Responding to the notification is your secondary priority.
  - This means that if you are too busy doing the robotics task, it is ok to miss a response.
  - You should scan over to the left monitor if you have extra time to see if the notification is there.
- If you are able to respond to the notification, do so as quickly as possible.

3

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More Information

- The side task will be present during all types of tasks.
- Don't worry if you are able to pay more attention to it during some tasks and less during others.
- Remember, press the left side button on the Rotational Hand Controller to dismiss the notification.

4

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Training Schedule

- ✓ Session 1: Overview
- ✓ Session 2: Basic Skill
  - ✓ Fly-to and Grapple
  - ✓ Advanced Concepts
- ✓ Session 3: Task Training
  - ✓ HVT Track and Capture
  - ✓ EVA Astronaut Support
- ▪ Session 4: Strategy Practice
  - ▪ Singularity & Clearance Tips
  - ▪ Reducing Task Time
- ▪ Session 5: Final Evaluation

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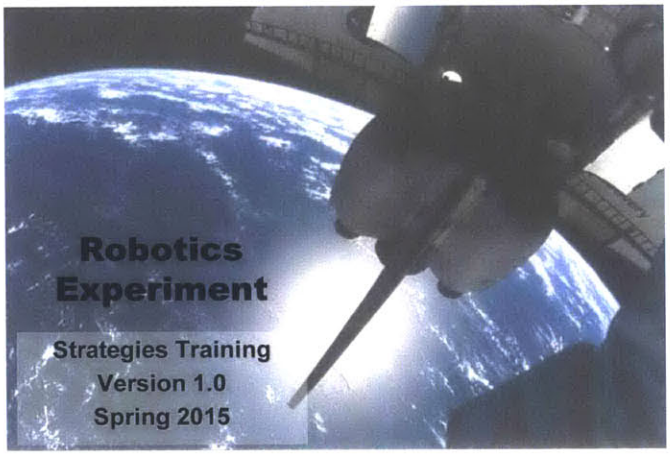
C.2.4 Session 4

Slide Notes:

S16: Be sure that the subjects are completing the trails that correspond to each strategy.

S23: Explain the concept of parallax if they are unfamiliar

S24: Tell the subject that there is a fifth trial that combines all the strategies.



Training Schedule

- ✓ Session 1: Overview
- ✓ Session 2: Basic Skills
- ✓ Session 3: Task Training
- ➢ Session 4: Strategy Practice
- Session 5: Final Evaluation

< 6 month break >

- Session 6: Return Evaluation

Session 4:
Strategy Practice

- Recap Sessions 1, 2 & 3
- Learn Arm Movement Strategies
- Record Refresher Training Video

Objective: You will be able to move the arm more effectively to predict and avoid violations

Virtual Environment Recap

- ISS components include modules, the truss and solar arrays, and the robotic arm.
- The modules form the port/starboard axis of the ISS
- The truss is oriented along the forward/ aft axis.
  - The Z1 truss with the Ku-band antenna is located on the port side of the truss. (Box with Green X)
  - The grey US modules are on the starboard side of the truss.

Robotics Recap

- The **end-effector** is 1m long with an orange camera on top.
- **Hardstops** mark the end of a joint's range of motion
- The arm has three **singularities**:
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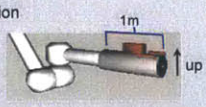
  - 3) Wrist Over Shoulder
- Make **smooth** movements with the hand controllers.
- Try to move in more than one axis at a time.
- Monitor all views while controlling the arm; do not focus solely on the end-effector.



The THC (Translation) is on the Left and **moves** the EE

The RHC (Rotation) is on the Right, and **rotates** the arm around EE

Flight Rules

1. When you are within 1 meters of any structure, you must operate in "Vernier" rate, by pressing 'v'
2. There is a clearance limit of 0.6m between any part of the arm and ISS structure. Do not go break this limit unless grappling.

Clearance Violation COLLISION

Remember that the arm can hit itself! Watch out for self-collisions

3. Apply the break when you are not operating the arm

Unofficial Flight Rules:

1. Use the Acronym CFRM to remember to check all settings
   - Verbalize as you do the checklist, so the instructor knows you did it!
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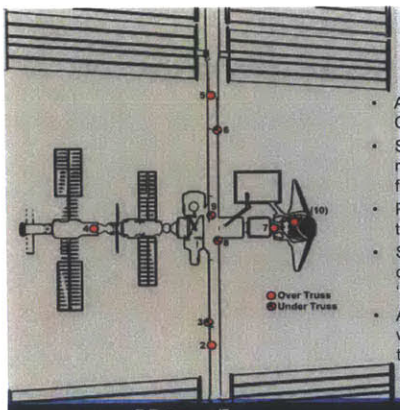


C: Cameras

- Always have a Big Picture, Clearance, and Task view.
- Switch the camera displayed in a monitor with 'F1', 'F2', or 'F3', followed by the camera number.
- Pan or Tilt the active camera using the joystick hat.
- Switch pan & tilt control to a different monitor with the '1', '2', or '3' key.
- Always think about which camera will give you the best view for your task

F: Control Frame Recap

External frame is fixed with respect to the ISS.

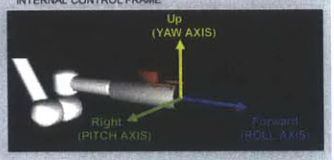
- Use the external frame when making large arm movements.

Internal frame is fixed to the tip of the end-effector.

- Use the internal frame for small movements and alignment.

EXTERNAL CONTROL FRAME

INTERNAL CONTROL FRAME



- Press '**e**' to switch into the external control frame.
- Press '**i**' to switch into the internal control frame.

R: Rate of Motion

- Switch to slower Vernier Mode using 'v'
- Operate in Vernier when near structure

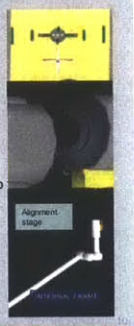
M: Mode (Un)Loaded

- Press 'l' to enter Loaded mode, and enter the object I.D.
- Unload with 'u'

Review of Fly-to Concepts

- Objective
  - Fly-to and grapple maneuvers are used to pick up objects, including nodes, cargo, and astronauts, and to move them from one location to another.
- Grapple Tolerance
  - White dot in white circle
  - White line level within 5 deg
  - Inner green lines on edge of large gray circle
  - Crosshairs centered in circle

- Stages
  - 1: Fly-to
    External Command Frame
    End-effector goal is 2m the target.
  - 2: Align
    Internal Command Frame
    End-effector goal is 1.5m and perpendicular to target.
  - 3: Grapple
    Internal Command Frame
    Vernier Rate
    Enter grapple envelope, touching the grapple pin, and pull the trigger.



Review of Track & Capture

- You will have 90 seconds in which to grapple the HTV.

- When in the grapple envelope, pull the trigger to latch onto the HTV.
  - The white dot is in the white circle.
  - The long white line is within 5 degrees of level.
  - The inner green lines are just inside the edge of the large gray circle.
  - The crosshairs are centered in the gray circle.

Review of EVA Support

- During EVA Support, you will assist an Astronaut in repairs.
- Fly the astronaut to the specified location.
- Listen to the GCA directions from the astronaut.
- When they are done with the repairs, fly them to the final location specified in the procedures

Number 1: Know how the arm moves

- As you go through the practice tasks, think about how the arm is moving.
  - If you pitch the end-effector down, what happens to the elbow? When you pitch up? What about Yaw?
  - If the elbow is getting too close to the KU antenna, what will input move it away?
- Knowing how your commands affect the rest of the arm joints can help you get out of a tight spot, or avoid them entirely.

Complete the next trial with this strategy in mind

TRY IT OUT

Number 2: Predicting Limitations

- Once you understand how the arm moves, you can avoid things like hardstops and singularities.
  - If you are working at the edge of the arm's reach, think about how you can orient & move the end-effector to give the elbow more play.
- Two of the singularities happen at specific joint angles (EP=0, WY=+/-90). Keep an eye on the Joint Angle display and be cautious when you are working near these angles.
  - Be aware that the rate of the elbow joint changes rapidly when you get close to 0 degrees

➢ When you identify a hazard coming, Verbalize! Then the instructor won't think you just got lucky!

Complete the next trial with this strategy in mind

TRY IT OUT

Number 3: Know your Clearances

- Use what you have:
  - When you need to calculate a distance, use the nearest known object to judge. (Things that are closer to the camera look larger)
  - If the astronaut is on the end of the arm, use her / him to judge your distances. The astronaut is about 1.5m tall and the foot plate is about 0.5m wide.
  - If there is no astronaut, use the End Effector (1.0m long)
- Watch the Hazard Spots
  - The upper boom hitting the Truss while you work on the portside.
  - The 'hand' boom hitting the 'forearm' at extreme Wrist-Yaw angles.
  - The elbow joint hitting the KU antenna.

Complete the next trial with this strategy in mind

TRY IT OUT

Number 4: Reducing Task Time

- The best way to reduce your time is to move in *more than one* direction at a time
  - You can cut your time in half by simply moving in more than one direction. Try to orient the end effector while in transit!
- Plan Ahead!
  - Plan the most direct route that avoids arm limitations: those few seconds will save time if you avoid getting stuck in a hotspot.
- Think on the fly and *pay attention*:
  - Many times we don't see the hazard until it's right in our face.
- Know when enough is enough!
  - On final approaches or placements, you don't have to be perfect, just within the tolerances.

Complete the next trial with this strategy in mind

TRY IT OUT

Number 5: Understanding Parallax

- If the camera you are looking through isn't perpendicular to what you are looking at, you can't really trust it.
- This is especially true for very large differences in height.
- Keep your cameras current, always use the best view available.
- If you aren't sure if your camera is the best, check.
- When aligning the end effector or payloads, use perpendicular cameras.

Complete the next trial with this strategy in mind

TRY IT OUT

10 Min

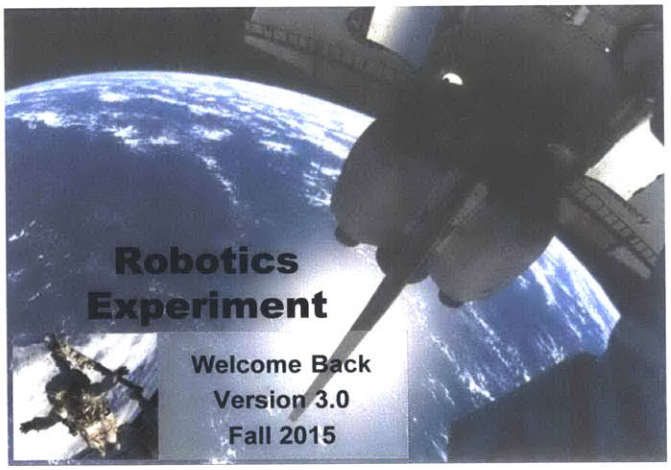
COFFEE BREAK

Record Training Video

- You now have one hour to record and edit a training video.
- You can include anything you wish
- The skills you have learned are:
  - ✦Grapple Training
  - ✦Advanced Fly-to Control
  - ✦Track & Capture
  - ✦EVA Support
- The instructor will help you record yourself and to edit the video.

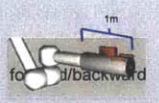
C.2.5 Refresher Training Slides

Slide Notes: You are able to answer questions during the refresher training time, but not during the evaluation itself



Robotics Recap

- You are in charge of operating the Robotic arm on the ISS
- The arm is 17m long when fully extended, and the end-effector (the end segment) is 1m long.
- The end-effector may move left/right, up/down, or may pitch, yaw, or roll.



- The Orange Camera is on the TOP of the end-effector
- The brake should be applied whenever the arm is not in motion.
  - Press 'b' to toggle the brake on/off.

BRAKE ON

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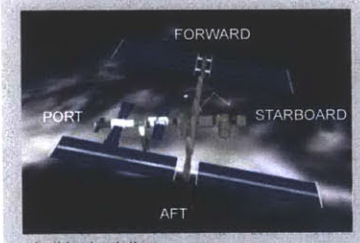
Virtual Environment Recap



- In this simulation:
  - -The modules are located on the port/starboard axis of the ISS.
  - -The truss is oriented along the forward/ aft axis.
  - -The Z1 truss with the Ku-band antenna is located on the port side of the truss.

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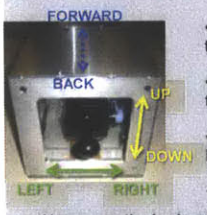
Hand Controllers Recap



- Left hand controls **translation**, moving the tip of the end-effector.
- Right hand controls **rotation**, rotating the arm about the tip of the end-effector.
- Make **smooth** movements with the hand controllers.
- Move in more than one axis at a time.

- Always use the **brake** when not paying attention or actively controlling the arm.
- Monitor all views while controlling the arm; do not focus solely on the end-effector.

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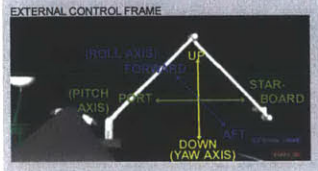
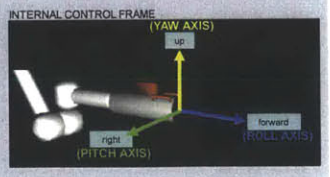
Control Frame Recap

- The ***external frame*** is fixed with respect to the ISS.
  - -Use the external frame when making large arm movements.
- The ***internal frame*** is fixed to the tip of the end-effector.
  - -Use the internal frame for small movements and alignment.

EXTERNAL CONTROL FRAME



INTERNAL CONTROL FRAME



- ➢ Press 'e' to switch into the external control frame.
- ➢ Press 'i' to switch into the internal control frame.

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Arm Limitations Recap

- Joints have a finite range of motion; a **hard-stop** is the limit on how far a joint can rotate.

HARDSTOP

- The arm has three kinematic limitations, known as **singularities**:
  1) **Elbow** Pitch joint at 0° or ±180°
  2) **Wrist Yaw** joint at ±90°
  3) **Wrist Over Shoulder**

Singularity

- Monitor all three views and pay attention to what each of the arm's joints is doing, not just to where the end-effector is going.
- If you encounter a hardstop or singularity, **reverse** direction to free the arm.
- Pressing 'Shift+r' will reset the arm, but be aware that resetting the arm will hurt your score.

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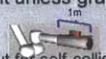
Flight Rules Review

1. When you are within 1 meter of any structure, you must operate in "Vernier" rate, by pressing 'v'
2. There is a clearance limit of 0.6m between any part of the arm and ISS structure. Do not go break this limit unless grappling.

Clearance Violation



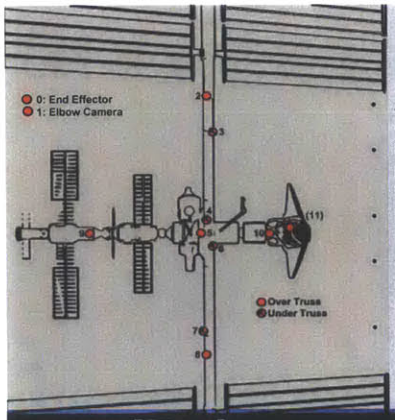
Remember that the arm can hit itself! Watch out for self-collisions

COLLISION

3. Apply the brake when you are not operating the arm

Use the acronym "CFRM" to make sure the arm is set up.
Cameras, **F**rame of reference, **R**ate of motion, **M**ode (Un)loaded

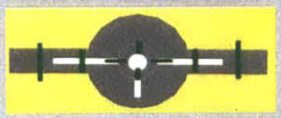
Cameras



- Always have a Big Picture, Clearance, and Task view.
- Switch the camera displayed in a monitor with 'F1', 'F2', or 'F3', followed by the camera number.
- Pan or Tilt the active camera using the joystick hat.
- Switch pan & tilt control to a different monitor with the '1', '2', or '3' key.
- Always think about which camera will give you the best view for your task

Review of Grapple Concepts

- The grapple maneuver is used to pick up objects, including nodes and cargo, and to move them from one location to another.
- Pull the trigger to grapple
- Press 'l' to enter loaded mode
- After placing, ungrapple with trigger and change to unloaded mode ('u')



Stages

- 1: Fly-to
  External Command Frame
  Goal: end-effector is 2m above the target.
- 2: Align
  Internal Command Frame
  Goal: end-effector is 1.5m above and perpendicular to the target.
- 3: Grapple
  Internal Command Frame
  Vernier Rate
  Enter grapple envelope, just touching the grapple pin, and pull the trigger.

The Grapple Envelope

- You are in the grapple envelope when the following conditions are met:

1. The white dot is in the white circle.
2. The long white line is within 5 degrees of horizontal.
3. The inner green lines are just inside the edge of the large gray circle.
4. The crosshairs are centered in the gray circle.

Review of Important Concepts

- Camera Viewpoints
  - The ISS environment has **multiple viewpoints**.
  - It is important to monitor big picture, clearance, and task views.
- Hand Controllers
  - ➢ **Translational** (box)
  - ➢ **Rotational** (joystick)
  - Use both at the same time, and move in multiple axes simultaneously whenever possible.
- Arm Limitations
  - **Hardstops** are the limit on how far a joint can rotate.
  - The arm's configuration includes three types of **singularities**.

    E:0 WY:90 W / S
- Control Frame
  - **External** control frame axes are fixed to the ISS.
  - **Internal** control frame axes are fixed to the tip of the end-effector.

Robotics Recap

- The brake should be applied whenever the arm is not in motion.
  - Press 'b' to toggle the brake on/off.

BRAKE ON

- The end-effector may move left/right, up/down, forward/backward or may pitch, yaw, or roll.

- The end-effector is 1m long.
- 'L' / 'U' Load and unload the arm
- 'M' Sends messages
- Watch out for **Singularities & Hardstops**, 'Shift + R' to reset arm

Track and Capture Task

- Scenarios will load with the proper camera views selected for you:

- The brake is engaged, command frame is internal, and rate is vernier.
- The arm will be in position as if having just finished a fly-to, roughly perpendicular and approximately 2m from the grapple fixture on the HTV.
- When in the grapple envelope, pull the trigger to latch onto the HTV.
- **You will have 90 seconds in which to grapple the HTV**

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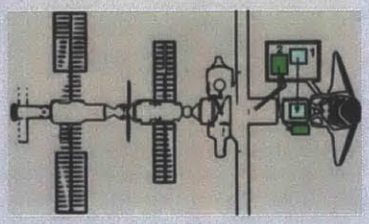
Payload Positioning Task

Move payloads from the platform to final position in the procedure
When the payload is in place, pull the trigger to ungrapple



Press 'Shift + D' to end the trial

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Payload Positioning Task

Move payloads from the platform to final position in the procedure

- Command Frames
  - Use the internal frame for final alignment and grappling. ('**i**')
  - Use the external frame for large arm motions. ('**e**')
- Rate of Motion
  - Apply vernier rate during the grapple stage and for fine alignment, as well as when operating within 1m of structure or payloads. ('**v**')
- Cameras
  - Maintain big picture, task, and clearance views by changing the monitors. ('**F1**', '**F2**', '**F3**')
- Mode
  - '**L**' to enter Loaded mode
  - '**u**' to enter Unloaded mode
- Task Procedure
  - Refer to scenario sheets for:
    1. *Task Description*
    2. *Final Placement*

Press 'Shift + D' to end the trial

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EVA Support Task

- During EVA Support, you will assist an Astronaut in repairs.
- Fly the astronaut to the specified location. Put on the break and press 'm' to message the astronaut that you are in position.
- Listen to the directions from the astronaut.
- When they are done with the repairs, fly them to the final location specified in the procedures

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