HUMAN-ROBOT INTERACTION FOR TELEMANIPULATION BY SMALL UNMANNED AERIAL SYSTEMS

BY

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DISSERTATION

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ABSTRACT

This dissertation investigated the human-robot interaction (HRI) for the *Mission Specialist* role in a telemanipulating unmanned aerial system (UAS). The emergence of commercial unmanned aerial vehicle (UAV) platforms transformed the civil and environmental engineering industries through applications such as surveying, remote infrastructure inspection, and construction monitoring, which normally use UAVs for visual inspection only. Recent developments, however, suggest that performing physical interactions in dynamic environments will be important tasks for future UAS, particularly in applications such as environmental sampling and infrastructure testing. In all domains, the availability of a *Mission Specialist* to monitor the interaction and intervene when necessary is essential for successful deployments. Additionally, manual operation is the default mode for safety reasons; therefore, understanding *Mission Specialist* HRI is important for all small telemanipulating UAS in civil engineering, regardless of system autonomy and application.

A 5 subject exploratory study and a 36 subject experimental study were conducted to evaluate variations of a dedicated, mobile *Mission Specialist* interface for aerial telemanipulation from a small UAV. The Shared Roles Model was used to model the UAS human-robot team, and the *Mission Specialist* and *Pilot* roles were informed by the current state of practice for manipulating UAVs. Three interface camera view designs were tested using a within-subjects design, which included an egocentric view (perspective from the manipulator), exocentric view (perspective from the UAV), and mixed egocentric-exocentric view. The experimental trials required *Mission Specialist* participants to complete a series of tasks with physical, visual, and verbal requirements.

Results from these studies found that subjects who preferred the exocentric condition performed tasks 50% faster when using their preferred interface; however, interface preferences did not affect performance for participants who preferred the mixed condition. This result led to a second finding that participants who preferred

the exocentric condition were distracted by the egocentric view during the mixed condition, likely caused by cognitive tunneling, and the data suggest tradeoffs between performance improvements and attentional costs when adding information in the form of multiple views to the *Mission Specialist* interface. Additionally, based on this empirical evaluation of multiple camera views, the exocentric view was recommended for use in a dedicated *Mission Specialist* telemanipulation interface.

Contributions of this thesis include: i) conducting the first focused HRI study of aerial telemanipulation, ii) development of an evaluative model for telemanipulation performance, iii) creation of new recommendations for aerial telemanipulation interfacing, and iv) contribution of code, hardware designs, and system architectures to the open-source UAV community. The evaluative model provides a detailed framework, a complement to the abstraction of the Shared Roles Model, that can be used to measure the effects of changes in the system, environment, operators, and interfacing factors on performance. The practical contributions of this work will expedite the use of manipulating UAV technologies by scientists, researchers, and stakeholders, particularly those in civil engineering, who will directly benefit from improved manipulating UAV performance.

To my parents, for their love and support.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
AR	Augmented Reality
AV	Augmented Virtuality
DoF	Degrees of Freedom (Mechanics)
EDA	Electrodermal Activity
FAA	Federal Aviation Administration
FOV	Field of View
HMI	Human Machine Interaction
HRI	Human Robot Interaction
IMU	Internal Measurement Unit
JCS	Joint Cognitive System
LOA	Level of Autonomy
LOS	Line of Sight
M	Arithmetic Mean
MPC	Model Predictive Control
MR	Mixed Reality
PID	Proportional–Integral–Derivative
RC	Remote Control
RMSE	Root Mean Square Error
ROS	Robot Operating System

ROV	Remotely Operated Vehicle
SA	Situation Awareness
SD	Standard Deviation
SUS	Small Unmanned System
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UUV	Unmanned Underwater Vehicle
VR	Virtual Reality
VTOL	Vertical Takeoff and Landing

LIST OF SYMBOLS

a^β	Body Frame Acceleration
df	Degrees of Freedom (Statistics)
f	Cohen's f-Statistic
F	F-Test Statistic
k	Kurtosis
N	Population Sample Size
n	Subpopulation Sample Size
p	Statistical Significance; Position, World Frame
$\dot{p}$	Translation, World Frame
p^*	Desired Position
Φ	Body Frame Orientation
$\dot{\Phi}$	Body Frame Angular Velocity
ϕ	Roll, Rotation Around the x Axis
ψ	Yaw, Rotation Around the z Axis
q	Orientation, World Frame
$\dot{q}$	Angular Velocity, World Frame
q^*	Desired Orientation
ρ_p	Pearson Correlation Coefficient
ρ_s	Spearman Correlation Coefficient
s	Skewness

t	T-Test Statistic
θ	Pitch, Rotation Around the y Axis
W	Shapiro-Wilk W Value
χ^2	Chi-Squared Test Statistic
Z	Z-Score Test Statistic

CHAPTER 1

INTRODUCTION

Unmanned aerial vehicles (UAVs) are an accessible and ubiquitous technology for remote sensing applications in many domains, including environmental monitoring and measurement [1, 2, 3, 4, 5], infrastructure inspection [6, 7, 8, 9], and search and rescue [10, 11]. Emerging applications, such as construction [12, 13], environmental sensing and sampling [14, 15], and infrastructure testing [16, 17], indicate that physical interaction and manipulation in dynamic environments will be an important task for small UAVs.

Research on physical object manipulation by small UAVs has primarily focused on the dynamics and control of the robot, with an emphasis on fully autonomous operation in controlled laboratories [18, 19, 20, 21, 22, 23, 24, 25, 26]. Research trends in perception [27], motion planning [28], and real-time control [29] indicate that the autonomous capabilities of small unmanned aerial systems (UAS) are advancing; however, completing autonomous manipulation tasks in real-world, dynamic environments still remains a challenge in robotics [30, 31]. Having a *Mission Specialist* available as part of a human-robot team, in addition to the *Pilot*, to monitor the interaction and intervene or assist when necessary is essential in dynamic environments, such as construction sites or post-disaster scenarios [32]. Even for autonomous systems, operators require robot status and data in real time and the option to dynamically re-task and re-plan when the situation changes [33]. Additionally, manual operation will be the go-to default mode for safety and precision reasons; therefore, understanding the appropriate human-robot interaction (HRI) for a *Mission Specialist* is important for all small UAS deployments, regardless of system autonomy.

This work investigates the *Mission Specialist* role and required HRI for aerial telemanipulation tasks using small UAVs. Human teams deploying UAVs in civil and environmental engineering are normally not robotics experts, but their domain expertise affords the ability to identify areas of interest where it is necessary to investigate with a manipulating UAV. One example of a civil engineering-related application might be deploying acoustic probes to measure wall thickness in hollow turbine blades. Unfortunately, there is a paucity of focused human-machine interaction (HMI) research on *Mission Specialist* telemanipulation tasks using small UAVs, which impedes the large scale application and deployment of manipulating UAVs by non-expert users and *ad hoc* teams. Understanding how a *Pilot* and *Mission Specialist* interact with each other and the UAV will inform unmanned system designers, expedite the use of UAV manipulation technologies, and improve overall UAS human-team performance.

Small, manipulating UAVs are likely to continue advancing along a deployment trajectory from controlled laboratory settings to unstructured environments with increasing levels of autonomy. Operation in unstructured environments for domain-specific applications will nearly always require a *Mission Specialist*, if only to initiate or support semi-autonomous platform capabilities. Additionally, it is recommended to design autonomous capabilities that augment, not replace, the *Pilot* and *Mission Specialist* duties when in hazardous and human-safety related domains [10]. This supplemental automation requires implementing the Shared Roles Model [34], a framework for HRI in which the roles are shared between the human and robot.

1.1 Research Questions

The primary research question that this dissertation addresses is: *What is the appropriate human-robot interface for a Mission Specialist role in a small unmanned aerial system to successfully perform telemanipulation tasks in a three-dimensional remote environment?*

Focused work on HRI for aerial telemanipulation does not readily appear in the literature (as evidenced by the review of related work in Chapter 2), which poses a challenge for scientists, researchers, and designers who would benefit from manipulating UAV systems. This lack of HRI knowledge for UAS also creates a barrier to the adoption of these systems by *ad hoc* users. Research has focused on telemanipulation by undersea vehicles [35, 36, 37], ground vehicles [38, 39, 40], and stationary manipulators [41, 42, 43, 44], but due to inherent differences in UAVs compared to these other platforms (e.g., three-dimension stability issues, constrained operation times), additional research is necessary to determine if previous telemanipulation HRI findings apply to UAS. No focused human factors analyses with a physical UAV capable of manipulation have been identified to the best of the authors knowledge, which inhibits researchable improvements of designing a human operator on or in the loop.

The primary research question is decomposed into the following sub-questions:

1. *What is the current state of human-robot interfacing for a Mission Specialist role in small unmanned aerial system for telemanipulation operations?* This question is addressed in Chapter 2 through a review of the current research literature on *Mission Specialist* and operator interfacing for telemanipulation by unmanned systems.

2. *What display form (eye-in-hand view, global view, hybrid) and elements (size, placement, toolkit) are necessary for remote physical interaction with the environment from a UAV?* This question is addressed in Chapters 5 and 7 through two empirical evaluations of a dedicated *Mission Specialist* interface for aerial telemanipulation, which included over 40 *ad hoc* users. Multiple hypotheses are evaluated to evaluate the effects of different types of visualization on *Mission Specialist* performance.

3. *How do emotional (e.g., stress) and personality (e.g., extroversion) factors affect human operator performance when performing telemanipulation tasks with a small UAV?* This question is addressed in Chapters 7 and 8 which analyze and discuss the relationships between individual variations in experience and personality with *Mission Specialist* performance.

1.2 Why Focus on the *Mission Specialist* Role

Three team roles (*Flight Director*, *Mission Specialist*, and *Pilot*) have been established for small UAS [45, 46]. Of those three, the *Mission Specialist* is the role responsible for operating the UAV payload (or in some cases verbally directing the *Pilot* for payload control). In the case of visual reconnaissance missions, the *Mission Specialist* inspects the video and image data streaming from the on-board camera, and HRI requirements for these types of visual data acquisition missions have been studied in the literature [45, 47, 48], but the *Mission Specialist* role must adapt and change as UAV capabilities advance from two-dimensional visual inspection to three-dimensional manipulation. Understanding the HRI requirements of a *Mission Specialist* during aerial telemanipulation is critical for any system that operates without full autonomy; however, research and development of manipulating UAVs has almost entirely focused on vehicle dynamics and control [18, 19, 20]. A HRI approach to supporting human-in or on-the-loop aerial telemanipulation is not well-studied, and focusing on the *Mission Specialist* role affords the evaluation of telemanipulation-specific HRI requirements for small UAS.

1.3 Understanding Small Unmanned Aerial Vehicles (UAVs)

There is no universally accepted standard classification system for UAVs; however, UAVs are typically categorized based on size, altitude, endurance, and operational range [45, 49]. This work focuses on small vertical take-off and landing (VTOL) vehicles. VTOL vehicles are practical for object manipulation because they have the ability to stabilize and hover, enabling the grasping of an object while the vehicle remains in a stationary position (as opposed to a fixed-wing vehicle).

Small UAVs are generally one meter or less in size and have flight times ranging from 10 minutes to one hour, depending on the payload and flight conditions. The range and altitude capabilities are often larger than the line-of-sight (LOS) requirement, although the United States Federal Aviation Administration (FAA) regulations restrict operating distance to LOS and have a operating ceiling height of 122 meters (400 feet) above ground level. The maximum payload size is typically around one kilogram, which includes both the manipulation mechanism as well as the weight of the object retrieved or delivered. Note a few large VTOL platforms can carry around a five kilogram payload (e.g., DJI Matrice 600), although these are the upper bound for size of VTOL platforms. Table 1.1 includes a summary of commercially available VTOL UAVs.

Table 1.1: Survey of Small Unmanned Aerial Vehicles (UAVs) Suitable for Physical Object Manipulation[1].

Manufacturer and Model	Width x Height [m]	Weight [kg]	Max. Payload [kg]	Range [km]	Altitude [km]	Endurance [min]
Aeryon SkyRanger	1.0 x 0.2	2.4	1.0	3.0-5.0	0.2	50
DJI Inspire 2	0.6 x 0.3	3.3	0.7	7.0	5.0[2]	27
Draganflyer™ Commander	0.8 x 0.3	2.75	1.0	0.6	2.4	15-40
AR.Drone Parrot 2.0	0.7 x 0.15	0.4	0.1	0.5-1.0	1.0	12-20
AirRobot® AR180	1.9 x 0.3	4.9	1.5	2.5	0.3	40
Microdrones MD4-1000	1.0 x 0.5	2.65	1.2	0.5	2.0	45
DJI Matrice 600	1.5 x 0.7	15.1	5.5	5	2.5	18-30

[1] Maximum operational parameters are reported and referenced from manufacturer specification sheets - operational parameter values will normally be lower and domain dependent.
[2] With optional high-altitude propellers.

1.3.1 Grasping Configurations for Small UAVs

The physical grasping of objects by a VTOL UAV is limited to three manipulator configurations due to the physical structure of the platform: frontal, dorsal, and ventral (see Figure 1.1) [50]. Two frontal planes (upper and lower) form a spatial region across and between the rotor blades where no interaction is recommended. The regions of interaction elsewhere on the platform determine the types of applications that are feasible with a small UAV, and there are advantages and limitations associated with each configuration.

Frontal Interaction: This type of interaction occurs parallel to the frontal plane, anterior to the transverse plane of the UAV, with manipulators in a fixed location that rely on the position and control of the vehicle to complete the interaction [50]. Research on the controls and stability of frontal configurations shows that lateral offsets do not significantly affect the stability of the system (as opposed to manipulators high above the aircraft) [51]. Successful frontal manipulation tasks include knob turning [52], door opening [52], and docking [53, 54].

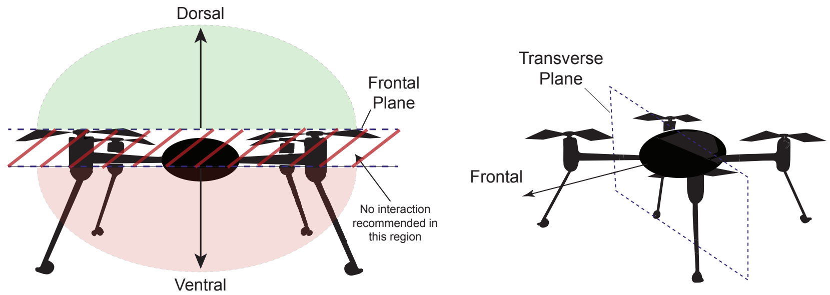


Figure 1.1: The Three Interaction Spaces for Manipulation by Small UAVS. The Two Frontal Planes Create a Region Where the Rotor Blades Are Located Where No Interaction is Recommended. The Dorsal Region is Above the Upper Frontal Plane, and the Ventral Region is Underneath the Lower Frontal Plane; Both Regions Are Hemispherical. The Frontal Region is Anterior to the Transverse Plane.

Dorsal Interaction: The least studied configuration for physical manipulation by small UAVs is in the dorsal side of the upper frontal plane, which forms a hemisphere above the top frontal plane [50]. Successful applications for dorsal interaction are limited, and research has focused mainly on the controls and stability of the platform [51]. There are two major barriers to successful dorsal interaction: i) suction effects above the UAV that can disturb the manipulated objects, and ii) required clearance of the rotor blades to avoid vehicle damage. Some useful applications of dorsal interaction include placing sensors underneath structures, such as a bridge, or sampling beneath a tree canopy.

Ventral Interaction: The most studied configuration for manipulation by small UAVs occurs within the ventral side of the UAV, in a hemispherical space below the lowest part of the rotor blades [50]. The region of interaction for a fixed manipulator is limited to the space between the platform and landing gear; for manipulators that can fold (e.g., multiple degree-of-freedom arms) the interaction space is increased during flight. Research on ventral interaction for small UAVs includes dynamic stability [22], control [19, 23], hovering [55], and perching [56, 57]. One limitation of ventral interaction is the air turbulence present below the rotor blades when the UAV is near the ground, also known as ‘ground effect’ [58]. The object of interest can be affected in unpredictable ways even when the UAV maintains stability in the presence of turbulence near the ground [55]. Domain-specific applications for ventral configurations include sensor retrieval and deployment for environmental monitoring, cooperative material transport in construction, and perching for nondestructive structural testing.

1.4 Importance to Civil and Environmental Engineering

The advent of commercial UAV platforms has transformed civil and environmental engineering industries through applications such as surveying, remote infrastructure inspection, and construction monitoring, which have used UAVs in a "look-don't-touch" approach. Cooperative and adaptive interaction between the system and remote operator will enable domain experts and specialists in civil engineering applications to use this technology without requiring piloting expertise. For example, the AIRobots project aims to develop an aerial service robot that represents a "flying hand that allows the specialist to perform tasks as if they were on-site" [59]. Other literature also recognizes that autonomous aerial manipulation tasks in the civil and environmental engineering domains are difficult and express the need to intentionally design humans into the system [16].

UAVs are already integrated into the production workflow in professional civil and environmental engineering projects, and the commercial aircraft industry has adapted to new guidelines, safety rules, and federal regulations that oversee the use of UAS in industry. With this regulatory infrastructure already in place, the adoption barriers are much lower for manipulating UAVs to enter the marketplace when the technology has matured. Additionally, there is no shortage of valuable applications for manipulating UAVs in civil engineering, many of which already use UAS for visualization. For example, UAS in construction zones can transport materials in addition to monitoring progress. In structural engineering, UAVs can performing nondestructive testing after performing visual inspections [16]. In environmental engineering, site accessibility is a major barrier to collecting samples in dangerous or unreachable locations (e.g., arctic regions, mountainous regions, or regions separated by small bodies of water). Deploying a UAS capable of physical sampling would enable the acquisition of materials that are otherwise inaccessible. In all of these examples, having a *Mission Specialist* available to monitor the interaction and intervene when necessary is essential [32]. Additionally, manual operation will likely be the go-to default mode for safety reasons; therefore, understanding the *Mission Specialist* HMI is important for all small telemanipulating UAS in civil engineering, regardless of system autonomy and application.

1.5 Contributions

Contributions of this dissertation include: i) the first focused human-robot interaction study for aerial telemanipulation tasks, ii) identification of factors, both physical and personal, that affect operator performance during telemanipulation, iii) creation of new UAV interface guidelines and recommendations for aerial telemanipulation, and iv) development of an open-source framework for building a manually-operated telemanipulating UAV system controlled by a mobile tablet device.

1.5.1 First Focused Study of Aerial Telemanipulation HRI

This work presents the first focused study of the *Mission Specialist* role for aerial telemanipulation using a physical robot platform and explicitly fills a gap in HRI research on performing telemanipulation tasks using small UAVs. Previous works investigated the required interfacing and visual information for telemanipulation using ground vehicles, underwater vehicles, and stationary telemanipulators; however, these findings cannot necessarily be extrapolated to aerial systems without proper evaluation. To the best of the author's knowledge, only one additional HRI study on aerial telemanipulation exists; however, this study was conducted in simulation [60]. Simulated robots do not produce the same system responses to operator input as would a physical platform; additionally, simulation environments do not afford realistic visualizations in a *Mission Specialist* interface. Findings from this dissertation using a physical UAV system in the real world are expected to serve as a foundation on which to build future HRI research for telemanipulating aerial systems. This study synthesized the results into a set of interface design recommendations to be shared with the HRI community, informed by individual performance of over 40 *ad hoc*, non-expert users.

1.5.2 Identification of Factors that Affect Telemanipulation Performance

The results from this study identified personal, emotional, and physical factors that affect operator performance during telemanipulation tasks. These identified factors and evaluative model describe the "how" for aerial telemanipulation HRI, which is a complement to the abstraction of the Shared Roles Model that addresses the "what" and "why" of coagency in a human-robot team. Understanding what factors impact *Mission Specialist* performance, and overall team performance, will inform unmanned system designers, expedite the use of UAV manipulation technologies by *ad hoc* users, and improve the overall UAS human-team performance.

1.5.3 Creation of New Interface Guidelines and Recommendations for Aerial Telemanipulation

The findings from this empirical study using this model were used to inform design recommendations for *Mission Specialist* telemanipulation interfaces, including the use of an exocentric view, and identifying additional areas for future exploration, including dynamic interfaces with flexibility regarding the egocentric view. The practical and social impacts of this work include informing future interface designs, as this work recognizes that not all *Mission Specialists* perform the same and provides an interface that meets a minimum level of information required to successfully complete tasks. These technologies can then be adopted by a wider range of users (e.g., not just "experts" or those who consider themselves *Pilots*).

1.5.4 Development of an Open-Source Telemanipulating UAV Framework

This work provides open-source tools (i.e., code, hardware designs, system architectures) to enable the reproduction of the UAV telemanipulation system used in this study. The economic impact of developing open-source tools will likely result in an increase in the adoption of these technologies by researchers, practitioners, and government agencies who can benefit from aerial telemanipulation applications. Social impacts include encouraging other researchers and makers to contribute to and build upon this existing technology and extend it to other applications. Other domains in addition to civil engineering, including agriculture, search and rescue, and biological sciences, would benefit by having access to this type of technology. Additionally, embracing the open-source, maker environment and providing development tools promotes the widespread adoption and use of manipulating UAVs for both research and hobbyist applications.

1.6 Organization of the Dissertation

This dissertation is organized as follows. Chapter 2 serves as a review of the HMI practices and interface technologies for small unmanned systems (SUS) capable of telemanipulation. The chapter surveys the human operator interfacing for over 70 teleoperated systems, summarizes the effects of physical and visual interfaces on user performance, and provides recommendations for both physical and perceptual interface implementations based on these findings. Chapter 3 explains the theory and approach behind implementing the Shared Roles Model, and describes the *Mission Specialist* role and its function within the Shared Roles Model. Chapter 4 describes the implementation of the UAV control system, manipulator system, and interface software. Chapter 5 includes results of 5 subject Exploratory Study and provides recommendations for the experimental study. Chapter 6 describes the experimental design of a 36 subject experimental study, and Chapter 7 presents descriptive and inferential statistical results of this study. Chapter 8 discusses the experimental results, while Chapter 9 provides conclusions of this work and suggestions for future research.

CHAPTER 2

LITERATURE REVIEW AND RELATED WORK

This chapter surveys the human-machine interaction (HMI) practices and interface technologies for small unmanned systems (SUS) capable of telemanipulation and surveys the existing manipulating UAV platforms found in the literature. "Small" unmanned systems are self contained, portable by humans, and advantageous for performing remote manipulation when the task or environment is too dangerous, complex, costly, or difficult for a human to perform themselves [49].

The complexity and variety of telemanipulation tasks by SUS make their categorization and classification difficult, but primary tasks generally include the retrieval or deployment of objects. Domain-specific examples include urban search-and-rescue [43, 61], law enforcement [40, 62], construction [13, 63, 64], space exploration [65, 66, 67] and environmental sampling [14, 68, 69]. In addition to object deployment and retrieval, unmanned systems can also perform specialized tasks such as bomb disposal [40], door opening [52, 70], valve turning [71], and maintenance and service tasks [39]. In addition to unmanned aerial vehicles (UAVs), this section also includes unmanned ground vehicles (UGVs) and remotely operated vehicles (ROVs).

UGVs are multi-purpose ground-based mobile robots equipped with sensing equipment and manipulators. ROVs are a subset of unmanned underwater vehicles (UUVs) tethered to a main vessel and used for deep-sea explorations, normally equipped with manipulators designed for teleoperation, not autonomous manipulation [72]. UAVs are aircraft piloted by remote control or on board computers, and UAV platforms suitable for telemanipulation are limited to vertical take-off and landing (VTOL) vehicles because they have the ability to stabilize and hover in place, as opposed to fixed-wing UAVs that require continuous motion in-flight [50]. Note that this study excludes teleoperated systems with unusually large workspaces (e.g., excavation vehicles), with prohibitively long time delays (e.g., space operation), or that require highly specialized training (e.g., telesurgery).

A primary challenge associated with SUS telemanipulation is maintaining situation awareness of the manipulator and vehicle in space [32]. Methods for mitigating loss of situation awareness through improving remote presence include enhanced visualizations [73], multimodal displays [74, 75], and feedback systems [76, 77, 78]. Additional HMI considerations include methods for direct remote control [79, 80] (especially when fine-tuned movements are necessary [81, 82]), type of controller hardware [38, 83], and controller feedback methods [60, 84, 85].

This chapter is organized as follows. Section 2.1 reviews manipulating UAVs found in the literature, and Section 2.2 describes common interface technologies used for telemanipulation operator input. Section 2.3 presents the physical factors that affect telemanipulation, and Section 2.4 describes the visualization types that affect telemanipulation performance.

2.1 Review of Manipulating UAVs

This section presents the UAV grasping configurations and manipulator designs found in the literature, and Table 2.1 presents a summary of results. Manipulation tasks with UAVs include grasping, pushing, payload acquisition and drop-off, perching, probing, and other physical interactions with the environment. This chapter also discusses the advantages and limitations tasks and manipulator designs, from simple claw-like mechanisms to complex robotic arms.

2.1.1 Single Degree-of-Freedom Manipulators

Early manipulating UAVs used simple one or two degree-of-freedom (DoF) impactive grippers, such as claws or pinchers. Impactive grippers physically grab the object upon contact and apply a sufficient force to overcome gravity to lift the object. Ghadiok et al. [25] developed a single DoF impactive gripper that flattened itself prior to landing and takeoff and successfully gripped objects using visual detection with an IR sensor. Quentin et al. [63] mounted a servo-actuated, single DoF gripper to a quadrotor to autonomously grasp rectangular modules for construction of cubic structures. Pounds et al. [55] constructed an underactuated manipulator with four fingers, mounted on a T-Rex 600 ESP RC helicopter for grasping and retrieval of objects. Thomas et al. [86] used a similar underactuated gripper (based on the design in [91]) to perform avian-inspired grasping at high velocities to increase the grasping time window.

Table 2.1: Summary of Platforms. Manipulators, Tasks, and Controls for Manipulating UAVs Found in the Literature.

Manufacturer & Model	Type of Manipulator	Items Grasped	Manipulator Controls	Ref.
T-Rex 600 ESP helicopter	4 fingered, 1 DoF gripper; 2 elastic joints each finger	Block, cylinder, softball, tool case	Autonomous control via GCS	[55]
GAUI 350 quadrotor	Three 2 DoF manipulators	Items less than 200g	Joystick and keyboard	[23]
GAUI 500X quadrotor	Two 4 DoF arms with grippers	Foam blocks	Joystick and keyboard	[23]
3D Robotics Quadrotor	Two 2 DoF arms with grippers	Valve grasping/turning	Autonomous control via GCS	[71]
AscTec Hummingbird	Rotating arm with claw	Object grasping	Autonomous control via GCS	[86]
Custom-built quadrotor	i) Suction cups ii) Decoupled drive arm and soft bag actuator	i) Door opening ii) Knob turning	Autonomous control via GCS	[52]
AscTec Pelican	6 DoF system: 3 active DoF & 3 passive DoF end effector	Ultrasonic testing	Autonomous control with location from VisualEyez	[16]
AscTec Hummingbird	Ingressive grippers: (i) 4 flex arms hooks; (ii) 4 servo-driven hooks	Ingressive attachment to porous materials	Autonomous control using ROS/Matlab on GCS	[24, 87]
Custom-built prototype	Under-actuated gripper	Objects up to 7.5cm	Autonomous control via GCS	[25]
AscTec Hummingbird	1 DoF servo-driven gripper	Rectangular modules	Autonomous control via GCS	[63]
DJI F550 Hexacopter	2 DoF arm with three links	Generic objects	Autonomous control via GCS	[88]
Smart Xcopter	2 DoF arm with two links with servo-actuated gripper end-effector	Objects up to 3.2cm wide	Autonomous control via GCS	[89]
AscTec Firefly	Water sampling mechanism & passive safety tether	3x20*ml* water samples/flight	Autonomous control via GCS	[14]
MK-hexa2	Multiple DoF robotic arm	Generic objects	Autonomous control via GCS	[90]
AscTec Pelican	2 DoF robotic arm	Object grasping	NA (simulated flights only)	[18]

2.1.2 Multiple Degree-of-Freedom Manipulators

Impactive grippers are useful for pick-and-place operations; however, increasing the number of manipulator DoF enables the end-effector to track the object of interest more precisely in the presence of platform instability. Orsag et al. [23] mounted three 2 DoF serial chain manipulators to a quadrotor, where each manipulator had small hooks mounted on the ends so the arms could push and pull objects. Morton et al. mounted a 2 DoF arm to a DJI F550 hexacopter and tested stability of the aircraft with the manipulator in stow, reach forward, and drop forward positions during takeoff, grasping, and landing [88]. Kim et al. developed a similar two-link 2 DoF arm mounted to a Smart Xcopter for precision grasping experiments using a Vicon system [89] and a vision guidance approach [90]. Fanni and Khalifa [18] developed a 2 DoF manipulator designed to track a 6 DoF trajectory to maximize utility while minimizing the number of actuators. Suarez et al. [92] constructed two human-sized dual arm prototypes, each with 5 DoF, mounted on an octo-rotor platform.

2.1.3 Ingressive Manipulators

Ingressive grippers, similar to impactive grippers, are also used to transport objects by UAVs [24, 87] as they can penetrate the surface of porous materials to retrieve objects rather than overcoming gravity via normal and frictional forces. Ingressive grippers were mounted to a Hummingbird quadrotor in [24] to retrieve wooden objects on a stable aircraft. Mellinger et al. [87] used multiple UAVs to simultaneously locate, grip (using a similar version of the mechanism in [24]), and transport different configurations of wooden structures to a new location. Ingress grippers are advantageous because they can engage with any point on the material; however, the types of objects suitable for penetration for manipulation are obviously limited due to material properties.

2.1.4 Manipulators for Specialized Tasks

In addition to object deployment and retrieval, aerial platforms can also perform highly specialized manipulation tasks. Korpela et al. [71] mounted dual 2 DoF manipulators to a quadrotor and implemented a visual valve detection algorithm for valve turning from a flying aircraft. Tsukagoshi et al. [52] developed a customized UAV platform to perch on a door with suction cups and use the lift forces generated by the vehicle's propellers to subsequently push open the door; if the door had a knob, a pneumatically actuated soft-bag manipulator twisted the knob and opened the door. McArthur, Chowdhury, and Cappelleri [70] designed a UAV frontal manipulator capable of opening an electrical box handle using computer vision algorithms. Researchers in [16, 93] designed and prototyped a structural inspection system consisting of an active 3 DoF structure and a Cardan gimbal with 3-passive DoF; these elements resulted in 6 DoF relative to the UAV, allowing it to perform nondestructive testing with a variety of different sensors. Ore et al. [14] developed a water sampling quadrotor capable of capturing three 20 ml samples per mission while maintaining a safe altitude above the surface.

2.1.5 Summary

UAV and manipulator systems rely more directly on sophisticated control algorithms and sensor data to automate tasks as aerial manipulation tasks increase in complexity. For example, motion capture sensors can enable precision tracking of the UAV position relative to the object of interest [13, 25, 71, 86, 89]. In laboratories, reliance on tracking software and visual sensors to complete the manipulation is practical; however, tasks in real-world scenarios are highly uncertain and will require human operators [32, 33], especially for *ad hoc* teams where there is little to no prior training or exposure to the robot. Although a large number of manipulating UAVs appear in the literature, the HMI for nearly all manipulating UAS is either i) undocumented, or ii) consists of a ground control station with no further detail about the human interfacing. Dynamics and controls are currently the primary research focus for manipulating UAVs, and *Mission Specialist* HMI remains a largely unstudied research topic. Due to the lack of focused HMI studies for manipulating UAVs, the remaining sections also survey literature on telemanipulation for UGVs, ROVs, and stationary telemanipulation systems.

2.2 Operator Interfaces Used for Telemanipulation Inputs

This section describes interfaces, both hardware and software, used for operator telemanipulation inputs. Hardware interfaces are first discussed, including semi-automatic controls and master-slave devices. Then this section examines software interfaces, including computer and touch-based tablet software.

2.2.1 Hardware Interfaces

A master-slave controller, joystick, or other physical device maps hardware inputs to actuators to control manipulators, typically under direct control. Hardware interfaces can control each degree of freedom individually, or a subset of the degrees of freedom, under varying levels of autonomy. Operator inputs can directly map to manipulator movements or scale movements down or up [94]. This section describes multiple hardware devices used for telemanipulation.

2.2.1.1 Master Slave Controllers

A common telemanipulation input device is a master-slave configuration where the master controller is geometrically similar to the manipulator at certain scales [95]. In this setup, operator inputs from the master arm map directly to the slave arm, and the position and force responses of both master and slave devices may be identical or scaled proportionally, depending on the task. Additionally, the master is often a kinematic replica of the slave, providing an intuitive interface [83]. Remote surgery, also known as "telesurgery", is an archetypal example of master-slave control. Master-slave surgical devices enable operators to perform accurate, small-scale manipulation tasks. (For a review of medical telerobotic systems, see [96, 97].)

Tethered ROVs normally use master-slave controllers to perform sub-surface manipulation and exploration. Commercially available manipulators, such as the seven degree of freedom Orion (Schilling Robotics, USA), are commonly deployed with ROVs due to their robustness in deep-sea environments and readily available master controllers [35, 98, 99, 100]. The master controller for these systems is a scaled-down kinematic replica attached to a console panel with push keys, a small screen, and status indicators. Master joint movements produce an equivalent or scaled movement of the slave arm joint, and the keys determine manipulator control mode (e.g., rate or position) and functions (e.g., freezing or enabling hydraulics).

2.2.1.2 Semiautomatic Input Devices

Semiautomatic input devices enable remote control and human-assisted control during telemanipulation tasks. These devices have geometries dissimilar to the manipulator [95], such as joysticks or other physical controllers. Joysticks can operate under either position or rate control; under position control the joystick commands the desired position of the joint or end effector, and under rate control the joystick commands the desired velocity. In both cases, the input commands are proportional to the joystick displacement [83]. Dual joysticks, such as gamepad controllers, provide input if the slave manipulator requires control for both orientation and translation [83]. Joysticks and gamepad controllers can operate manipulators on ROVs [101, 102], UGVs [38], and simulated UAVs [60].

Non-joystick, three-dimensional semiautomatic devices are also used for telemanipulation input under direct and human-assisted control. Examples include the Novint Falcon haptic device (Novint Technologies LLC, U.S.), a three DoF version of the original delta-robot configuration [103], and the Geomagic®Touch^{TM} (3D Systems, U.S.). These smaller, inexpensive master controllers are widely studied for applications in robotics and gaming [78, 104] and can provide force feedback based on user input. These controllers normally have smaller working volumes compared to traditional master-slave configurations.

2.2.2 Software Interfaces

Operators can control unmanned systems via accessible networks through computer or tablet software that provides the means for human control of the system. Operators can give either high level directives or control the manipulator position directly. Software-based interfaces for manipulator control normally run on ground control station computers or tablets, are for specific manipulation tasks or platforms, and include a combination of mouse, keyboard, and touch inputs. This section describes features of computer and tablet-based software used for telemanipulation.

2.2.2.1 Computer Software

Networked SUS are normally controlled through user interface software implemented on a computer, which requires a keyboard and/or mouse for user input

[105]. Operators control the manipulator by deciding where to click within the interface or through keystroke inputs. Computer software controls manipulators by position and requires 2D user input to map to locations in 3D space. Full 3D representation includes interface elements that control for each DoF separately (e.g., control in the x, y, and z axes [106]), or control the position of the end effector through inverse kinematics [107]. In general, computers can process and display large amounts of data and complex mixed visualizations [108, 109, 110]; however, an constraint of computer software is providing an adequate 2D representation of the manipulator and robot that exist in a 3D remote environment. This is normally attempted through visualizations such as video streams [111, 112], stereo vision [43, 62], or mixed reality displays [65, 113].

2.2.2.2 Tablet Software

A fixed control station is inappropriate and mobile operation is essential for a majority of unmanned systems operating over an extended range [109], and an attractive alternative to stationary computer control stations are portable consumer electronics (e.g., tablets or smart phones). Mobile tablets are an appealing interface technology to use for telemanipulation control because they are widely available, are low cost, and use standard gestures [114, 115, 116]. The development of intuitive telemanipulation interfaces for these handheld devices is becoming increasingly important; however, some challenges remain, including intuitively mapping 2D inputs to 3D space [111], decreased computational power and the need for efficient algorithms [41, 109], and designing effective touch gesture-based controls [116]. Additionally, mobile device visualizations are less complex compared to computers, as bandwidth constraints limit how much sensor data and information streams to the device. Touch-based interfaces are generally intuitive for non-expert users [116], but the interface elements that control the manipulation affect operator performance.

2.3 Physical Factors Affecting Telemanipulation

This section discusses the types of physical factors that affect SUS operator performance during telemanipulation, including controller form factors and variations of manual control. Table 2.2 presents an overview of the physical interface implementations surveyed in this section, and Table 2.3 includes a summary of the findings.

2.3.1 Input Form Factor

Control input devices are a critical link between an operator and the unmanned system in a remote environment [117, 118]. The form factor and design of input devices influence intuitiveness and learning requirements, which subsequently affects operator performance [38, 60]. The sections below discuss capabilities and general effects on operator performance of the following telemanipulation interfaces: physical hand controllers, computer devices, and touch-based mobile devices.

2.3.1.1 Physical Hand Controllers

Common telemanipulation hand controllers include master-slave devices, joysticks, and other three dimensional devices. Depending on the level and location of control within the manipulator, each design affords different types of interaction between the controller device and robot. For example, hand controllers that are geometrically similar and retain all robotic manipulator DoFs are normally easier for users to learn because they intuitively map user input directly to output [35, 38]. A remote operator identifies their body and immediate environment with the remote vehicle and its environment; therefore, a geometrically similar device better enables the match between their own movements to the remote manipulator attached to the vehicle [119].

Joysticks are also commonly used input devices, but because they are geometrically dissimilar to manipulators, visual motor mapping between the end-effector and joystick affects task completion [120, 121]. Maintaining situation awareness of the vehicle's orientation in space and the surrounding environment is necessary to achieve proper mental mapping between the SUS manipulator and joystick [122]. To improve performance, joystick input should be analogous (i.e., moving the joystick to the left moves the vehicle to the left); however, this becomes difficult as manipulators increase in complexity and planer movements do not correspond directly to responses in the system. While joysticks may not be as intuitive as master-slave devices for direct joint control, they can be effective if used for end effector control [35].

Some studies have specifically compared the effects of using joysticks versus master controllers as input devices for telemanipulation tasks. Nixon [60] found that joystick input increased task completion time compared to a 3D haptic input device when performing a simulated manipulation task with a UAV. Vozar [38, 111] studied the effects of a master-slave device and dual joysticks for teleoperating a UGV manipulator and found that the master-slave device was more effective than a traditional gamepad controller [38]. This is consistent with previous findings that position master-slave configurations are more suitable for dexterous manipulation tasks because they have a natural correspondence in time and space as the operator performs movements [117, 119].

2.3.1.2 Computer Input Devices

Computer input devices facilitate control of systems that have higher levels of automation and complexity. Computer keyboards and mice are widely available physical interfaces that non-expert operators are likely accustomed to using. A limitation of these systems, however, is the lack of mobility of networked workstations that require operation in close proximity to their operator.

Common input modes for computer control include "click-and-drag", where the user clicks a point on the robot and drags the cursor to indicate desired translation, or "point-and-click", where the user defines a goal end-effector position by clicking within the remote environment [108]. You and Hauser [123] compared multiple click-and-drag mouse input schemes for manipulator control, including: direct joint control, inverse kinematics, reactive potential field, and a real-time motion planner. Their real-time motion planning strategy improved safety, reduced task completion time, and rated favorably by users, likely because it allowed users to focus more on the positioning task, instead of on constructing paths.

A potential issue when using a computer for manipulator control input is precise positing in a 3D remote environment. Materna et al. [110] developed an interface that used a 2D mouse used to interact with and set the 3D scene, but a 3D mouse set the end effector goal pose within that space. The 3D mouse was comfortable and intuitive, and enabled precise manipulation of the end effector.

Buttons, including keyboard strokes or clicking buttons with a mouse on a computer interface, should primarily generate sequences of actions (e.g., behavior chaining), rather than directly control manipulators [112, 124, 125]. The operator control unit for the SURROGATE ground vehicle ran on a computer desktop and operated with a standard keyboard and mouse. Using this interface, operators sent entire sequences of actions by chaining behaviors together to reduce operator interaction time [125]. In contrast, using keyboards and buttons for direct control degrades task performance, although some operators prefer the kinesthetic feedback from physically pressing buttons [124].

Table 2.2: Summary of Physical Interface Devices for Telemanipulation[1].

Reference	Input Device					Control				Level of Autonomy			
	Master-Slave	Joystick	Mouse	Keyboard	Touch Device	End-Effector	Joint Position	Bilateral Feedback	Virtual Fixtures	Remote Control	Human-Led	Human-Delegated	Human-Supervised
[126]	•					•			•		•		
[127]	•						•		•	•	•		
[128]	•						•	•		•			
[80]	•						•			•			
[84]	•						•	•		•			
[60]	•	•					•			•			
[113]		•				•				•			
[73]		•					•			•			
[35]		•	•	•		•	•			•	•	•	
[85]		•					•	•		•			
[44]		•				•	•			•			
[36]		•		•		•				•			
[79]		•					•			•			
[108]			•	•		•					•	•	
[129]			•	•		•			•	•	•		
[130]	•			•		•			•		•		
[123]			•	•		•	•			•	•		
[110]			•	•	•	•					•	•	
[131]			•	•	•							•	
[41]					•	•				•			
[132]					•						•		
[133]					•							•	
[115]					•		•			•			
[125]					•							•	
[116]					•		•			•			
[124]					•	•				•			

[1] Some systems had multiple control modes (e.g., full remote control vs. human-led options).

2.3.1.3 Touch Input Devices

A variety of 2D touch elements enable the operation of manipulators in 3D environments. Lopez et al. [116] created a touch-based version of direct control hardware; their interface contained four control element options, including virtual buttons, virtual joysticks, touchscreen gestures, and tilting the device. Touch-based buttons and joysticks yielded the best task completion scores because they enabled more precise control of manipulator movements (compared to the tilt and gesture-based interfaces).

Other tablet interface implementations have taken a direct manipulation design approach, where users can touch the screen to control the robot "directly" in the remote environment. Hashimoto et al. [115] developed a touch screen based application in which users directly manipulated the robot by touching it on a view of the world, as seen from a third person view obtained by pointing a camera at the robot. While the touch controls were intuitive, some users requested a stylus pen to enable more precise interaction, and others reported it was difficult to understand the depth of the space from a single view. Singh et al. [124] also developed a direct touch-screen control method where operators could touch and drag the manipulator end effector in a desired trajectory, which reduced task completion time and mental workload.

Another method to directly manipulate in three dimensions on a 2D screen is multi-touch gesturing. In [132], participants used two fingers to draw axes of rotation and translation; additional gestures sent movement commands and verified autonomously generated motion paths. The interface interpreted multi-touch gestures as actions and sent the location where the user touched (single screen points) as targets to the remote manipulator.

While touch-based gestures may be effective, limited bandwidth and computational power limit the use of advanced data visualizations and control algorithms on tablets and smart phones [109]. Mobile devices only afford simplified data visualizations and interaction elements as it is impractical to send and display all robot and sensor data [109]. Additionally, when designing kinematic algorithms for touch-and-drag control (which is often preferred by users [124, 115]), they must be computationally efficient enough to run on tablet devices. For example, Parga et al. [41] and Singh et al. [124] developed touch-based interfaces with inverse kinematic solvers capable of running on small tablet devices.

Direct control can be difficult on a touch-based 2D environment due to a lack of precision [115, 116], but operators can more readily program behavior and action sequences when using a mobile device. In [133] a pictorial tablet interface enabled human-delegated inspection tasks by "teaching" the robot desired navigation paths and inspection tasks, after which the robot autonomously completed the same inspection mission. Herbert et al. [125] developed a tablet interface designed for field operations which only needed high-level directives and relied on autonomy to carry out individual actions by first selecting the object in the image, followed by selecting the appropriate behavior sequence. Saito and Suehiro developed Titi (TeachIng Tablet Interface) with a 2D input screen to enable pick-and-place operations by a portable manipulator [131]. Operators drew pick-up and place frames on the 2D screen and assigned them to predefined trajectories for the system to complete, effectively teaching the robot to perform manipulation.

2.3.2 Variations of Manual Control

The manner in which control inputs map to output affects performance [38, 44, 117] when the operator has some level of manual control of the manipulator (e.g., remote control or human-led). This section includes the following variations of manual control: direct control (including both position and rate control with no feedback), bilateral control (haptic feedback), and virtual fixtures. Additionally, this section includes information on the location of control in the manipulator, for example, if the user controls only the end-effector or has command over individual degrees-of-freedom.

2.3.2.1 Direct Control with No Feedback

Under direct position control, operators control each joint or DoF of the manipulator individually, and a reference position maps from the input device to the output device [117]. Master-slave and joystick interfaces are commonly used for direct control, and can operate by controlling either the position or rate of each joint. Early studies [134, 135, 136] analyzed the effects of position and rate control on target acquisition and found that position controlled joysticks resulted in higher index of performance (Fitts's Law) compared to velocity controlled joysticks. Experiments by Kim et al. [79, 137] examined pick-and-place tasks using two isotonic joysticks and also found better operator performance under position control; however, if the control device is slow, superior performance of position control diminishes, and it is recommended to use position control for small workspace tasks and rate control for slow-workspace tasks [79].

Whether the operator has control over the end effector or each joint has an affect on performance, and the optimal location of control depends on the importance of speed versus accuracy on the task. Atherton and Goodrich [44] found that participants worked faster with a joystick under joint control compared to end-effector control, but joint control resulted in more collisions with the environment. Additionally, operators may be imprecise in positioning the end effector at the desired location and tended to overshoot the target when operating a master-slave controller under position control [138]. Draper [117] also notes that when the operator is in constant manual control of a remote manipulator, the user should be in control of the end-effector as direct joint control can be inefficient.

Achieving transparency under position control has traditionally been the goal of master-slave manipulator systems [139]. Master-slave kinematic laws have generalized this type of system for mixed position and rate control [85]; however, when controlling both manipulator position and rate, the process for switching between these modes affects user performance [80, 118]. Herdocia et al. [80] found that a manual switch between position and rate control resulted in slow performance and higher error rates than a differential-end-zone coordination scheme, where a fixed inner space controlled position, and velocity control occurred at the boundary of the inner space.

Operator fatigue is another issue that can arise when operating large master-slave devices [117, 138]. Due to the complexity of these master controllers, operator fatigue under remote control can degrade operator performance [72]. For example, Gupta et al. [138] found that operators became tired after repeating pick and place tasks (after approximately N = 30) when using a master controller, despite that a majority of users became proficient within a few minutes.

Position control enhancements can reduce fatigue in master-slave operators. Love and Book [140] found that an adaptive impedance manipulator controller reduced the total energy output of the operator when executing remote tasks compared to non-adaptation. Force scaling can reduce the required magnitude of operator input by scaling input forces up when operating large devices, or scaling down when performing micromanipulations [139]. Implementing smaller working volumes for the master controller also reduces operator fatigue [141], and fatigue likely decreases after being adequately trained with the master controller [142].

Table 2.3: Categories of Physical Factors that Affect Telemanipulation.

Physical Factor	Summary of Findings	Refs.
Type of Hardware:		
Physical Devices	Geometrically similar master controllers can be easier to use, are more intuitive, and improve performance compared to joysticks; if using joysticks, inputs and outputs should be analogous.	[38, 111, 35, 60, 120, 118]
Computer Devices	Keyboard or button-only interfaces can negatively impact performance, but "click-and-drag" and "point-and-click" inputs are effective with computer mice.	[108, 110, 123, 124]
Touch Devices	Precise control is possible, but can be difficult to achieve; touch-based devices are effective for programmatically performing sequences of behaviors to complete tasks.	[115, 116, 133, 131, 125]
Control Scheme:		
Position Control	Joysticks offer better performance when operated under position instead of rate control; should use end-effector position control when emphasizing precision; operator fatigue is a potential issue when controlling large master controllers.	[134, 135, 136, 79, 44, 138, 117]
Bilateral Feedback	Can decrease task completion time, reduce error rate, and magnitude of applied forces; does not necessarily improve performance under control time delays.	[143, 144, 128, 85, 84, 76]
Virtual Fixtures	Can increase precision, reduce mental workload, and decrease task completion time; improves performance in the presence of time delays; must know remote environment *a priori* or model it correctly in real-time to be effective.	[127, 126, 130, 145, 146, 147]

2.3.2.2 Bilateral Force Feedback

Force feedback (also known as haptic feedback) is a broad term that includes both tactile and kinesthetic information. In general, forces felt by the robot using tactile and other sensors are then fed to a haptics device to provide force feedback to a user [148]. Feedback and additional cues from force and tactile sensors in teleoperation systems complement visual information, increase spatial awareness of the remote environment, and reduce error rate and magnitudes of applied forces [144, 149].

Task completion time is generally decreased when haptic feedback is present. Implementing haptic feedback with proximity sensors for grasping tasks reduced completion time compared to visual-only feedback, despite that users were not requested to be time-efficient [128]. Additional vibratory feedback from contact and proximity sensors, when used in conjunction with surface reconstruction, also resulted in reduced task completion times for object identification [75]. Salcudean et al. [85] found that providing contact force feedback improved a joystick telemanipulation system under both position and rate control.

In addition to decreased task completion time, haptic feedback can also reduce average and maximum applied forces [76, 84]. Haptic feedback in a master controller reduced contact forces and the occurrence of large robot-environment interaction forces during telemanipulation [84]. In [76], acceleration haptic feedback significantly reduced peak and average contact forces when grasping flexible objects. A reduction in manipulator force is especially important for operations where the object being manipulation is highly sensitive to force, which is why a majority of telesurgery systems implement haptic feedback (for a review on the benefits of haptic feedback in telesurgery, see [149]).

While haptic feedback has the potential to improve performance and reduce task completion time, it is unlikely that the benefits of haptic feedback remain significant under time delay. Yip et al. [84] studied an insertion tasks under different time delays for multiple haptic feedback modes (lateral, graphic, and bilateral) and found that as the delay increased up to 500 ms, task completion times increased significantly for all feedback variations. Additionally, introducing haptic feedback with time delays of 0.2 ms degraded performance during UAV obstacle avoidance, including increased number of collisions and operator workload [150]. In general, however, for short-range SUS deployments when communication delays between the operator and vehicle are not significant, haptic feedback with small workspace controllers will offer performance benefits for direct or human-led control operations.

2.3.2.3 Virtual Fixtures

Virtual fixtures are task-dependent computer-generated guides overlaid on a reflection of the remote workspace [151]. They provide force feedback similar to general haptics discussed in the previous section; however, virtual fixtures assist the operator with force feedback for a specific, structured teleoperation task. Examples of virtual fixture implementations include a guide from the robot gripper to an object in the remote workspace [126] or force clues influencing the trajectory of the gripper [130].

Virtual fixtures are either "guidance" or "forbidden region" virtual fixtures: *guidance virtual fixtures* assist in keeping the manipulator on desired paths or surfaces, while *forbidden region virtual fixtures* physically prevent motion in the remote workspace in specific forbidden zones [147] (note that guiding fixtures are likely better at micro scales due to slight inaccuracies in system control [152]). Virtual fixtures have been successful in guiding remote control operations, providing localized references, reducing mental workload, and increasing precision [151, 153].

Studies show that virtual fixtures can reduce task completion time for manipulation and positioning tasks [126, 127]. Authors in [126] significantly reduced completion time through a human-led control scheme where the operator positioned the gripper close to a position fixture, and the system autonomously completed the task using the virtual force cues. Kuang et al. [130] similarly found improved positioning with the assistance of haptic and graphic virtual fixtures. Li and Okamura [146] improved execution time by recognizing operator performance and adaptively applying virtual fixtures when appropriate based on the current task.

Virtual fixtures also improve telemanipulation performance in the presence of time delays, primarily because static virtual fixtures are immune to temporal distortions in sensory data due to delayed communications [145]. Xia et al. [127] used virtual fixtures to limit manipulator movement to a given workspace and influence its motion along a desired path. After inserting a four second time delay, the implementation of virtual fixtures decreased task completion times and limited the number of adverse effects (e.g., tearing) on the material handled by the manipulator. Authors in [129] used guiding virtual fixtures to assist with remotely retrieving objects at the bottom of the ocean floor using an ROV. They inserted artificial time delays of either 5, 10, or 15 seconds, and the virtual fixtures enabled the operator to overcome significant time delays to complete the task.

One limitation of implementing virtual fixtures is their dependency on *a priori* knowledge of the nature and geometry of the task. The implementation of virtual fixtures works well for controlled tasks such path following or manufacturing; however, SUS deployments are often highly dynamic and uncertain, and *a priori* knowledge of the remote environment is highly unlikely. One potential solution is to use remote sensing methods to develop graphical models of the remote environment at the site of manipulation in real time [127, 154], which is only possible if the system is accurately modeled. In changing environments, adaptive virtual fixtures can help overcome new obstacles [155]; however, these systems require training data sets to learn desired paths prior to dynamic environmental changes. More research is needed regarding the modeling and development of virtual fixtures in real time in unstructured environments before the benefits of virtual fixtures can be fully realized for SUS.

2.3.3 Summary of Physical Factors that Affect Telemanipulation

Physical control input devices are an important link between the remote system and human operator, and form factor of the device facilitates the type and level of autonomy (LOA) of interaction with the system. Nearly all master-slave and joystick controllers (and variations of physical controllers) only allow for direct remote control or human-led operations, which require constant input from the operator. Control should generally be at the end-effector when operating physical controllers under manual teleoperation, instead of each individual joint. While continuous teleoperation using physical systems can be fatiguing, control enhancements such as haptic feedback or assistive virtual fixtures improve overall performance. Virtual fixtures allow humans to safely cope with more complex and unstructured tasks and remain within the control loop, but adaptive fixtures require additional research to develop constraints in near real-time, as this work is in its early stages [153]. Mobile devices with computing power, such as laptops or tablets, afford goal-oriented input and directives from the operator when systems have advanced autonomous capabilities. Additionally, the past 5-10 years has seen a trend of increased mobile tablet use for controlling unmanned systems, which will likely continue to increase as computing power and connectivity evolve; however, further evaluation of touch-based gesturing and interaction is needed to develop effective manipulator direct control through mobile devices.

2.4 Visual Display Types that Affect Telemanipulation

This section discusses multiple types of visual displays that affect SUS operator performance during telemanipulation. Common remote manipulation displays include mixed reality (including augmented reality and augmented virtuality), virtual reality, and stereo vision/depth imagery. Table 2.4 presents an overview of the visual interface implementations surveyed in this section, and Table 2.5 includes a summary of findings.

2.4.1 Mixed Reality Displays

Mixed reality (MR) is a display subclass that spans between the extrema on the reality-virtuality continuum that juxtaposes real and virtual objects within a scene [156] (see Figure 2.1). Contrary to virtual environments where the user is totally immersed in and able to interact with a purely synthetic world, MR interfaces integrate elements of both virtual and real worlds. They provide a user with additional or enhanced information which can aid in reducing operator mistakes [157], communicate processed sensor data [158], and improve human-robot collaboration [159]. MR displays are classified as either augmented reality (AR), where a display of the real environment is augmented by virtual objects, or augmented virtuality (AV), where a virtual environment augmented with real world objects or imagery [156].

2.4.1.1 Augmented Reality

AR interfaces display real world imagery (usually in the form of a video stream) with synthetic object and indicator overlay cues and aids. This section focuses on monitor-based AR displays with computer-generated objects overlaid onto the imagery, as opposed to immersive environments. These object overlays, such as coordinate systems [42, 113], depth information [38, 158], or virtual handles [115, 132], aid in manipulator positioning under remote control or human-assisted teleoperation.

Table 2.4: Summary of Visual Interface Implementations for Telemanipulation.

Ref.	Visualization				Sensors			Device[1]		Level of Autonomy			
	Real Environment	Augmented Reality	Augmented Virtuality	Virtual Environment	Video Feed (RGB)	Stereoscopic Imagery	Laser/Range Scanning	Touchpad Device	Computer System	Remote Control	Human-Led	Human-Delegated	Human-Supervised
[40]	•					•			•	•			
[160]	•				•	•			•	•	•		
[161]	•				•				•	•			
[113]		•			•				•	•			
[42]		•			•				•	•			
[38]		•		•	•				•	•			
[158]		•			•	•			•		•		
[115]		•			•			•		•			
[132]		•			•		•	•			•		
[44]			•		•		•		•	•			
[43]			•		•	•	•		•	•		•	
[62]			•			•			•	•		•	
[162]				•		•			•	•	•	•	
[39]				•	•				•	•		•	•
[163]				•	•	•			•	•		•	
[37]				•	•		•[2]		•	•			•
[35]				•					•			•	•

[1] Device that displays the interface.
[2] This underwater vehicle also used sonar sensors to create virtual reconstructions of the environment.

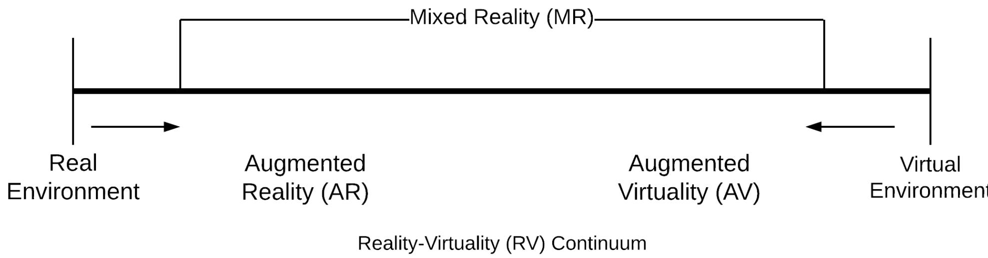


Figure 2.1: The Reality-Virtuality Continuum based on Milgram and Kishino, 1994 [156]. This Continuum Represents Multiple Classes of Objects Rendered in a Display. The Left Corresponds to Environments Consisting Solely of 'Real' Objects, for Example, a Live Video Stream. The Right End Defines Environments Consisting Solely of Virtual Objects, Typically Rendered Using a Computer.

Augmented coordinate system displays can improve the operator's mental model of the position and orientation of the manipulator in space and reduce operation errors. Chintamani et al. [42] found that augmenting a video stream with the end-effector coordinate system reduced participant reversal errors and total distance traveled by the end effector. Nawab et al. [113] generated virtual color-coded co-ordinate systems on the end-effector of the robot that mapped to similarly color-coded joysticks for controlling position and orientation. They also reduced total distance traveled and reversal errors when using augmented coordinate systems.

Virtual handles, or three-dimensional widgets [164], in an AR interface alert the user to the types of allowable interactions within a remote environment. For example, a three-dimensional ring with arrows indicates potential rotation movement. Hashimoto et al. [115] implemented two virtual handles, a lever to indicate manipulator movement and a ring to indicate rotation movement, which participants found intuitive to use. Chen et al. [132] also implemented virtual rings to indicate rotation direction around an object identified by the robot.

The use of augmented depth information informs an operator of how far away objects are and when an object of interest is within reach of the manipulator. An early implementation of AR depth sensing was the Augmented Reality through Graphical Overlays on Stereovideo (ARGOS) system by Milgram et al. [165, 166]. Their system used virtual pointers and tape measures to calculate and display distances between user-selected points, which positively affected user performance [167]. Vozar and Tilbury [38] implemented a virtual crosshair that changed from black to either green (if the object was within reach), or red (if the object was out of reach) to provide depth cuing. Users felt enhanced presence in the remote workspace when using the AR interface, but their performance dropped compared to using a video-only interface.

Depth distortions due to calibration errors can negatively affect performance [168]; therefore, AR systems should draw digitally generated graphics with the same calibration parameters as the video so users can accurately align graphic objects to real objects [169, 170]. Additionally, digitally overlaid objects will always occlude objects in the video, and interface designers should create object displays to minimize occlusion [168]. For example, instead of using solid reconstructions of remote objects (which might appear the most realistic), wireframe reconstructions reduce occlusion yet accurately represent object shape, size, and location [115, 166, 171].

2.4.1.2 Augmented Virtuality

AV displays use virtual environments augmented with real objects [156]. Generating AV is more computationally intensive than AR, and the quality of the virtual environment is primarily dependent on the quality of sensor used in reconstruction [172]. Generation of virtual 3D reconstructions of remote environments requires laser scanners (e.g., LiDAR) [43, 44] or imagery from multiple views [74].

Moore et al. [43] developed an interface to display a virtual reconstruction of a ground vehicle using stereo imagery and LiDAR data, augmented by both real-world imagery of objects in the remote scene and virtual handles. Atherton and Goodrich [44] developed an AV interface to display a virtual environment and manipulator generated by a range imaging scanner, and augmented the virtual environment with video from a camera mounted on the end-effector. Results from user experimentation include decreased mental workload and increased situation awareness; however, their AV interface increased task time, likely caused by non-optimal calibration of the virtual elements. When designed carefully, however, virtual elements can potentially result in teleoperation performance comparable to line of sight performance [112].

Table 2.5: Types of Visual Interface Displays that Affect Telemanipulation.

Type of Display	Summary of Findings	Refs.
Augmented Reality	Task performance benefits gained from augmented coordinate system displays and depth information; calibration is important to avoid negative performance; typically used to aid in remote control or human-led operations.	[42, 113, 165, 166, 167, 38, 170, 168]
Augmented Virtuality	Can improve telepresence and situation awareness of the remote environment, if designed and calibrated appropriately.	[44, 112]
Virtual Reality	Virtual reconstructions typically used for motion planning and trajectory confirmation under human-led or human-delegated operation; especially useful for deep sea applications when poor visibility is an issue.	[35, 163, 62, 173, 39, 74]
Depth Imagery	Generally improves task performance and end-effector placement; limitations on scenarios and tasks for which depth sensing is beneficial.	[39, 174, 40, 175, 176]

2.4.2 Virtual Reality

Virtual reality (VR) is an extrema on the reality-virtuality continuum where the environment consists solely of virtual objects [156]. A VR display can improve situational awareness and partially compensate for communication delays between the vehicle and operator, especially in deep sea explorations [162, 177]. To reconstruct a virtual environment based on a robot's surroundings, sensors such as stereo cameras, laser scanners/range finders, or multiple camera views are necessary to capture both depth and position information. Virtual environments enable the operator to test, preview, and verify planned sequences of motion.

To facilitate human-led or human-delegated operation, virtual reconstruction environments can display a preview of pre-defined manipulator actions before they are physically carried out. The VR interface in [62] provided users with a planning tool to assist in creating and reviewing manipulator sequences on a ground vehicle. Mast et al. [39] included 3D reconstructions in a VR interface that showed an animated preview of the planned trajectory based on a user-specified target position for the gripper. Authors in [173] developed a VR interface that also enabled testing and optimization of an ROV manipulator, and users noted that small manipulation behaviors during system tuning were easier to see in the VR reconstruction as opposed to on the real manipulator.

Virtual reconstructions especially aid in visualization of ROV manipulators in underwater environments where limited viewing angle, turbidity, and poor lighting can obstruct images. The VR interface in [35] allowed the operator to input the desired ROV end-effector position with a single click to generate and preview a manipulator trajectory. Zhang et al. [163] also simulated motion command inputs in a VR environment before the ROV semi-autonomously completed the movements.

Without accurate representation of the vehicle's surroundings in the virtual reconstruction, operators may find the model misleading or incomplete due to lack of information. The interface for Nomad, a ground vehicle for desert operations [66], included a VR representation of the robot's state. Their system did not transmit detailed local terrain models, and operators choose not to view the VR reconstruction because of a lack of contextual information.

On the contrary, 3D displays that are too information-rich can impair performance. Olmos et al. [178] found that when one view in a split-screen display is more information-rich (e.g., 3D immersive environment), operators inappropriately allocate attention to that display, even when the task requires attention on a different display. Similarly, Thomas and Wickens [179] observed a "cognitive tunneling" effect when participants used an immersive display compared to an egocentric display, likely caused by a failure to integrate information accurately across two different frames of reference. Interfaces should combine visual and auditory alerts with multiple information-rich VR views to improve attention allocation and lessen visual loading [32, 178, 180].

2.4.3 Stereo Vision and Depth Imaging

Stereo vision is widely used in teleoperation [181] and requires two cameras at a fixed displacement to obtain two different views of the scene. A majority of teleoperation studies found that stereo 3D displays are beneficial and indicate clear, positive performance benefits for spatial manipulations compared to monoscopic displays [174]. In particular, stereovision is beneficial for aiding in end-effector positioning in a remote workspace. Mast et al. [39] found that stereo vision integrated into a larger display improved completion time for positioning a service robot manipulator for grasping tasks. Stereo video also improved deep sea exploration in unknown environments using the Virtual Environment Vehicle Interface (VEVI) control software developed by NASA, which enabled successful collection and sampling using a robotic ROV manipulator [162].

Depth sensors, such as time-of-flight and structured-light sensors [182], are also used to acquire and display 3D image data in two dimensions. Active range imaging systems use light pulses and resolve distances based on the known speed of light. Day et al. [40] used active range sensors in a bomb disposal interface to track and display distance from the end effector to objects of interest. Their interface was successfully tested by subject matter experts who found the display generated by the range sensor desirable. One limitation of active depth sensors, however, is low resolution [40, 182, 183], although time-of-flight and stereo vision data create more precise depth maps when combined [184].

Although often beneficial, stereoscopic depth displays do not always yield better performance over monoscopic displays. Drascic et al. [175] found that stereovision decreased task completion time only after the user gained enough operational experience. Additionally, Draper et al. [176] found that stereovision was better only under highly difficult task conditions. Additionally, limited research exists comparing the usage of imagery from stereo vision to active time-of-flight range sensors for performing manipulation tasks.

2.4.4 Summary of Visual Factors that Affect Telemanipulation

Visual enhancements using processed sensor data offer great potential for improving telemanipulation performance of SUS. Depth sensing through stereoscopic or time-of-flight sensors can enhance overall task performance and end-effector placement. Visual cues using AR (such as coordinate system displays or virtual handles) offer task performance benefits during direct control operations for minimal computational effort; however, the virtual objects calibrate appropriately. Complete VR environments, typically used for motion planning and trajectory confirmation, are effective for systems operating at levels of autonomy higher than remote control, especially when poor visibility of the remote environment is prohibitive. It is recommended that additional research compare AV to VR and AR, as researchers suggest AV offers the benefits of both virtual reconstructions and real world imagery and makes relationships in the environment perceptually evident to the user [44]. Overall, the quality and type of visual display greatly affects operator performance, and the appropriate type of visual display depends on SUS capabilities and manipulation task.

CHAPTER 3

THEORY AND APPROACH

This section presents the theoretical foundations and approach for implementing the Shared Roles Model and focusing on the *Mission Specialist* role. First, this section presents a *Mission Specialist-Pilot* focused version of the Shared Roles Model, including descriptions of each role synthesized from the literature. Then, methods for evaluating the effectiveness of a *Mission Specialist* interface are described. The final section presents the foundations of the *Mission Specialist* interface developed in this study, which includes the use of a mobile, touch-based device, multiple cameras, and virtual dials to enable aerial telemanipulation.

3.1 Shared Roles Model for Small Unmanned Aerial Systems

The Shared Roles Model is based on observations of *ad hoc* team process and communication during eight disasters and over 20 field exercises [185, 186, 187, 34] and provides a framework for evaluating human-robot team interaction. The Shared Roles Model is a compromise between two opposing approaches - the Taskable Agent Model (full platform autonomy) and the Remote Tool Model (no platform autonomy) - emphasizing its ability to capture an appropriate balance of robot semiautonomy and the connectivity needs of the human team [34].

In this model, the robot has some platform or payload autonomy and is no longer operated as a tool. The roles are now divided between the human and robot to take full advantage of the autonomous capabilities, and together they share complete control of the system; this is represented by an overlapping of the payload/platform elements with the *Pilot* and *Mission Specialist* in Figure 3.1. Results from the use of the Shared Roles Model enable a better understanding of individual and team performance; however, these results must be hypothesis-driven due to the empirical nature of the model.

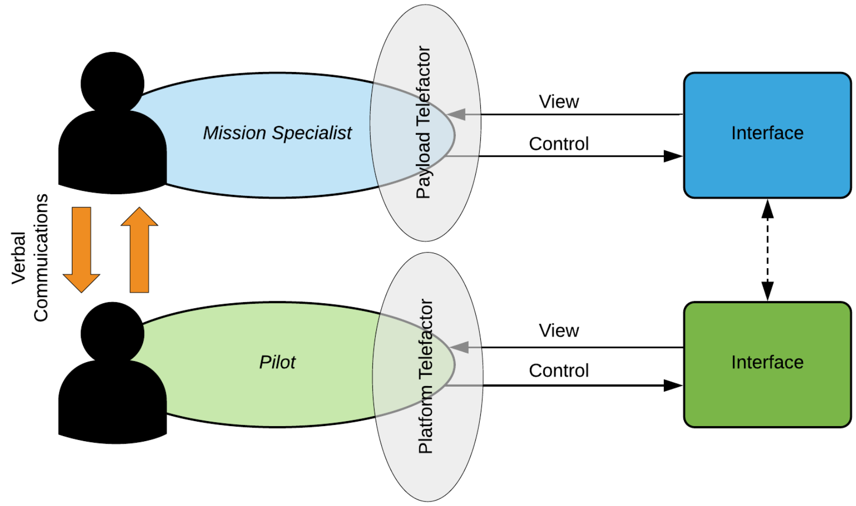


Figure 3.1: A *Pilot* and *Mission Specialist* Focused Version of the Shared Roles Model, Adapted and Modified from [34].

3.1.1 Human Role Descriptions

Three team roles (*Flight Director*, *Mission Specialist*, and *Pilot*) are established for small UAS [45, 46] and included in the Shared Roles Model. These roles are present in nearly all UAS operations and have been synthesized from the research literature. These roles represent trends in role function and are not associated with any specific UAV platform [48].

Pilot is the role that operates (and primarily navigates) the UAV and is responsible for the overall airworthiness and general maintenance of the vehicle. In addition to the *Flight Director*, the *Pilot* has the authority to cease the flight at any point. Due to the FAA restrictions, the *Pilot* is responsible for ensuring the vehicle is only operated within LOS and stays within the maximum altitude of 400 feet above ground level.

Mission Specialist is the role responsible for operating the UAV payload (or in some cases verbally directing the *Pilot* for payload control). In the case of visual reconnaissance missions, the *Mission Specialist* inspects the video and image data streaming from the on-board camera. In the case of physical object manipulation, the *Mission Specialist* will be the role responsible for operating the manipulator.

Flight Director (also referred to as *Safety Officer*) is the role responsible for the overall safety, management, and situation awareness of the team, including both human and UAV. The *Flight Director* also performs an initial site safety assessment and has the authority to cease the flight at any point if safety becomes a concern.

To adapt the Shared Roles Model for telemanipulation by small UAS, the model implementation excludes the *Knowledge Worker* and *Safety Officer* roles. The focus is on team members directly involved in telemanipulation tasks in a controlled study: the *Mission Specialist* and *Pilot*.

3.2 Evaluating the Effectiveness of a *Mission Specialist* Interface

Since its development, Shared Roles has been a natural, yet abstract, framework for evaluating the effects of autonomy on performance and identifying bottlenecks in communication and coordination, emphasizing the "what" and "why" of coagency between the humans and robots [34], which can only be assessed through *post hoc* empirical analysis of team behavior, team communication, and robot failure rates [188]. A goal of this work, in addition to the "what" and "why", is to evaluate "how" a *Mission Specialist* engages with the *Pilot* and interface to perform aerial telemanipulation, and ultimately identify the appropriate HMI for a dedicated *Mission Specialist* interface and develop a set of interface recommendations for future HRI work. To investigate the "how", multiple dependent variables and covariates are measured, including individual characteristics regarding personality, experience, and role empowerment, stress levels, verbal engagement, and multiple measures of task performance.

3.2.1 Individual *Mission Specialist* Characteristics

It is valuable to understand how individual *Mission Specialists* perform differently given the current state of the human-robot team. For example, identifying what factors influence a *Mission Specialist* to begin issuing commands to the *Pilot*, or determining if fluctuations in stress levels throughout a mission affect performance. Individual behaviors, however, may vary due to differences in cognitive mechanisms that are not directly observable and vary widely between participants. Stress [189], role empowerment [47], personality, and perception of the robot are *unobservable* factors hypothesized to influence the *Mission Specialist* performance. Biophysical measurements, specifically electrodermal activity (EDA), were measured as stress level indicators. Note that stress in this context refers to internal state anxiety, or situational stress [189]. A suite of individual characteristics were measured before each trial, including but not limited to indicators of extroversion, locus of control, and amount of previous interaction with robots.

3.2.2 *Post Hoc* Performance Measurements

Communication and behavior are observable variables used to evaluate performance and compared to individual characteristics. Audio and video recordings were codified after each experiment to determine the frequency and type of verbal communication with the *Mission Specialist* and *Pilot* [186, 190]. In addition to codified audio and video, post-assessments were administered to understand each *Mission Specialist*'s confidence and comfort in individual and team abilities to complete tasks during the trials. Multiple measurements of task performance, including success rate and completion time, were also calculated after each experiment. Additional detail regarding all data collected and measurements made in this study are described in detail in Chapter 6

Internal cognitive mechanisms are unobservable by nature, and real-time variables were measured as proxies. Biophysical measurements, specifically heart rate and heart rate variability (HRV), were measured as stress level indicators [191]. A custom script captured touch gesture inputs from the *Mission Specialist* touch device. The robot state (location, battery, operation mode) were also recorded for the duration of the experiment using a motion capture system. Each of these measures captured aspects of individual processes that would have been otherwise unobservable from audio/video coding protocols and were used to determine if there is are existing relationships between these measurements (e.g., stress) and team performance, with a focus on the *Mission Specialist*.

3.3 Foundations of the *Mission Specialist* Interface

3.3.1 Use of a Mobile, *Mission Specialist* Interface

The use of a dedicated *Mission Specialist* interface (or equivalent) is established in the literature [11, 34, 35, 38, 47, 115]; however, the characteristics of small UAS result in stricter interface design constraints compared to other platforms that use stationary control stations. Hardware devices that have proven successful in other telemanipulation applications, such master-slave configurations, are not suitable for UAS field applications that require mobility and fast deployment. Additionally, payload limitations restrict the number, size, and quality of sensors, and visualization on multiple screens to enhance visual displays is logistically challenging in field situations. UAS interface developers and designers must carefully consider the sensor types and feedback modalities necessary to achieve and maintain greater situation awareness in the remote environment.

Recent efforts to make control of manipulators and robot arms more intuitive incorporate planar control movements on touch-screen interfaces and mobile tablets, such as touch-based joystick elements [116] or touch-and-drag movements [124], as described in Chapter 2. These controls are promising for *ad hoc* UAS operations; in their design guidelines for *Mission Specialist* interfaces, authors in [47] recommend they be designed for natural human interaction and take on a mobile form factor. In their study, an Apple iPad interface enabled pinching, zooming, and tapping to control a camera payload. Limited work has been conducted on touchscreen-based interface elements for telemanipulation control, but elements that afford direct control and interaction with the manipulator have shown to improve performance over gesture and tilt based interaction [116]; therefore, this study implemented two virtual knobs capable of rotation to move each link of the manipulator directly, and multiple buttons that enable preset positions for ease of use.

3.3.2 Evaluating Multiple Viewpoints in the *Mission Specialist* Interface

It is well known that interfaces with limited fields of view are prone to a host of perceptual problems that can affect performance [32, 186, 192, 193, 194, 195]. The remote operation and telemanipulation of small UAS requires the use of cameras to capture the environment in which the robot is navigating; however, human operator performance is often compromised due to inadequate placement, number, or quality of video streams [180]. Only a portion of the remote environment can effectively be captured by a on-board cameras or sensors, and the operator often has to use additional cognitive effort to gain situation awareness beyond direct viewing [32]. Remote perception due to limited field-of-view (FOV) includes impaired target detection [196], reduced self-identification within a remote environment [196], lost distance cues [193], and degraded depth perception [193].

One way to ameliorate these issues is to combine multiple views in an attempt to provide more complete information about the remote environment.

The ideal view or views for successfully performing telemanipulation by small UAS likely depends on the task, and precise camera location and image quality must be carefully designed to maximize sensor utility with payload constraints (e.g., limited number of sensors). Overall awareness and recognition are optimized by exocentric views, while the immediate environment is better viewed egocentrically [32, 179]. In the context of a manipulation task for *Mission Specialists*, an egocentric view is obtained by cameras placed directly on the end effector, sometimes referred to as an "eye-in-hand" view, while the exocentric view looks at the entire manipulator from the UAV's perspective, providing a third person view of the manipulator. The *Pilot* may additionally have an orientation view of the vehicle's location in a map, as well as a similar or duplicate exocentric view of the manipulator. To investigate effects of viewpoint on telemanipulation, this study implements a mobile tablet-based interface on the Apple iPad for the *Mission Specialist* with three visualization variations: an exocentric view, an egocentric view, and a mixed egocentric-exocentric view. Results from this study indicate which views are most appropriate for a dedicated *Mission Specialist* interface to improve telemanipulation performance.

CHAPTER 4

HARDWARE AND SOFTWARE IMPLEMENTATIONS

This chapter describes the hardware and software implementations for the UAV control system, manipulator, and interface software and is organized as follows. Section 4.1 describes the UAV and manipulator hardware development. Section 4.2 presents the UAV system identification, and Section 4.3 details the control implementation. Finally, Section 4.4 describes the interface software.

4.1 Hardware Description and Implementation

4.1.1 UAV Platform

The UAV used in this study was a DJI Matrice 100 quadcopter (DJI Science and Technology Co., Ltd., China), which is an affordable developer platform on the consumer market. The Matrice 100 (M100) has a 650 mm diagonal wheelbase and a maximum takeoff weight of 3.6 kg. A 22.8V LiPo battery powers the vehicle and provides approximately 19 minutes hovering time with the maximum payload. A DJI N1 flight controller publishes IMU data including acceleration, angular velocity, and quaternion at 100 Hz and controls the vehicle's low level functions. Table 4.1 shows the weights of individual components and the total weight of the system, and Figure 4.1 shows the coordinate system of the M100.

Table 4.1: Weights of Components Used With the DJI Matrice 100 (M100) Platform, With182 g Leftover for Payload Capacity.

Component	Weight (g)
M100 base platform with NUC and battery	2,133
TB48D intelligent battery	676
Manipulator and controller	519
On board camera	90
	Total Weight: 3,418 g

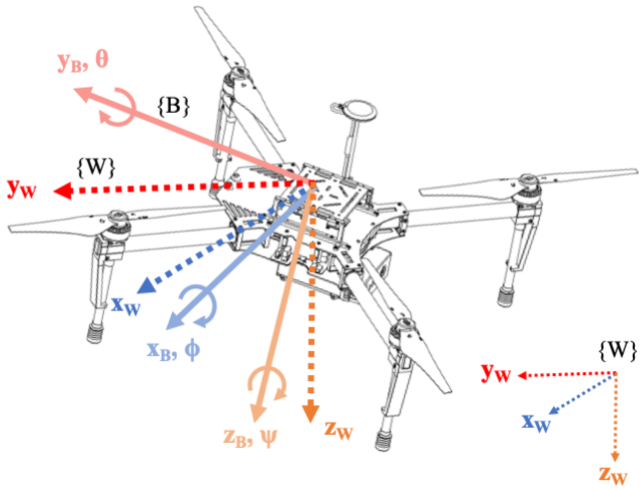
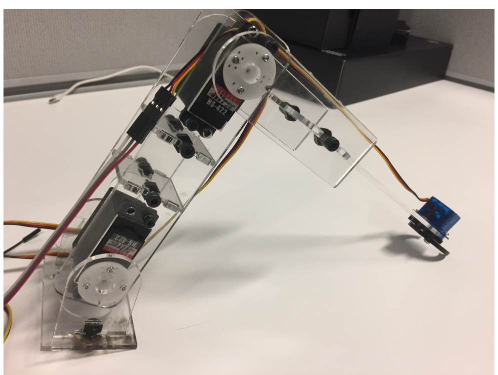


Figure 4.1: Coordinate Frame of the DJI Matrice 100 (Modified Image From [197]). The Rotation of the Aircraft Around the x, y, and z Axes Are Roll (ϕ), Pitch (θ), and Yaw (ψ), Respectively. The World Body Frame W Uses the North, East, Down (NED) Convention as Shown, With the Vehicle Heading North. B is the Body Frame of the UAV Also Using the NED Convention Specified by DJI.

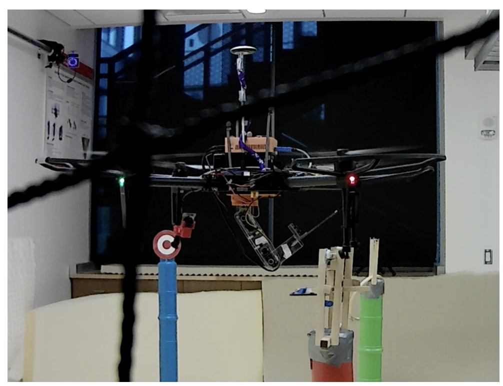
An Intel NUC Core Dawson Canyon (NUC7i5DNKE) with an i5 processor was the on-board computer. This unit has 8 GB of DDR4 SDRAM memory, with an 128 GB M.2 SATA solid-state drive and ran Ubuntu 14.04 and ROS Indigo. Onboard XT30 and XT60 power ports connected to the TB48D battery provided power to other devices (NUC, manipulator controller, camera) without an additional power supply. Other components also mounted to the aircraft included a custom-built robotic manipulator, Arduino controller, USB cameras, and power adapters. Note that only 182 g is leftover as remaining payload before the system reaches the maximum takeoff weight of 3.6 kg. This payload capacity could easily be increased by using a larger platform (e.g., the DJI Matrice 600); however, the indoor lab space required this study to use the M100 due to safety reasons.

4.1.2 Manipulator Design and Fabrication

A two-link manipulator with two degrees-of-freedom (DoF) was mounted for manipulation in the ventral region of the UAV (see Figure 4.2). This design was chosen for two reasons: a) reproducibility and b) frequent appearance in the literature [18, 23, 88, 89], making the results from this HRI study applicable to existing platforms. The manipulator was CAD modeled using Creo 4.0 (PTC, Needham, MA, USA). Each manipulator segment was initially designed to be a unit component and manufactured using 3D printing technology; however, the available 3D printing equipment, Lulzbot TAZ 6 (Aleph Objects, Loveland, CO, USA), was not accurate enough to print the required parts. The structure of the manipulator was assembled from laser cut pieces of acrylic board cut using an Epilog Fusion 32 Machine (Epilog Laser, Golden, CO, USA) during the next design iteration. Laser cutting technology was preferred for manufacturing the structural components due to being highly a efficient and precise process.



(a)



(b)

Figure 4.2: (a) The Assembled Manipulator With Two Hs-422 Servos Controlling the Base and Elbow Joint, and a Stationary Gripper End Effector, and (b) the Arm Attached to the Ventral Region of the UAV, Shown In Flight.

The manipulator had two servo motors: one at the base joint and one at the elbow joint between each link. Two HS-422 (Hitec, South Korea) servo motors located in the skeleton actuated the manipulator links. The length of the top link was 10.5 cm and the bottom link was 14.4 cm; the total weight of the manipulator was 472 g. An Arduino UNO board controlled the motors and communicated via serial connection to the on board computer. A local network enabled the remote Arduino control through the ground control station or tablet application. Note that the tasks did not require the use of a functioning gripper end effector, but the design of the manipulator included a gripper for future use.

4.1.2.1 Manipulator Dynamic Analysis

To ensure the servos motors could provide adequate torque, the dynamic behavior of manipulator was described in terms of the time rate of change of its configuration in relation to the joint torques exerted by the actuators. The resulting equations of motion represent this relationship in a set of differential equations that govern the dynamic response of the robot linkage to input joint torques. The dynamic model for a two DOF robot (shown in Figure 4.3) was developed using Newton's Euler approach, and separate dynamic equations for each link were evaluated in numeric or recursive manner. In this scenario, the sum of forces is equal to variation of linear momentum, and the joint torques are coupling moments. For single torque calculation, the equation is:

$$M(\theta)\ddot{\theta} + C(\theta)\dot{\theta} + G(\theta) + U = \tau \tag{4.1}$$

where M is the inertia matrix, θ is a vector of coordinates $[\theta_1\theta_2]'$, $\dot{\theta}$ is angular velocity, $\ddot{\theta}$ is angular acceleration, C is a matrix containing centripetal forces, $G(\theta)$ contains conservative forces, U are torque inputs, and τ is a resulting torque. For a two degree of freedom manipulator, the matrix of torques is shown below:

$$\begin{bmatrix} M_{1,1} & M_{1,2} \\ M_{2,1} & M_{2,2} \end{bmatrix} \theta + \begin{bmatrix} C_{1,1} & C_{1,2} \\ C_{2,1} & C_{2,2} \end{bmatrix} \theta + \begin{bmatrix} g_1 \\ g_2 \end{bmatrix} \theta = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix}. \tag{4.2}$$

This matrix set of equations was solved using MATLAB with the appropriate parameters for the robotic manipulator, resulting in maximum torques of 3.98 kg-cm and 1.34 kg-cm, and actuator inertias of 2.35 kg·cm^2 and 0.587 kg·cm^2. The rated torque of the HS-422 motors was 4.1 kg-cm and are sufficient to actuate the robotic manipulator links. Figure 4.4 contains an illustration of the robotic manipulator relative to the vehicle.

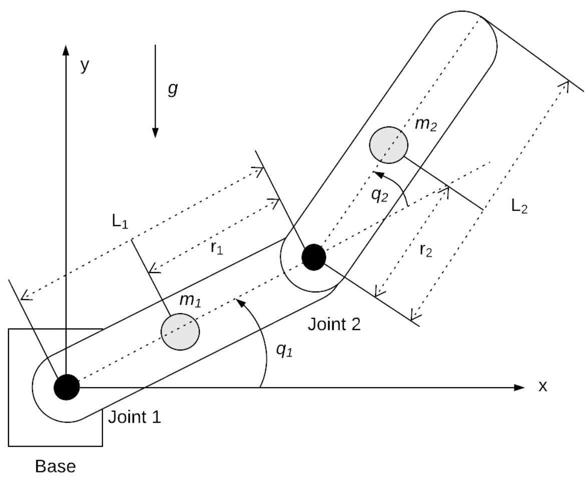


Figure 4.3: Schematic of a Two-Link Serial Chain Manipulator Illustrating the Length of Each Manipulator, Joint Angles, and Relative Positive and Negative Axes.

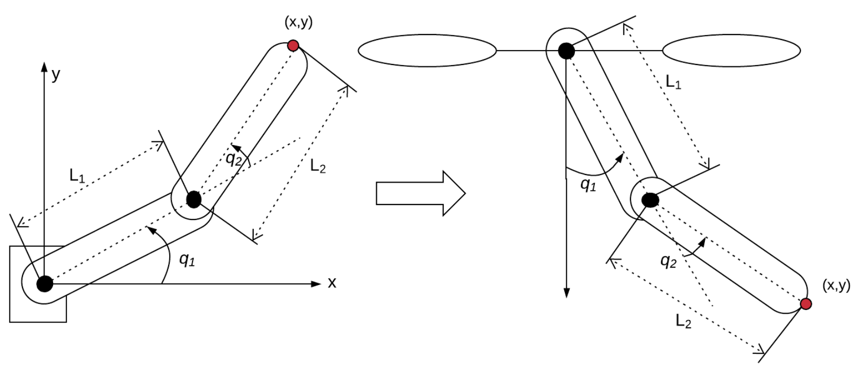


Figure 4.4: Original Schematic of the Two-Link Serial Chain Manipulator, and an Illustration of the Rotated Schematic Relative to the Plane of the Rotor Blades of the UAV, With the End Effector Position at (x, y) (Not to Scale).

4.1.3 Motion Capture System

A motion capture system consisting of 10 Vero 2.2 Megapixel infrared cameras (Vicon Motion Systems, Oxford, UK) provided position feedback of the vehicle in the flight arena. Data from the cameras was streamed via the Tracker 3.0 Network, which is a proprietary object tracking software application developed by Vicon that provides data integration with robotic control systems. For integration with the UAV platform controllers that use a Robot Operating System (ROS) framework, the `vicon_bridge` driver [198] initiated a connection with the Vicon data source (Tracker software) and published the data streams as ROS topics.

4.1.4 UAV System Architecture

An overview of the complete system architecture is presented in Figure 4.5. The DJI software development kit (SDK) ROS implementation enables communication between the ground control station and the N1 flight controller, in a ROS environment.

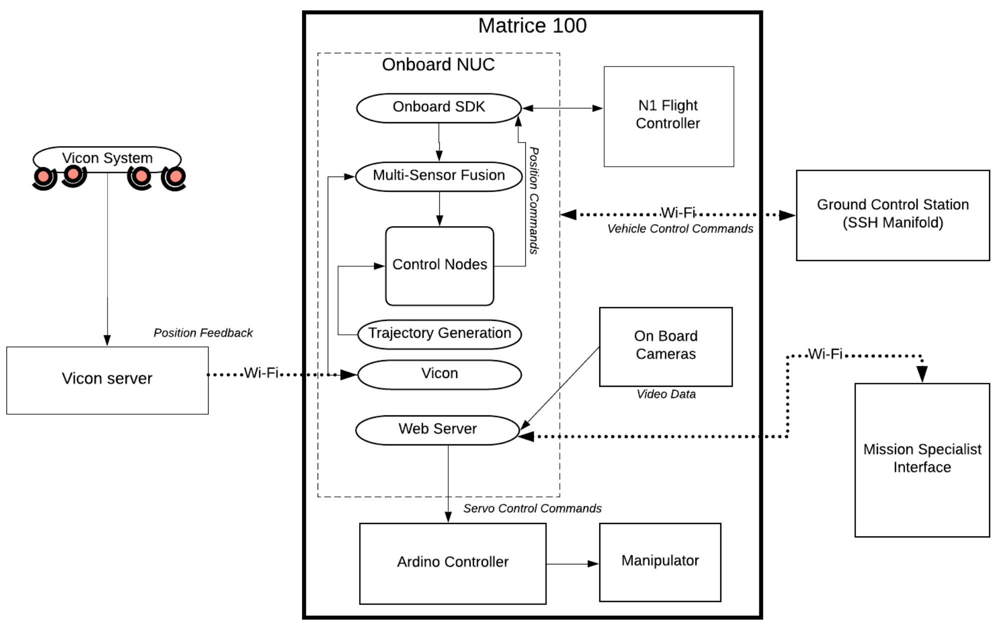


Figure 4.5: An Overview of the System Architecture, Including the On-Board Computer, *Mission Specialist* Interface, Vicon System, and Arduino Controller.

An Intel NUC6CAYH Mini PC with 128GB SSD and 8GB RAM was the UAV ground control station and ran Ubuntu 14.04 and ROS Indigo for compatibility with the UAV on board computer. The ground control station remotely accessed the on board computer via SSH connection over a local 5 GHz wireless network. The motion tracking system captured positioning of the UAV using five infrared reflective markers. Global position information was published at a rate of 30 Hz from the Vicon server, fed to the control implementation, and stored locally.

Figure 4.6 contains a diagram of the control architecture. The onboard computer communicated to the flight controller or DJI aircraft through a UART interface. For flight control and navigation, the onboard computer ran the DJI SDK, multi-sensor fusion framework, MPC formulation, low-level attitude P/PID controllers, trajectory generation, and Vicon ROS client; these were accessed through SSH by the ground control PC. The IMU in the flight controller sent and received position data, u, through the DJI SDK. The DJI SDK received orientation, angular velocity, and body frame acceleration $[\Phi, \dot{\Phi}, a^{\beta}]$ from the IMU at 100 Hz. A Vicon server published position, orientation, translation and angular velocity as $[p, q, \dot{p}, \dot{q}]$ over a wireless connection at 30 Hz. A multi-sensor fusion framework [199] filtered noisy measurements and compensated for possible delays in the Wi-Fi connection; results from this framework were used in the roll, pitch, yaw, and height controllers. The desired position $[p^{*}, q^{*}]$ was set on the ground station by either publishing position as a ROS topic or by the RC transmitter. For this trials, positions were published as a ROS topic using `rqt_ez_publisher` [200].

4.2 System Identification

Quadrotor dynamics have been widely studied and modeled as a rigid body frame with four attached motors [201]; however, for precision control and trajectory tracking, more accurate and detailed system models and control techniques based on these models are necessary. The development of accurate dynamic models is non-trivial. System identification can be performed through *a priori* modeling, which normally requires a physical test bed and 3D CAD models, or by taking a *posteriori* modeling approach, which relies on experimental data [202]. Developing detailed quadrotor models to account for these is often difficult due to nonlinear dynamics, air and flapping effects, and system noise, especially for consumer electronics where detailed information is normally not available; therefore, this work takes a data-driven modeling approach to identify the relationship between system inputs and outputs.

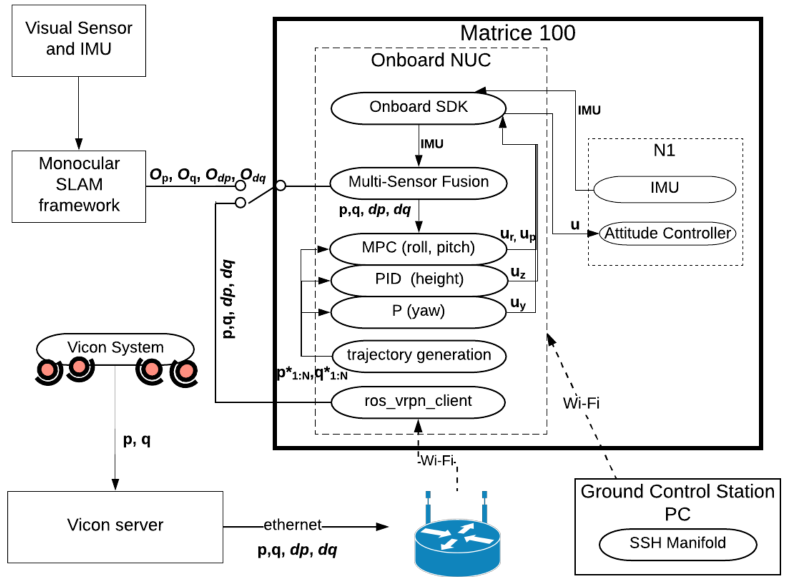


Figure 4.6: Detailed Diagram of the Control Architecture Illustrating the Control Nodes and Communication Between the Vicon System, On-Board Computer, and M100 Flight Controller.

The dynamic system model for the Matrice 100 has been previously identified and modeled from test flight data by Sa et al. [203]; however, the M100 used in this study was modified via the addition of a custom manipulator, which required an updated dynamic system model. A similar data-driven approach to the one used in [203] was implemented on the modified M100 with the attached manipulator. The on board computer recorded input commands from the RC controller and system outputs from the onboard IMU. Table 4.2 contains the input and output data and transfer functions used for system identification.

Table 4.2: Input and Output Data For Each Parameter Used During the System Identification Process [203].

System	Input	Output	Transfer Function
Roll	RC roll (rad)	IMU roll (rad)	1^{st} and 2^{nd} order
Pitch	RC pitch (rad)	IMU pitch (rad)	1^{st} and 2^{nd} order
Yaw Rate	RC yaw rate (rad/s)	IMU yaw rate (rad/s)	1^{st} and 2^{nd} order
Vert. Vel.	RC vert. vel. (m/s)	IMU vert. vel. (m/s)	1^{st} order

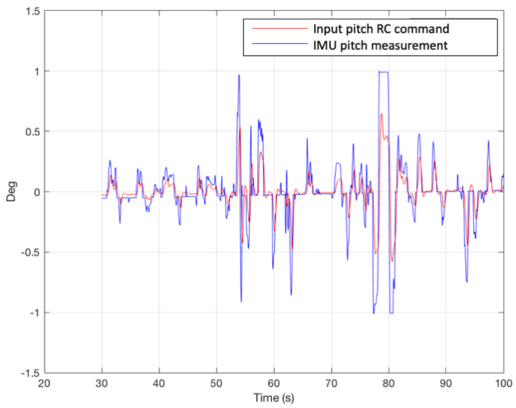
System identification required scaling the input RC commands to match the output response recorded on the IMU for roll, pitch, yaw rate, an vertical velocity commands. The scaling parameters were identified using the following nonlinear least squares optimization formulation [7]:

$$\boldsymbol{\lambda}^* := \arg\min_{\boldsymbol{\lambda}} \sum_{k=1}^{T} \left\| z_k^{\text{Meas}} - \boldsymbol{\lambda} u_k^{\text{cmd}} \right\|^2 \tag{4.3}$$

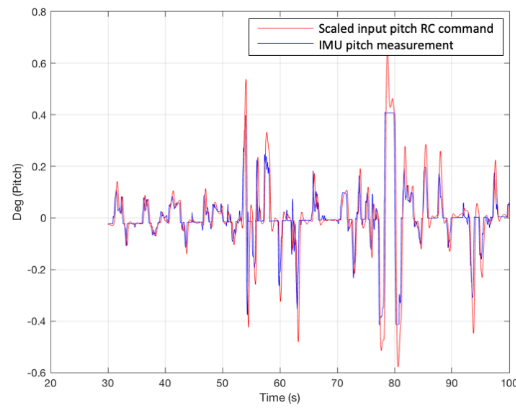
Where $\boldsymbol{\lambda} = [\lambda_\phi, \lambda_\omega, \lambda_{\dot\psi}, \lambda_{\dot z}]'$ contains the scaling parameters, $z_k^{\text{Meas}} = [\phi, \theta, \dot\psi, \dot z]'$ obtained from onboard the vehicle, and $u_k^{\text{cmd}} = [u_\phi, u_\theta, u_{\dot\phi}, u_{\dot z}]$ from the RC commands. Table 4.3 contains the resulting parameters, and Figure 4.7 shows the regression results for roll, pitch, yaw rate and vertical velocity systems. Using the command scaling parameters identified in the regression step, the underlying pitch, roll, yaw rate, and vertical velocity dynamics were identified using flight data from two separate experiments (one for identification and one for verification) and MATLAB R2018a [204, 205]. Both first and second order system transfer functions were used to estimate the system plant for all dynamics but vertical velocity, which only used the first order system. Table 4.2 contains a summary of the parameters used for dynamic system identification, and Figures 4.8-4.14 shows the system identification results (MATLAB outputs are included in Appendix A).

Table 4.3: Virtual RC Input Scaling Commands.

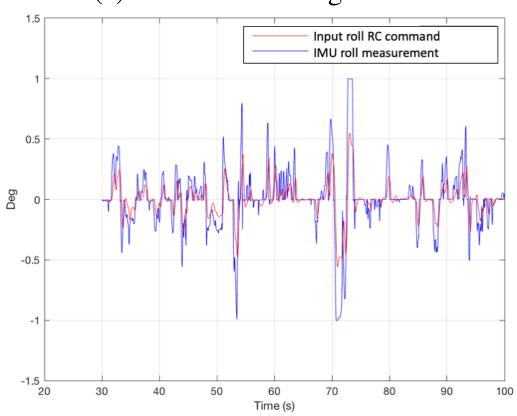
Param.	Experiment 1	Experiment 2	Experiment 3	Average
λ_ϕ	0.4601	0.4790	0.4180	0.4524
λ_ω	0.4675	0.4686	0.4108	0.4490
$\lambda_{\dot\psi}$	1.244	1.340	1.443	1.343
$\lambda_{\dot z}$	0.8162	0.7447	0.6447	0.7352



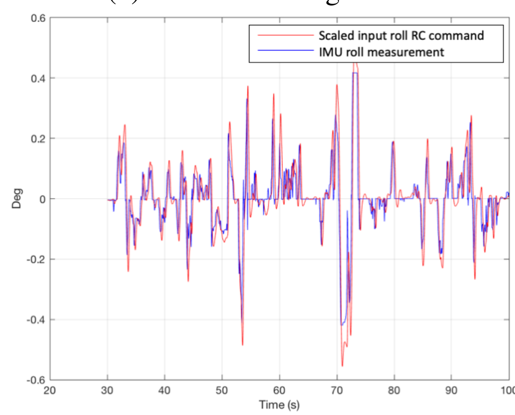
(a) Pitch: Before Regression.



(b) Pitch: After Regression.



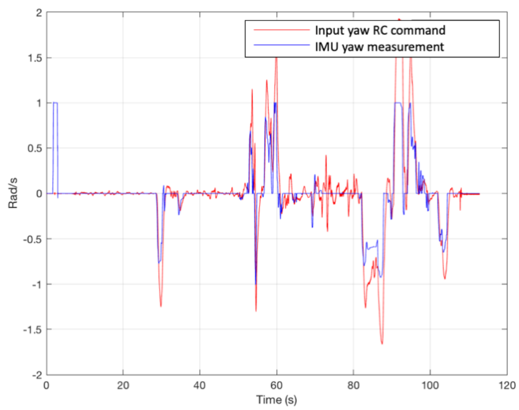
(c) Roll: Before Regression.



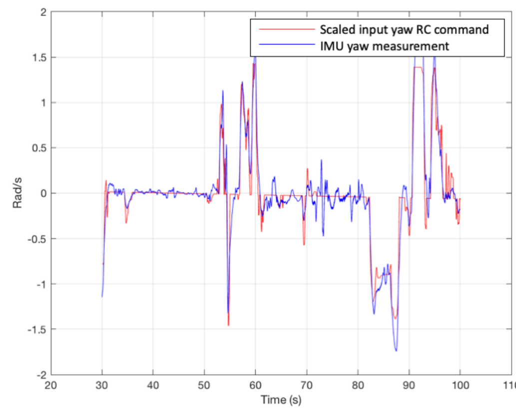
(d) Roll: After Regression.

Figure 4.7: Results for Input Command Scaling Regression for Pitch, Roll, Yaw Rate, and Thrust, Including Before (Left Column) and After (Right Column) Regression.

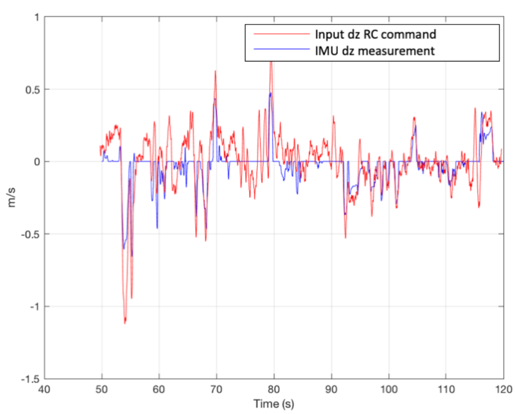
Figure 4.7: (Continued).



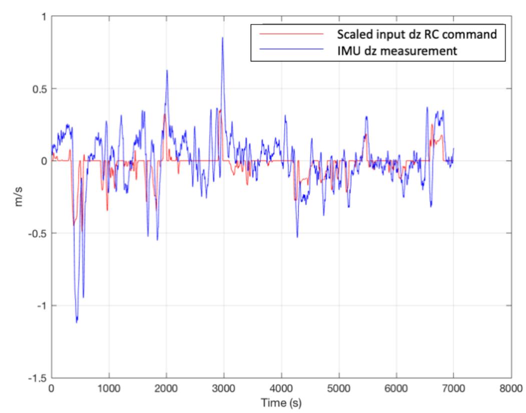
(e) Yaw Rate: Before Regression.



(f) Yaw Rate: After Regression.



(g) Thrust: Before Regression.



(h) Thrust: After Regression.

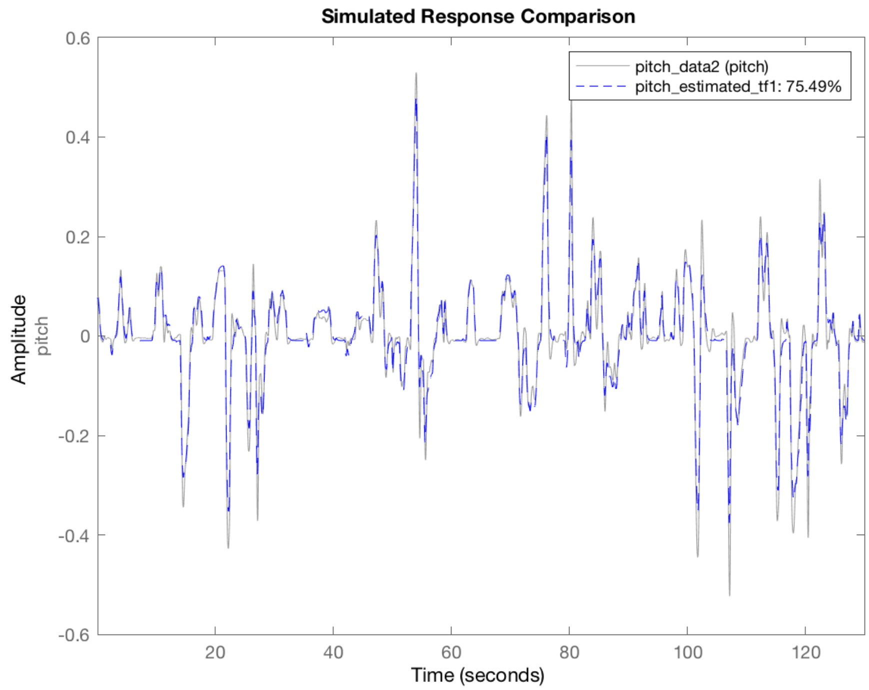


Figure 4.8: Estimated Pitch Using a 1^{st} Order Model With a 75.49% Fit.

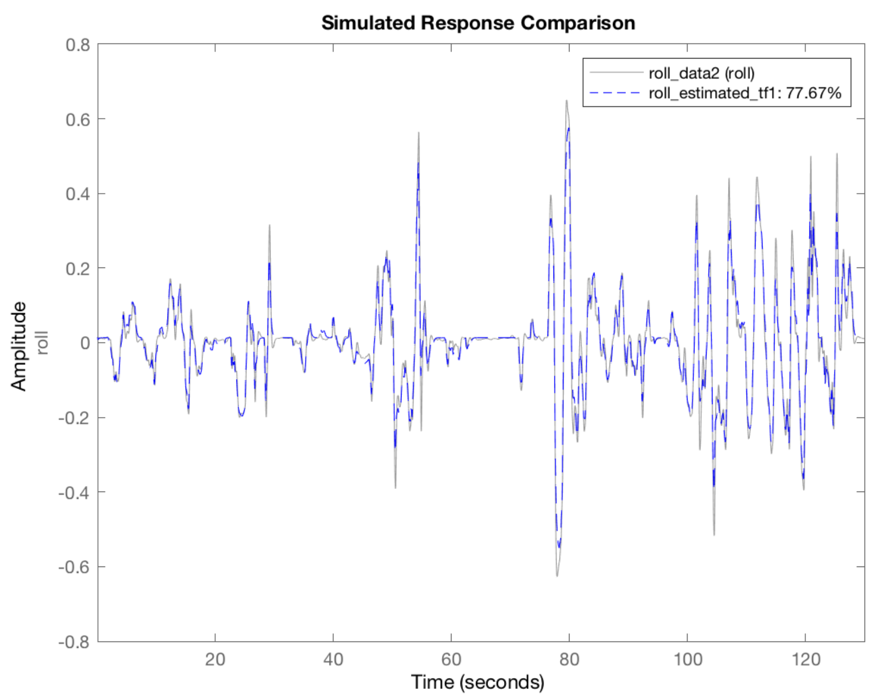


Figure 4.9: Estimated Roll Using a 1^{st} Order Model With a 77.67% Fit.

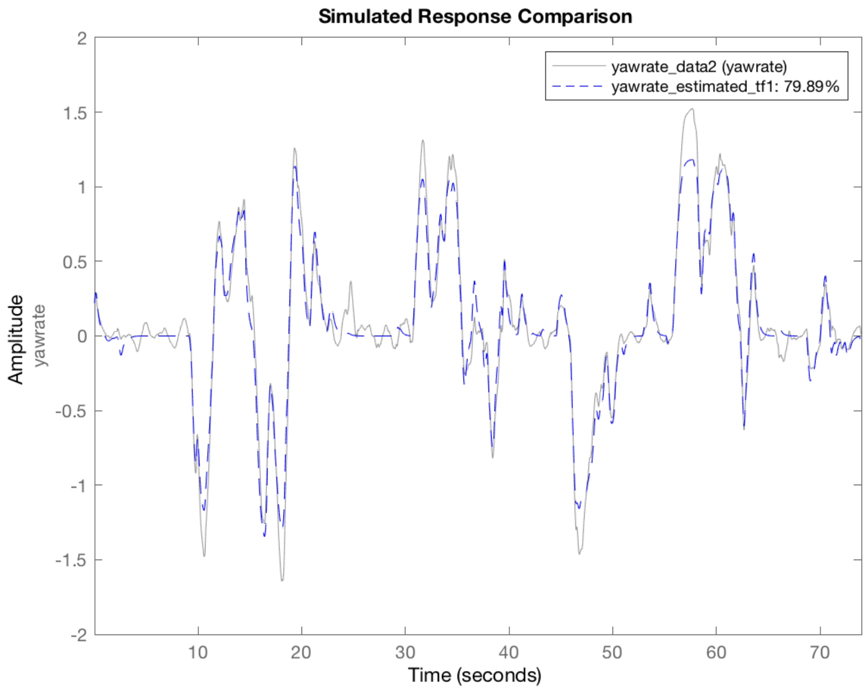


Figure 4.10: Estimated Yaw Rate Using a 1^{st} Order Model With a 79.89% Fit.

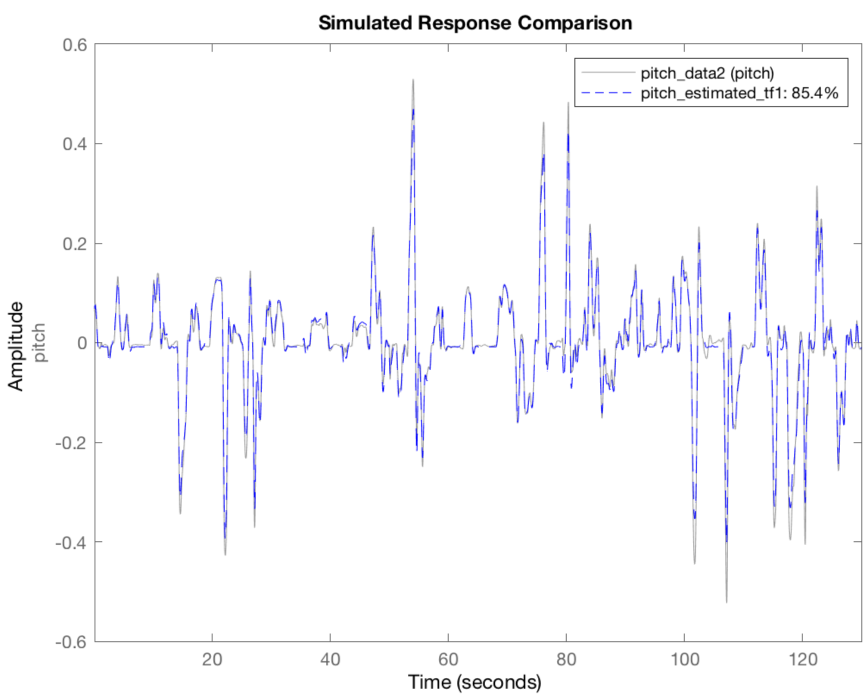


Figure 4.11: Estimated Pitch Using a 2^{nd} Order Model With a 85.4% Fit.

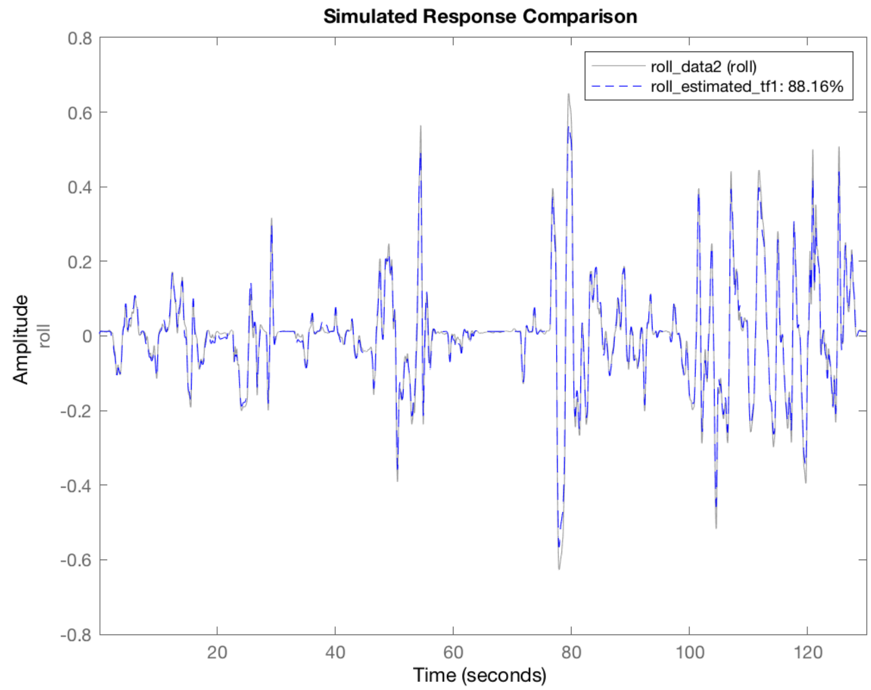


Figure 4.12: Estimated Roll Using a 2^{nd} Order Model With a 88.16% Fit.

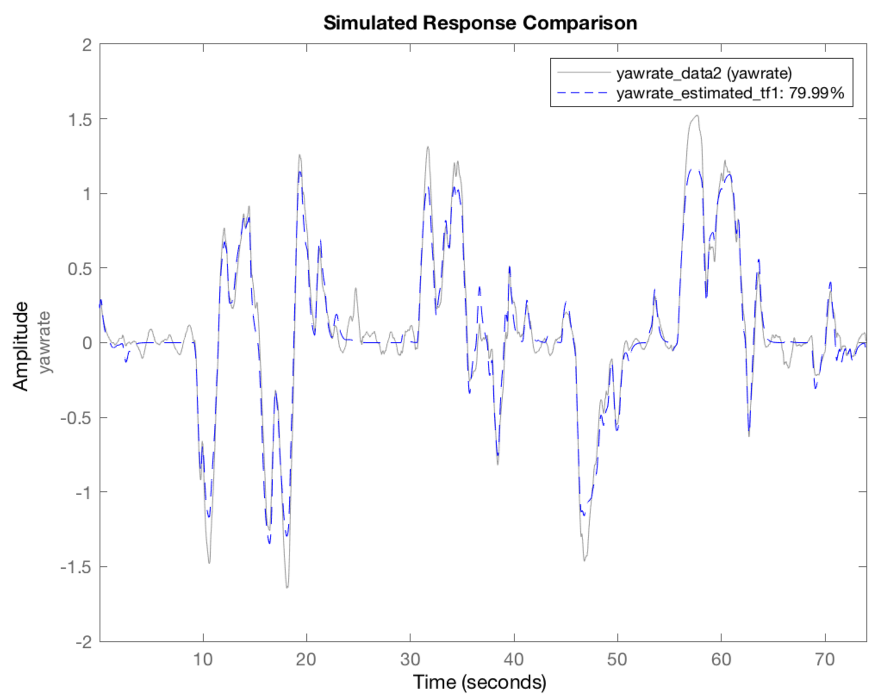


Figure 4.13: Estimated Yaw Rate Using a 2^{nd} Order Model With a 79.99% Fit.

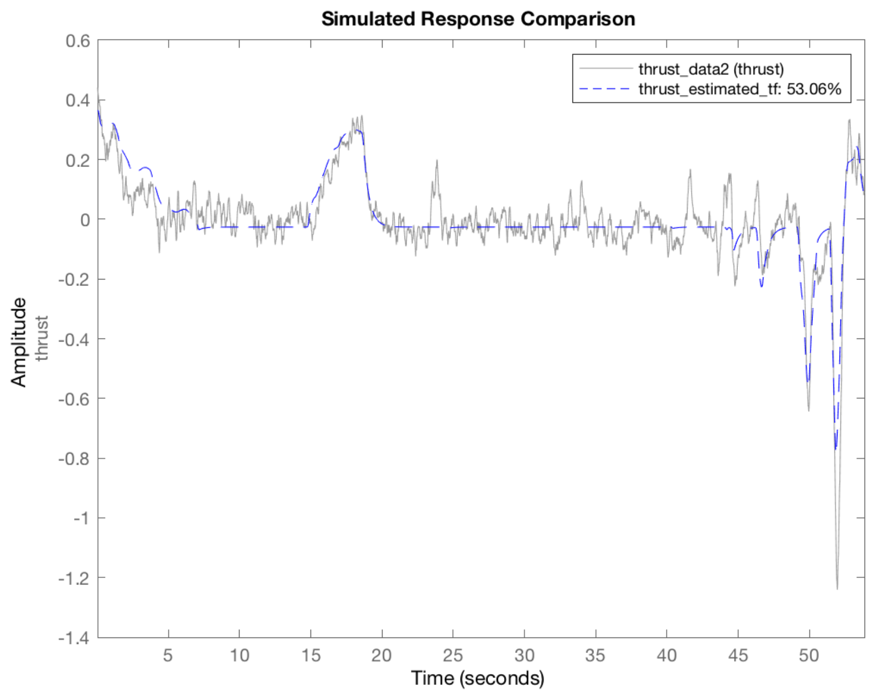


Figure 4.14: Estimated Vertical Velocity Using a 1^{st} Order Model With a 53.06% Fit.

4.3 Control Implementation

Table 4.4 contains a summary of the identified system dynamics. These time constants and gains were used in a model predictive control (MPC) scheme for roll and pitch, and PID and P controllers for thrust and yaw rate, respectively, following the procedures in [203].

Table 4.4: Identification of System Dynamics Parameter Summary.

	Roll	Pitch	Yaw Rate	Vertical Velocity
1st order	$\tau_{roll} = 0.180$	$\tau_{pitch} = 0.175$	$\tau_{yaw} = 0.266$	$\tau_{height} = 0.395$
Input: VRC	$\kappa_{roll} = 1.260$	$\kappa_{pitch} = 1.260$	$\kappa_{yaw} = 1.049$	$\kappa_{height} = 2.515$
Output: IMU	Fit=77.67%	Fit=75.49%	Fit=79.89%	Fit=53.06%
2nd order	$\omega_{roll} = 7.937$	$\omega_{pitch} = 7.662$	$\omega_{yaw} = 20.910$	
Input: VRC	$\kappa_{roll} = 1.157$	$\kappa_{pitch} = 1.132$	$\kappa_{yaw} = 1.046$	N/A
Output: IMU	$\zeta_{roll} = 0.543$	$\zeta_{pitch} = 0.512$	$\zeta_{yaw} = 2.779$	
	Fit=88.16%	Fit=85.40%	Fit=79.99%	

4.3.1 Roll and Pitch Controllers

A linear MPC implementation controlled the lateral position of the vehicle, linearized around the hovering condition [206]. The following MPC scheme from Sa et al. was solved for a prediction horizon of $N = 20$ [203]:

$$\min_{U,X} \sum_{k=0}^{N-1} \Big((x_k - x_{\text{ref}:k})^T Q_x (x_k - x_{\text{ref}:k}) + (u_k - u_{\text{ref}:k})^T R_u (u_k - u_{\text{ref}:k}) + (u_k - u_{k-1})^T R_\Delta (u_k - u_{k-1}) \Big) + (x_N - x_{\text{ref}:N})^T P (x_N - x_{\text{ref}:N}) \tag{4.4}$$

Subject to:

$$x_{k+1} = Ax_k + Bu_k + B_d d_k; \tag{4.5}$$

$$d_{k+1} = d_k; k = 0, ..., N-1 \tag{4.6}$$

$$u_k \in \mathbb{U} \tag{4.7}$$

$$x_0 = x(t_0), \quad d_0 = d(t_0). \tag{4.8}$$

where $Q_x \geq 0$ is the state error penalty, $R_u \geq 0$ is the penalty on the control input error, $R_\Delta \geq 0$ is the penalty on the control change rate, and P is the penalty on the terminal state error [206]. The state vector is defined as $x = (x, y, v_x, v_y, w_\phi, w_\omega)$, the control input vector as $u = (w_{u_\phi}, w_{u_\theta})$, the state sequence is $X^T_{\text{ref}} = [x^T_{\text{ref:0}}, ..., x^T_{\text{ref:}N}]^T$, the control input sequence as $U = [u^T_0, ..., u^T_{N-1}]^T$, and the steady state input sequence as $U^T_{\text{ref}} = [u^T_{\text{ref:0}}, ..., u^T_{\text{ref:}N-1}]^T$. The k_{th} reference state and control input are defined as $x_{\text{ref:k}}$ and $u_{\text{ref:k}}$, respectively. The optimization problem in equation 4.4 was solved using the FORCES Pro [207] framework over a horizon of 20. FORCES Pro generates a tailored algorithm to compute optimal solutions to the given MPC problem, and the result is generated as executable C code [207].

4.3.2 Yaw and Altitude Controllers

The following PID controller was used to control velocity:

$$u_{\dot{z}}(t) = K_p e_z(t) + K_i \int_0^t e_z(\tau)d\tau + K_d \frac{d}{dt} e_z(t) \tag{4.9}$$

where $e_z(t) = z^* - z$, z^* is the desired height, z is the current height measurements, and K_p, K_i, K_d are coefficients for the proportional, integral, and derivative terms respectively. The yaw was controlled using a simple P controller:

$$u_{\dot{\psi}}(t) = K_\psi e_\psi(t) \tag{4.10}$$

where $e_\psi(t) = \psi^* - \psi$ is the yaw angle heading error and K_ψ is the coefficient for the proportional term.

4.3.3 Hovering Test

The UAV was tested hovering in the (x, y, z) =(0,0,1) meters position using the control implementations described above. This goals of this test were to measure precision in station-keeping and determine the effects of propeller wash and air turbulence present in the motion capture arena. Figure 4.15 shows results of a hovering test with a one minute duration. The average position and root-mean square error (RMSE) values for this test were as follows: $\bar{x} = -3.32$ cm, $\text{RMSE}_x = 2.37$ cm, $\bar{y} = 5.04$ cm, $\text{RMSE}_y = 3.21$ cm, $\bar{z} = 98.4$ cm, $\text{RMSE}_z = 5.34$ cm.

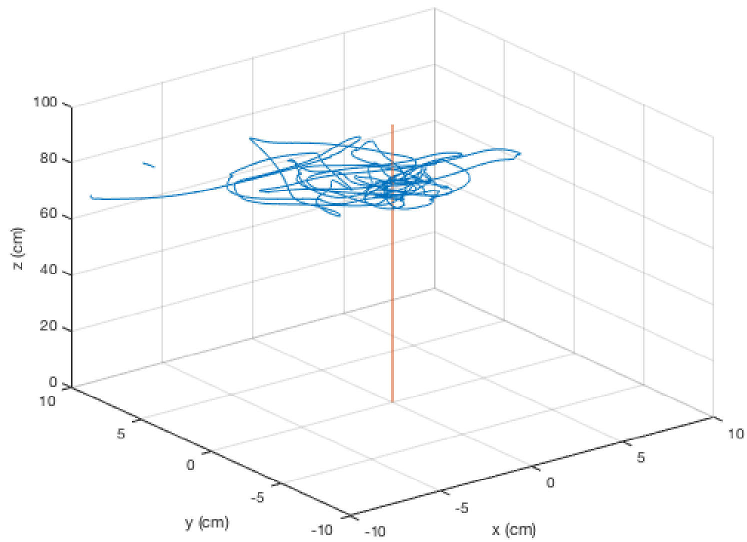


Figure 4.15: Hovering Test of the M100 Set to Position (0,0,100) cm, With the Following Average Position and Root-Mean square Error (RMSE) Values: $\bar{x} = -3.32$ cm, RMSE$_x = 2.37$ cm, $\bar{y} = 5.04$ cm, RMSE$_y = 3.21$ cm, $\bar{z} = 98.4$ cm, RMSE$_z = 5.34$ cm. The red line goes through $x = 0, y = 0$.

4.4 Software Description and Implementation

Previous studies found that *Mission Specialists* preferred a filtered display with *Pilot*-only artifacts removed from the interface [48]; therefore, the *Mission Specialist* interface in this study contained only the information relevant for their tasks and goals (i.e., for telemanipulation, not navigation). Figure 4.16 contains an image of the interface, and Figure 4.17 details interface system architecture.

4.4.1 Web Server

The web server consists of two main components: the first handles the web server implementation, and the second handles the interaction between the Arduino and manipulator. The web server was built using the Flask (v1.0.2) framework for Python (v3.6) [208]. In this framework, a user requests an HTML file from a browser to interact with by opening up port 80 on the host machine. The requested HTML file consists of five main elements: the elbow joint knob, the base joint knob, task reset button, stow arm button, and camera views. When any of the touch elements change state, it invokes a JavaScript method to send a POST request back to the server with the new states. Then, the server saves these new states in a list and returns a new HTML page with updated information back to the browser. After this exchange is made, the second component of the web server performs its function.

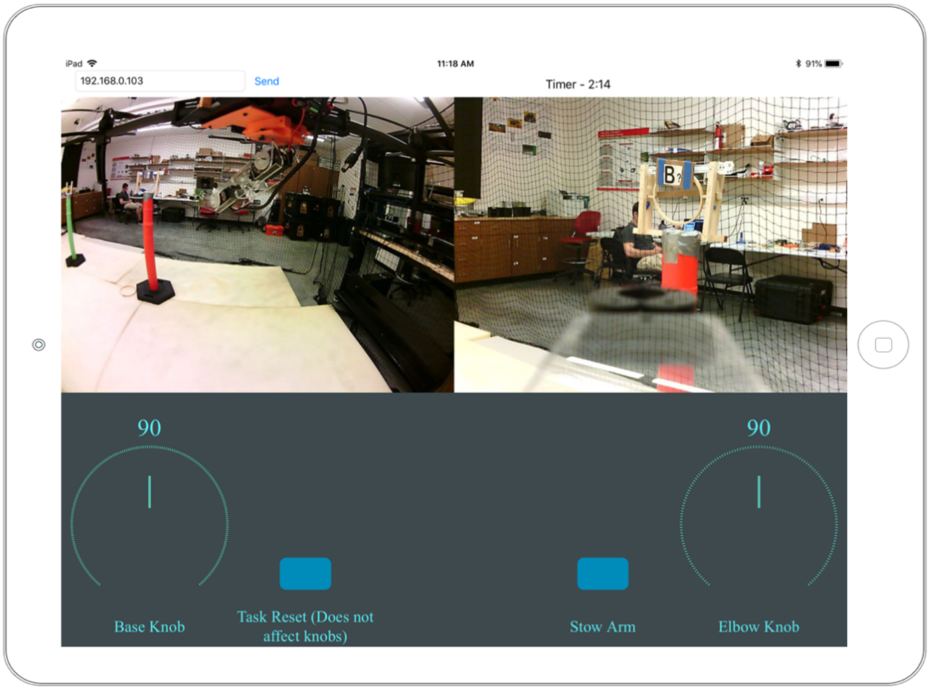


Figure 4.16: *Mission Specialist* Interface Developed for this Study. The Mixed View is Shown Here With Both the Exocentric View (Left) From a Camera Mounted on the Back Left Leg of the UAV, and an Egocentric Camera (Right) From a Camera Mounted on the Manipulator.

The second component of the web server handles the interaction with the Arduino, which controls the manipulator servos. A method called “sendCommand” takes no arguments and uses serial communication to communicate with the Arduino. This method runs on a second thread to allow the web server and serial communication to work in parallel. The method works by checking the current state, or value, of the knobs and buttons respectively against their previous values to see if any states have changed. If they have changed, a command with the syntax “<” + name + “,” + value + “>” is constructed and sent over serial to move the servo to the requested updated position.

4.4.2 Arduino Sketch

The Arduino sketch runs on the on-board Arduino and is responsible for handling all movement of the robotic manipulator. The manipulator consists of two servos, each connected to a different data pin on the Arduino. The Arduino receives a command over serial and parses it using preset delimiters. Depending on which servo is requested to change position, the sketch will invoke a separate method to send the new position to the respective data line. These new positions can range anywhere from $0°$ to $140°$ for the elbow, $0°$ to $180°$ for the base, and pre-determined positions for the Task Reset and Stow Arm buttons.

4.4.3 Video Stream

The video streaming implementation uses done using the OpenCV library in C++ to receive, process, and send camera data to the user interface. A large portion of the C++ code was developed for an open source project at the University of Texas [209], which was modified in this study to support two cameras instead of one. The video stream program searches for two cameras connected via USB to the host machine and assigns each camera to a separate object. These two objects take pictures at a predetermined rate, encode them in a ".jpg" format, and either stitch the images together (for the mixed condition) or send each over separately (for the egocentric and exocentric conditions) using UDP to the user interface. On a second thread, this program awaits user input to select which view they would like to send to the user (exocentric, egocentric, mixed).

4.4.4 iPad User Interface

The iPad user interface is an application written in the Swift and Objective-C++ languages. Swift is Apple's primary programming language, and Objective-C++ enabled iPad support of the OpenCV library. The interface contains an HTML container, which displays the HTML page sent from the web server, and a UIImage view, which displays images to the screen. Upon opening the "Robotic Manipulator Interface" application, the user first sees a blank text box and a 'Send' button. This text box requires the IP Address of the web server, which tells the server to send back an HTML page for the HTML container to display. It also allows the application to start receiving view data from the video stream application on the host machine. It should be noted that the web server and the video stream operate independently, but the application requires video feed in order to process the HTML page. This is a precaution to ensure that both the video and the web server are running on the host machine.

Due to Apple's support for Objective C and C++ when migrating to Swift, the open-source code from [209] was added to the existing web server implementation with few modifications. This code listens on a UDP socket for incoming messages, and upon receiving one of these messages, it stitches together all packets that make a single image and passes them through a decoder. This decoder converts the image from a ".jpg" to its original format. Using a function from OpenCV, the new image is converted from an OpenCV data type to an UIImage, which is then returned and displayed to the user's screen. Note that the server originally streamed video data over a 2.4 GHz wireless network which resulted in dropped frames and lagging video. The network was then changed to a 5 GHz network prior to conducting the study to improve performance and reduce time delays in the video stream, which were then negligible.

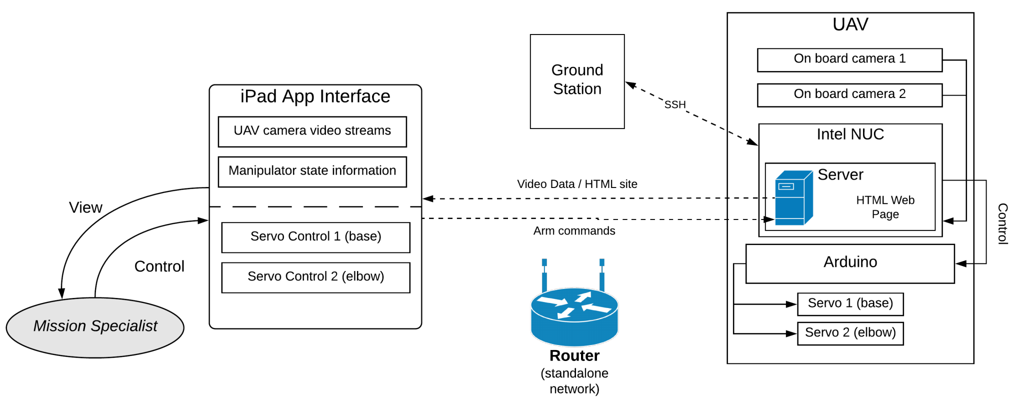


Figure 4.17: Diagram of the Interface Architecture, Including the Web Page Hosted on a Server On-Board the NUC and the Tablet Interface With the Appropriate Information Displayed.

CHAPTER 5
EXPLORATORY STUDY

This chapter presents results from a 5 subject exploratory study that evaluated the UAV system, interface software, and three tasks. First, descriptions of the tasks are presented, followed by an overview of participants. Then, results from the pre- and post-questionnaires, task performance data, and biometric data are presented. Finally, recommendations for the follow-up study are made, which include: i) resetting the manipulator position before each task, ii) record eye tracking during the mixed trials, and iii) vary the task starting points between trials.

5.1 Overview and Purpose

The purpose of the exploratory study was to: i) rigorously test the *Mission Specialist* interface (see Figure 5.1), and ii) explore the types of tasks suitable for manipulation by small UAS. The exploratory study took place at the Peschel Research Group indoor flying arena located in the Biorenewables Complex at Iowa State University. The evaluated tasks included the following: i) grasping and dropping differently sized hoops, ii) probing and target acquisition, iii) pushing or flipping up a small sign, and iv) verbally reading out the text written on the sign.

Each participant completed three flights, one flight per interface condition (egocentric, exocentric, mixed views). Each flight included three tasks to complete at predefined waypoints and a series of questions related to visualization to answer during the flight. During each flight, the *Pilot* positioned the vehicle in a starting location, and the *Mission Specialist* could verbally direct the *Pilot* to adjust the position as needed. The maximum duration of each flight was limited to eight minutes for consistency and battery life considerations. The order of the interface conditions was randomized for each subject to reduce learning effects and counterbalance the exploratory study. Participants were allowed up to three minutes of practice time with the *Mission Specialist* interface before completing the trials.

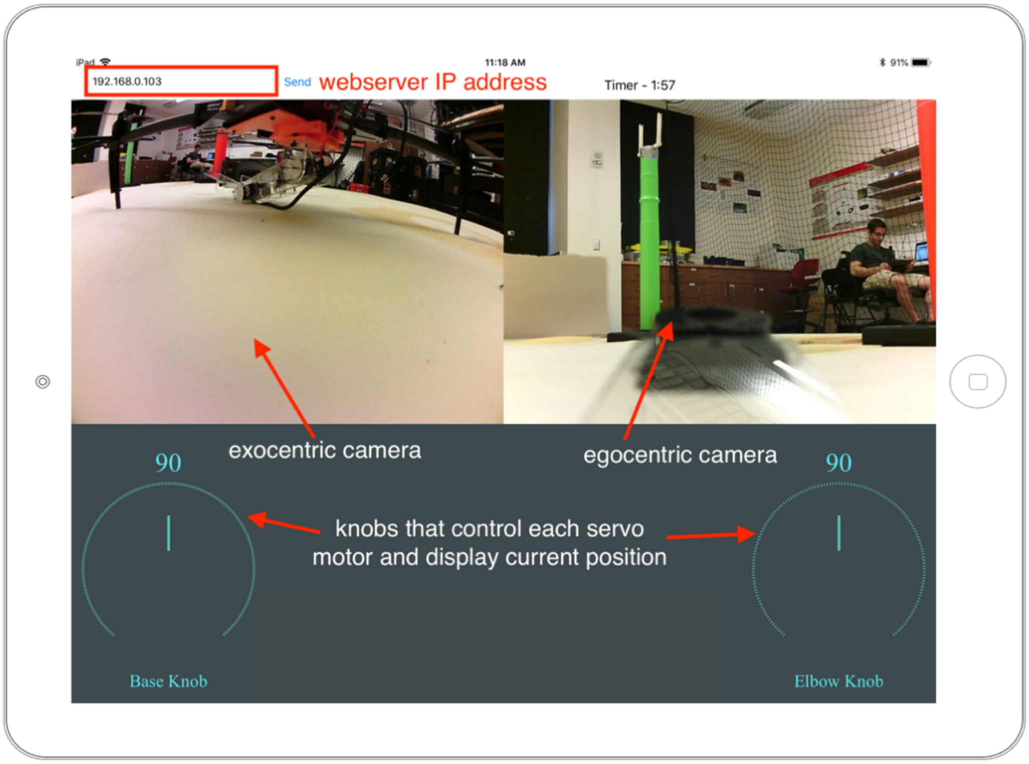


Figure 5.1: Interface Used in the Exploratory Study, Including Touch-Based Control Knobs for the Manipulator and Egocentric and Exocentric Views Developed in a Standalone iPad Application.

5.2 Participants

Exploratory Study participants were other graduate and undergraduate researcher assistants with a connection to the research lab group who had little to no flying experience. Detailed demographic information about each participant was collected through a pre-assessment questionnaire consisting of 35 questions. Of the five participants, one was a woman and four were men. A total of four participants were under 25 years of age, and one participant was between ages 25 and 34. All subjects were either undergraduate or graduate students.

5.2.1 Pre-Assessment Survey Results

Summaries of responses from the pre-assessment questionnaire are included in Figures 5.2-5.5. A majority of participants had some prior experience using mobile touch and pen-based tablet devices, with a 80% of participants using touch-based devices continuously throughout the day. Four of the subjects considered their use of digital photographs/video and electronic geographic information for decision making to be “average”, while 40% of subjects said they never used mobile apps for decision-making in their current job. Additionally, a majority of subjects did not create apps or geographic information for decision-making in their current job.

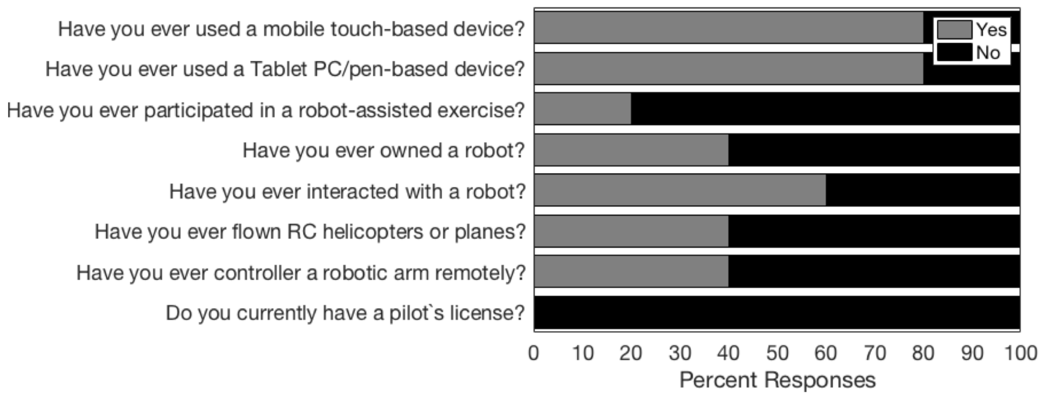


Figure 5.2: Pre-Assessment Responses for the Exploratory Study Participants ($N = 5$ Participants) Related to Robot and Technology Experience.

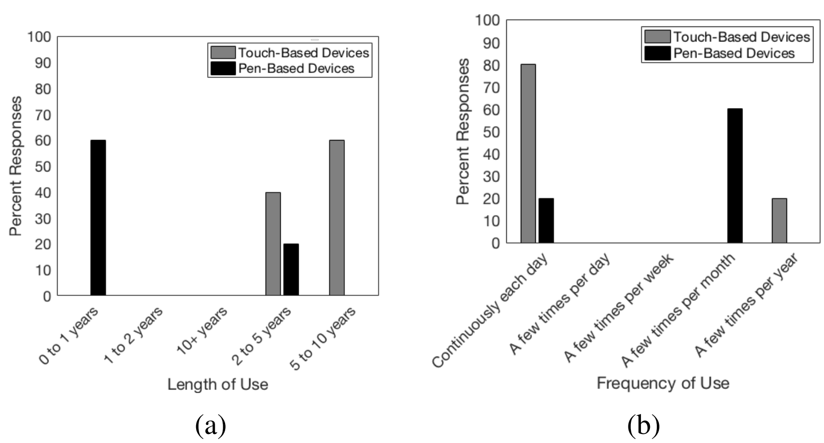


Figure 5.3: Pre-Assessment Responses ($N = 5$ Participants) Related to the (a) Length of Technology Usage and (b) the Frequency of Technology Usage.

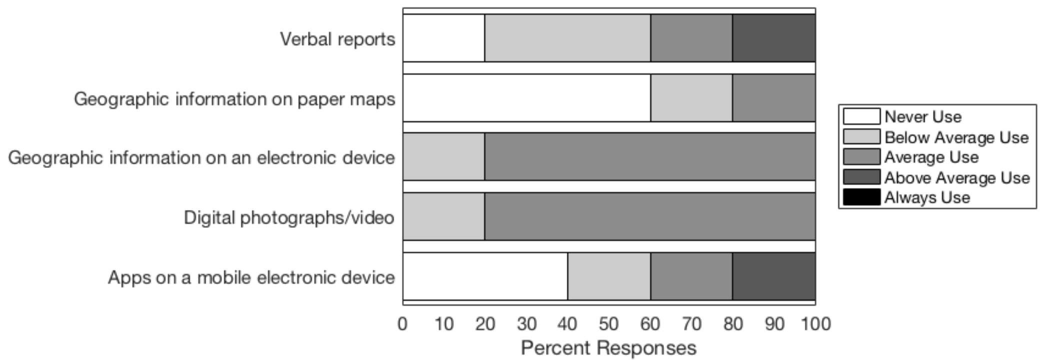


Figure 5.4: Pre-Assessment Responses ($N = 5$ Participants) Related to the Use of Technologies for Decision-Making in a Subject's Current Job.

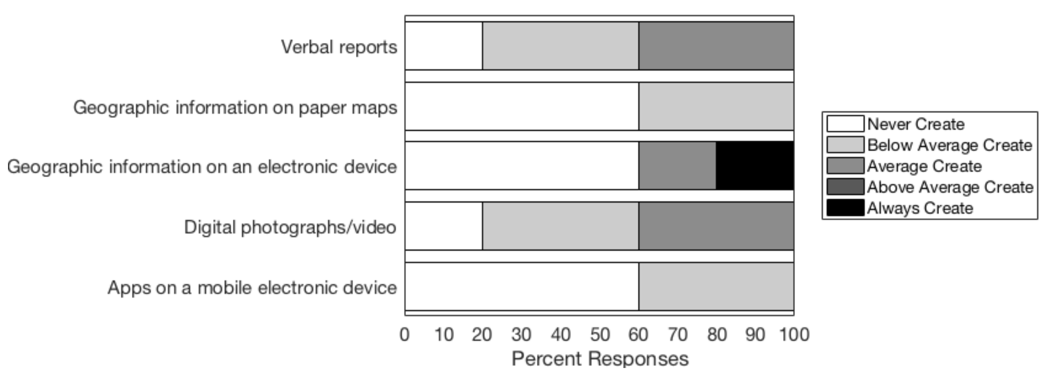


Figure 5.5: Pre-Assessment Responses ($N = 5$ Participants) Related to the Creation of Technologies Used for Decision-Making in a Subject's Current Job.

5.3 Measurements

There were four different types of data collected taken during the exploratory study: i) task performance metrics, ii) pre- and post-assessment surveys, iii) biophysical measurements, and iv) audio and video recordings. The section below describes results from each of these measurements.

5.4 Results

5.4.1 Task Performance

Task performance measures included task completion time, task completion rate, number of servo commands sent to the manipulator, number of manipulator reversals, and stress indicator data (EDA response).

5.4.1.1 Task Completion Data

Table 5.1 contains the task completion time data for the exploratory study. On average, the probing and target acquisition task took the shortest amount of time to complete for all three conditions. The task completion rates, on average, were 80% for the egocentric condition, 100% for the exocentric condition, and 83% for the mixed condition. The difference in completion rates was not statistically significant, but the pushing task was the most often missed task. Missed tasks occurred when participants took a long time to complete a given task, and due to limited flight time and battery during the experiment, facilitators choose to end the flight or proceed to the next task which resulted in the task being incomplete.

Table 5.1: Mean (M) and Standard Deviation (SD) of the Task Completion Times For All Three Interface Conditions During the Exploratory Study in Seconds.

Condition	Probe		Grasp		Push	
	M	SD	M	SD	M	SD
Egocentric	45.30	42.69	77.18	39.22	55.93	68.39
Exocentric	35.10	23.03	57.34	25.54	68.53	48.00
Mixed	30.22	7.72	59.67	21.71	100.98	17.99

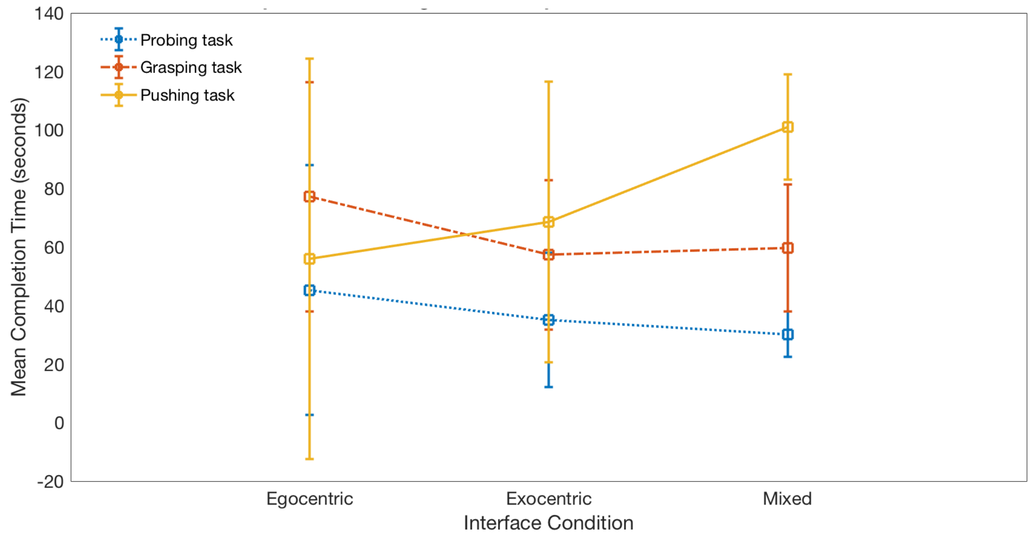


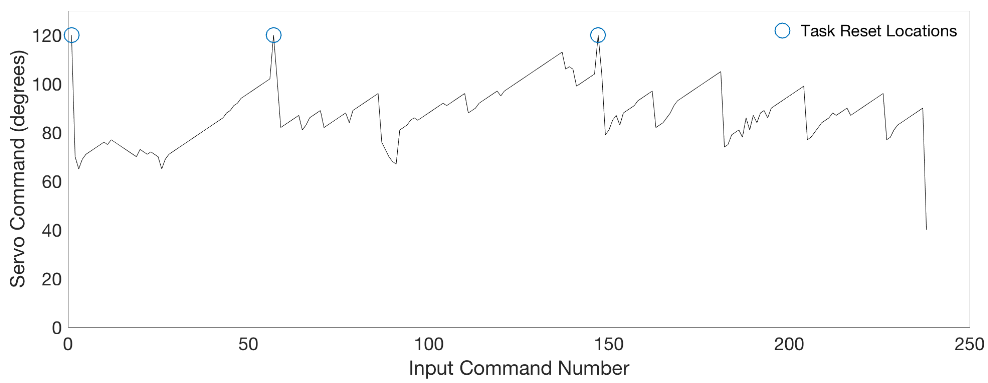
Figure 5.6: Comparison of Task Completion Times for the Probing, Grasping, and Pushing Tasks Across All Three Conditions ($N = 5$ Participants).

5.4.1.2 Servo Input Commands

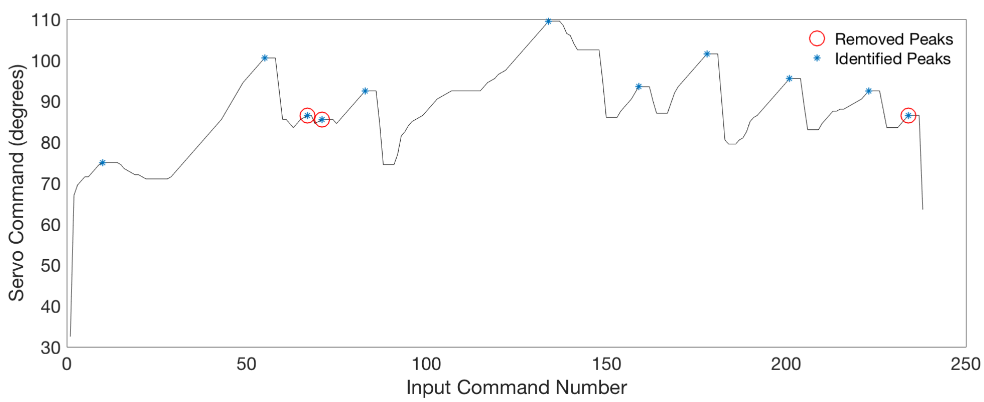
The servo input commands were recorded for each flight for all five participants. On average, subjects sent 1,060 commands to the elbow joint, 705 commands to the base joint, and 1,765 commands total. A command was saved to a text file each time the value in the servo control knobs changed in value, which trigged a POST request. Note that a POST request was sent to the server each time the knob interface elements changed by a single degree; therefore, the total number of POST requests sent is not representative of single motion arm movements from one starting position to another, but instead provides and estimate which joint was more frequently operated by the subjects.

In addition to total number of servo commands, the total number of reversals was calculated from the raw servo data. A "command reversal" was defined as repeated similar movements that occurred one directly after another. These repeated movements appeared as a peak when plotting the manipulator POST requests; if any given peak has a prominence greater than three, the movement was considered a reversal. Figure 5.7a is an example of raw servo data for the base joint. These data were filtered using a one-dimensional median filter, and the peaks and peak prominence values were calculated using the `findpeaks` MATLAB function. Any peak with a prominence less than three was discarded. As seen in Figure 5.7b, the circle marker appears when the identified peak is not a true reversal, which occur on the positive or negative sloping side of the identified peaks.

The average number of reversals for the elbow joint was 16.3, for the base joint was 14.8, and total average reversals was 31.2. When analyzed by condition, the total average reversals for the egocentric condition was 27.6, for the exocentric condition was 25.8, and for the mixed condition was 41, with the base joint resulting in more reversals on average compared to the elbow joint.



(a)



(b)

Figure 5.7: (a) Example of Raw Data for the Elbow Joint Commands Collected During the Exploratory Study, with Task Reset Locations Identified by Circles (for This Subject a Task Reset Protocol Was Tested). (b) Filtered Data With Star Markers Identifying the Identified Peaks of Command Reversals and Circles Representing Removed Peaks That Were Not Identified as Reversals.

5.4.2 Stress Levels

The E4 wristwatch measured electrodermal (EDA) skin response during the Exploratory Study trials. Baseline data was not captured for two of the participants, and stress response deviations from baseline could not be calculated for those participants. For the remaining three participants, average baseline, condition, and task-specific EDA responses were calculated from E4 data. The average deviation from baseline for the egocentric condition was 0.222 μS, for the exocentric condition was 0.446 μS, and for the mixed condition was 0.886 μS. The average EDA deviation from baseline was greater than zero (indicating that stress levels are higher during the trials), but the sample size for the Exploratory Study was underpowered and this difference is not statistically significant. These EDA data do indicate a trend, however, that may result in significant differences when the statistical power and sample sizes increase during a future experimental study.

Table 5.2: Average Post-Assessment Response Scores Separated by Condition.

	Question	Ego.	Exo.	Mix.
1.	How confident did you feel in your ability to control the manipulator with the interface?	4.2	4.25	4.5
2.	How comfortable did you feel in your ability to control the manipulator with the interface?	4	4	4
3.	How confident did you feel in your team's ability to perform the touching/probing task?	4.6	3.75	5
4.	How comfortable did you feel in your team's ability to perform the touching/probing task?	4.4	4.5	4.75
5.	How confident did you feel in your ability to instruct the Pilot to accurately control the vehicle?	4.4	3.75	4.5
6.	How comfortable did you feel in your ability to instruct the Pilot to accurately control the vehicle?	4.4	3.25	4.25
7.	How confident did you feel in your team's ability to perform the pushing task?	3.6	3.5	3.5
8.	How comfortable did you feel in your team's ability to perform the pushing task?	3.6	3.75	3.5
10.	How confident did you feel in your team's ability to perform the grasping task?	4.4	4.75	5
11.	How comfortable did you feel in your team's ability to perform the grasping task?	4	4.75	4.5

5.4.3 Role Empowerment and Interface Preferences

Table 5.2 includes summaries of the post-assessment responses collected after each trial. Although not significant, reported confidence levels were less on average in the egocentric condition compared to both the exocentric or mixed conditions as reported in questions 1, 4, 10 and 11. Comfort generally remained the same across all conditions, indicated by responses to questions 2, 7, and 8. Additionally, subjects reported higher levels of confidence and comfort for completing the pushing and probing tasks under the egocentric condition, indicating that *Mission Specialist* participants preferred a close-up view of the end effector during certain tasks.

5.5 Recommendations for Future Studies

Based on results and observations from this exploratory study, three primary recommendations were made for the subsequent experimental study:

1. *Reset the position of the manipulator before the UAV reaches the task station to prevent participants setting the arm in a desired configuration.* Subjects often situated the manipulator in a position ready to complete the next task before being instructed to begin; therefore, subjects who used this"pre-planing" strategy could reduce their task completion times compared to participants who wait for explicit instructions to begin. Any subsequent experimental study should include a task reset button in the interface for participants to use prior to completing each task so the manipulator starting position is identical across all tasks, participants, and conditions.

2. *Record eye tracking to observe the amount of time spent on each view and switching frequency between views in the mixed condition.* Performance between the exocentric and mixed conditions generally seemed to be improved compared to the egocentric condition; however, there was no significant benefit to the mixed condition during the exploratory study. To further investigate how participants allocate their attention when given multiple views, it is recommended to place a camera directly above the interface to record facial expressions and eye movements across the left and right views on the interface. This camera setup was implemented for the last participant in the exploratory study, and the data confirmed that eye tracking was visible when recording from a camera mounted directly above the iPad interface and provided valuable attention-related data for future trials.

3. *Offset the starting position differently for tasks in each trial to avoid learning effects.* Each trial consisted of three sets of similar tasks with slight vari-

ations. To introduce more variation between tasks across trials, the starting position of the UAV at each station should be offset slightly, but at a different location and direction from the task for each trial. This recommendation prevents participants from memorizing or learning the required verbal commands to the *Pilot* to navigate the UAV to a suitable position to complete the manipulation task.

CHAPTER 6

EXPERIMENTAL METHODS AND DESIGN

This chapter describes the experimental design and protocol for a 36-subject experiment to evaluate a focused *Mission Specialist* interface. First, an overview of the study is presented followed by a description of the experimental design and tasks. Next, the research hypotheses and expected findings are presented. The final section includes a description of the data collection techniques.

6.1 Overview

The purpose of the experimental study was to: i) evaluate which field of view is the most appropriate for a *Mission Specialist* performing aerial telemanipulation tasks, and ii) observe and measure performance indicators and behaviors exhibited by the *Mission Specialist*. All of the experimental trials took place in an indoor laboratory in the Biorenewables Complex at Iowa State University. Participants completed a series of tasks during each flight, which included probing, grasping, and pushing-type tasks. The tasks were designed to be non domain-specific and represent of a wide range of physical interactions that are possible with a UAV in the ventral region. A total of 36 participants were included in a within-subjects study, and the use of a dedicated *Mission Specialist* interface was evaluated under three conditions: a) egocentric view from a camera mounted to the manipulator (sometimes referred to as "eye-in-hand" view), b) exocentric view of the manipulator from a camera mounted to the back leg (third-person view), and c) a mixed exocentric–egocentric view. An overview of the experimental planning and design process included in this chapter is shown in Figure 6.1.

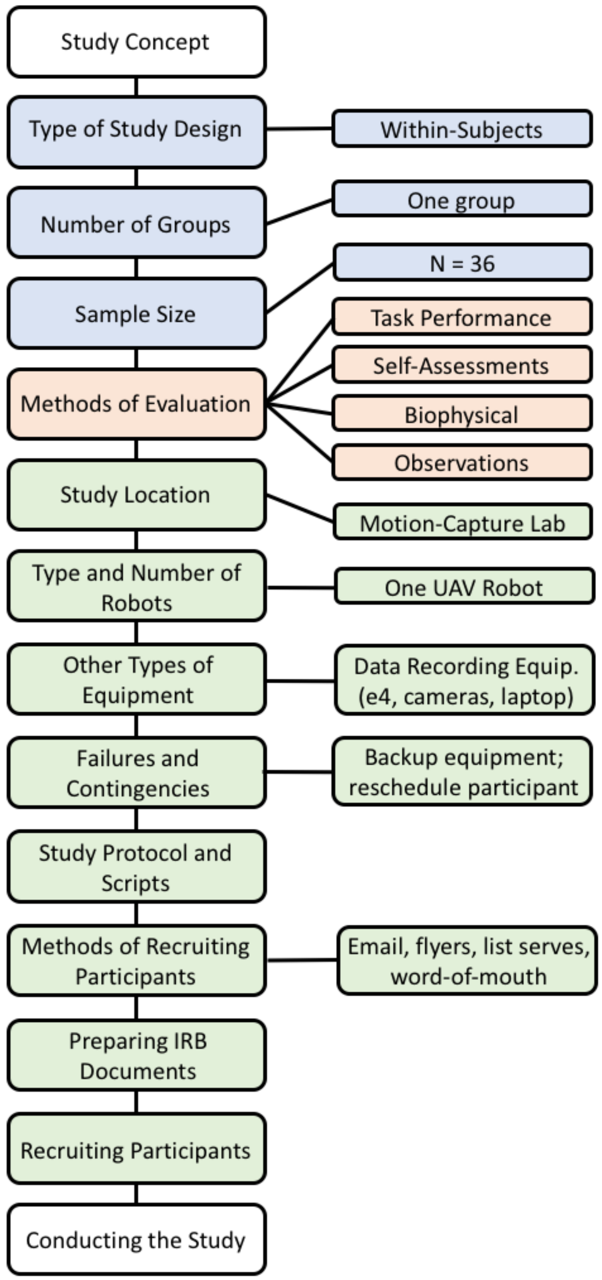


Figure 6.1: Overview of the Experimental Design Procedures Completed for Planning, Designing, and Executing this Human-Robot Interaction Study on Aerial Telemanipulation (Adapted From [210]).

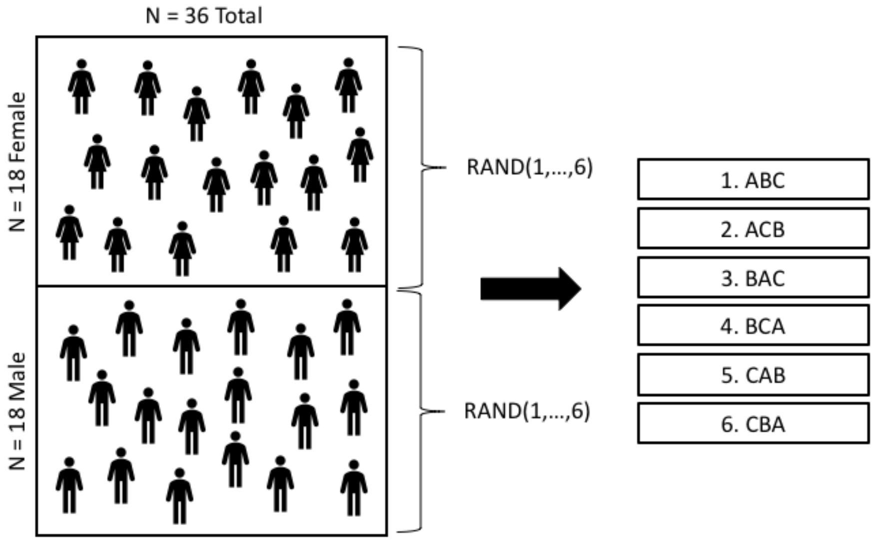


Figure 6.2: Random Condition Assignment Ensures Counterbalancing Across All Six Possible Interface Order Conditions. Condition Assignment Also Included Balancing for Gender.

6.2 Experimental Design

This section presents the experimental design and research hypotheses for this study to determine the most appropriate and preferred view for the *Mission Specialist*. A 36 participant within-subjects study was designed using guidelines in Bethel et al. [210]. The G*Power software [211] calculated the number of participants based on an *a priori* power analysis with the following parameters: power equal to 0.90, single within-group design with three measures (conditions), alpha equal to 0.05, an estimate of mean correlation for repeated measures of 0.50, and a medium desired effect size (f = 0.25). Each participant performed a single trial with each of the three interface conditions for a total of three trials per subject. Figure 6.2 illustrates the random condition order assignment and counterbalancing applied to avoid confounds and reduce learning effects. Randomization occurred without replacement to ensure an equal number of participants in each of the six categories for condition order.

6.3 Description of Tasks

Participants completed three tasks per trial: a probing task, grasping task, and combined compound pushing and visualization task. Figures 6.3 through 6.5 contain photos of the task stations. The task objects were mounted to the top of a traffic monitoring cone approximately 1.4 m from the ground. The probing task requirements remained the same for each trial, and participants were instructed to touch the end effector as close as possible to the center of the target. To complete the grasping task, participants were instructed to lift up the ring with the manipulator and then release it to the ground. The grasping task used two different sized rings: trials one and three used a ring with a 19 cm diameter, and trial two used a ring with a 14 cm diameter. The pushing task required participants to lift up the rectangular plate attached to the ring until it snapped to magnets at the top. Participants were told to read aloud the numbers, letters, or characters written on the plate. The example shown in Figure 6.3, "B?", was used for trial three. Trial one used the numbers "625", and trial two used the letters "MAN".

Figure 6.3: The Probing and Target Acquisition Station. Participants Were Instructed to Touch the End Effector as Close as Possible to the Center of the Target, But Any Contact Between the End Effector and Target Completed the Task. The Ring That Each Participant Touched With the Manipulator Was Recorded for All Trials.

Figure 6.4: The Grasping Task Station. Participants Were Instructed to Lift Up The Ring With the Manipulator, and Then Release it to the Ground. The Grasping Task Used Two Different Sized Rings: Trials One and Three Used a Ring With a 19 cm Diameter, and Trial Two Used a Ring With a 14 cm Diameter. The Ring Shown in These Images is the 14 cm Diameter Ring.

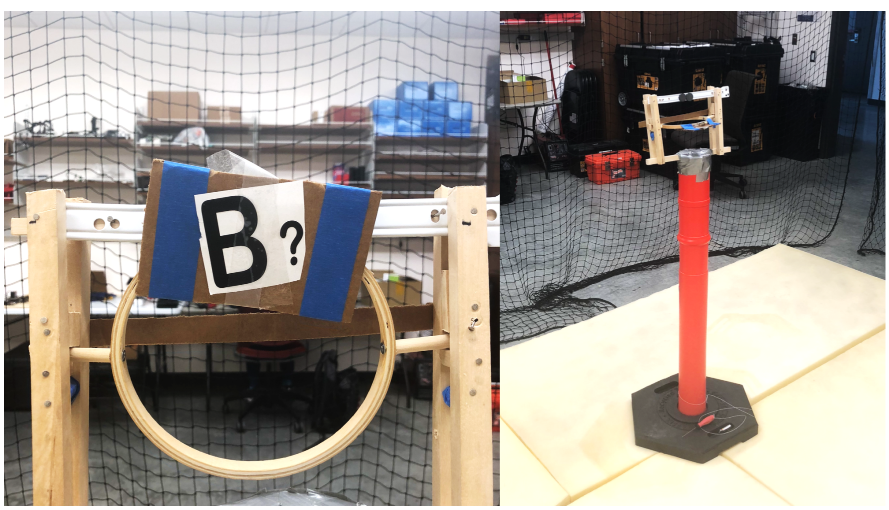


Figure 6.5: The Pushing and Visualization Task Station. Participants Were Instructed to Lift Up the Rectangular Plate Attached to the Ring Until it Snapped to Magnets at the Top. Participants Were Then Told to Read Aloud The Numbers, Letters, or Characters Written on the Plate. The Example Here, “B?”, Was Used for Trial Three. Trial One Used the Numbers “625”, and Trial Two Used the Letters “MAN”.

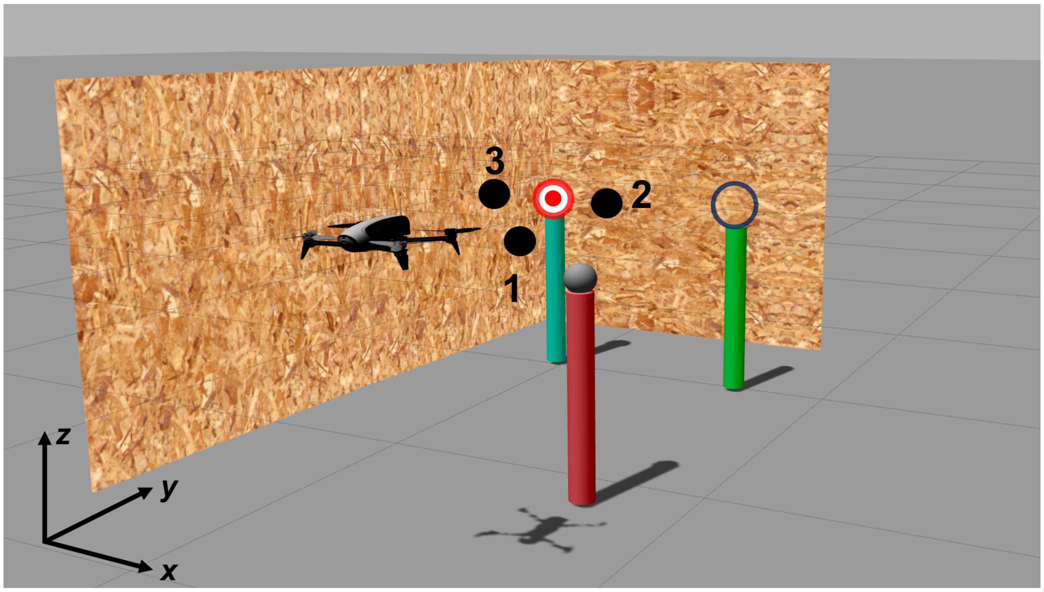
The UAV's starting position before each task was slightly altered each trial to prevent participants from learning the required verbal commands issued to the *Pilot* to get the UAV in the proper position. Table 6.1 shows the specific offset values in the x and y axes for each task, where the zero position is perfectly aligned with the task station. Note that for the probing task, the vehicle's $+x$ axis aligned with the global $+y$ axis, but for the grasping and pushing tasks, the vehicle and global $+x$ axes were aligned. Additionally, the *Pilot* controlled the z positioning for the duration of the experiment for safety reasons, so there were no offset positions in the z axis for any task. The task order and starting offset positions were the same for each trial, and only the condition assignment was randomized for each participant.

Table 6.1: Task Order and Offset Positions in Centimeters for Each Trial. The Order and Starting Position Remained the Same Across All Three Trials for Each Participant, and Only the Condition Order Was Randomly Assigned and Varied Between Participants.

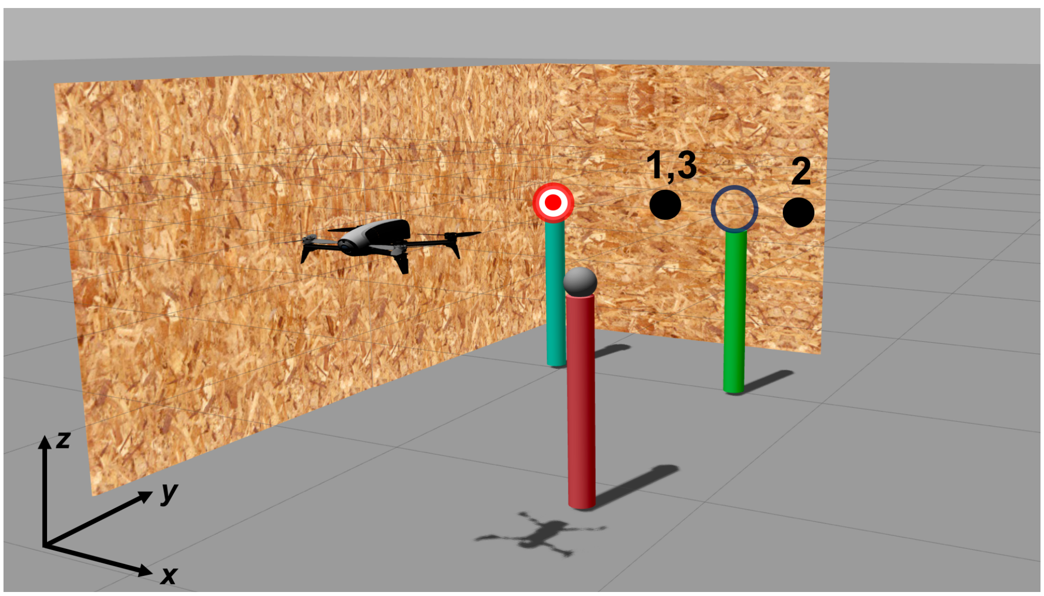
Trial	Task Order	x offset	y offset
1	Probe	0	-15
	Grasp	0	15
	Push	-15	5
2	Push	-15	-5
	Grasp	0	-10
	Probe	-10	0
3	Grasp	-5	10
	Probe	15	0
	Push	-15	5

6.4 Description of Interface Modifications

Based on recommendations after the exploratory study, a few modifications were made to the *Mission Specialist* interface and study protocol. Figure 6.7 shows the *Mission Specialist* interface used in the experimental study. The additions included a task reset button and a stow arm button, as well as a timer at the top of the screen. Participants were instructed to press the task reset button before the UAV navigated to the task station; this ensured the starting position of the manipulator was the same for each participants for all tasks and prevented participants from pre-planning to complete the task before arriving at the station.



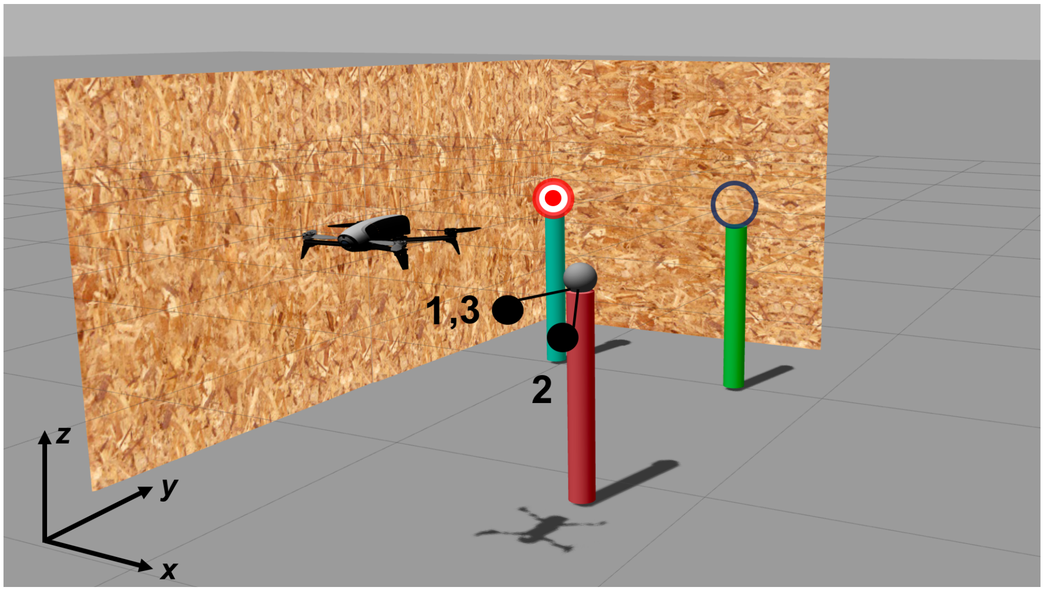
(a)



(b)

Figure 6.6: (a) Schematic of the Probing Task Starting Positions; (b) Schematic of the Grasping Task Starting Positions, and (c) Schematic of the Pushing Task Starting Positions. The Numbers Indicate the Approximate Location of the Starting Position for that Trial Number. See Table 6.1 for Exact Starting Offset Locations.

Figure 6.6: (Continued).



(c)

At the end of each flight, participants were also instructed to press the stow arm button to make sure the manipulator was in a position that avoided damage during landing. The timer at the top of the screen allowed participants to self-monitor their time during each task, although the experimental moderator verbally announced the beginning and end of each task.

6.5 Experimental Protocol

The general experimental procedure is outlined below. See section 6.6 for detailed descriptions of data collected during the trials. The research assistant was responsible for all other activities in the protocol below, unless they involve operating the UAV; in that case, the *Pilot* was responsible for those tasks. Note that the *Pilot* remained the same individual for all participants and trials throughout the experiment.

1. Administer a consent form and verbally read it aloud to each participant. Instruct participants to sign the form if they are interested in participating.

2. Administer the 35 question pre-assessment to assess prior robot experience, personality, leadership experience, and touch device usage. (This question-

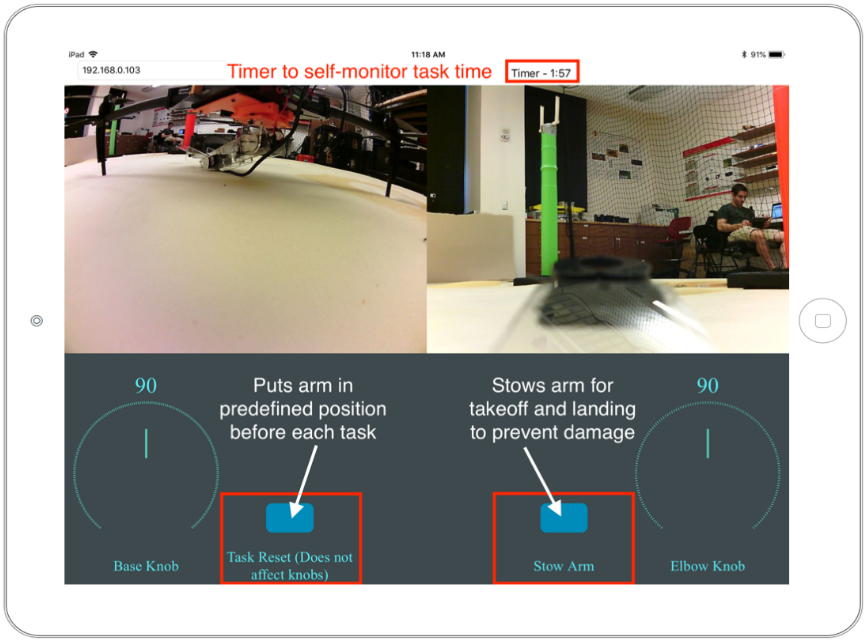


Figure 6.7: The *Mission Specialist* Interface Used in the Experimental Study. The Modifications Include a Task Reset Button to Reset the Manipulator Before Each Task, a Stow Arm Button to Ensure a Safe Landing on the Manipulator, and a Timer for Participants to Keep Track of Their Time Remaining During the Tasks.

naire is included in Appendix 9.2.2). Use this questionnaire as a screening tool for participation; if a participant considers themselves an "expert", exclude them from the study.

3. If the participant meets all inclusion criteria, give them an instruction and command protocol sheet to use during the experiment.

4. Allow the participant to practice using the interface on the mobile touch-based tablet device for no more than five minutes prior to the first trial. No performance data is collected during the practice time, but begin baseline EDA data collection.

5. After practicing, assign the participant an order of experimental conditions based on the previous randomized condition assignment protocol, participant number, and gender.

6. Explain the mission and tasks (read aloud from the Mission Script which can be found in Appendix 9.2.2). Make sure the participant understands what they are required to do during the experiment.

7. Begin recording of video, audio, Vicon, manipulator, and wristwatch data.

8. Set up and turn on the UAV and navigate to the first station. Instruct the participant to begin the first task. During the experiment, read the Mission Script aloud as the participant progresses through each task. (A description of the tasks can also be found in Appendix 9.2.2).

9. After completion of the first task, navigate the UAV to the next station and instruct the participant to hit the Task Reset button. Once arriving at the station starting position, instruct the participant to complete the second task as noted in the Mission Script. Navigate the UAV to the final stations after the participant completes the tasks as directed.

10. Return the UAV to the launch point and dis-arm the motors. Enter the arena and turn off the vehicle. Cease all data collection.

11. After each trial, administer the appropriate post-assessment to record participants' self-reported confidence and comfort when using each interface.

12. Repeat steps 8 through 11 for the second and third interface conditions.

13. At the end of the experiment, ask participant what their preferred interface view is and why they chose their preference.

6.6 Data Collection and Measurements

The experiment consisted of a within-subjects trial with four separate methods of evaluation to achieve accurate results and convergent validity, based on the guidelines given in [210, 212]. The different data types collected during each experiment included: i) pre- and post-assessment surveys, ii) biophysical measurements, iii) task performance metrics, and iv) audio/video recordings.

6.6.1 Questionnaires

Questionnaires administered in this study included a 35 question pre-assessment and a three 15 question post-assessments; each of these assessments is described in greater detail below.

6.6.1.1 Pre-Assessment Survey

A pre-assessment survey was administered to each participant to assess individual background knowledge, technology and robot experience (e.g., with hobbyist vehicles and tablets), and leadership experience (see Appendix 9.2.2 for the complete 35 question pre-assessment survey). This assessment served as a screening tool to ensure that participants did not self-identify as expert pilots or RC hobbyists, to identify the types of robots (if any) participants had experience with, and to ensure they had some experience operating touch-based devices. In addition to questions about technology and robot experience, the pre-assessment contained two personality assessment instruments to measure the following: i) scales of domineering and submissiveness, and ii) locus of control.

The personality portion contained items from the Computerized Adaptive Testing-Personality Disorder (CAT-PD) instrument [213], which was built upon the International Personality Item Pool (IPIP) [214, 215] and targeted two specific scales: domineering and submissiveness. Items from the IPIP are widely accepted in the field of psychology and have been used in over 600 publications to-date [214]. The domineering scale reflects the tendency to be controlling, dominant, and forceful in relationships, while submissiveness reflects the yielding of power to others and a lack of self-confidence in decision-making [214, 215]. The second personality assessment tool targets the concept of locus of control. Originally developed by Rotter [216], locus of control is psychological concept describing the extent to which people believe events occur as the product of their own controllable actions or uncontrollable factors (e.g., luck or fate). People who lean towards having an internal locus of control strongly believe their own actions and behavior dictate the outcome of events [217]. On the contrary, people who lean towards having an external locus of control strongly believe outcomes are determined by forces outside of their control [217]. These two personality assessment instruments were chosen because these traits are hypothesized to affect the level of interaction between the *Mission Specialist* and *Pilot*, and task performance.

6.6.1.2 Post-Assessment Survey

Post-assessment surveys were given to evaluate self-reported role empowerment (confidence and comfort) for each *Mission Specialist* participant. There were three post-assessment surveys, one for each experimental condition, each consisting of 15 questions. These surveys were given immediately after each trial for the appropriate condition. Responses addressed confidence and comfort in using the interface, completing tasks, and interacting with the *Pilot* measured on a standard 5-point Likert scale. Appendix 9.2.2 includes these post-assessment surveys.

6.6.2 Operator Performance

This study used the following measures of operator performance: i) success rate (percent task completion), ii) task completion time, and iii) manipulator reversal rate.

- *Success rate (effectiveness):* S_r. The percentage of tasks successfully completed each trial, measured by reviewing video captured of the robot during each trial and recording the number of completed and incomplete tasks.

- *Task completion time (efficiency):* T_c. The total amount of time required to complete a task, measured from the time instruction was given (or when they began controlling the manipulator if they started early) to when the task was completed. This is also measured by reviewing synced video and audio from three cameras placed strategically around the arena.

- *Reversal rate (control effort):* n_{rev}. The number of times the servo control inputs reversed direction. A command reversal happens when similar manipulator movements occur directly one after another. This measure was calculated using recorded input commands sent from the *Mission Specialist* interface to the UAV.

6.6.3 Biophysical Measurements

Biophysical measurements, specifically sympathetic nervous system activation, were measured as stress level indicators [191]. Sympathetic activation increases with stressors, whether these are physical, emotional, or cognitive. Due to the nature of these experiments, it is unlikely that participants experienced any significant physical stress while in a seated, stationary position during the trials; therefore, sympathetic activation is assumed to be caused by emotional or cognitive stressors. The skin is the only organ that is purely innervated by the sympathetic nervous system and not affected by parasympathetic activation. To measure sympathetic nervous system activation, each participant wore the Empatica E4 wristband (Empatica, Inc., Cambridge, USA) containing an EDA sensor to monitor subtle electrical changes across the surface of the skin. Participants wore the wristband on their non-dominant hand to avoid confounds in extra movement, which can create a noisy signal in the data. Data recording was managed through the E4 Realtime App, and an event marker controlled by the researcher flagged the start of each experiment and synced the biophysical data to video data. The data were uploaded to E4 Connect, a secure cloud storage platform managed by Empatica. Additionally, baseline measurements were obtained by each participant wearing the wristband before the first trial.

Figure 6.8: The Empatica E4 Wristband, AaWearable Research Device That Offers Real-Time Physiological Data Acquisition and Software for In-Depth Analysis and Visualization.

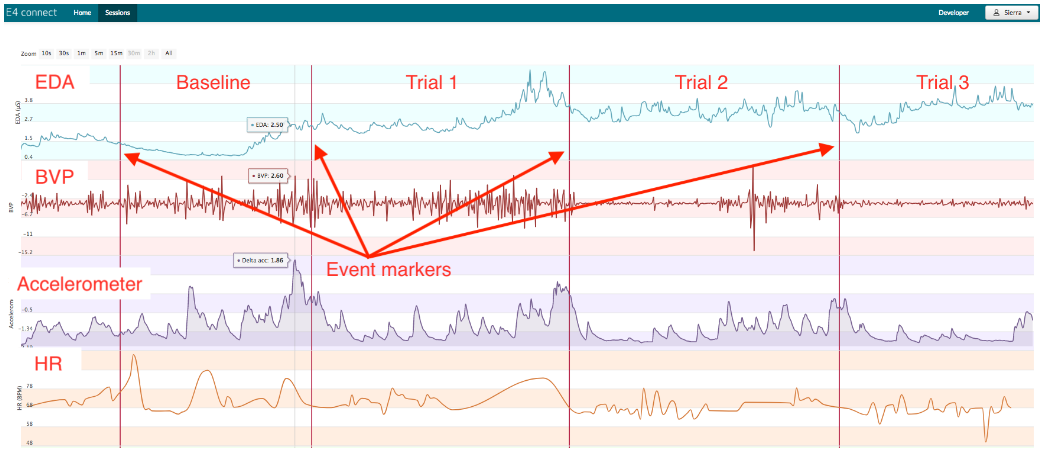


Figure 6.9: An Example of a Session Measured With the E4 Wristband, Including Electrodermal Activity (EDA) (Also Known as Galvanic Skin Response (GSR)), Blood Volume Pulse (BVP), Acceleration, and Heart Rate (HR). The Red Lines are Event Markers that Correspond to a Specific Time Point in the Experimental Video, Flagging the Start of Each Trial and Enabling Synchronization Between the Two Data Streams.

6.6.4 Video and Audio Recordings

Three cameras at stationary locations throughout the arena captured video recordings with audio for each trial, including a wide-angle view of the entire scene as the primary data source (as recommended in [218]). The task completion times, success rates, task order, and total flight times were determined by coding the start and end of each task and flight. Verbal communication from these recordings were codified after each experiment to identify the frequency, type, and time stamp of commands issue by the *Mission Specialist* to the *Pilot*. The Datavyu [219] software was used for all video coding analyses. Additionally, a camera placed directly above the tablet interface facing each *Mission Specialist* participant captured eye tracking movements. The total time spent viewing each camera and the switching frequency between the camera views were manually processed and measured for the mixed condition using a custom binary variable counter tool.

6.7 Research Hypotheses and Expected Findings

There were three primary hypotheses for the formal evaluation of a focused *Mission Specialist* interface that assessed the effects of interface FOV on task performance and user preference. The hypotheses address task performance, individual preferences, and personality effects.

6.7.1 Hypothesis 1

The mixed interface view condition will improve overall *Mission Specialist* task performance. A limited field-of-view can cause erroneous depth and speed judgments [32], as well as negatively impact self-location in the remote environment when viewing it through a video feed [196]. Multiple camera views are normally used to enhance the operator's sense of remote presence and improve self-location identification [180]. A potential issue with multiple viewpoints is inappropriate attention allocation to either display [179]; however, the displays used in this study are not overtly sensory rich (e.g., virtual environments) and cognitive tunneling is not anticipated to be significant. Additionally, self-reported confidence and comfort are expected to correlate with improved task performance. Performance indicators measured in this study associated with this hypothesis include post-assessment responses, task completion measures, manipulator performance, and electrodermal response (stress) [189, 191].

6.7.2 Hypothesis 2

***Mission Specialist* personality will positively influence performance if they are domineering or have an internal locus of control, and negatively affect performance if they are submissive or have an external locus of control.** *Mission Specialist* participants operate as part of a human-robot team with the *Pilot*; therefore, personality traits related to locus of control, domineering, and submissiveness are hypothesized to affect human-team performance and function. The extroversion of a participant, which is partly indicated by scales of domineering and submissiveness, may influence their confidence and comfort levels in verbally engaging with the *Pilot* and affect performance. Additionally, their locus of control scale, or the extent to which they believe they have the potential to influence certain outcomes, has been found to affect effort exertion [220] and persistency [221] when completing tasks. In addition to the performance measures previously mentioned, this hypothesis will be evaluated with the responses to the pre- and post-assessments.

6.7.3 Hypothesis 3

Tasks that *Mission Specialists* rate as the most difficult to complete will be more stressful and result in lower overall task performance compared to tasks that were rated easier to complete. Actively engaging with objects in the remote environment requires depth perception, accurate mental models of the manipulator and vehicle, and situational awareness. Participants are likely to rate tasks to be more difficult if they have poor situation awareness and are unable to create an accurate mental model of the robot and task. The perception of task difficulty may vary with the level of information available in separate interfaces, and the perception of task difficulty is hypothesized to negatively affect overall task performance if tasks are perceived to be more difficult.This hypothesis will be measured by task completion time, task completion rate, and post-assessments/self-reporting. Additionally, electrodermal response deviation from baseline as a stress indicator will be measured for individual tasks across all conditions.

CHAPTER 7

EXPERIMENTAL RESULTS

This section presents the results from a 36 subject study to evaluate the appropriate *Mission Specialist* interface visualization for aerial telemanipulation. First, this section describes the demographics of participants included in this study. Then, descriptive and inferential statistical results from the following data collection methods are presented: pre-assessment questionnaire, task performance measurements, manipulator control data, biometric data, verbal commands issued by the *Mission Specialist*, eye tracking movements (mixed interface condition only), and the post-assessment questionnaires.

7.1 Participants

Participant recruitment occurred on the campus of Iowa State University through the use of flyers, email announcements, word of mouth, and community groups and organizations. Targeted participants were students and professionals on campus in civil, environmental, agricultural, or a related field of engineering. A total of 37 participants were run through the study, with 36 participants successfully completing all trials whose data are included the following analyses. Tables 7.1 and 7.2 contain summaries of demographic information, including gender, age, and occupation. Of the 36 total participants, 29 participants (80%) self-identified as Caucasian, three participants (8%) self-identified as Asian, one participant (3%) self-identified as Middle Eastern, two participants (6%) self-identified as Hispanic, and one participant (3%) self-identified as South Asian.

Table 7.1: Summary of the Number of Participant's (n) in Each Gender and Age Category.

	Women		Men	
Age Group	n	%	n	%
Under 25 years	5	29	8	40
25 to 34 years	4	24	9	45
35 to 44 years	7	41	2	10
45 to 54 years	1	6	0	0
55 years and older	0	0	1	5
Total:	17	47%	19	53%

Table 7.2: Summary of the Number of Participants (n) in Each Occupation Category.

Occupation	n	% of Total
Undergraduate Student	11	31
Graduate Student	12	33
Postdoctoral Researcher	2	6
University Staff (e.g., lab coordinator, lecturer)	4	11
University Faculty	7	19
Total	36	100

7.2 Pre-Assessment Results

This section provides descriptive statistical results of responses from the pre-assessments administered to each participant before the experiment, including questions related to technology, robot experience, and two personality assessments. The pre-assessment questions can be found in Appendix 9.2.2.

7.2.1 Technology and Robot Experience

Figures 7.1–7.4 include summaries of participant responses to the pre-assessment questions that focused on prior experience with touch devices, robots, and flying UAVs, and the types of technologies used for decision making in their current occupation. All participants had touch device experience, with 86% of participants operating touch devices continuously each day. In general, participants used touch-based devices longer and more frequently than pen-based devices. The most common technologies used for decision-making by participants included digital media, verbal reports, and geographic information on electronic devices, and the most common technologies created for decision-making also included digital media and verbal reports. Applications on mobile devices were not frequently used and almost never created by a majority of participants for decision-making in their current job.

A total of $n = 9$ participants previously owned robots: four participants owned small, off-the-shelf quadrotors, two participants owned educational robots, three participants owned RC toy cars, one participant owned an RC helicopter, and one participant owned a cleaning robot (note that some participants owned more than one robot). A total of $n = 11$ participants had experience flying unmanned aircraft: seven flew RC quadrotors, three flew RC helicopters, and one flew a fixed wing aircraft. No participants with prior flying experience claimed to have expert-level piloting skills. A total of $n = 6$ participants previously operated a robot arm (four were in a school laboratory or classroom, one was a self-built hobbyist arm, and one was operated in a museum). Only one participant had a pilot's license; however, this license was for commercial aircraft and they had no prior experience flying unmanned aircraft. A total of $n = 14$ participants were in a job with a leadership role, with nine participants leading a research or lab group, four participants leading students in an academic capacity, and one participant in a business management position.

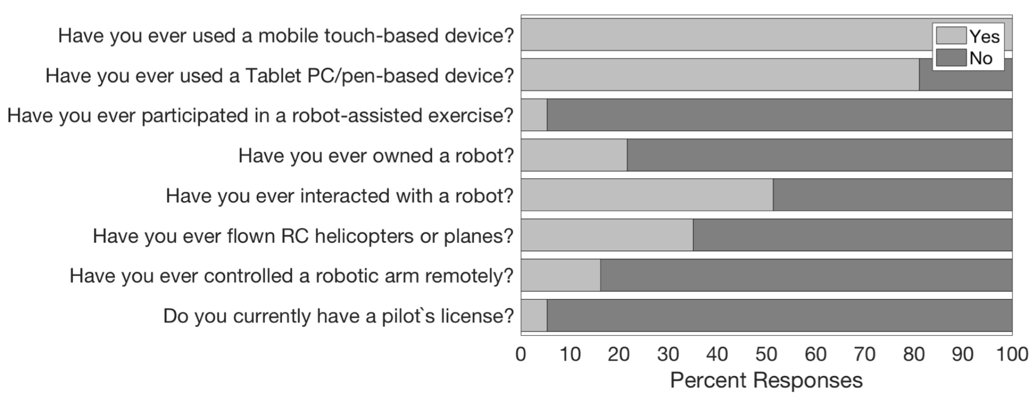
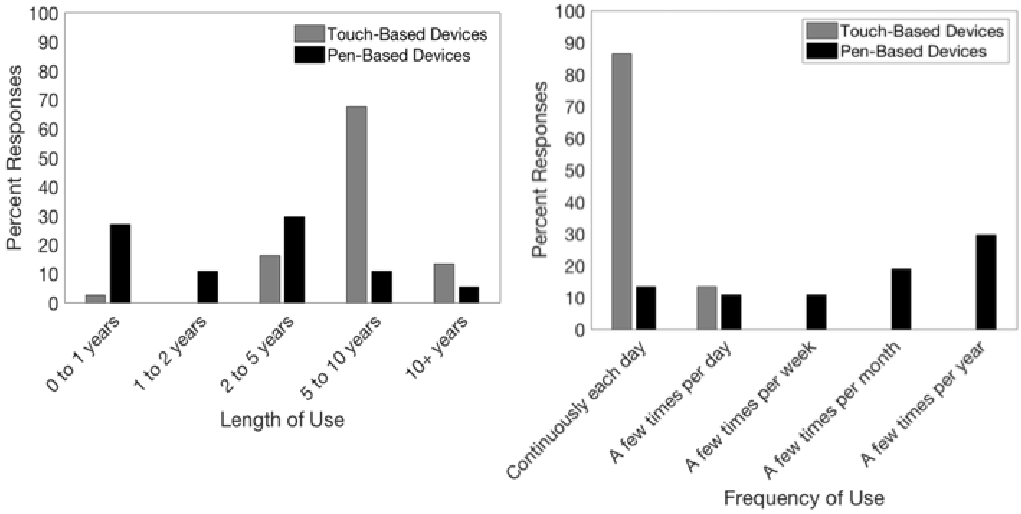


Figure 7.1: Pre-Assessment Responses Related to Prior Robot and Technology Experience, Including Questions Related to Touch-Based Devices, Tablet-Based Devices, Robot Ownership, and RC Vehicles.



(a) (b)

Figure 7.2: Pre-Assessment Responses Related to the Length and Frequency of Touch and Pen-Based Tablet Usage. A Majority of Participants Had 5 to 10 Years Experience with Touch-Based Devices and Used Them Continuously Each Day.

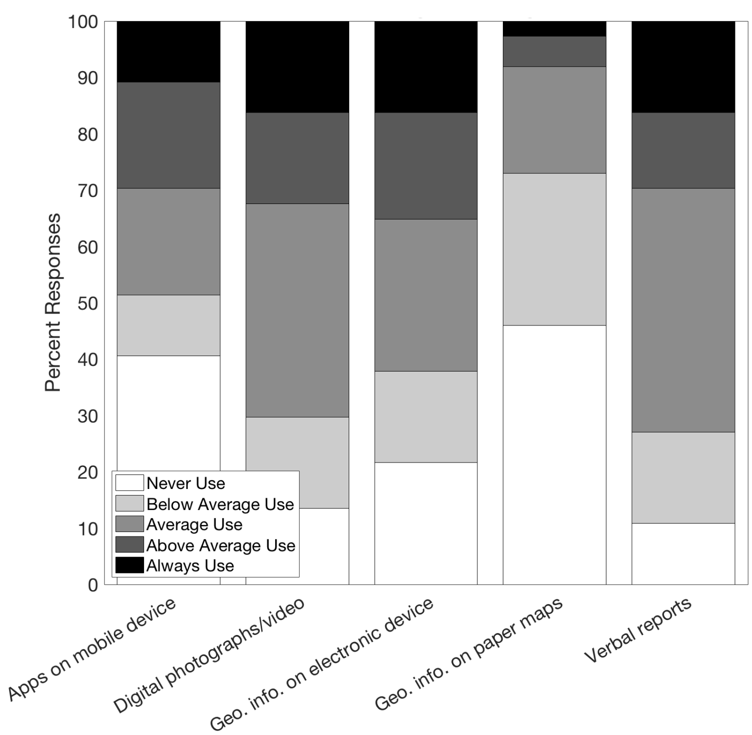


Figure 7.3: Pre-Assessment Responses Related to the Use of Technologies for Decision-Making in a Participant's Occupation. Digital Photographs and Verbal Reports Were Used Most Frequently, and Geographic Information on Paper Was Used Least Frequently.

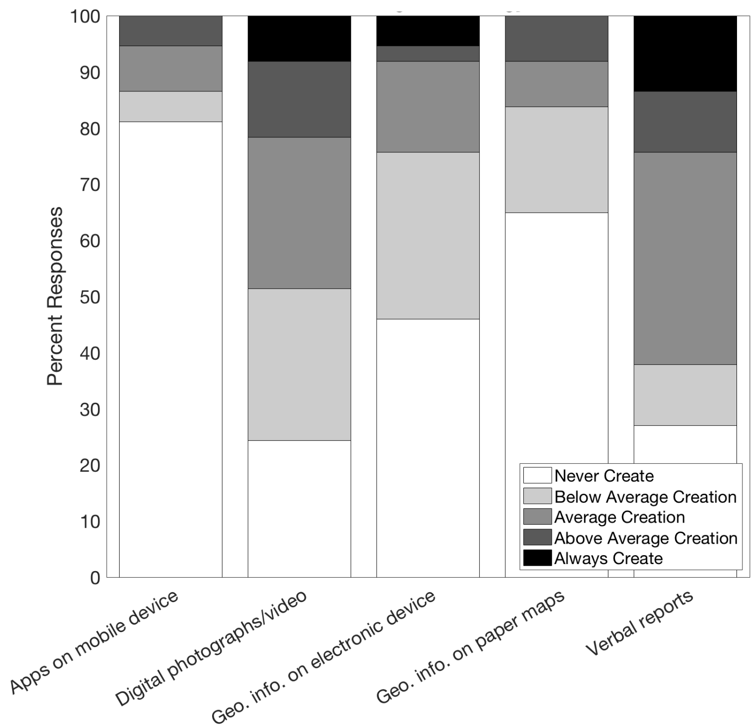


Figure 7.4: Pre-Assessment Responses Related to the Creation of Technologies Used for Decision-Making in a Participant's Occupation. Digital Photographs and Verbal Reports Were Created Most Frequently, and Mobile Apps Were Created Least Frequently.

7.2.2 Personality Assessments

This section presents results from two personality assessments given in the pre-assessment questionnaire: a focused, abbreviated version of the Computerized Adaptive Testing-Personality Disorder (CAT-PD) instrument [213] focused on submissiveness and domineering scales, and locus of control measured by the Internal Control Index (ICI) [222].

7.2.2.1 CAT-PD: Domineering and Submissiveness

The questionnaire targeted two specific scales from the CAT-PD instrument: domineering and submissiveness. The domineering scale reflects the tendency to be controlling, dominant, and forceful in relationships, while submissiveness reflects the yielding of power to others and a lack of self-confidence in decision-making [214, 215]. Table 7.3 contains summary statistics for the domineering and submissiveness scales, separated by gender. In total, six question responses were averaged to scale domineering, and six separate question responses were averaged to scale submissiveness. Values were reported on a five-point Likert scale. Figure 7.5 contains a scatterplot of domineering versus submissiveness scales, separated by gender. There was no correlation between domineering and submissiveness ($\rho_s = .031$), and there was no difference in domineering ($Z = 0.286, p = .775$) or submissiveness ($Z = -0.144, p = .886$) scales between men and women.

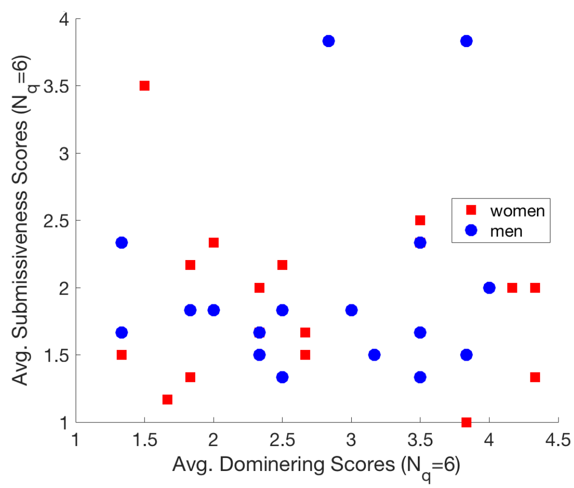


Figure 7.5: Pre-Assessment Responses for Submissiveness and Domineering Scales from Responses Recorded Based on a Five-Point Likert Scale. A Total of Six Questions Were Used to Calculate the Average Scores for Both Domineering and Submissiveness Scales. There Was No Correlation Between Domineering and Submissiveness ($\rho_s = .031$), and There Was No Difference in Domineering ($Z = 0.286, p = .775$) or Submissiveness ($Z = -0.144, p = .886$) Scales Between Men and Women.

Table 7.3: Descriptive Statistical Results for Domineering and Submissiveness Personality Traits from the CAT-PD Scale. Responses Were Recorded on a Five-Point Likert Scale (1=Low, 5=High).

	Women			Men			
Scale	n	M	SD	n	M	SD	p-value
Domineering	17	2.73	1.02	19	2.78	0.811	.775
Submissiveness	17	1.89	0.607	19	1.95	0.725	.886

7.2.2.2 Locus of Control

Locus of control was measured using a 28-question tool developed by Duttweiler [222], resulting in an Internal Control Index (ICI) for each participant. Table 7.4 contains summary statistics for the computed ICI values. A maximum high internal locus of control response results in a score of 140, while a minimum low internal response results in a score of 28 [222]. There was no difference in locus of control between men and women participants ($Z = -1.00, p = .318$).

Table 7.4: Descriptive Statistical Results for Internal Control Index (ICI) Locus of Control Scores. A Maximum High Internal Locus of Control Response Results in a Score of 140, While a Minimum Low Internal Response Results in a Score of 28. There Was No Difference In Locus of Control Between Men and Women Participants ($Z = -1.00, p = .318$).

		Statistics			
Gender	n	M	SD	min	max
Women	17	108	8.4	92	123
Men	19	104	9.2	82	114

7.3 Task Performance Measures

This section presents the results for task performance measures, including the total trial completion time, individual task completion times, and task success rate.

7.3.1 Total Completion Time

This section presents descriptive and inferential statistical results for the total task completion time. The total time for each participant to complete all three tasks was calculated for each of the three conditions by reviewing coded recorded video and audio after each experiment and summing completion times for all tasks for each participant.

7.3.1.1 Preliminary Analyses

A key assumption of using repeated measures analysis of variance (ANOVA) is that the distribution of the dependent variable is approximately normal. This assumption was tested using the Shapiro-Wilk test of normality [223], measures of kurtosis and skewness, and visual inspection of the data.

The Shapiro-Wilk test, skewness, and kurtosis measures indicated that the total task completion times were not normally distributed and positively skewed ($W = 0.95, p = .001, s = 0.79, k = 3.70$); similar results were found for completion times of the probing task ($W = 0.86, p < .001, s = 1.22, k = 3.61$), grasping task ($W = 0.89, p < .001, s = 1.27, k = 4.40$), and pushing task ($W = 0.90, p < .001, s = 0.226, k = 1.64$). Figure 7.6 contains normal probability plots and histograms of the task completion time data.

The log transformation was used to transform the data to a normal distribution. The Shapiro-Wilk test results from the log-transformed data indicate that they came from a normal distribution ($W = 0.99, p = .403$), with skewness $s = -0.109$ and kurtosis $k = 2.45$. Figure 7.7 contains normal probability plots and histograms of the log transformed task completion time data.

In addition to an assumption of normality, the validity of repeated measures ANOVA relies on an assumption of sphericity, which assumes homogeneity of variances of the differences between conditions. The assumption of sphericity was evaluated using Mauchly's test [224]:

$$s^2_{1-2} \approx s^2_{2-3} \approx s^2_{1-3} \tag{7.1}$$

where s^2_{A-B} is the variance of the difference between conditions A and B. Results from Mauchly's test for the log-transformed task completion time data indicate that the conditions of sphericity were met ($W = 0.99, p = .985$).

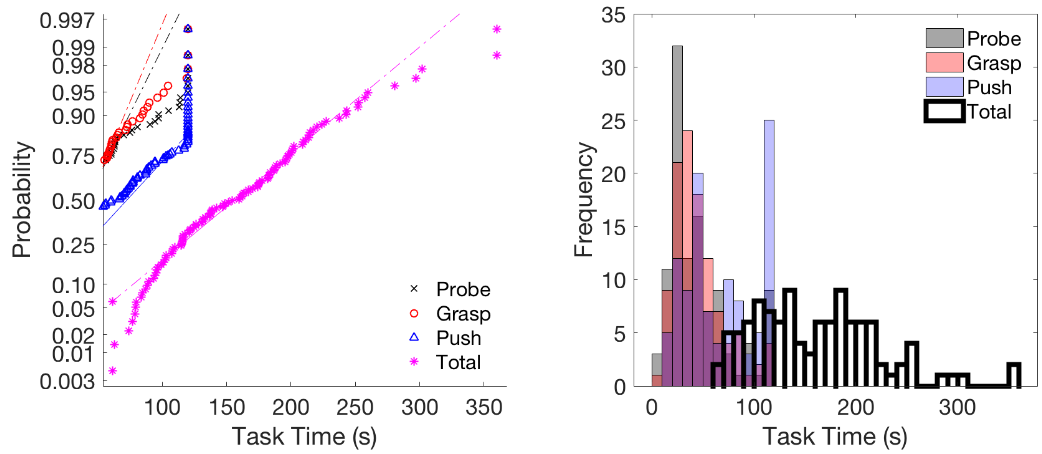


Figure 7.6: Normal Probability Plot (Left) and Histogram (Right) of the Positively Skewed Task Completion Time Data for the Probing Task, Grasping Task, Pushing Task, and Total Task Completion Time ($s = 0.79$, $k = 3.70$, Shapiro-Wilk Test: $W = 0.95, p = .001$).

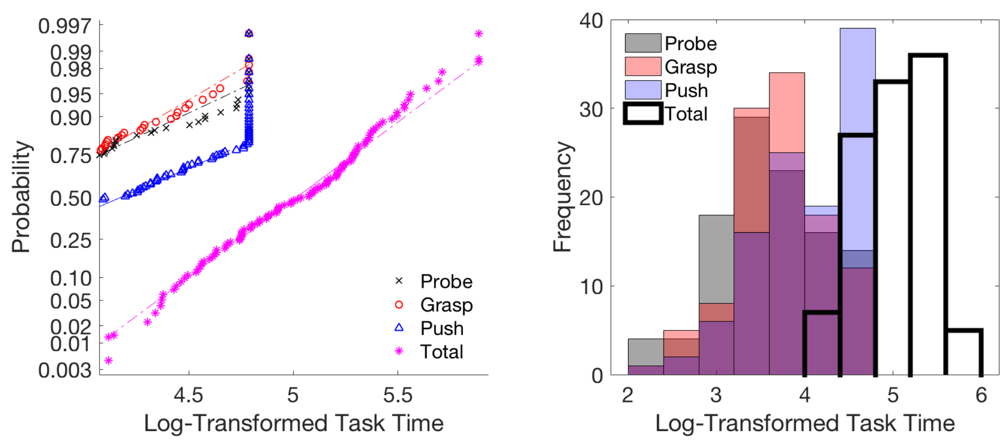


Figure 7.7: Normal Probability Plot (Left) and Histogram (Right) of the Log-Transformed, Normally Distributed Task Completion Time Data for the Probing Task, Grasping Task, Pushing Task, and Total Task Completion Time ($s = -0.109$, $k = 2.45$, Shapiro-Wilk Test: $W = 0.99, p = .403$).

7.3.1.2 Effect of Interface Condition on Total Task Completion Time

Table 7.5 presents the descriptive statistics for the total task completion time data for each interface condition, including mean (M), standard deviation (SD), minimum, and maximum. Figure 7.8 contains box and dot plots of the total task completion time data. A one-way repeated measures ANOVA was used to test the effects of interface condition on total task completion time. Results indicate that there was no difference in total task completion time between interface conditions ($F(2, 70) = 2.37, p = .101$), and Hypothesis 1, which states that the mixed condition will improve task completion time compared to the egocentric and exocentric conditions, was not supported with these data.

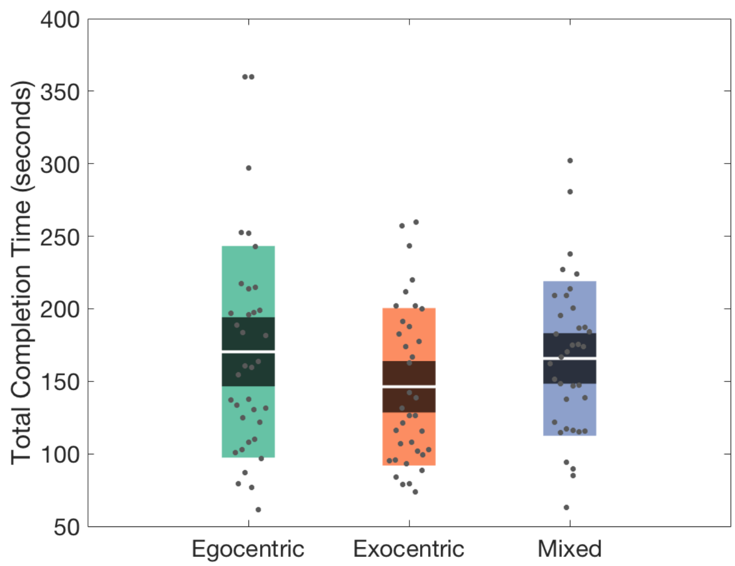


Figure 7.8: Box and Dot Plots of Total Trial Completion Times for All Conditions. Results of a Repeated Measures ANOVA Indicate That There Was No Difference in Total Task Completion Time Between Interface Conditions ($F(2, 70) = 2.37, p = .101$). The White Bar Represents the Mean (M), the Dark Shaded Area is the Standard Error of the Mean (SEM), and the Lighter Colored Shaded Areas Represent One Standard Deviation (SD).

Table 7.5: Descriptive Statistical Results for the Total Time in Seconds Required to Complete All Tasks (Probing, Grasping, and Pushing) for Each Condition. The Maximum Allowable Time for Individual Tasks Was 120 Seconds, With a Total Maximum Allowable Time of 360 Seconds.

		Statistics			
Condition	N	M	SD	min	max
Egocentric	36	170	72.9	61.4	360
Exocentric	36	146	54.3	74.0	260
Mixed	36	166	53.3	62.0	302

7.3.1.3 Gender Effects on Total Task Completion Time

In total, 17 participants were women and 19 participants were men. Table 7.6 contains descriptive statistics for total task time separated by gender. A unpaired Welch's *t-test* was conducted to determine the effects of gender on total task completion time. Results indicate there was no gender effect on total task completion time for the egocentric condition ($t(34) = 1.64, p = .111$), exocentric condition ($t(34) = -0.01, p = .989$), or the mixed condition ($t(34) = 1.08, p = .286$).

Table 7.6: Descriptive Statistical Results for the Total Time in Seconds Required to Complete All Tasks Categorized by Gender and Condition. There Was No Gender Effect on Total Task Completion Time for the Egocentric Condition ($t(34) = 1.64, p = .111$), Exocentric Condition ($t(34) = -0.01, p = .989$), or the Mixed Condition ($t(34) = 1.08, p = .286$).

	Women			Men			
Condition	n	M	SD	n	M	SD	p-value
Egocentric	17	152	58.2	19	191	83.5	.111
Exocentric	17	146	48.3	19	146	61.7	.989
Mixed	17	157	49.7	19	176	56.7	.286

7.3.1.4 Learning Effects for Total Task Completion Time

One concern of a within-subjects design is the presence of “learning effects’”, or improved performance of a single participant between subsequent trials. A one-way repeated measures ANOVA was used to test for effects of trial number on total task completion time. Results indicate that no learning effects were present, as there was no difference in total task completion time between trials ($F(2,70) = 1.33, p = .271$). Table 7.7 contains descriptive statistics for total task completion time for the ordered trials.

Table 7.7: Descriptive Statistical Results for the Total Time in Seconds Required to Complete All Tasks by Trial Number. There Was No Difference In Total Task Completion Time Between Trials ($F(2,70) = 1.33, p = .271$).

		Statistics			
Trial	N	M	SD	min	max
1	36	172	62.2	61.9	360
2	36	155	59.6	78.8	360
3	36	155	61.8	61.4	302

7.3.2 Task Completion Times

This section presents descriptive and inferential statistical results of completion times for the probing task, grasping task, and pushing task. Figure 7.9 contains box and dot plots of the individual task completion time data across all three conditions.

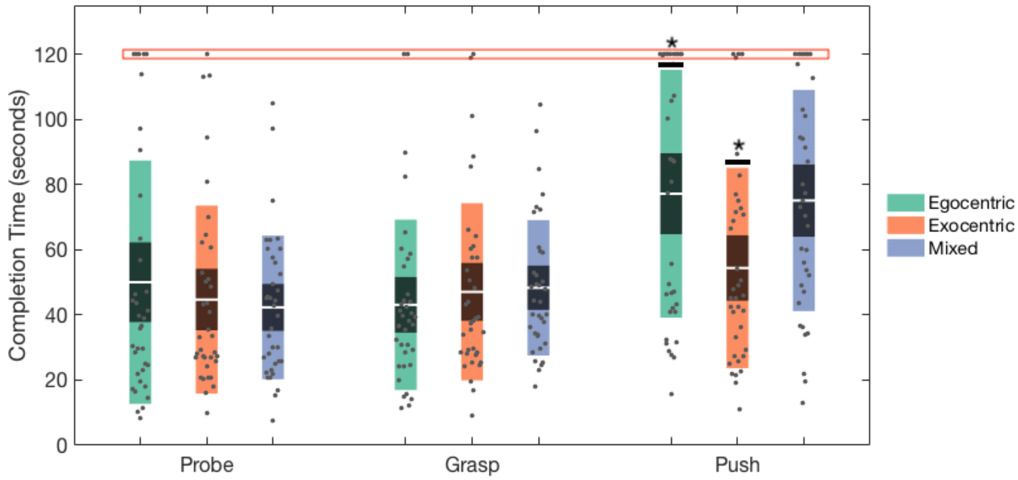


Figure 7.9: Box and Dot Plots of the Task Completion Times for Tasks Across All Conditions. The Black Horizontal Bars and * Indicate A Difference Between The Pushing Task Time for Egocentric and Exocentric Conditions at $p < .01$. The Red Horizontal Bar at the Top Indicates Tasks that Failed at 120 Seconds and Reached the Maximum Time Limit for Task Completion.

7.3.2.1 Probe-Type Task Completion Time

Descriptive statistics for the probing task completion times for each condition are shown in Table 7.8. Results from a one way repeated measures ANOVA indicate there was no effect of interface condition on probing task completion time ($F(2, 70) = 0.029, p = .950$), and Hypothesis 1 was not supported.

Table 7.8: Descriptive Statistical Results for the Probe-Type Task Completion Time in Seconds for Each Condition. There Was No Difference In Probing Task Completion Time Between Conditions ($F(2, 70) = 0.029, p = .950$).

		Statistics			
Condition	N	M	SD	min	max
Egocentric	36	50.0	37.3	8.48	120
Exocentric	36	44.7	28.8	9.71	120
Mixed	36	42.3	22.0	7.60	105

7.3.2.2 Grasp-Type Task Completion Time

Descriptive statistics for the grasping task completion times for each condition are shown in Table 7.9. Results from a one way repeated measures ANOVA indicate there was no effect of interface condition on grasping task completion time ($F(2, 70) = 1.41, p = .251$), and Hypothesis 1 was not supported.

Table 7.9: Descriptive Statistical Results for the Grasp-Type Task Completion Time in Seconds for Each Condition. There Was No Difference In Grasping Task Completion Time Between Conditions ($F(2, 70) = 1.41, p = .251$).

		Statistics			
Condition	N	M	SD	min	max
Egocentric	36	43.1	26.1	11.3	120
Exocentric	36	47.1	27.2	9.20	120
Mixed	36	48.3	20.8	18.22	104

7.3.2.3 Push-Type Task Completion Time

Descriptive statistics for the pushing task completion times for each condition are shown in Table 7.10. Results from a one way repeated measures ANOVA indicate that there was a difference in pushing task completion time between conditions ($F(2, 70) = 4.49, p = .014$). A *post hoc* analysis with Bonferroni adjustment to compensate for multiple comparisons was used to locate the differences between means, and the pushing task completion time for the egocentric condition was greater than the exocentric condition ($p < .01$). The other pairwise comparisons were not different, and Hypotheses 1 and 3 was only partially supported.

Table 7.10: Descriptive Statistical Results for the Push-Type Task Completion Time in Seconds for Each Condition. There Was a Difference In Pushing Task Completion Time Between Conditions ($F(2, 70) = 4.49, p = .014$). The Pushing Task Completion Time for the Egocentric Condition Was Greater Than the Exocentric Condition ($p < .01$).

		Statistics			
Condition	N	M	SD	min	max
Egocentric	36	77.2	38.0	15.7	120
Exocentric	36	54.4	30.8	11.0	120
Mixed	36	75.1	33.9	13.0	120

7.3.2.4 Task Completion Time Within Conditions

This section compares task times within each condition (see Figure 7.10). One-way, repeated measures ANOVA tests were used to compare task time for the probing, grasping, and pushing tasks separately for each condition. Results indicate that there was a difference in completion times between tasks for the egocentric condition ($F(2, 70) = 3.96, p < .001$). A *post hoc* multiple comparisons test indicate that the pushing task ($M = 77.2, SD = 38.0$) took longer than the grasping task ($M = 43.1, SD = 26.1, p < .001$) and probing task ($M = 50.0, SD = 37.3, p = .002$) for the egocentric condition. For the exocentric condition, there was no difference between completion time for the probing ($M = 44.7, SD = 28.8$), grasping ($M = 47.1, SD = 27.2$), and pushing tasks ($M = 54.4, SD = 30.8$), $F(2, 70) = 1.34, p = .270$. For the mixed condition, results indicate there was a difference between task completion times ($F(2, 70) = 13.7, p < .001$). A *post hoc* multiple comparisons test indicate that the pushing task ($M = 75.1, SD = 33.9$) took longer than the grasping task ($M = 48.3, SD = 20.8, p < .001$) and probing task ($M = 42.3, SD = 22.0, p < .001$). Hypothesis 3, which states the pushing task will be the most difficult for *Mission Specialists* to complete, was supported by these data.

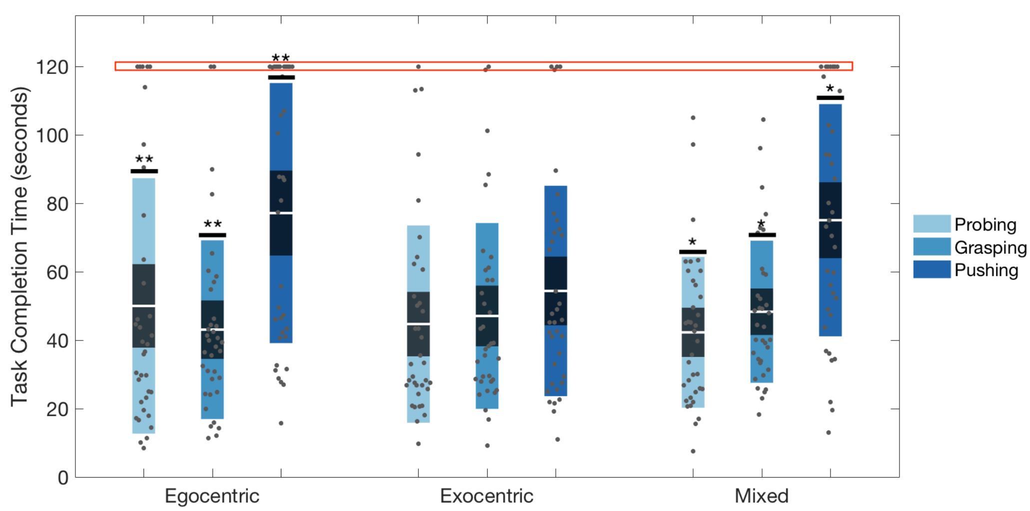


Figure 7.10: Box and Dot Plots of the Task Completion Times for All Tasks Within Each Condition. **Pushing Task Time Greater Than Probing ($p = .002$) and Grasping ($p < .001$); *Pushing Task Time Greater Than Both Probing and Grasping at $p < .001$. The Red Horizontal Bar at the Top Indicates Tasks that Failed at 120 Seconds and Reached the Maximum Time Limit for Task Completion

7.3.3 Task Success Rate

Success rate S_r for each participant was measured as the number of tasks completed per trial, with possible values $S_r \in [0, 3]$. These data were measured through scales that are not intervally distributed and did not meet the assumptions of ANOVA; therefore, the non parametric Friedman's two way analysis of variance was used to test if the repeated success measures are from the same distribution [225].

7.3.3.1 Effect of Condition on Task Success Rate

Descriptive statistics for the task success rate for each condition are shown in Table 7.11, and Figure 7.11 contains a bar chart summarizing the number and type of tasks missed for all conditions. Of the total $N = 38$ missed tasks, the probing task was missed $n = 6$ times, the grasping task was missed $n = 10$ times, and the pushing task was missed $n = 22$ times.

Results from Friedman's test show that there was a difference in task completion success rate between conditions ($\chi^2(2, N = 36) = 10.7, p = .005$). A *post hoc* test with Bonferroni adjustment was used to located the differences. Results show that the task success rate for the egocentric condition had a mean column rank smaller than the success rate for both the exocentric condition ($p = .016$) and the mixed condition ($p = .012$), but the success rates for the exocentric and mixed conditions were not different ($p = .999$). Hypothesis 1 was partially supported with these data.

Table 7.11: Descriptive Statistical Results for the Number of Tasks Successfully Completed for Each Condition.There Was a Difference in Task Completion Success Rate Between Conditions ($\chi^2(2, N = 36) = 10.7, p = .005$), and the Success Rate for the Egocentric Condition Was Less Than Both the Exocentric Condition ($p = .016$) and Mixed Condition ($p = .012$).

		Statistics			
Condition	N	M	SD	min	max
Egocentric	36	2.36	0.90	0	3
Exocentric	36	2.78	0.48	1	3
Mixed	36	2.81	0.40	2	3

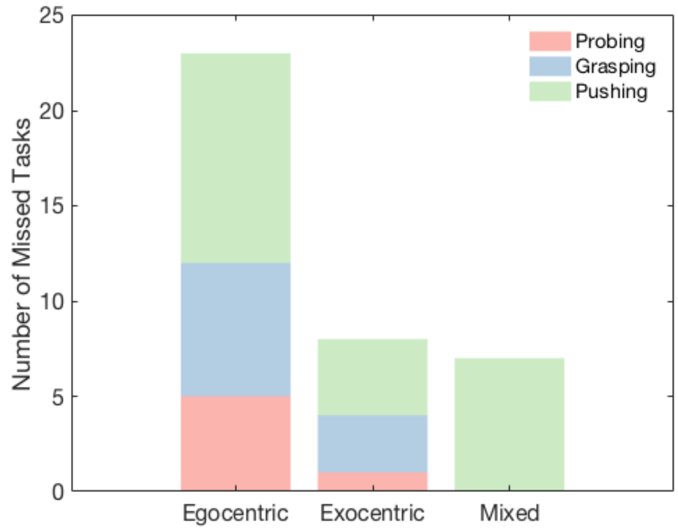


Figure 7.11: Number of Tasks Missed During the Trials, Categorized by Interface Condition and Task Type (Total Number of Missed Tasks for All Conditions and Trials Was $N = 38$).

7.3.3.2 Effect of Trial on Task Success Rate

Descriptive statistics for the task success rate for the ordered trials are shown in Table 7.12. Results from Friedman's test show that there was a difference in task completion rate between trials ($\chi^2(2, N = 36) = 6.42, p = .040$). A *post hoc* test with Bonferroni adjustment indicates that the success rate for the first trial had a mean column rank smaller than the success rate for the third trial ($p = .036$), but the mean column rank of the first and second trials ($p = .970$) and second and third trials ($p = .381$) were not different.

Table 7.12: Descriptive Statistical Results for the Number of Tasks Successfully Completed for Each Trial. There Was a Difference in Task Completion Rate Between Trials ($\chi^2(2, N = 36) = 6.42, p = .040$), and the First Trial Had a Smaller Success Rate Than the Third Trial ($p = .036$). The Success Rates for the First and Second ($p = .970$) and Second and Third ($p = .381$) Trials Were Not Different.

		Statistics			
Trial	N	M	SD	min	max
1	36	2.5	0.74	0	3
2	36	2.63	0.72	0	3
3	36	2.81	0.47	1	3

7.4 Manipulator Performance

This section presents statistical results for measures of manipulator performance, including the number of commands sent to the manipulator and the manipulator reversal rate.

7.4.1 Manipulator Commands Sent

The total number of commands sent to the manipulator from the mobile interface was recorded for each trial. A command was logged as a single POST request, and each individual degree change in either the base or elbow joint triggered a single request. For example, if a participant moved the manipulator from 85 degrees to 95 degrees, ten POST requests were logged; therefore, the manipulator command data were an indication of a participant's amount of interaction with each joint knob within the interface.

7.4.1.1 Preliminary Analyses

Normal probability and histogram plots were used to visually assess the normality of the manipulator command data, and the Shapiro-Wilk test, and skewness and kurtosis parameters were used as quantitative measures of normality. The distribution of total number of manipulator commands sent was positively skewed ($s = 1.45$, $k = 5.54$), and the results from the Shapiro-Wilk test ($W = 0.88, p < .001$) indicate the data were not from a normal distribution (see Figure 7.12).

A logarithmic transformation was applied to the servo command data to transform them to a normal distribution. The log-transformed command data had parameters of skewness $s = 0.17$ and kurtosis $k = 2.73$; additionally, performing the Shapiro-Wilk test resulted in failing to reject the null hypothesis that the data came from a normal distribution ($W = 0.99, p = .851$). Figure 7.13 shows the normal probability plots and histograms for the log-transformed data. Additionally, results from Mauchly's test indicate that the conditions of sphericity were met for the total number of manipulator commands sent ($\chi^2 = 0.305, p = .858$).

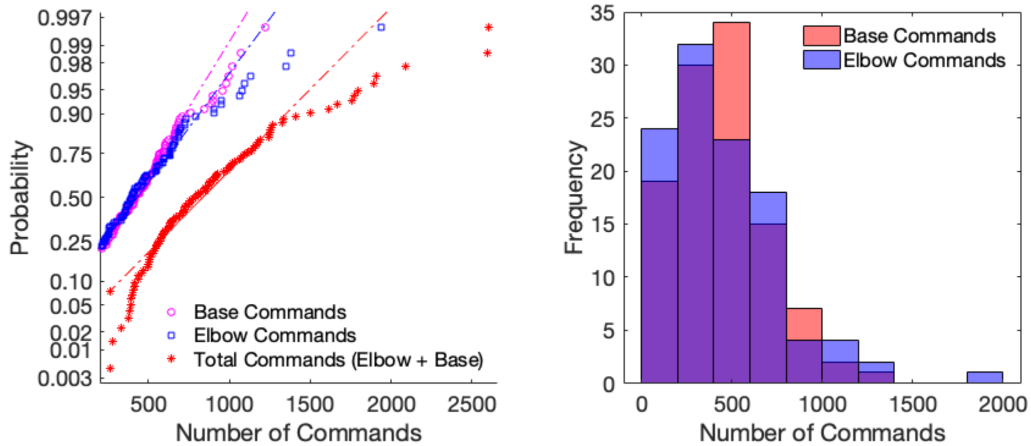


Figure 7.12: Normal Probability Plot (Left) and Histogram (Right) of the Positively Skewed Manipulator Command Data for the Elbow and Base Joints ($s = 1.45$, $k = 5.54$, Shapiro-Wilk Test: $W = 0.88, p < .001$).

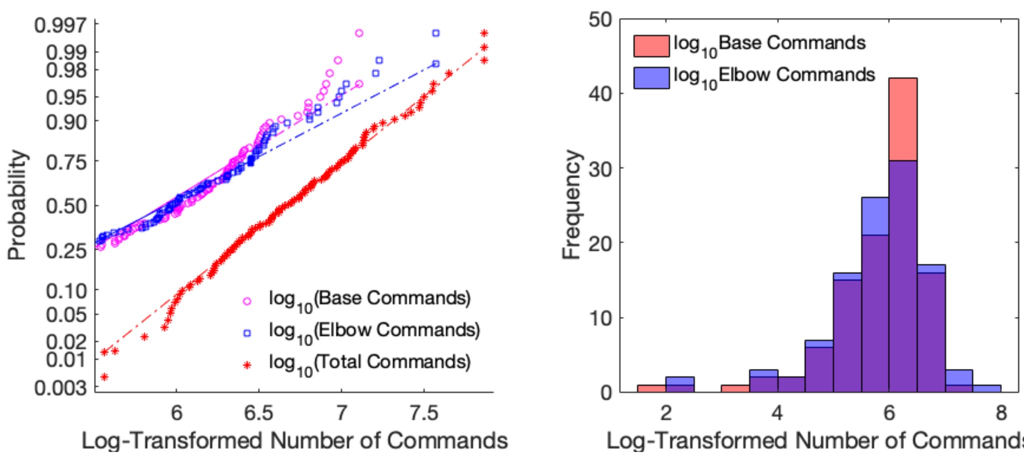


Figure 7.13: Normal Probability Plot (Left) and Histogram (Right) of the Log-Transformed, Normally Distributed Manipulator Command Data for the Elbow and Base Commands ($s = 0.17$, $k = 2.73$., Shapiro-Wilk Test: $W = 0.99, p = .851$).

7.4.1.2 Effect of Condition on Manipulator Commands

Descriptive statistics are shown in Table 7.13 for number of commands sent to the base, elbow, and total number of commands for each condition. There was no effect of interface condition on the number of commands sent to the base ($F(2,70) = 0.87$, $p = .425$), the number of commands sent to the elbow joint ($F(2,70) = 0.46, p = .631$), or the total number of commands sent to the manipulator ($F(2,70) = 1.12, p = .332$). Additionally, there was no interaction between interface condition and manipulator joint to which the commands are sent ($F(2,140) = 0.59, p = .56$).

Table 7.13: Descriptive Statistical Results for the Number of Manipulator Commands for Each Condition ($N = 36$). There Was No Effect of Interface Condition on the Number of Commands Sent to the Base ($F(2,70) = 0.87$, $p = .425$), the Number of Commands Sent to the Elbow ($F(2,70) = 0.46$, $p = .631$), or the Total Number of Commands Sent to the Manipulator ($F(2,70) = 1.12, p = .332$)

	Base		Elbow		Total	
Condition	M	SD	M	SD	M	SD
Egocentric	492	299	481	341	973	502
Exocentric	387	237	467	361	853	512
Mixed	429	219	418	256	847	333

7.4.1.3 Effect of Trial Number on Manipulator Commands

Descriptive statistics are shown in Table 7.14 for the total number of servo commands sent for each ordered trial. There was no effect of trial number on the number of commands sent to the base joint ($F(2,70) = 0.08, p = .921$), the number of commands sent to the elbow joint ($F(2,70) = 0.38, p = .683$), or the total number of commands sent to the manipulator ($F(2,70) = 0.29, p = .746$).

Table 7.14: Descriptive Statistical Results for the Number of Manipulator Commands for Each Trial ($N = 36$). There Was No Effect of Trial Number on the Number of Commands Sent to the Base Joint ($F(2, 70) = 0.08, p = .921$), the Elbow Joint ($F(2, 70) = 0.38, p = .683$), or the Total Number of Commands ($F(2, 70) = 0.29$, $p = .746$).

	Base		Elbow		Total	
Trial	M	SD	M	SD	M	SD
1	424	234	435	366	859	487
2	454	254	454	326	908	483
3	431	281	476	273	907	405

7.4.2 Manipulator Reversal Rate

This section presents statistical results for the number of reversals performed with the manipulator. The reversal rates were calculated on per trial basis, not for individual tasks, because the manipulator control POST requests were not time-stamped, and time synchronization with other data streams was not possible.

7.4.2.1 Preliminary Analysis

Normal probability and histogram plots were used to visually assess the normality of the manipulator command data, and the Shapiro-Wilk test, and skewness and kurtosis parameters were used as quantitative measures of normality. Figure 7.14 contains normal probability plots and histograms of the reversal rate data, which were positively skewed ($s = 2.15$, $k = 10.1$). Results from the Shapiro-Wilk test conducted on the total reversal rate data ($p < .001, W = 0.81$) also indicate they were not from a normal distribution.

A logarithmic transformation was applied to the base, elbow, and total reversal rate data. The log-transformed total reversal rate data resulted in skewness $s = 0.18$ and kurtosis $k = 3.11$; additionally, the Shapiro-Wilk test failed to reject the null hypothesis that the data came from a normal distribution ($p = .482, W = 0.99$). Figure 7.15 shows the normal probability plots and histograms for the log-transformed data. Results from Mauchly's test indicate that conditions of sphericity for the log-transformed data were met ($\chi^2 = 0.107, p = .948$).

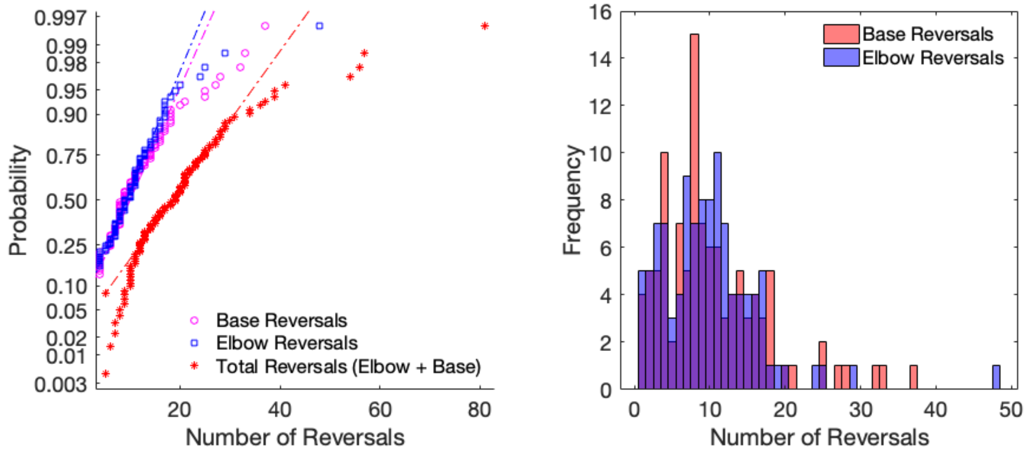


Figure 7.14: Normal Probability Plot (Left) and Histogram (Right) of the Positively Skewed Manipulator Reversal Rate Data ($s = 2.15$, $k = 10.1$, Shapiro-Wilk Test: $p < .001, W = 0.81$).

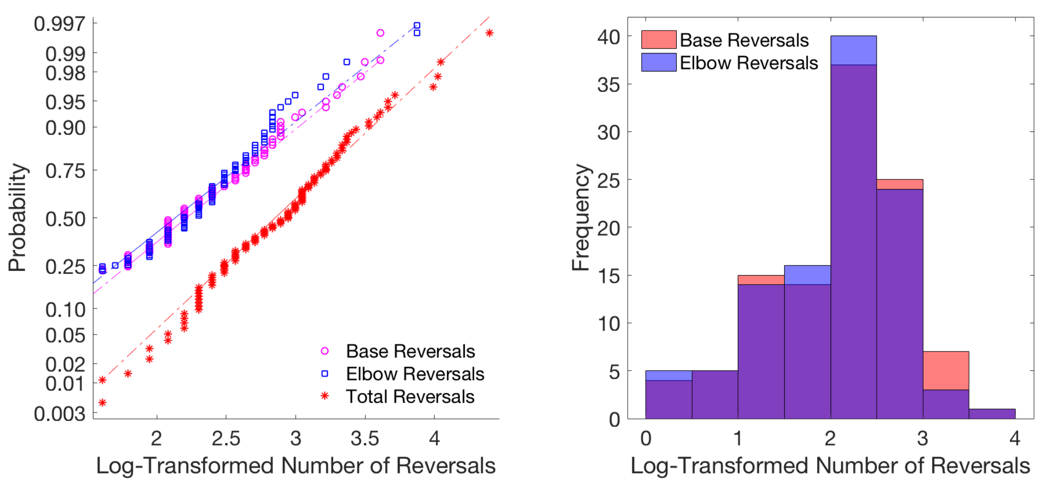


Figure 7.15: Normal Probability Plot (Left) and Histogram (Right) of the Log-Transformed, Normally Distributed Reversal Rate Data ($s = 0.18$, $k = 3.11$ Shapiro-Wilk Test: $p = .482, W = 0.99$).

7.4.2.2 Effect of Condition on Manipulator Reversal Rate

Descriptive statistics are shown in Table 7.15 for the base, elbow, and total number of command reversals for each condition; box and dot plots of these data are shown in Figure 7.16. A one-way repeated measures ANOVA test was used to determine the effects of interface condition on manipulator reversal rates. Results indicate there was no effect of interface condition on number of reversals for the base ($F(2,70) = 0.208, p = .813$), elbow ($F(2,70) = 1.72, p = .187$), or the total number of reversal rates with the manipulator ($F(2,70) = 1.83, p = .169$).

Table 7.15: Descriptive Statistical Results for the Number of Manipulator Command Reversals for Each Condition. There Was No Effect of Interface Condition on Number of Reversals for the Base Joint ($F(2,70) = 0.208$, $p = .813$), Elbow Joint ($F(2,70) = 1.72, p = .187$), or the Total Number of Reversal Rates with the Manipulator ($F(2,70) = 1.83, p = .169$)

		Base		Elbow		Total	
Condition	N	M	SD	M	SD	M	SD
Egocentric	36	11.4	8.4	10.8	6.2	22.2	12
Exocentric	36	9.8	6.5	9.1	8.0	18.9	13.0
Mixed	36	9.9	6.3	9.8	5.4	19.8	9.3

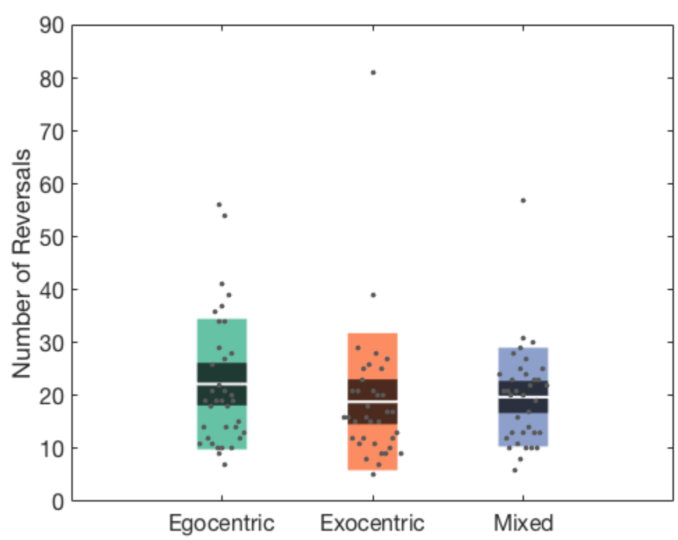


Figure 7.16: Box and Dot Plots of the Manipulator Reversal Rate for All Conditions. The Mean Number of Total Reversals was $M = 22.2$ for the Egocentric Condition, $M = 18.9$ for the Exocentric Condition, and $M = 19.8$ for the Mixed Condition.

7.4.2.3 Effect of Trial Number on Manipulator Reversal Rate

Descriptive statistics are shown in Table 7.16 for the total number of reversal rates for the base, elbow, and total command reversals for each ordered trial. A one-way, repeated measures ANOVA test was used to determine the effect of trial number on reversal rates. Results indicate that trial number did not affect the number of reversals for the base joint ($F(2, 70) = 0.149, p = .862$), elbow joint ($F(2, 70) = 0.265, p = .775$), or the total number of reversal rates with the manipulator ($F(2, 70) = 0.264, p = .769$).

Table 7.16: Descriptive Statistical Results for the Number of Manipulator Command Reversals for Each Trial. There Was No Effect of Trial Number on The Number of Reversals for the Base Joint ($F(2, 70) = 0.149, p = .862$), Elbow Joint ($F(2, 70) = 0.265, p = .775$), or the Total Number of Reversal Rates With the Manipulator ($F(2, 70) = 0.264, p = .769$).

		Base		Elbow		Total	
Trial	N	M	SD	M	SD	M	SD
1	36	9.8	7.0	9.7	5.7	19.5	10.6
2	36	10.8	7.8	10.7	8.0	22.4	14.0
3	36	10.6	6.5	9.3	6.0	19.9	10.2

7.5 Biometric Data

This section presents descriptive and inferential statistical results for the electrodermal (EDA) response data in micro Siemens (μS) collected from the Empatica e4 wristwatch during the trials. Data from three participants were removed due to technical issues with the Empatica wristband which resulted in data not being properly collected. In total, data from $N = 33$ participants were used for the following analyses, with $n = 19$ men and $n = 14$ women.

7.5.1 EDA Response Deviation from Baseline

This section provides statistical analyses for the average EDA response deviation from baseline calculated for each experimental condition. The Empatica wristwatch data were synced to the video data at the beginning of each trial, and the time stamps for the beginning and ending of each trial were calculated from the coded video and audio. Using these synchronized data, the EDA responses for the duration of each trial (three total per participant) were calculated and filtered to removed artifacts. Then, the EDA response time series were averaged for each condition. Finally, the average baseline response (measured during the practice flight) was subtracted from the averaged data from each trial; this accounted for individual differences in EDA levels and provided a basis for comparison.

7.5.1.1 Preliminary Analyses

Normal probability and histogram plots were used to visually assess the normality of the EDA response data, and the Shapiro-Wilk test, and skewness and kurtosis parameters were used as quantitative measures of normality. The sum of the biometric data distributions was positively skewed (skewness $s = 2.08$, kurtosis $k = 10.49$) as can be seen from Figure 7.17 and the results from the Shapiro-Wilk test ($W = 0.69, p < .001$). The log and Box Cox transformations were unable to transform the eye tracking data to a normal distribution; therefore, nonparametric tests were used to analyze these data.

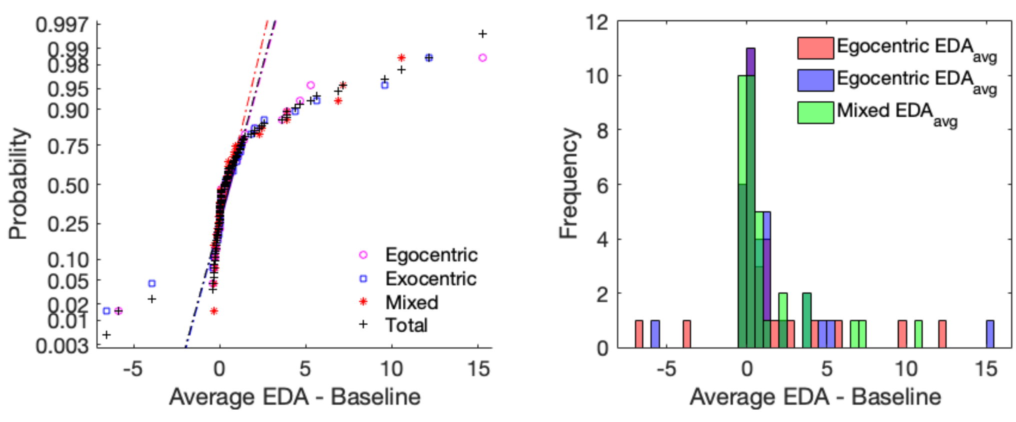


Figure 7.17: Normal Probability Plot (Left) and Histogram (Right) of the Positively Skewed EDA Response Data for All Conditions. ($s = 2.08$, $k = 10.49$, Shapiro-Wilk Test: $W = 0.69, p < .001$).

7.5.1.2 Effect of Condition on EDA Response

Descriptive statistics are shown in Table 7.17 for the average EDA response deviation from baseline in micro Siemens (μS) for each condition, and Figure 7.18 contains box and dot plots of these data. Results from the Wilcoxon signed rank test show that the EDA deviations from baseline were from a distribution with a mean larger than zero for the egocentric ($Z = 3.06, p = .001$), exocentric ($Z = 2.86, p = .002$), and mixed conditions ($Z = 3.02, p = .001$). The nonparametric Friedman's test was used to determine the effects of condition on average EDA response deviation from baseline. Results indicate there was no effect of condition on EDA response deviation from baseline ($\chi^2(2, N = 33) = 0.240, p = .886$).

Table 7.17: Descriptive Statistical Results for the Average EDA Response (μS) Deviation from Baseline for Each Condition. There Was No Effect of Condition on EDA Response Deviation From Baseline ($\chi^2(2, N = 33) = 0.240, p = .886$)

		Statistics			
Condition	N	M	SD	min	max
Egocentric	33	1.14	3.15	-5.86	15.3
Exocentric	33	1.08	3.23	-6.59	12.1
Mixed	33	1.27	2.51	-0.364	10.5

7.5.1.3 Effect of Trial Number on EDA Response

Average deviations from baseline were calculated using the same procedure from the previous section; however, in this case the responses were evaluated by trial number, not condition. Descriptive statistics are shown in Table 7.18 for the average EDA response deviation from baseline in micro Siemens (μS) for the ordered trials; these data are also shown in box and dot plots in Figure 7.19. There was an effect of trial number on EDA deviation from baseline ($\chi^2(2, N = 33) = 6.54, p = .038$). A *post hoc* analysis with Bonferroni adjustment to compensate for multiple comparisons was used to locate the differences. The EDA deviations from baseline during the first trial were less than the second trial data ($p = .035$). The other pairwise comparisons were not different.

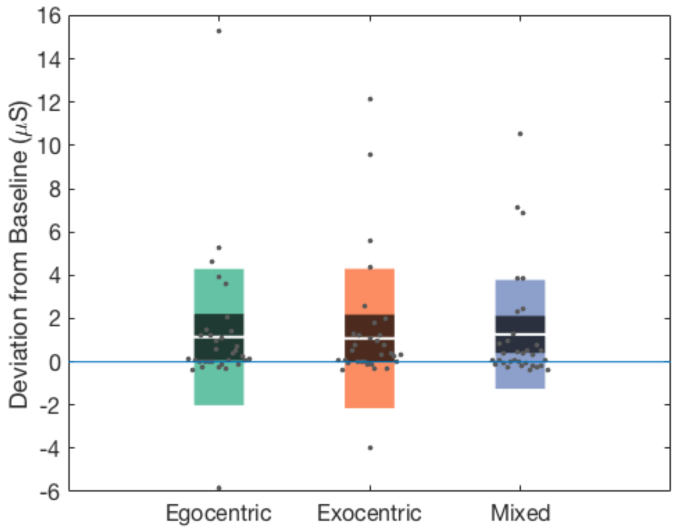


Figure 7.18: Box and Dot Plots of the EDA Response Deviation From Baseline in μS. The Average Response Deviation was $M = 1.14$ for the Egocentric Condition, $M = 1.08$ for the Exocentric Condition, and $M = 1.27$ for the Mixed Condition. Average EDA Responses Were Statistically Greater Than Zero for All Conditions (Blue Line), (all $p < .005$).

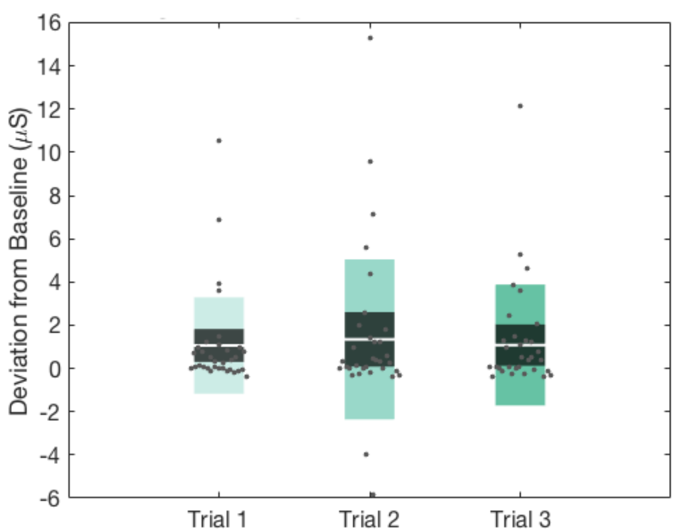


Figure 7.19: Box and Dot Plots of the EDA Response Deviation From Baseline in μS. The Average Response Deviation was $M = 1.06$ for Trial 1, $M = 1.35$ for Trial 2, and $M = 1.08$ for Trial 3. EDA Deviations From Baseline During Trial 2 Were Greater Than the Trial 1($p = .035$).

Table 7.18: Descriptive Statistical Results for the Average EDA Response (μS) Deviation from Baseline for Each Trial. There Was an Effect of Trial Number On EDA Deviation From Baseline ($\chi^2(2, N = 33) = 6.54, p = .038$), and the EDA Deviations From Baseline During Trial 2 Were Greater Than Trial 1 ($p = .035$).

		Statistics			
Trial	N	M	SD	min	max
1	33	1.06	2.23	-0.36	10.5
2	33	1.35	3.70	-5.86	15.3
3	33	1.08	2.78	-6.59	12.1

7.5.1.4 Effect of Task Type on EDA Response

The EDA responses for the duration of each task (3 tasks x 3 conditions = 9 total tasks) were calculated and filtered to removed artifacts. The task-specific EDA responses were averaged, and the baseline response was subtracted to account for individual differences in EDA levels. Descriptive statistics are shown in Table 7.19 for the average EDA deviation from baseline during each task in micro Siemens (μS) for all conditions; these data are also shown in Figure 7.20. Friedman's test was used to test the effects of condition on EDA response deviation from baseline. Results indicate there was no effect of condition EDA baseline deviations for the probing task ($\chi^2(2, N = 33) = 3.89, p = .144$), the grasping task ($\chi^2(2, N = 33) = 0.182, p = .913$), and the pushing task ($\chi^2(2, N = 33) = 2.36, p = .307$). Hypothesis 2 is not supported with these data.

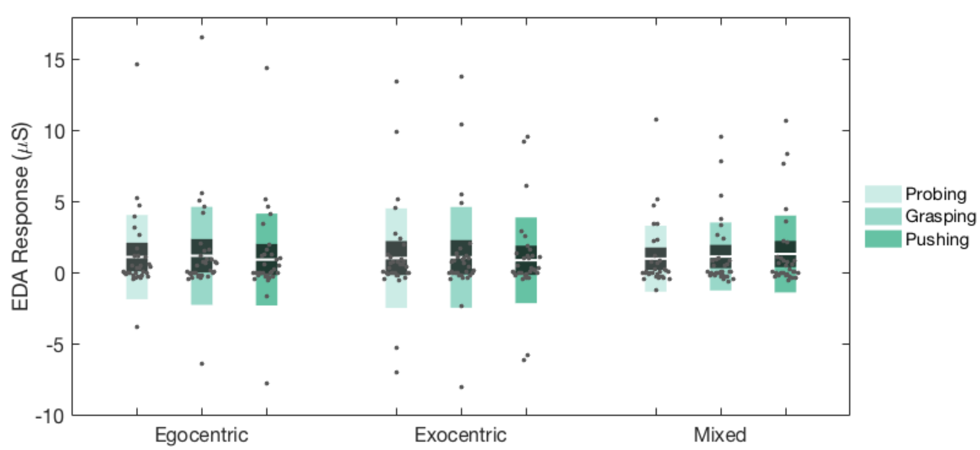


Figure 7.20: Box and Dot Plots of the EDA Response Deviation From Baseline in μS for All Tasks and Conditions. There Was No Condition Effect for Any Task (Probe: $\chi^2(2, N = 33) = 3.89, p = .144$, Grasp: $\chi^2(2, N = 33) = 0.182$, $p = .913$, Push: $\chi^2(2, N = 33) = 2.36, p = .307$).

Table 7.19: Descriptive Statistical Results for the Average EDA Deviation from Baseline for Each Condition. There Was No Condition Effect on EDA Baseline Deviations for Any Task (Probe: $\chi^2(2, N = 33) = 3.89, p = .144$, Grasp: $\chi^2(2, N = 33) = 0.182, p = .913$, Push: $\chi^2(2, N = 33) = 2.36, p = .307$).

		Probe		Grasp		Push	
Condition	N	M	SD	M	SD	M	SD
Egocentric	33	1.15	2.96	1.24	3.44	0.98	3.22
Exocentric	33	1.08	3.50	1.13	3.54	0.93	3.01
Mixed	33	1.04	2.31	1.19	2.34	1.37	2.70

7.6 Verbal Commands

This section presents statistical results for the total number of verbal commands given by the *Mission Specialist* to the *Pilot*. Only specific commands for vehicle control are included in this analysis, although all verbal communication by the *Mission Specialist* was recorded during video coding. Verbal commands included directions to move the vehicle left, right, forward, or backward.

7.6.1 Number of Verbal Commands

This section presents the descriptive and inferential statistical results for the number of verbal commands given by the *Mission Specialist* for each condition. The total number of verbal commands were calculated by summing the number of commands given for each task recorded during the video coding procedure.

7.6.1.1 Preliminary Analyses

Normal probability and histogram plots were used to visually assess the normality of the verbal command data, and the Shapiro-Wilk test, skewness and kurtosis parameters were used as quantitative measures of normality. The verbal command data were positively skewed ($s = 1.51$, $k = 5.87$, Shapiro-Wilk Test: $W = 0.88, p < .001$) as can be seen from Figure 7.21.

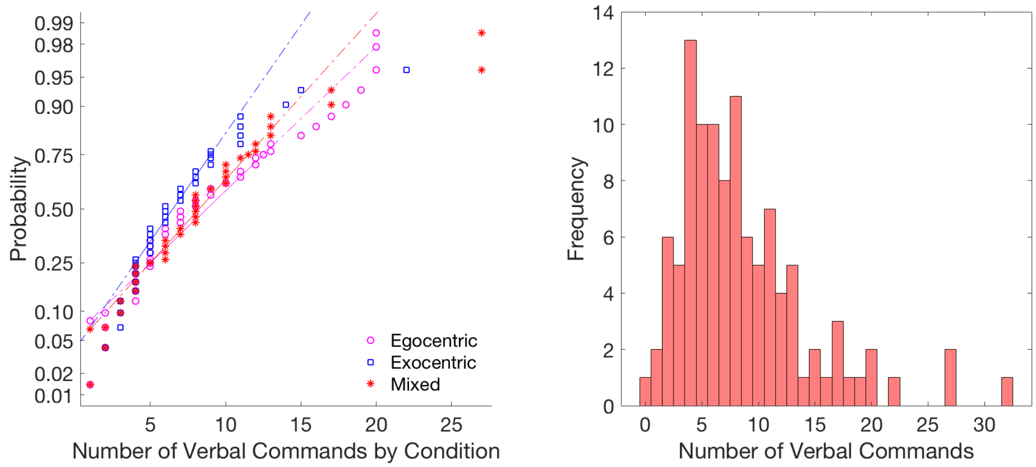


Figure 7.21: Normal Probability Plot (Left) of the Total Number of *Mission Specialist* Verbal Commands for Each Condition, and Histogram (Right) of the Total Number of Verbal Commands for All Conditions Combined ($s = 1.51$, $k = 5.87$, Shapiro-Wilk Test: $W = 0.88, p < .001$).

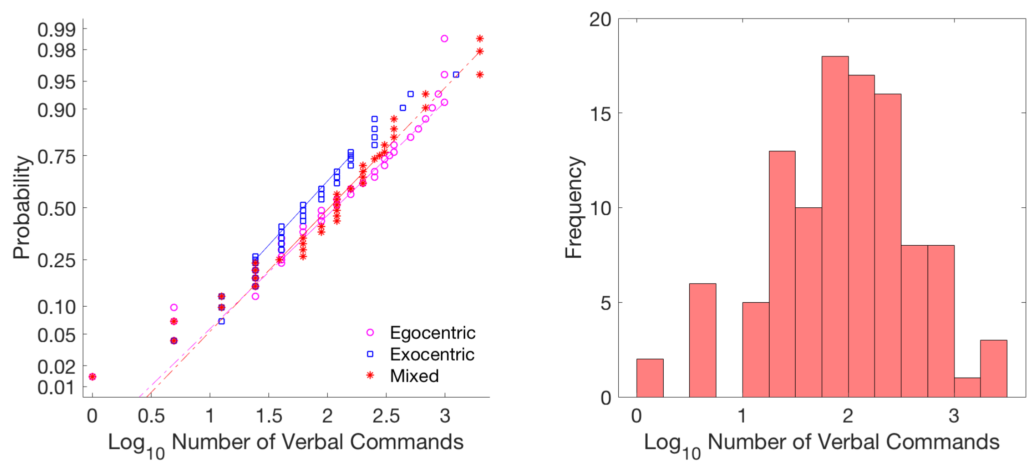


Figure 7.22: Normal Probability Plot (Left) of the Log-Transformed, Normally Distributed Verbal Command Data for Each Condition, and Histogram (Right) of the Log-Transformed Total Number of Verbal Commands ($s = -0.37$, $k = 3.29$, Shapiro-Wilk Test: $W = 0.98, p = .120$).

The verbal command data were log-transformed to a normal distribution (Shapiro-Wilk test $W = 0.98, p = .120$), with skewness $s = -0.37$ and kurtosis $k = 3.29$. The normal probability plots and histogram of the log-transformed data are shown in Figure 7.22. Conditions of sphericity were met for the log-transformed total number of verbal commands by the *Mission Specialist* ($\chi^2 = 2.48, p = .289$).

7.6.1.2 Effect of Condition on Number of Verbal Commands

Descriptive statistics are shown in Table 7.22 for the total number of commands given by the *Mission Specialist* for each condition. Friedman's test was used to test the effects of condition on total number of verbal commands given by the *Mission Specialist*. Results indicate there was no difference in the total number of verbal commands sent between conditions ($F(2, 70) = 0.79, p = .456$), and Hypothesis 3 was not supported.

Table 7.20: Descriptive Statistical Results for the Total Number of Verbal Commands Given for Each Condition. There Was No Difference in the Total Number of Verbal Commands Sent Between Conditions ($F(2, 70) = 0.79$, $p = .456$).

		Statistics			
Condition	N	M	SD	min	max
Egocentric	36	8.94	5.49	1.0	20
Exocentric	36	7.75	5.89	0.0	32
Mixed	36	9.00	5.94	1.0	27

7.6.1.3 Effect of Trial Number on Number of Verbal Commands

Descriptive statistics are shown in Table 7.21 for the total number of commands for each trial. Friedman's test was used to test the effects of trial on total number of verbal commands given by the *Mission Specialist*. Results indicate there was no difference in the total number of *Mission Specialist* verbal commands given between trials ($F(2, 70) = 2.00, p = .143$).

Table 7.21: Descriptive Statistical Results for the Total Number of Verbal Commands Given for Each Trial. There Was No Difference in the Total Number of *Mission Specialist* Verbal Commands Given Between Trials ($F(2, 70) = 2.00$, $p = .143$)

Trial	N	Statistics			
		M	SD	min	max
1	36	7.58	5.50	1.0	27
2	36	9.14	6.12	1.0	32
3	36	9.00	5.60	2.0	27

7.6.1.4 Effect of Task Type on Number of Verbal Commands

Descriptive statistics are shown in Table 7.22 for the total number of verbal commands given for all tasks and conditions; box and dot plots of these data are shown in Figure 7.23. A two-way, repeated measures ANOVA was used to test the effects of two independent variables (task type and condition) on the number of verbal commands. There was a main effect of task type ($F(2, 210) = 8.07, p < .001$), indicating differences in verbal commands between probing ($M = 2.24, SD = 1.19$), grasping ($M = 2.85, SD = 2.05$), and pushing ($M = 3.48, SD = 3.69$) tasks. There was an interaction between condition and task type ($F(4, 210) = 3.38, p = .010$). A *post hoc* analysis with Bonferroni adjustment was used to locate the differences. For the egocentric condition, the number of pushing task verbal commands was greater than the probing task ($p = .003$). There were no differences in verbal commands between tasks for the exocentric condition. For the mixed condition, the pushing task verbal commands were greater than the probing task ($p = .003$), and the number of commands given during the pushing task was greater than the grasping task ($p = .034$). These data indicate that the pushing task required more verbal commands and may have been more challenging, and Hypothesis 2 was partially supported with these data.

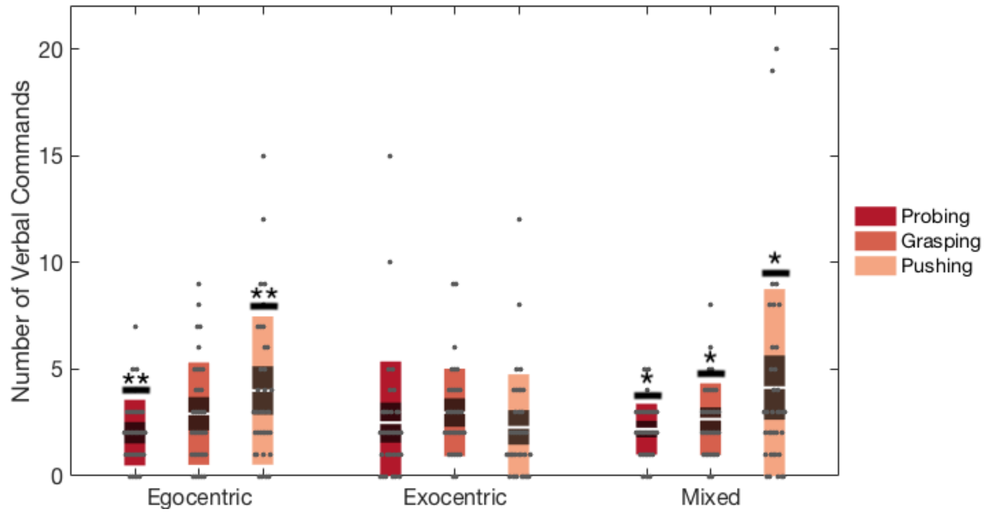


Figure 7.23: Box and Dot Plots of the Total Number of Verbal Commands Issues for Each Task and Condition. The Horizontal Bars Indicate That: **The Pushing Task Completion Time is Different From the Probing Task Completion Time for the Egocentric Condition at $p < .01$, and *The Pushing Task Completion Time Was Different From Both the Grasping and Probing Task Completion Times for the Mixed Condition at $p < .01$.

Table 7.22: Descriptive Statistical Results for the Total Number of Verbal Commands Given for Each Task, for All Conditions. There Was A Main Effect of Task Type ($F(2, 210) = 8.07, p < .001$), and an Interaction Between Condition and Task Type ($F(4, 210) = 3.38, p = .010$).

		Probe		Grasp		Push	
Condition	N	M	SD	M	SD	M	SD
Egocentric	36	2.03	1.54	2.91	2.39	4.00	3.47
Exocentric	36	2.50	2.86	2.97	2.05	2.31	2.46
Mixed	36	2.19	1.19	2.67	1.67	4.14	4.61

7.6.2 Verbal Command Rates

This section presents statistical results for the *Mission Specialist* verbal command rates. The verbal command rate was calculated for all trials and tasks as the total number of commands given by the *Mission Specialist* per minute.

7.6.2.1 Preliminary Analysis

Normal probability and histogram plots were used to visually assess the normality of the verbal command rate data, and the Shapiro-Wilk test, skewness and kurtosis parameters were used as quantitative measures of normality. The verbal command rate data (number of commands per minute) were positively skewed ($s = 1.10$, $k = 4.48$, Shapiro-Wilk $W = 0.92, p < .001$). Figure 7.24 contains normal probability plots and histogram of the verbal command rate data.

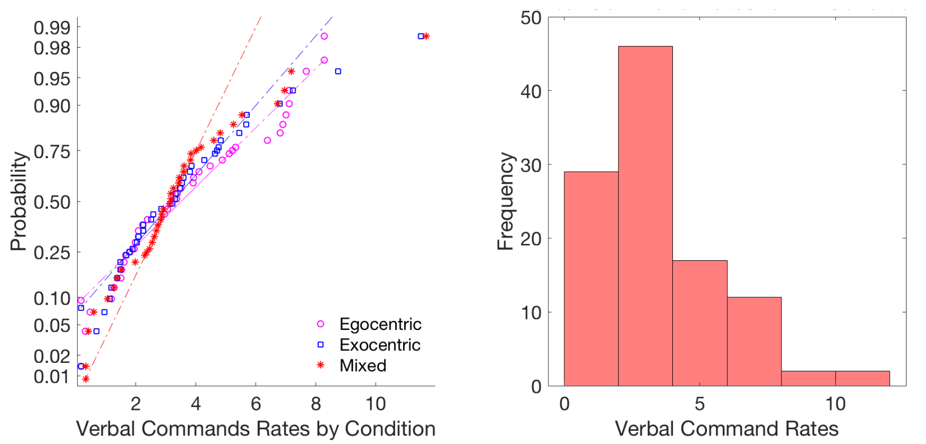


Figure 7.24: Normal Probability Plot (Left) and Histogram (Right) of the Positively Skewed Command Rate Data ($s = 1.10$, $k = 4.48$, Shapiro-Wilk Test: $W = 0.92, p < .001$).

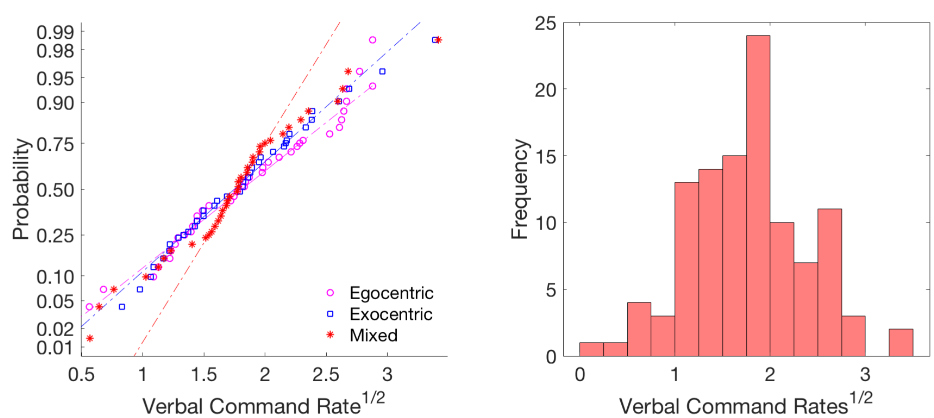


Figure 7.25: Normal Probability Plot (Left) and Histogram (Right) of the Normally Distributed Command Rate Data ($s = 0.038$, $k = 2.34$, Shapiro-Wilk Test: $W = 0.99, p = .600$).

The verbal command rate data were transformed using the square root function (the log transformation was too strong) to a normal distribution (Shapiro-Wilk test $W = 0.99, p = .600$), with skewness $s = 0.038$ and kurtosis $k = 2.34$. Conditions of sphericity were met for the square root transformed verbal command rate data ($\chi^2 = 2.96, p = .230$). The normal probability plots and histogram of the transformed verbal command rate data are shown in Figure 7.25.

7.6.2.2 Effect of Condition on Verbal Command Rate

Descriptive statistics are shown in Table 7.23 for the verbal command rates of the *Mission Specialists* for each condition, and Figure 7.26 contains box and dot plots of the verbal command rate data. A repeated measures ANOVA was used to test the effects of condition on *Mission Specialist* verbal command rate. Results indicate there was no difference in verbal command rate between conditions ($F(2, 70) = 0.081, p = .923$), and Hypothesis 3 was not supported.

Table 7.23: Descriptive Statistical Results for the Verbal Command Rate for Each Condition. There Was No Difference in Verbal Command Rate Between Conditions ($F(2, 70) = 0.081, p = .923$).

		Statistics			
Condition	N	M	SD	min	max
Egocentric	36	3.63	2.31	0.161	8.29
Exocentric	36	3.51	2.39	0.161	11.5
Mixed	36	3.44	2.21	0.321	11.7

7.6.2.3 Effect of Trial Number on Verbal Command Rate

Descriptive statistics are shown in Table 7.24 for the verbal command rates for each trial. A repeated measures ANOVA was used to test the effects of trial number on *Mission Specialist* verbal command rate. Results indicate there was an effect of trial order on verbal command rate ($F(2, 70) = 4.47, p = .015$). A *post hoc* comparison found that the verbal command rate for trial two was greater than trial one ($p = .049$), and the verbal command rate for trial three was marginally greater than trial one ($p = .076$).

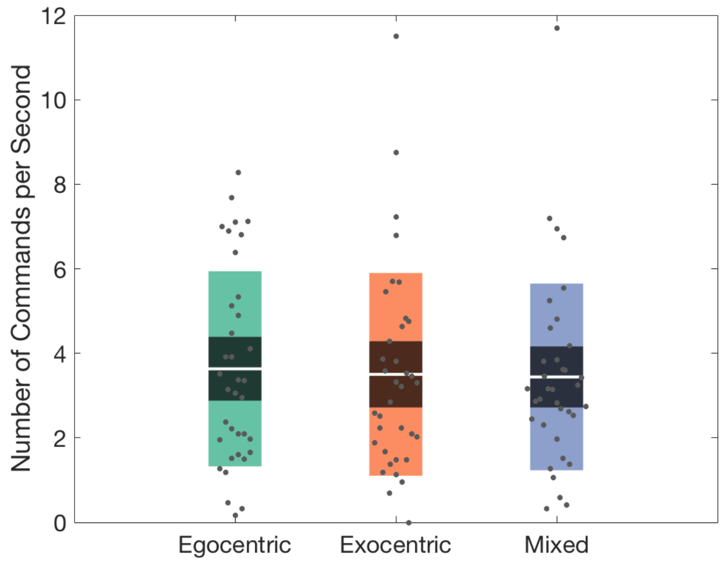


Figure 7.26: Box and Dot Plots of the Verbal Command Rate Data for Each Condition. The Average Verbal Command Rate (Commands Per Minute) for the Egocentric Condition Was $M = 3.63$, for the Exocentric Condition Was $M = 3.51$, and for the Mixed Condition Was $M = 3.44$. There Was No Difference in Verbal Command Rate Between Conditions ($F(2, 70) = 0.0782$, $p = .925$).

Table 7.24: Descriptive Statistical Results for the Verbal Command Rate for Each Trial. There Was an Effect of Trial Order On Verbal Command Rate ($F(2, 70) = 4.47, p = .015$).

		Statistics			
Trial	N	M	SD	min	max
1	36	2.91	1.08	0.319	7.19
2	36	3.91	2.59	0.161	11.5
3	36	3.80	2.28	0.415	11.7

7.6.2.4 Effect of Task and Condition on Verbal Command Rate

Descriptive statistics are shown in Table 7.25 for the verbal command rate data for each task and condition, and box and dot plots of these data are shown in Figure 7.27. A repeated measures ANOVA was used to test the effects of condition and task on verbal command rate. Results indicate there was a difference in verbal command rate for the tasks ($F(2, 210) = 6.24, p = .002$). There was no condition and task interaction ($F(4, 210) = 1.24, p = .292$). A *post hoc* multiple comparisons test found that the verbal command rate for the grasping task was larger than the pushing task for the exocentric condition ($p = .001$), and a trend that the exocentric probing command rate was smaller than the grasping rate ($p = .079$).

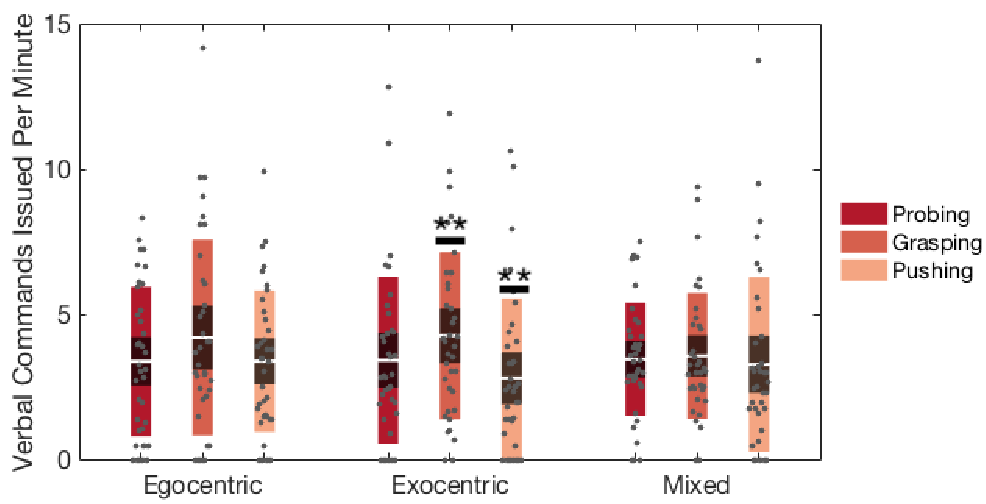


Figure 7.27: Box and Dot Plots of the Verbal Command Rates for Each Task and Condition. The Horizontal Bars Indicate That the **Pushing Verbal Command Rate Was Different From Grasping for the Exocentric Condition at $p < .005$.

Table 7.25: Descriptive Statistical Results for the Verbal Command Rate for Each Task, for All Conditions. There Was A Main Effect of Task Type ($F(2, 210) = 6.24, p = .002$), But There Was No Interaction Between Condition and Task Type ($F(4, 210) = 1.24, p = .292$).

		Probe		Grasp		Push	
Condition	N	*M*	*SD*	*M*	*SD*	*M*	*SD*
Egocentric	36	3.39	2.57	4.21	3.37	3.40	2.43
Exocentric	36	3.43	2.87	4.28	2.87	2.82	2.74
Mixed	36	3.47	1.94	3.58	2.16	3.30	3.00

7.7 Eye Movement Tracking for the Mixed Condition

This section presents the descriptive and inferential statistical results for the eye tracking data for the mixed condition only, which includes the following: i) the total duration (in seconds) that each participant spent viewing the egocentric and exocentric cameras, and ii) the total number of times participants switched between the two camera views. These data were collected separately for each task.

7.7.1 Total Duration Spent on Exocentric and Egocentric Views

This section presents descriptive and inferential statistical results for the total duration (in seconds) each participant spent on both the egocentric and exocentric views, which was calculated for each task during the mixed condition trial only.

7.7.1.1 Preliminary Analysis

Normal probability and histogram plots were used to visually assess the normality of the eye tracking data, and the Shapiro-Wilk test, skewness and kurtosis parameters were used as quantitative measures of normality. The duration of time spent on the egocentric ($s = 2.19$, $k = 9.27$, Shapiro-Wilk $W = 0.80, p < .001$) and exocentric ($s = 1.20$, $k = 4.19$, Shapiro-Wilk $W = 0.90, p < .001$) views were positively skewed, as can be seen from Figure 7.28. The log and Box Cox transformations were unable to transform all eye tracking data to normal distributions; therefore, nonparametric tests were used to analyze these data.

7.7.2 Difference in View Durations Between Egocentric and Exocentric Views

Descriptive statistics for the total time allocated to the egocentric and exocentric view during the mixed condition is shown in Table 7.26. The nonparametric Wilcoxon signed rank test was used to test if there was a difference in total time spent on the exocentric and egocentric views during the mixed trial. Results indicate that there was no difference between total time spent looking at the egocentric view compared to the exocentric view ($z = -1.08, p = .278$).

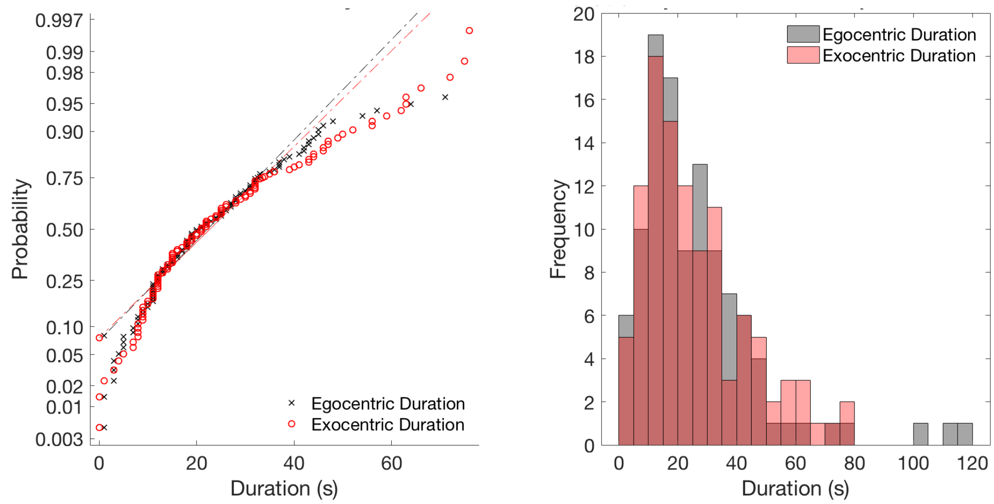


Figure 7.28: Normal Probability Plot (Left) and Histograms (Right) of the Duration Spent Viewing the Egocentric and Exocentric Views During the Mixed Condition (Egocentric: $s = 2.19$, $k = 9.27$, Shapiro-Wilk Test: $W = 0.80, p < .001$; Exocentric: $s = 1.20$, $k = 4.19$, Shapiro-Wilk Test: $W = 0.90, p < .001$).

7.7.3 Effect of Task Type on Egocentric and Exocentric View Durations

The nonparametric Friedman's test was used to test the effect of task type on the viewing duration of egocentric and exocentric views. Figure 7.29 contains box and dot plots of the total duration spent on the exocentric and egocentric views for all tasks. Results indicate that the task type affects the total time spent viewing the egocentric view ($\chi^2(2, N = 108) = 9.83, p = .007$), but task type did not have an effect on time spent viewing the exocentric view ($\chi^2(2, N = 108) = 0.290, p = .863$). A *post hoc* multiple comparisons test with Bonferroni adjustment indicate that the total amount of time spent on the egocentric view was less during the probing task compared to the grasping task ($p = .006$); the amount of time spent viewing the egocentric camera during the pushing task was not different from any other task.

Table 7.26: Descriptive Statistical Results for the Total Duration in Seconds Spent on Each Camera View for Tasks During the Mixed Condition. There Was No Difference in Total Time Spent Looking at the Egocentric View and the Exocentric View ($z = -1.08, p = .278$). The Amount of Time Spent on the Egocentric View During the Probing Task Was Less Than the Grasping Task ($p = .006$).

		Probe		Grasp		Push		Total	
View	N	M	SD	M	SD	M	SD	M	SD
Egocentric	36	19.4	13.3	30.9	21.2	27.2	25.3	77.5,	40.5
Exocentric	36	25.9	18.8	31.8	24.8	31.9	22.4	89.6	47.6

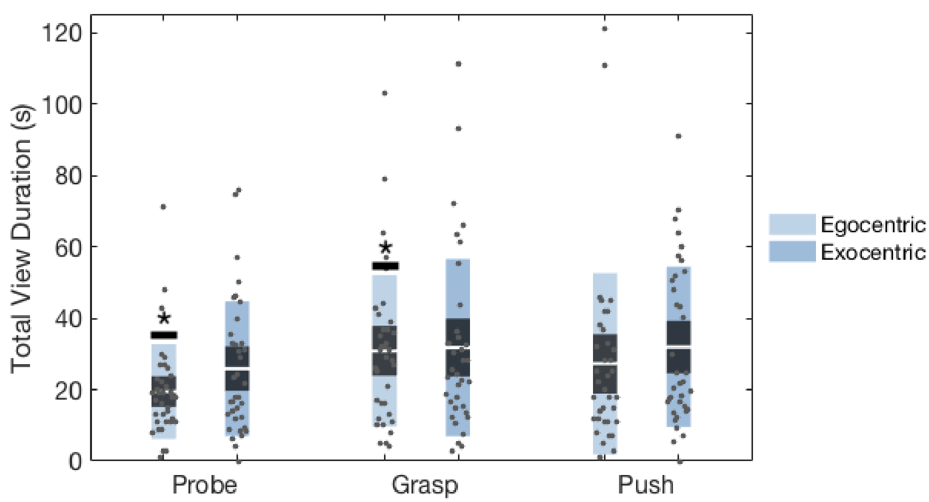


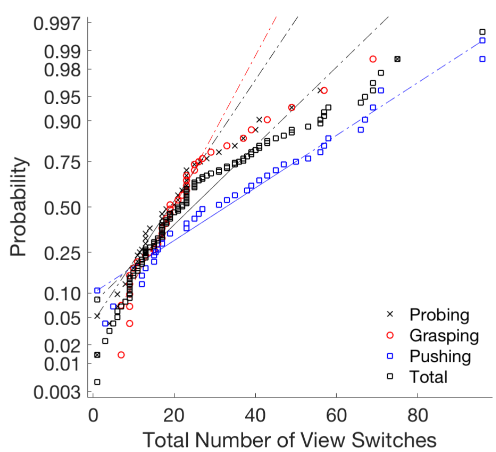
Figure 7.29: Box and Dot Plots of the Total Duration Spent on the Exocentric and Egocentric View for All Tasks. The Horizontal Bars Indicate That the *Egocentric Probing View Duration Was Less Than the Grasping View Duration at $p < .01$.

7.7.4 Switching Frequency Between Views

The total number of times each participant switched focus between the exocentric and egocentric views was measured for each task during the mixed condition.

7.7.4.1 Preliminary Analysis

The switching frequency data between the egocentric and exocentric views were positively skewed ($s = 1.27$, $k = 4.37$, Shapiro-Wilk $W = 0.89, p < .001$), as seen in Figure 7.30. The log and Box Cox transformations were unable to transform the switching frequency data to normal distributions; therefore, nonparametric tests were used to analyze these data.



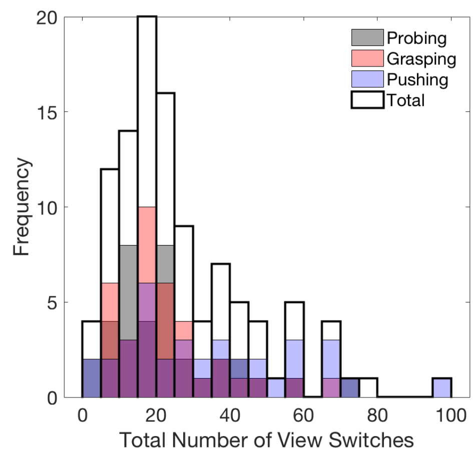


Figure 7.30: Normal Probability Plot (Left) and Histogram (Right) of the Positively Skewed View Switching Data for Each Task During the Mixed Condition ($s = 1.27$, $k = 4.37$, Shapiro-Wilk Test: $W = 0.89, p < .001$).

7.7.4.2 Effect of Task Type on View Switching

Descriptive statistics for the number of eye tracking switches between views is shown in Table 7.27, and box and dot plots of the data are shown in Figure 7.31. The nonparametric Friedman's test was used to test the effect of task type on the number of times participants switched between the egocentric and exocentric views. Results indicate that the task type affected the total number of view switches ($\chi^2(2, N = 36) = 11.7, p = .003$). A *post hoc* multiple comparisons test with Bonferroni adjustment showed that the total number of view switches was greater during the pushing task compared to both the grasping task ($p = .034$) and the probing task ($p = .004$). Descriptive statistics for the eye tracking switch rate, or the number of view switches per second, is shown in Table 7.28, and Figure 7.32 contains box and dot plots of the view switch rate data. The task type affected the view switching rate ($\chi^2(2, N = 36) = 9.55, p = .008$). A *post hoc* multiple comparisons test showed that the view switching rate was smaller for the pushing task compared to the probing task ($p = .007$).

Table 7.27: Descriptive Statistical Results for the Number of Eye Tracking Switches Between Views During the Mixed Condition for All Tasks. The Total Number of View Switches Was Greater During the Pushing Task Compared to Both the Grasping Task ($p = .034$) and Probing Task ($p = .004$).

		Statistics			
View	N	M	SD	min	max
Probe	36	22.0	15.5	1	75
Grasp	36	23.0	14.1	7	69
Push	36	34.0	22.8	1	96

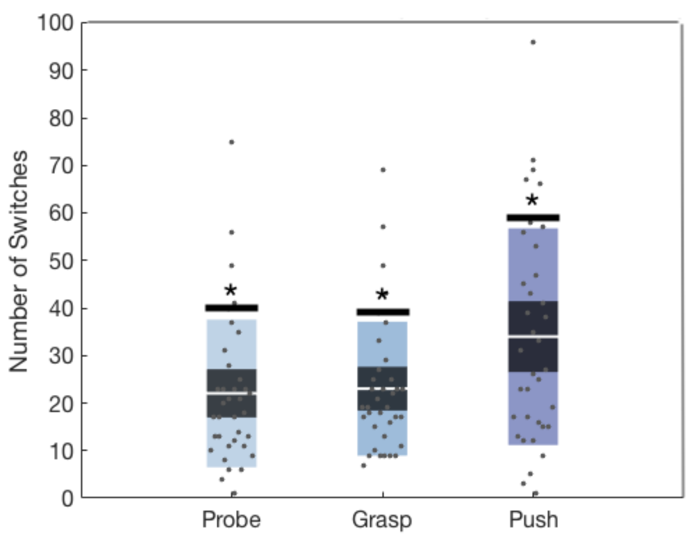


Figure 7.31: Box and Dot Plots of the Total Number of View Switches for Each Task. The Horizontal Bars Indicate That the Total Number of View Switches for *Pushing Task Was Different From Both the Probing $p < .05$ and Grasping $p < .005$ Tasks.

Table 7.28: Descriptive Statistical Results for the Eye Tracking Switch Rate Between Views During the Mixed Condition for All Tasks. The Switching Rate Was Smaller for the Pushing Task Compared to the Probing Task ($p = .007$).

		Statistics			
View	N	M	SD	min	max
Probe	36	0.532	0.240	0.039	1.03
Grasp	36	0.482	0.193	0.151	1.01
Push	36	0.452	0.210	0.014	0.891

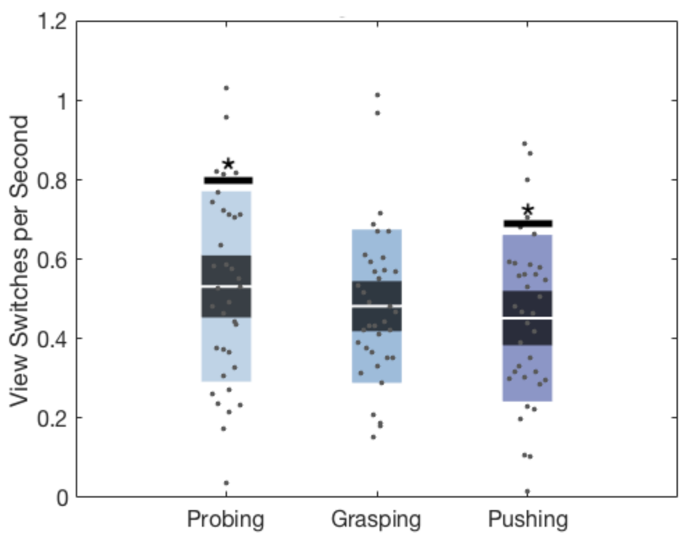


Figure 7.32: Box and Dot Plots of the View Switching Rate Data for Each Task During the Mixed Condition. The View Switching Rate for Pushing Task ($M = 0.452$) Different From Probing Task ($M = 0.532$) at $p < .01$.

7.8 Post-Assessment Results

This section presents results from the post-assessments administered to participants after each trial. The questions assessed participant's confidence and comfort in using the manipulator, verbally directing the *Pilot*, and completing the tasks. The assessment also included questions regarding task difficulty.

7.8.1 Confidence and Comfort

Descriptive statistics for the post-assessment questionnaire responses are shown in Tables 7.29 and 7.30. The nonparametric Friedman's test was used to assess the effect of condition on questionnaire responses for each individual question, and a multiple comparisons test with Bonferroni adjustment was used to locate the differences. Results indicate a trend in differences in confidence when using the manipulator between conditions ($\chi^2(2, 70) = 5.81, p = .055$). There is a trend that participants were more confident controlling the manipulator in the mixed condition compared to the egocentric condition ($p = .052$). Additionally, there was a difference in participant's opinion if the amount of information presented in the interface was adequate ($\chi^2(2, 70) = 8.00, p = .018$); participants thought the information presented in the mixed interface was more adequate than the exocentric ($p = .043$) and egocentric ($p = .043$) interfaces.

Trial number generally had greater effects on participant responses (see Table7.30). Results indicate that participants were more confident in controlling the manipulator during trial three compared to both trials one ($p < .001$) and two ($p = .020$). Participants were more comfortable in controlling the manipulator in both trials three ($p = .002$) and two ($p = .021$) compared to trial one. Participants were also more confident ($p = .004$) and comfortable ($p =< .001$) in their ability to instruct the *Pilot* during trial three compared to trial one. Confidence in participants ability to perform the grasping task also increased in trial three compared to trial one ($p = .021$).

Table 7.29: Descriptive Statistical Results for the Post Assessment Responses (1 to 5 Likert Scale, with 1=Low and 5=High) Related to Confidence and Comfort for Each Condition.

	Ego		Exo		Mix	
	M	SD	M	SD	M	SD
Confidence in controlling the manipulator	3.6	1.3	4.0	.93	4.2	.83
Comfort in controlling the manipulator	3.7	1.3	4.0	.90	4.1	.78
Confidence in ability to perform probing task	4.0	1.0	4.1	1.2	4.4	.86
Comfort in ability to perform probing task	4.9	1.1	4.1	.91	4.3	.80
Confidence in ability to instruct the *Pilot*	4.3	1.0	4.2	.94	4.3	.85
Comfort in ability to instruct the *Pilot*	4.4	1.0	4.1	1.1	4.2	.91
Confidence in ability to perform pushing task	3.7	1.2	3.9	1.0	3.9	1.1
Comfort in ability to perform pushing task	3.5	1.4	3.9	1.2	3.9	1.0
Confidence in ability to perform grasping task	4.1	1.2	4.3	.91	4.4	.55
Comfort in ability to perform grasping task	3.9	1.3	4.2	.99	4.4	.59

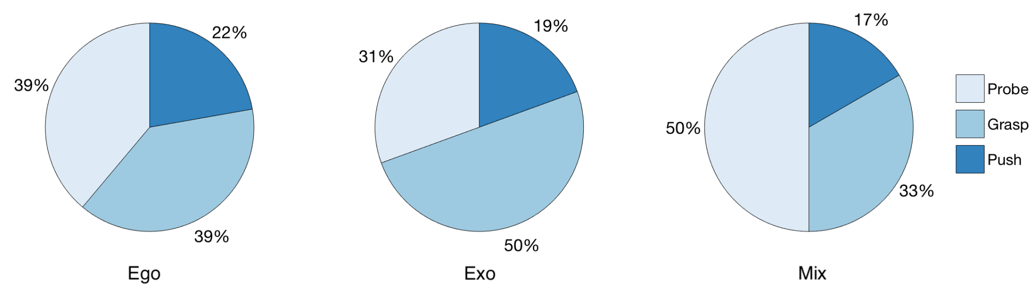
Table 7.30: Descriptive Statistical Results for the Post Assessment Responses (1 to 5 Likert Scale, with 1=Low and 5=High) Related to Confidence and Comfort for All Trials.

	Trial 1		Trial 2		Trial 3			
	M	SD	M	SD	M	SD	χ^2	p
Confidence in controlling the manipulator	3.5	1.2	3.9	1.1	4.4	.77	19.1	<.001
Comfort in controlling the manipulator	3.7	1.0	3.8	1.1	4.3	.81	12.7	.002
Confidence in performing the probing task	4.0	1.0	4.0	1.2	4.4	.72		
Comfort in performing probing task	4.0	1.1	4.0	1.1	4.2	.72		
Confidence in ability to instruct the *Pilot*	4.0	.96	4.2	1.0	4.6	.69	10.7	.005
Comfort in ability to instruct the *Pilot*	3.8	.99	4.3	1.0	4.5	.94	13.2	.001
Confidence in performing pushing task	3.7	1.0	3.9	1.2	3.9	.89		
Comfort in performing pushing task	3.6	1.2	3.7	1.2	3.9	1.1		
Confidence in performing grasping task	4.1	.90	4.1	1.2	4.5	.61	7.66	.02
Comfort in performing grasping task	4.1	.98	3.9	1.2	4.4	.77		

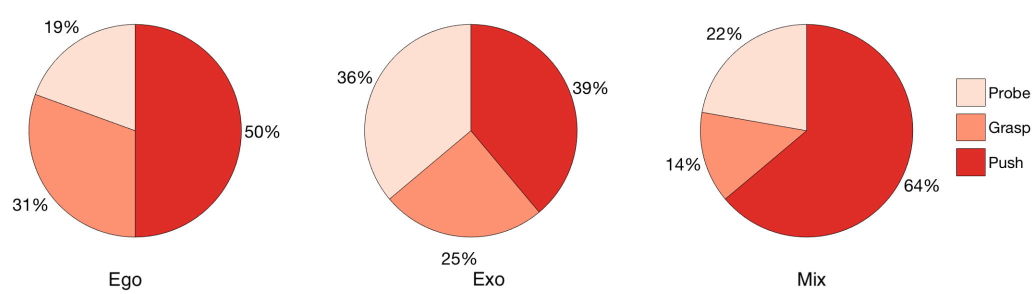
$\chi^2(2, 108), p$ values reported for significant results only.

7.8.2 Task Preferences

This section presents results from the post assessment responses to questions related to the easiest and most difficult tasks to complete for each condition. A large percentage of participants thought the grasping task was the easiest task to complete for the egocentric (39%) and exocentric (50%) conditions, and the probing task was easiest to complete for the egocentric (39%) and mixed (50%) conditions. A majority of participants found the pushing task to be the most difficult for the egocentric (50%) and exocentric (39%), and mixed conditions (64%). Hypothesis 3 was partially supported with these post-assessment response data.



(a)



(b)

Figure 7.33: Post-Assessment Responses Regarding What Participants Thought the (a) Easiest and (b) Hardest Tasks to Complete Were. A Large Percentage of Participants Thought the Grasping Task Was the Easiest to Complete for the Egocentric (39%) and Exocentric (50%) Conditions. A Majority of Participants Found the Pushing Task to be the Most Difficult for the Egocentric (50%), Exocentric (39%), and Mixed Conditions (64%).

7.9 Interface Preferences

This section presents results for participant preferences for interface condition. At the completion of each experiment, participants were asked which interface they preferred, and the reasons for selecting their preference.

7.9.1 Summary of Participant Preferences

Of the 36 total participants, $n = 2$ preferred the egocentric condition, $n = 9$ preferred the exocentric interface condition, and $n = 25$ preferred the mixed condition. Primary reasons for preference selection are shown in Table 7.31.

Table 7.31: Summary of Participant Reasons for Choosing A Preferred Interface*. The Primary Reason for Preferring the Exocentric Condition Was Feeling Distracted When Using the Mixed Interface, and the Primary Reason for Preferring the Mixed Condition Was Improved Depth Perception.

Preference	Reasons for Choosing	n
Egocentric	Better depth perception and location determination	2
Exocentric	Thought the mixed condition was distracting	8
	Preferred to see the entire arm only	2
Mixed	Improved depth perception	10
	Improved situation awareness	5
	Could use exocentric for some tasks, and egocentric for others	5
	Used egocentric for alignment and exocentric to control arm	3
	Enjoyed having the option to choose	2
	Better enabled the use of both manipulator joints	1

* Note: some participants gave more than one reason for identifying their preference, and all reasons mentioned by participants are included in this table.

7.9.2 Performance of Participants Related to Interface Preference

This section presents statistical results of performance for participants based on interface preference. Only the exocentric and mixed conditions were included because the sample size of participants who preferred the egocentric condition ($n = 2$) was underpowered for conducting statistical analyses.

7.9.2.1 Task Performance of Participants with Exocentric Preference

This section includes statistical results of performance for participants who preferred the exocentric condition only. A paired, single-tail *t-test* was conducted to compare total task performance time for the exocentric (preferred) condition to the mixed condition. For participants who preferred the exocentric condition, the total task completion time for the exocentric condition ($M = 129, SD = 61.0$) was faster than the total task completion time for the mixed condition ($M = 204, SD = 46.8$); $t(8) = -5.57, p < .001$. Figure 7.34 contains box plots and dot plots of the task completion time data for participants who preferred the exocentric condition.

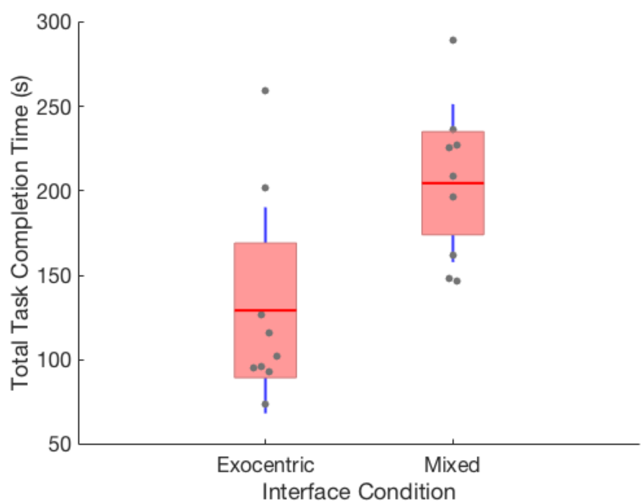


Figure 7.34: Box and Dot Plots of the Total Task Completion Times During the Exocentric and Mixed Conditions for Participants who Preferred the Exocentric Condition. Participants Who Preferred the Exocentric Condition Completed All Tasks More Than 50% Faster When Using the Exocentric Interface ($M = 129$ s) Compared to the Mixed Interface ($M = 204$ s) ($p < .001$). The Vertical Blue Lines Represent 1 SD, and the Pink Shaded Area Represents the SEM.

7.9.2.2 Task Performance of Participants with Mixed Preference

This section includes statistical results of performance for participants who preferred the mixed condition only. A paired, single-tail *t-test* was conducted to compare total task performance time for the mixed (preferred) condition to the exocentric condition. There was no difference between the total task completion time for the exocentric condition ($M = 154, SD = 61.0$) and the mixed condition ($M = 152, SD = 46.8$); $t(24) = 0.059, p = .316$. Figure 7.35 contains box plots and dot plots of the task completion time data for participants who preferred the mixed condition.

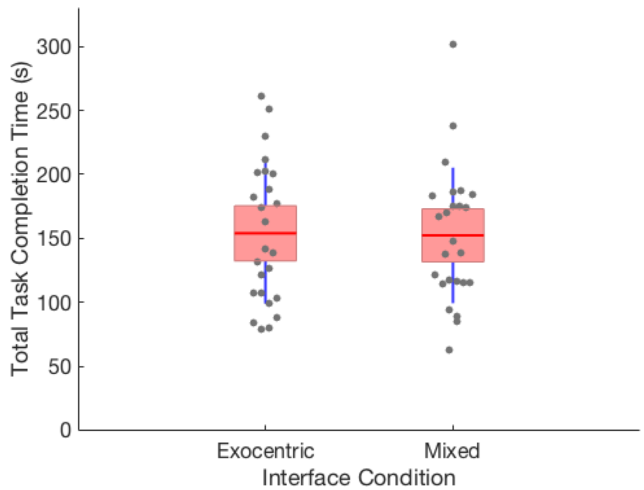


Figure 7.35: Box and Dot Plots of the Total Task Completion Times During the Exocentric and Mixed Conditions for Participants who Preferred the Mixed Interface. There Was No Difference in Performance Between the Exocentric ($M = 154$ s) and Mixed ($M = 152$ s) Conditions ($p = .316$).

7.9.3 Eye Tracking Analysis: Exocentric and Mixed Preferences

This section presents statistical results for the eye tracking data, including the total duration spent viewing the exocentric camera, the percentage of time spent viewing the exocentric camera, and the switching rate between the two views, based on participant preferences. Data included in this section are from the mixed condition only.

7.9.3.1 Proportion of Time Spent Viewing the Exocentric Condition

The Wilcoxon rank sum test was used to compare percentages of time spent viewing the exocentric camera for participants who preferred the exocentric condition to participants who preferred the mixed condition. There was no difference in percentage of time spent viewing the exocentric view between participants who preferred the exocentric condition ($M = 0.553, SD = 0.232, N = 9$) and participants who preferred the mixed condition ($M = 0.536, SD = 0.194, N = 25$), $Z = 0.390, p = .696$.

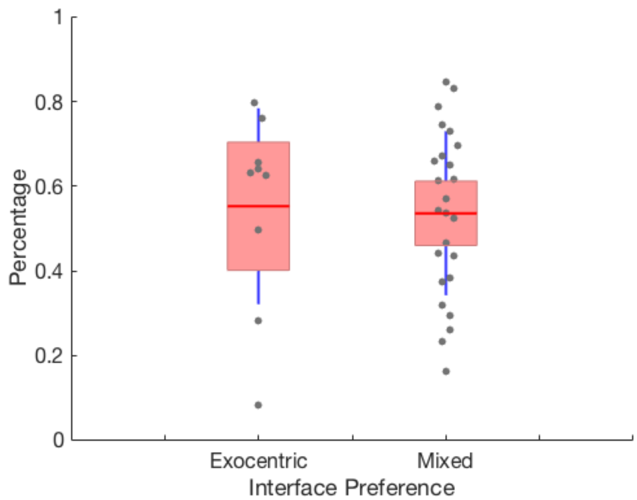


Figure 7.36: Box and Dot Plots for Percentage of Time Participants Spent Viewing the Exocentric Conditions, Categorized by Interface Preferences. There Was No Difference in Percentage of Time Spent Viewing the Exocentric View Between Participants Who Preferred the Exocentric Condition ($M = 0.553$) and Participants Who Preferred the Mixed Condition ($M = 0.536$), $p = .696$.

7.9.3.2 Switching Rate Between Views

The Wilcoxon rank sum text was used to compare the switching rate (number of view switches per second) between participants who preferred the exocentric condition to switching rates of participants who preferred the mixed condition. There was no difference in view switching rate between participants who preferred the exocentric condition ($M = 0.464, SD = 0.209, N = 9$) and participants who preferred the mixed condition ($M = 0.475, SD = 0.187, N = 25$), $Z = 0.0781, p = .938$.

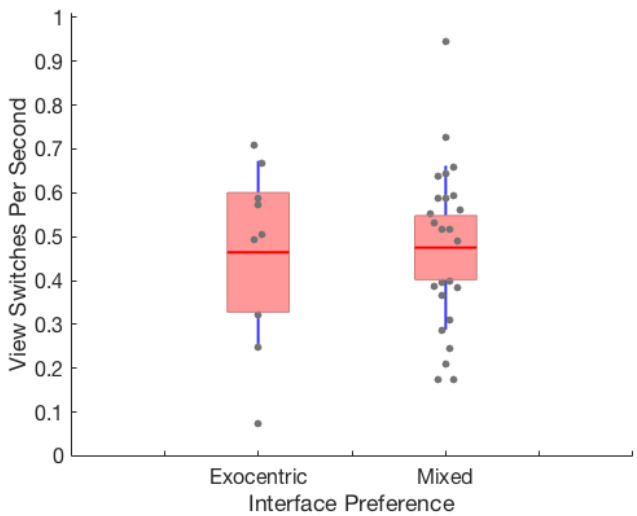


Figure 7.37: Number of View Switches Per Second for Participants who Preferred Either the Exocentric of Mixed Condition. There Was No Difference in Switching Rate Between Views Between Participants Who Preferred the Exocentric Condition ($M = 0.464$) and Participants Who Preferred the Mixed Condition ($M = 0.475$), $p = .938$.

7.10 Correlation Analysis

This section presents results from correlation analyses on experimental data, including task performance metric, manipulator performance, verbal commands, eye tracking data, personality, and post-assessment responses. The first section presents results from correlation analyses conducted on data aggregated at the trial level for each condition. The second section presents results from correlation analyses conducted on data collected at the task level for each condition. All correlation analyses used data from the entire participant pool ($N = 36$).

7.10.1 Trial-Based Data

Figures 7.39-7.41 contain correlation tables for data aggregated at the trial level for all conditions, and Figure 7.38 contains the legend for the correlation tables. The Spearman correlation coefficient was used for all analyses for comparison of ordinal/ordinal and ordinal/scale data. Results indicate a positive correlation between task time and the number of manipulator commands ($r_{ego} =$

$.578, r_{exo} = .686, r_{mix} = .575$, all $p < .001$) and number of manipulator reversals ($r_{ego} = .629, r_{exo} = .664, r_{mix} = .534$, all $p < .001$). There was also a negative correlation between verbal command rate (number of commands per minute) and both the number of manipulator commands ($r_{ego} = -.570, p = .001, r_{exo} = -.444, p = .010, r_{mix} = -.407, p = .019$) and the number of manipulator reversals ($r_{ego} = -.571, p = .001, r_{exo} = -.378, p = .030, r_{mix} = -.349, p = .047$).

Total task completion time was negatively correlated with both confidence ($r_{ego} = -.641, p =< .001, r_{exo} = -.542, p = .001, r_{mix} = -.403, p = .02$) and comfort ($r_{ego} = -.511, p = .002, r_{exo} = -.448, p = .009, r_{mix} = -.549, p = .001$) in participant's ability to control the manipulator (post response questions one and two). There was a positive correlation between the verbal command rate and confidence ($r_{ego} = .453, p = .008, r_{exo} = .542, p = .001$) and comfort ($r_{ego} = .418, p = .015, r_{exo} = .424, p = .014$) for the egocentric and exocentric conditions only. Additionally, there was a positive correlation between confidence and comfort responses for all trials ($r_{ego} = .823, r_{exo} = .823$, both $p = .009, r_{mix} = .688, p < .001$).

Overall, there were no correlations between personality traits and direct measures of task performance for the trial-based data. Locus of control scale was not correlated with any measure of performance for any condition. Domineering was correlated with total task time for the mixed condition only ($r_{mix} = -.388, p = .026$). Submissiveness scales were not correlated with any measures of performance for any trials. Hypothesis 2, which states that personality will positively influence performance if they are domineering or have an internal locus of control, and negatively affect performance if they are submissive or have an external locus of control, is not supported by these data.

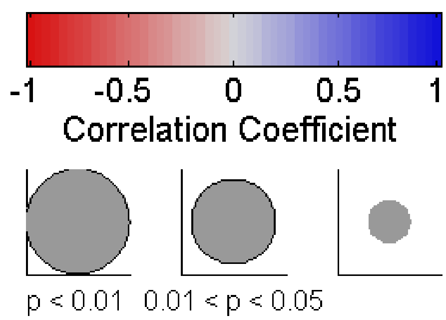


Figure 7.38: Legend To Aid In Viewing the Correlation Tables in Figures 7.39-7.50. The Size of the Circle Is Determined By the P-Value, and the Color of the Circle is Determined By the Correlation Coefficient Value $\rho_s \in [-1, 1]$.

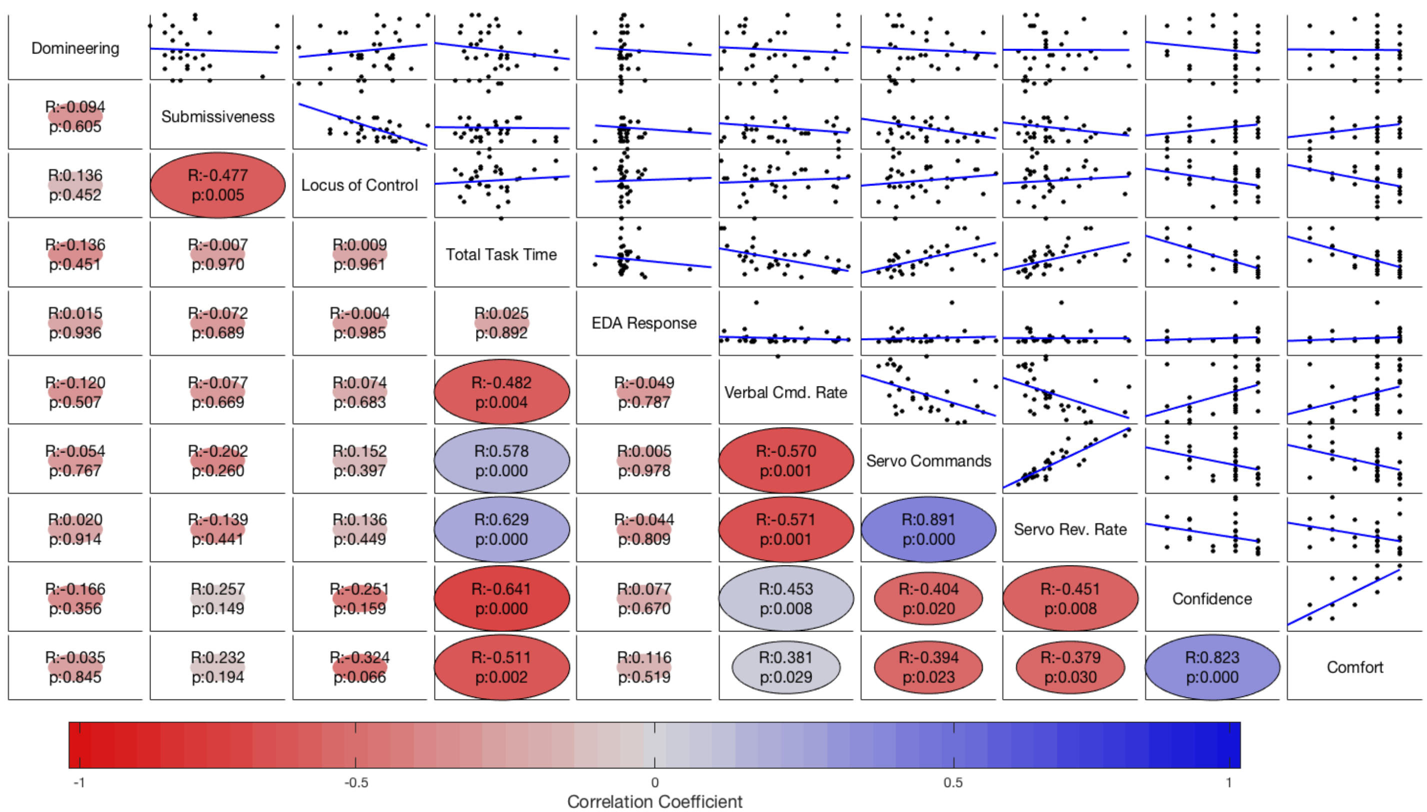


Figure 7.39: Correlation Table for Personality and Performance Data Collected During the Egocentric Trials. The Lower Triangle Includes the Color-Coded Correlation Coefficients ρ_s and Corresponding P-Values, and the Size of the Circle Represents the Significance Level (see Figure 7.38). The Upper Triangle Includes Scatter Plots With A Least Squares Linear Regression Line.

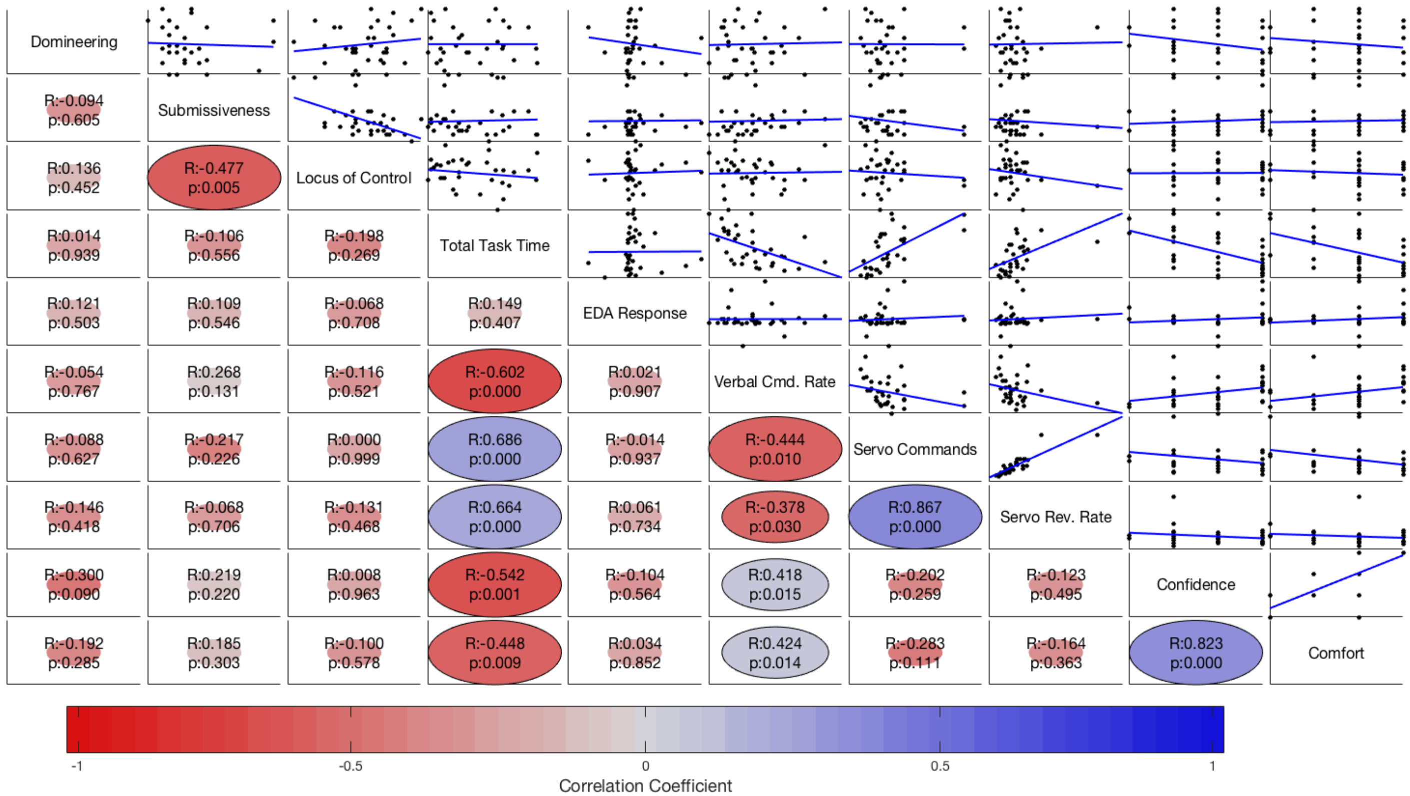


Figure 7.40: Correlation Table for Personality and Performance Data Collected During the Exocentric Trials. The Lower Triangle Includes the Color-Coded Correlation Coefficients ρ_s and Corresponding P-Values, and the Size of the Circle Represents the Significance Level (see Figure 7.38). The Upper Triangle Includes Scatter Plots With A Least Squares Linear Regression Line.

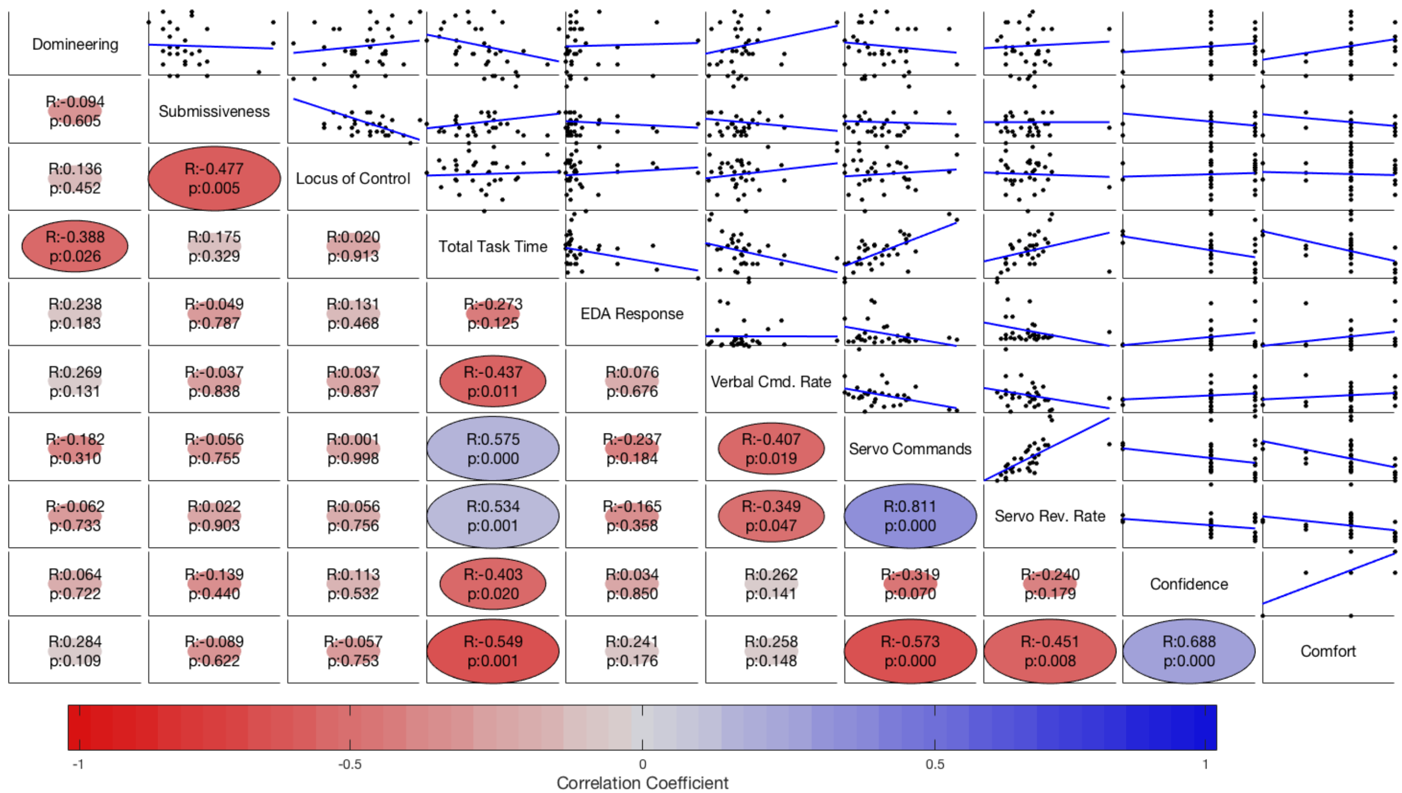


Figure 7.41: Correlation Table for Personality and Performance Data Collected During the Mixed Trials. The Lower Triangle Includes the Color-Coded Correlation Coefficients ρ_s and Corresponding P-Values, and the Size of the Circle Represents the Significance Level (see Figure 7.38). The Upper Triangle Includes Scatter Plots With A Least Squares Linear Regression Line.

7.10.2 Task-Based Data

Figures 7.42-7.50 contain correlation tables for data collected at the task level for all conditions. For the egocentric condition, task time was positively correlated with the time it took for participants to issue the first verbal command for the probing ($r_{ego} = .625, p < .001$) and grasping tasks ($r_{ego} = .479, p < .005$). Confidence and comfort in participant's ability to perform individual tasks were positively correlated for the probing ($r_{ego} = .712, p < .001$), grasping ($r_{ego} = .692, p < .001$), and pushing tasks ($r_{ego} = .665, p < .001$). For the exocentric condition, confidence and comfort in participant's ability to perform individual tasks were positively correlated for the probing ($r_{exo} = .727, p < .001$), grasping ($r_{exo} = .886, p < .001$), and pushing tasks ($r_{exo} = .780, p < .001$).

For the mixed condition, the task completion time was positively correlated with view switching frequency between cameras for the probing ($r_{mix} = .629, p < .001$), grasping ($r_{mix} = .538, p = .001$), and pushing tasks ($r_{mix} = .723, p < .001$). Task completion time was also positively correlated with duration spent viewing the exocentric camera for the probing ($r_{mix} = .656, p < .001$), grasping ($r_{mix} = .349, p = .047$), and pushing tasks ($r_{mix} = .499, p = .003$). Task completion time was negatively correlated with comfort levels in completing the probing ($r_{mix} = -.539, p = .001$) and pushing tasks ($r_{mix} = -.546, p = .001$). Additionally, confidence and comfort in participant's ability to perform individual tasks were positively correlated for the probing ($r_{mix} = .592, p < .001$), grasping ($r_{mix} = .355, p = .042$), and pushing tasks ($r_{mix} = .382, p = .028$).

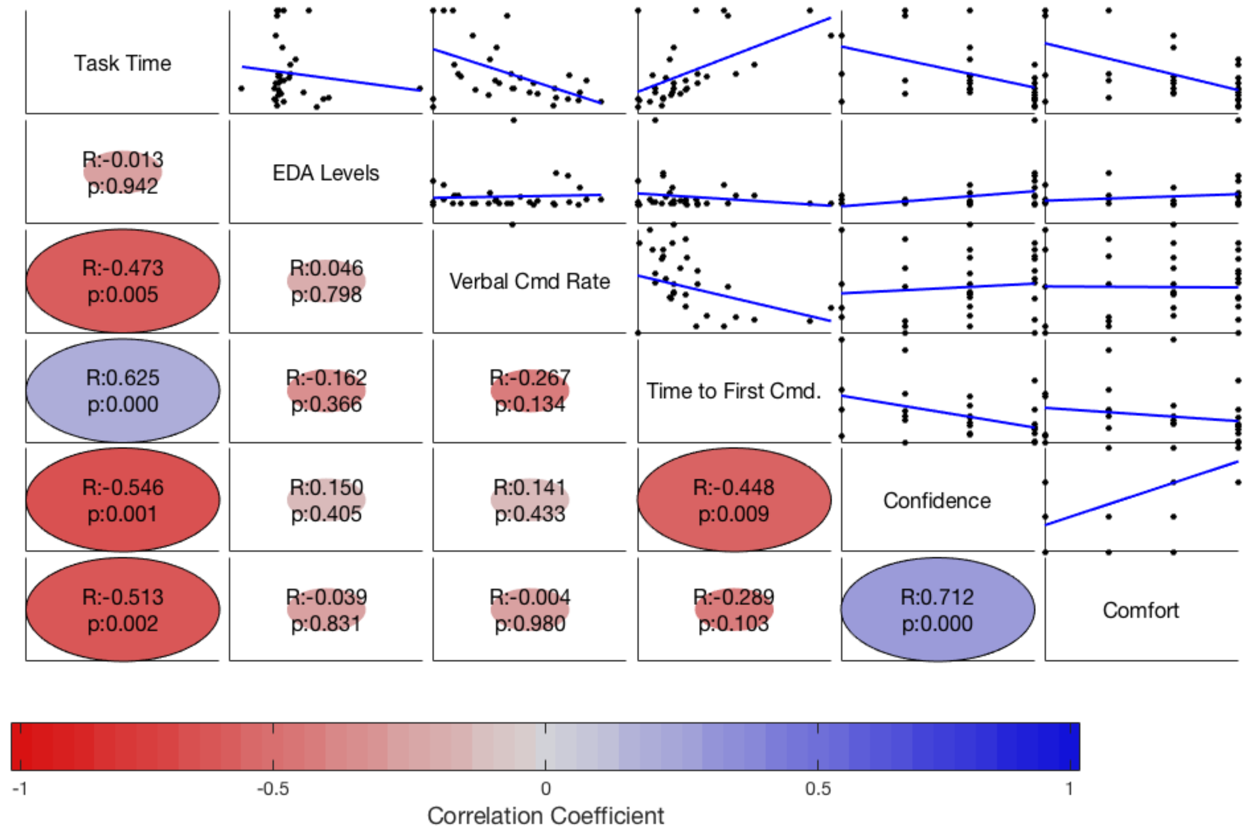


Figure 7.42: Correlation Table for Personality and Performance Data Collected for the Probing Task During the Egocentric Trials. The Lower Triangle Includes the Color-Coded Correlation Coefficients ρ_s and Corresponding P-Values, and the Size of the Circle Represents the Significance Level (see Figure 7.38). The Upper Triangle Includes Scatter Plots With A Least Squares Linear Regression Line.

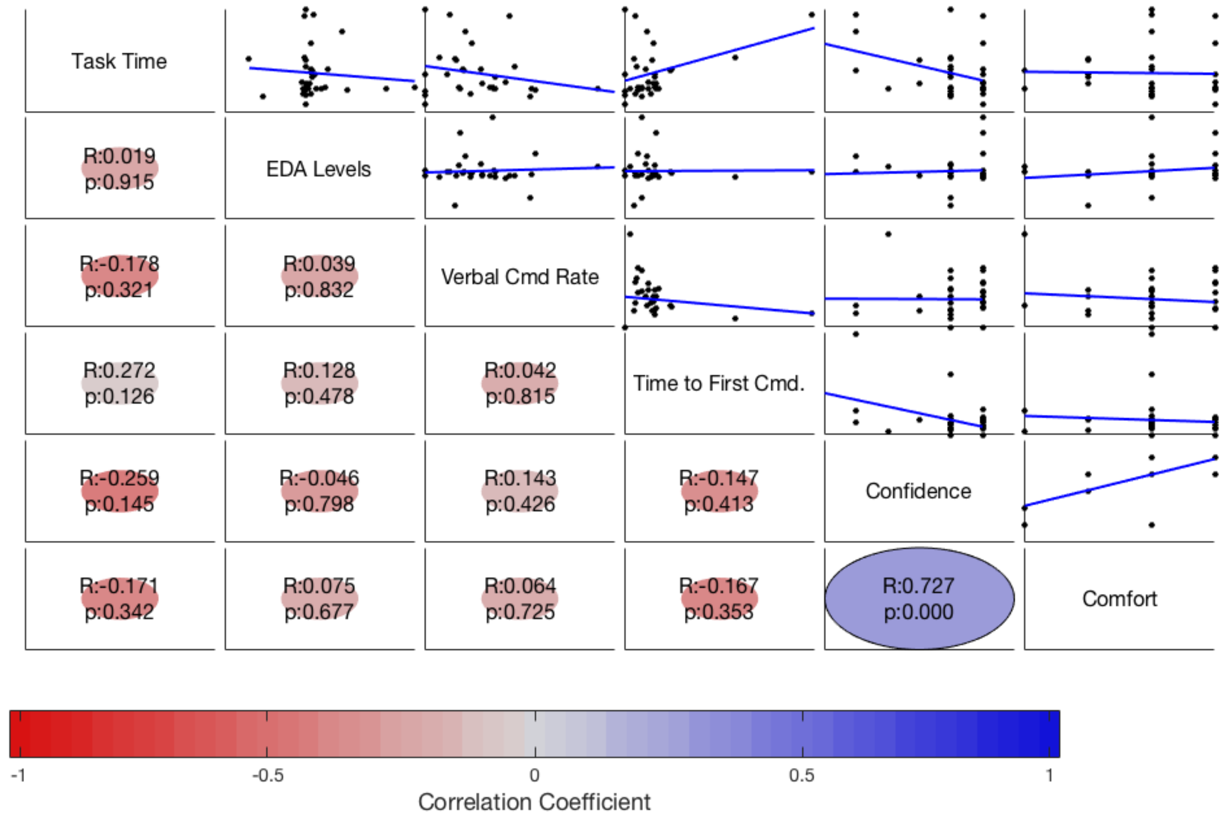


Figure 7.43: Correlation Table for Personality and Performance Data Collected for the Probing Task During the Exocentric Trials. The Lower Triangle Includes the Color-Coded Correlation Coefficients ρ_s and Corresponding P-Values, and the Size of the Circle Represents the Significance Level (see Figure 7.38). The Upper Triangle Includes Scatter Plots With A Least Squares Linear Regression Line.

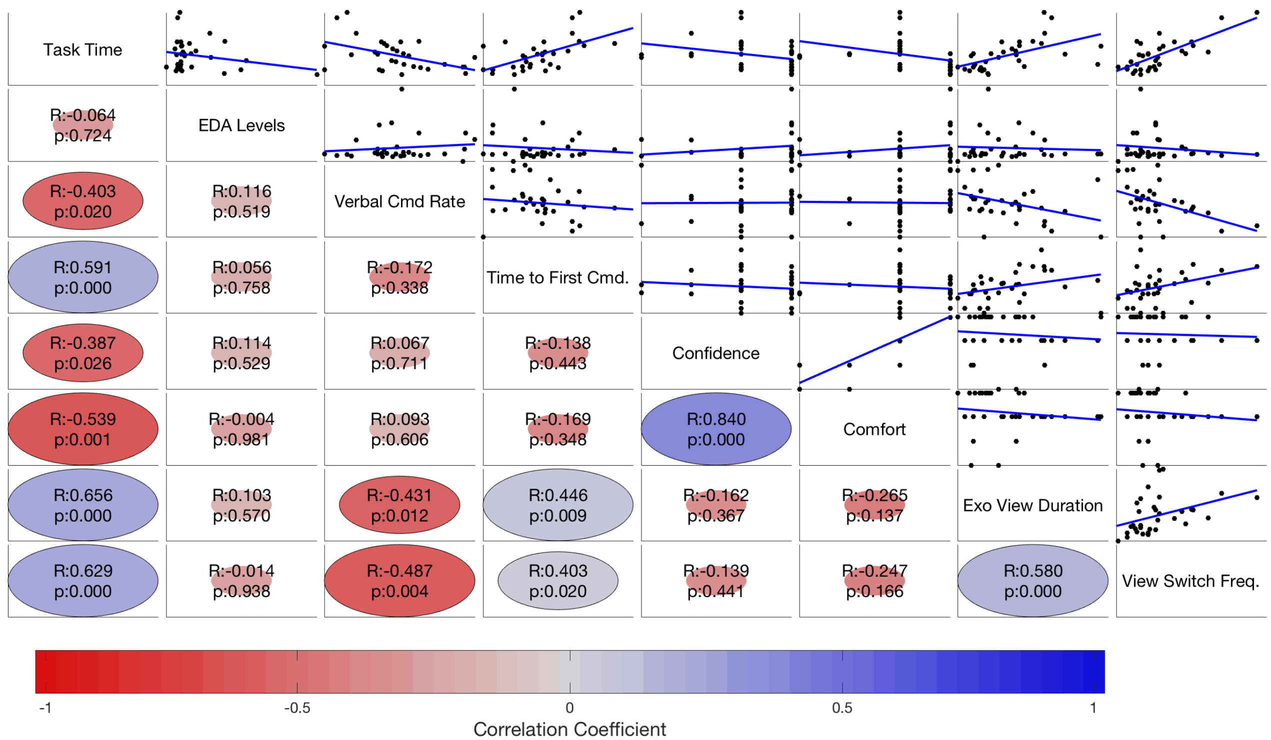


Figure 7.44: Correlation Table for Personality and Performance Data Collected for the Probing Task During the Mixed Trials. The Lower Triangle Includes the Color-Coded Correlation Coefficients ρ_s and Corresponding P-Values, and the Size of the Circle Represents the Significance Level (see Figure 7.38). The Upper Triangle Includes Scatter Plots With A Least Squares Linear Regression Line.

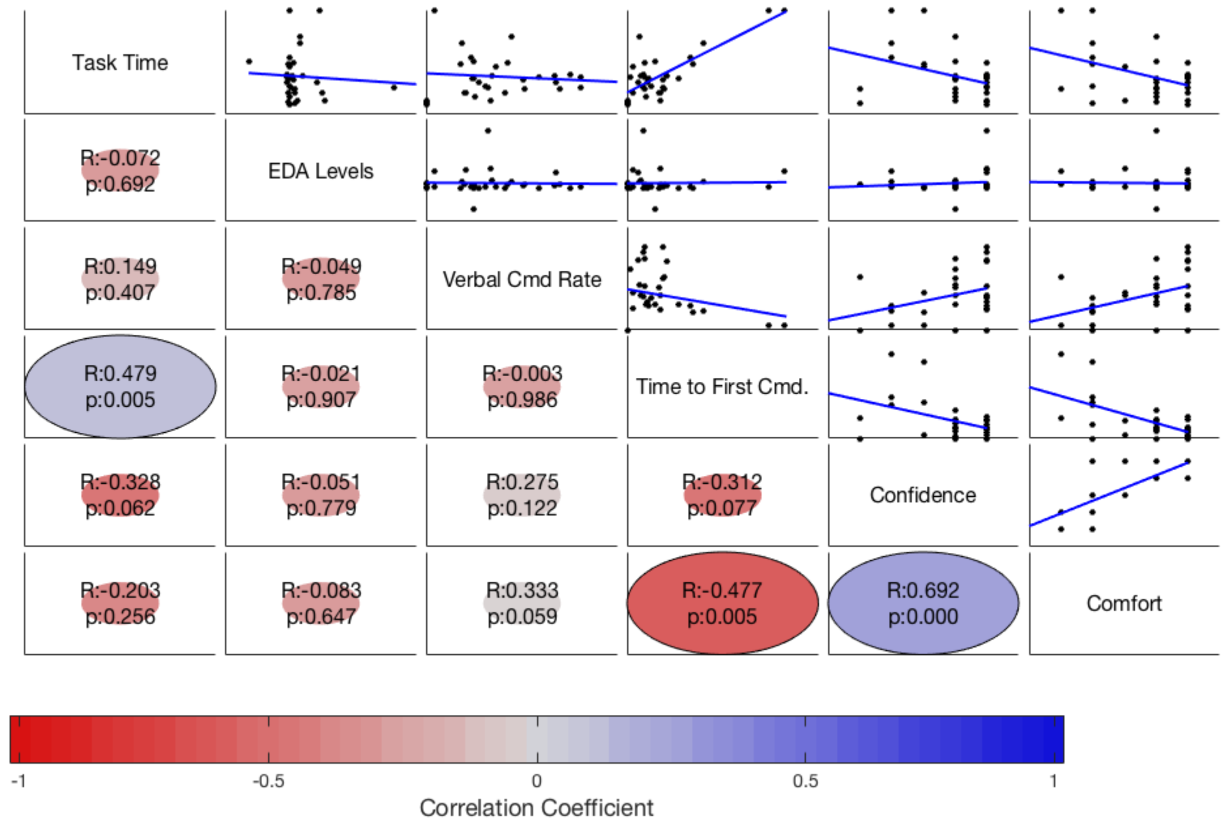


Figure 7.45: Correlation Table for Personality and Performance Data Collected for the Grasping Task During the Egocentric Trials. The Lower Triangle Includes the Color-Coded Correlation Coefficients ρ_s and Corresponding P-Values, and the Size of the Circle Represents the Significance Level (see Figure 7.38). The Upper Triangle Includes Scatter Plots With A Least Squares Linear Regression Line.

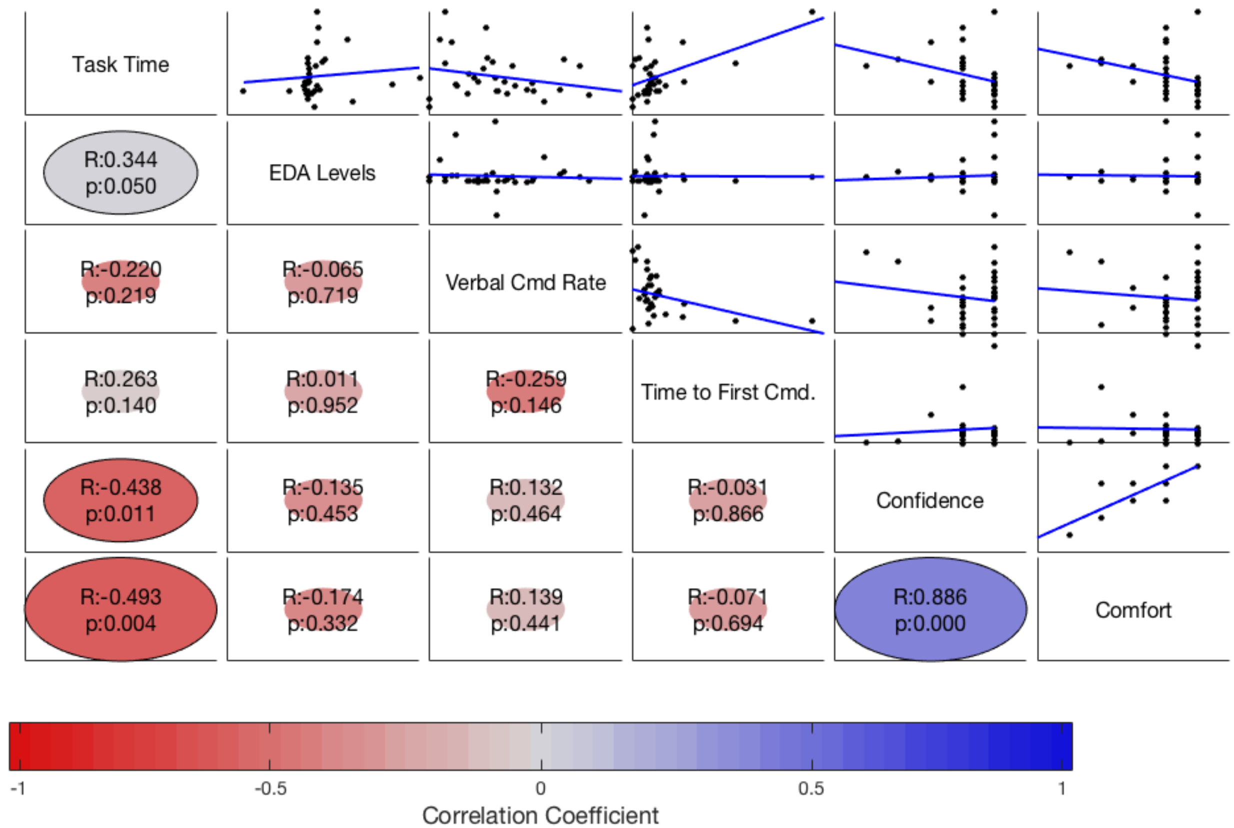


Figure 7.46: Correlation Table for Personality and Performance Data Collected for the Grasping Task During the Exocentric Trials. The Lower Triangle Includes the Color-Coded Correlation Coefficients ρ_s and Corresponding P-Values, and the Size of the Circle Represents the Significance Level (see Figure 7.38). The Upper Triangle Includes Scatter Plots With A Least Squares Linear Regression Line.

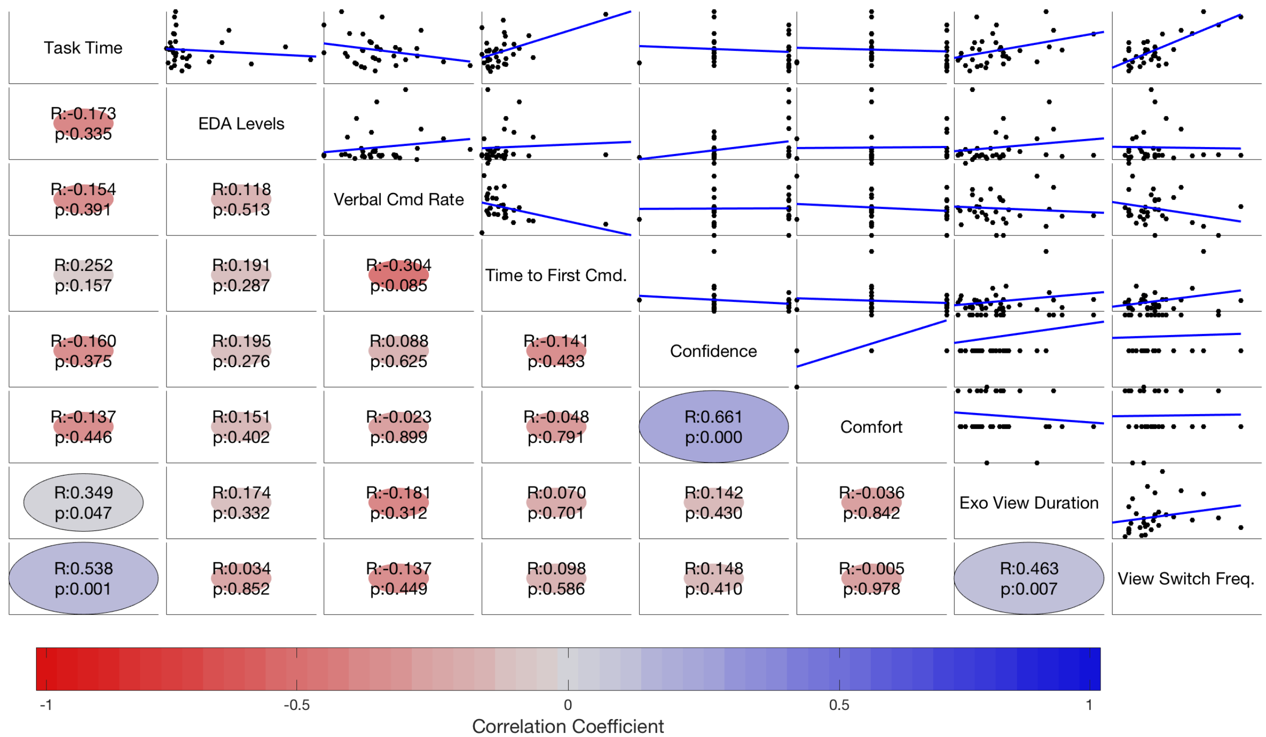


Figure 7.47: Correlation Table for Personality and Performance Data Collected for the Grasping Task During the Mixed Trials. The Lower Triangle Includes the Color-Coded Correlation Coefficients ρ_s and Corresponding P-Values, and the Size of the Circle Represents the Significance Level (see Figure 7.38). The Upper Triangle Includes Scatter Plots With A Least Squares Linear Regression Line.

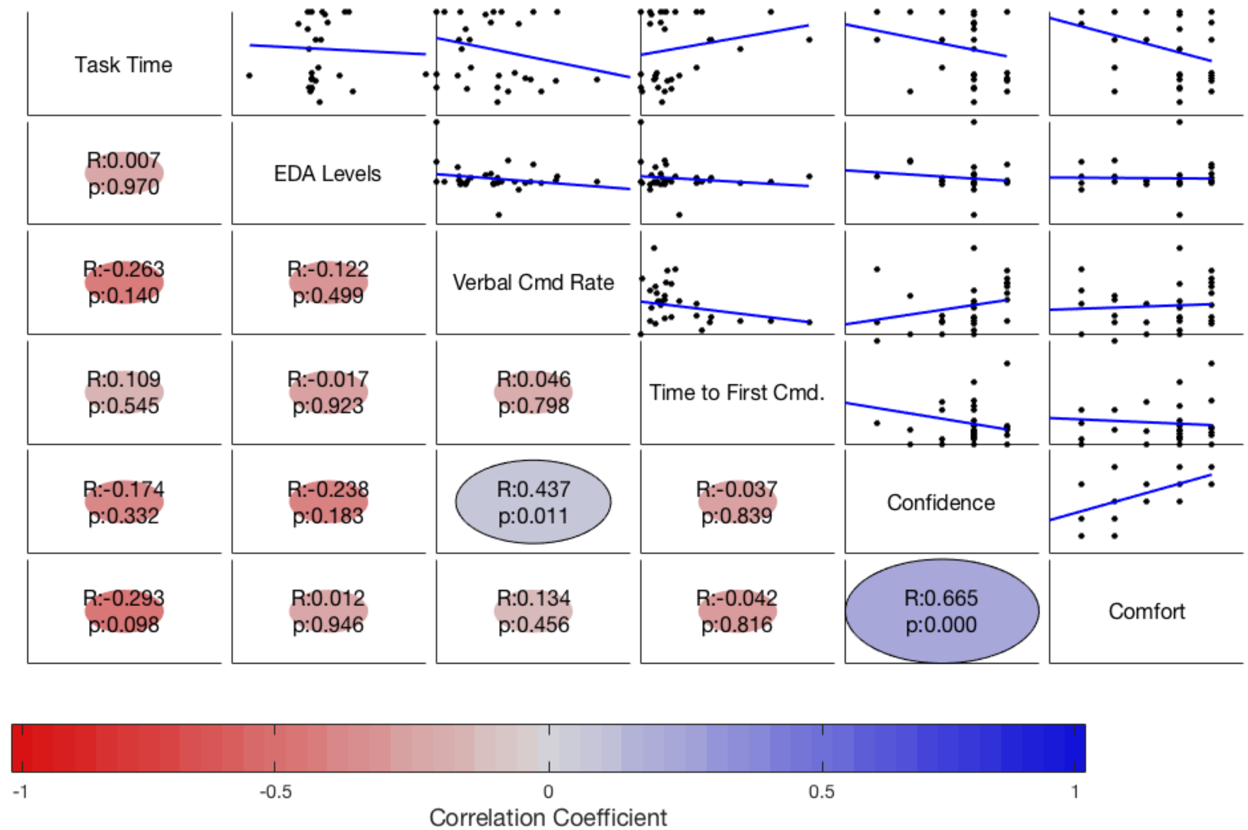


Figure 7.48: Correlation Table for Personality and Performance Data Collected for the Pushing Task During the Egocentric Trials. The Lower Triangle Includes the Color-Coded Correlation Coefficients ρ_s and Corresponding P-Values, and the Size of the Circle Represents the Significance Level (see Figure 7.38). The Upper Triangle Includes Scatter Plots With A Least Squares Linear Regression Line.

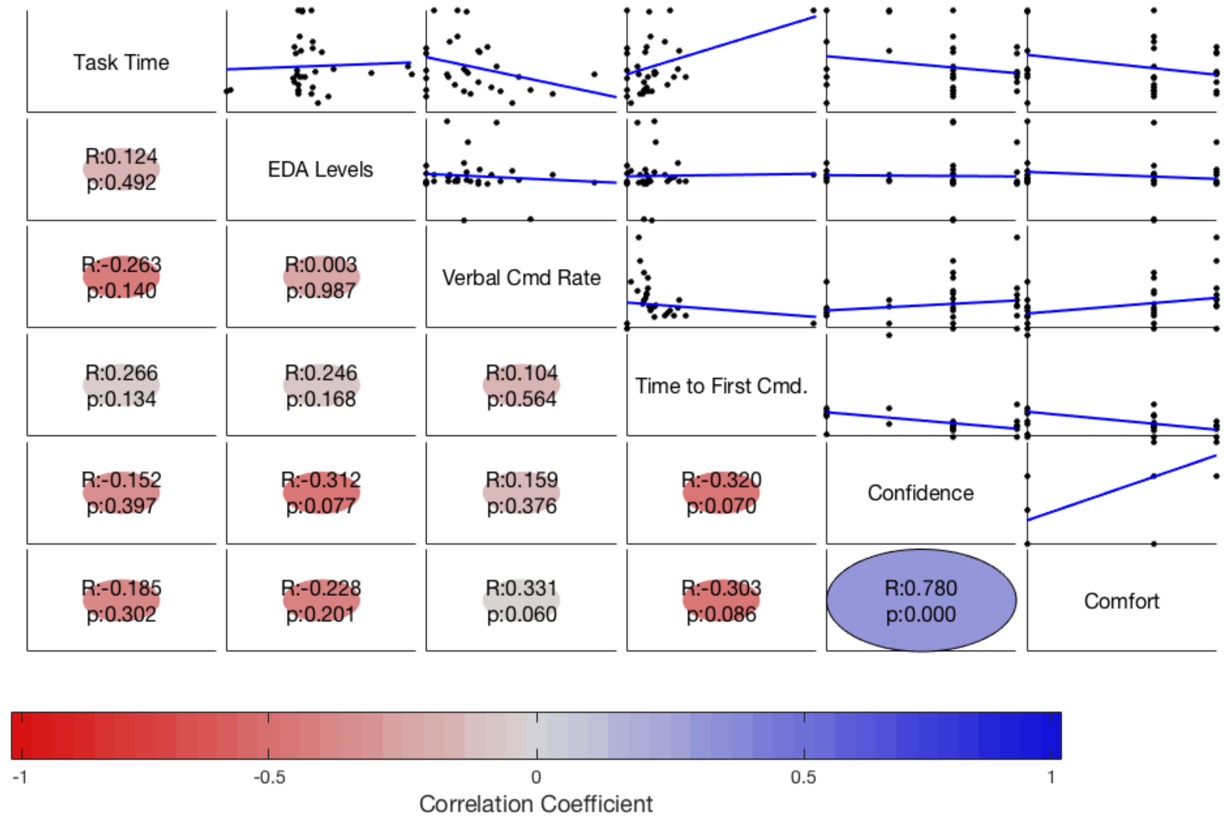


Figure 7.49: Correlation Table for Personality and Performance Data Collected for the Pushing Task During the Exocentric Trials. The Lower Triangle Includes the Color-Coded Correlation Coefficients ρ_s and Corresponding P-Values, and the Size of the Circle Represents the Significance Level (see Figure 7.38). The Upper Triangle Includes Scatter Plots With A Least Squares Linear Regression Line.

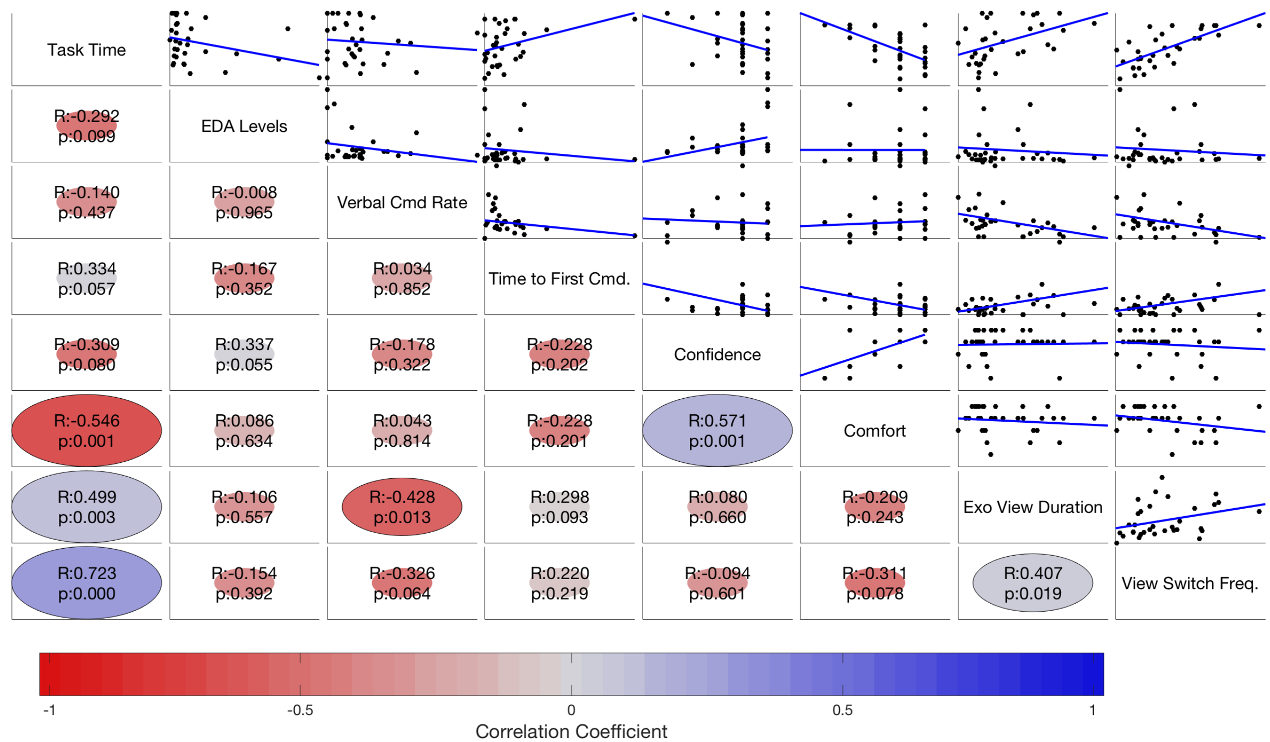


Figure 7.50: Correlation Table for Personality and Performance Data Collected for the Pushing Task During the Mixed Trials. The Lower Triangle Includes the Color-Coded Correlation Coefficients ρ_s and Corresponding P-Values, and the Size of the Circle Represents the Significance Level (see Figure 7.38). The Upper Triangle Includes Scatter Plots With A Least Squares Linear Regression Line.

7.11 Eye Tracking and Verbal Command Analysis

This section presents results of the eye tracking analysis in combination with the *Mission Specialist* verbal command data. The view that participants were using at the time of issuing verbal commands to the *Pilot* was recorded for all trials and tasks during the mixed condition. The commands included in this analysis were commands present on the Command Protocol Sheet, which included: forward, backward, left, and right, with optional distance specifiers.

7.11.1 Comparison of Exocentric and Egocentric Views

Table 7.32 presents summary statistics of the views that participants used when issuing verbal commands (see also Figure 7.51). The differences between the number of commands issued when viewing the egocentric and exocentric cameras were not normally distributed and were unable to be transformed into a normal distribution; therefore, the Wilcoxon signed-rank test was used to compare the data. Results indicate that the total number of commands issued while viewing the egocentric condition was greater than the exocentric condition ($Z(108) = 2.57, p = .010$). There was a difference in commands issued while viewing the egocentric condition for the probing task ($Z(36) = 2.88, p = .004$), but not for the grasping task ($Z(36) = 0.550, p = .583$) or pushing task ($Z(36) = 1.16, p = .247$).

Table 7.32: Descriptive Statistical Results for Number of Verbal Commands Give by *Mission Specialists* While Looking at Each Camera View. The Total Number of Commands Issued While Viewing the Egocentric Condition Was Greater Than the Exocentric Condition ($Z(108) = 2.57, p = .010$).

		Exocentric		Egocentric	
Task	N	M	SD	M	SD
Probing	36	0.61	0.87	1.58	1.25
Grasping	36	1.31	1.53	1.42	1.13
Pushing	36	1.31	1.75	2.33	3.43
Total	108	1.07	1.46	1.78	2.22

7.11.2 Comparison of Types of Verbal Commands Issued for Each View

The verbal commands given by *Mission Specialists* were separated into two categories: i) horizontal alignment ("left" and "right"), and ii) depth alignment ("backward" and "forward"). Figure 7.52 contains summaries of the percentages of each command type given while looking at the exocentric and egocentric views. The Wilcoxon rank sum test was used to compare the number of each type of command issued between the egocentric and exocentric views. Results indicate participants gave more verbal commands for horizontal alignment while looking at the egocentric view ($M = 0.731, SD = 0.756$) compared to the exocentric view ($M = 0.139, SD = 0.373$); $Z(108) = 5.83, p < .001$. There was no difference in number of depth alignment commands given while looking at the egocentric ($M = 0.935, SD = 1.90$) compared to exocentric ($M = 1.046, SD = 1.38$) view for all participants ($Z(108) = -0.0525, p = .958$).

A paired analysis was conducted determine if there is a difference in view that participants who preferred the exocentric condition used to issue verbal commands. Results indicate that on average, participants who preferred the exocentric condition used the egocentric view to issue more commands ($M = 2.07, SD = 2.20$) than the exocentric view ($M = 1.44, SD = 2.08$), although this difference was not significant ($Z(9) = 0.670, p = .503$).

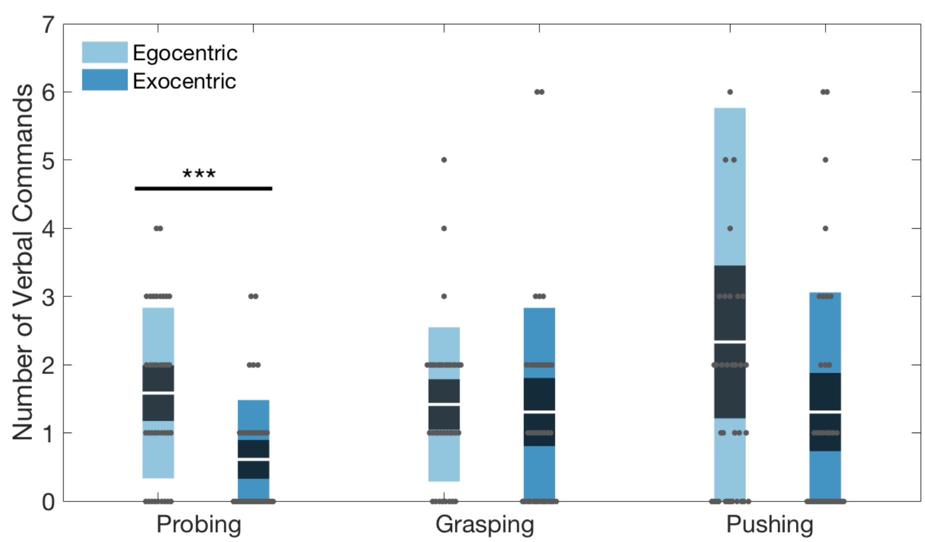


Figure 7.51: Number of Verbal Commands Issued from Participants During Each Task While Looking at the Egocentric and Exocentric Views. *** Egocentric ($M = 1.58$) Different From Exocentric ($M = 0.61$), $p < .005$.

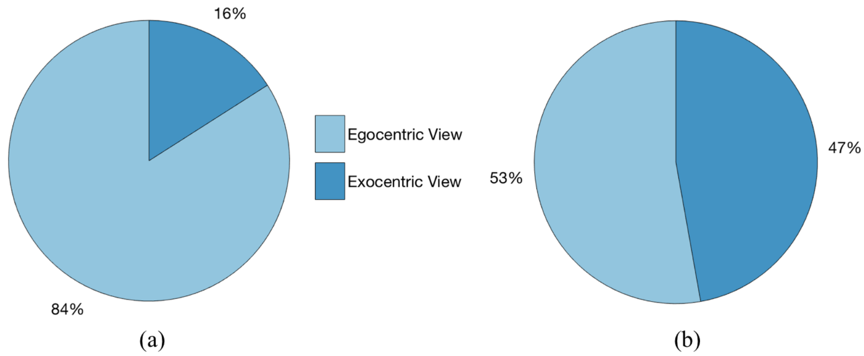


Figure 7.52: Percentages of (a) Horizontal Alignment and (b) Depth Alignment Verbal Commands Given by *Mission Specialists* While Looking at the Egocentric and Exocentric Views. On Average, Participants Used the Egocentric View More Often to Issue Horizontal Alignment Commands, But the Exocentric View Was Used Approximately Equally for Both Horizontal and Depth Alignment Commands.

7.12 Summary of Results

This section presents an overview of results from the experimental data for each section above. Results are labeled according to the section in this chapter that the statistical results are presented in.

Personality Assessments:

Result 7.2.1 There was no correlation between domineering and submissiveness scales, and no difference in domineering or submissiveness between men and women.

Result 7.2.2 There was no difference in locus of control scales between men and women.

Task Completion:

Result 7.3.1 There was no difference in total task completion time, probing task completion time, or grasping task completion time between conditions

Result 7.3.2 The pushing task completion time during the egocentric condition was greater than the exocentric condition; the pushing task completion time during the mixed condition was not different from any other condition.

Result 7.3.3 There were no gender or learning effects on total task completion times.

Result 7.3.4 The pushing task took longer than all other tasks during the egocentric and mixed conditions; there was no difference in completion times between tasks for the exocentric condition.

Result 7.3.5 The task completion success rate for the egocentric condition was less than the success rate for both the exocentric and mixed conditions.

Result 7.3.6 The task completion success rate for the third trial was greater than the success rate for the first trial.

Manipulator Performance:

Result 7.4.1 There was no effect of condition or trial order on the total number of commands sent to the base or elbow joints.

Result 7.4.2 There was no difference in number of manipulator reversals between condition or trials.

EDA Response:

Result 7.5.1 EDA response deviations from baseline were greater than zero for all conditions, but there was no effect of condition or task on EDA response.

Result 7.5.2 The EDA response deviation from baseline was greater during trial 2 than trial 1; the other pairwise comparisons were not different.

Verbal Commands:

Result 7.6.1 There was no difference in total number of verbal commands issued between conditions or trials.

Result 7.6.2 The number of verbal commands given during the pushing task was greater than the probing task for the egocentric and mixed conditions. There was no difference in verbal commands given between tasks in the exocentric condition.

Result 7.6.3 There was no difference in verbal command rate between conditions.

Result 7.6.4 The verbal command rate was greater in trial 2 compared to trial 1, and there was a trend that the verbal command rate in trial 3 was also greater than trial 1.

Eye Tracking (Mixed Condition):

Result 7.7.1 Task type affected the total amount of time spent on the egocentric view, which was less during the probing task compared to the grasping task.

Result 7.7.2 The task type affected both the total number of view switches and the view switching rate; the total number of view switches was largest during the pushing task, but the view switching rate was smaller for the pushing task compared to the probing task.

Confidence and Comfort:

Result 7.8.1 There was a trend that interface condition affected confidence and comfort levels in operating the manipulator, with the mixed condition resulting in higher role empowerment.

Result 7.8.2 Participants thought the information presented in the mixed interface was more adequate than both the exocentric and egocentric interfaces.

Result 7.8.3 Participants generally reported higher levels of confidence and comfort when controlling the manipulator and completing tasks in later trials compared to the first trial.

Interface Preferences and Performance:

Result 7.9.1 Of 36 total participants, only 2 preferred the egocentric interface, 9 preferred the exocentric interface, and 25 preferred the mixed interface.

Result 7.9.2 The primary reason for choosing the exocentric condition was feeling distraction during the mixed condition.

Result 7.9.3 The primary reason for choosing the mixed condition was reporting improved depth perception.

Result 7.9.4 The total task completion time for participants who preferred the exocentric condition was faster during the exocentric condition compared to the mixed condition.

Result 7.9.5 There was no difference in task completion time between the exocentric and mixed conditions for participants who preferred the mixed condition.

Result 7.9.6 There was no difference in percentage of time spent viewing the egocentric camera or the view switching rate between participants who preferred the exocentric view and the participants who preferred the mixed view.

Correlation Analyses:

Result 7.10.1 There was a positive correlation between task time and both the number of manipulator commands and manipulator reversal rate.

Result 7.10.2 Total task completion time was negatively correlated with confidence and comfort in ability to control the manipulator.

Result 7.10.3 Overall, there were no correlation trends between personality traits (submissiveness, domineering, locus of control) and direct measures of task performance.

Result 7.10.4 Task completion time was positively correlated with view switching rate for the mixed condition.

Eye Tracking and Verbal Commands:

Result 7.11.1 The number of commands issued while viewing the egocentric camera was greater than the number of commands issued while viewing the exocentric camera for the probing task, but not different for other tasks.

Result 7.11.2 Participants gave more horizontal alignment commands while looking at the egocentric view compared to the exocentric view.

Result 7.11.3 There was no difference in depth alignment verbal commands given while looking at the egocentric or exocentric view.

Result 7.11.4 There was a trend that participants who preferred the exocentric condition used the exocentric view to issue more commands than the egocentric view.

CHAPTER 8
DISCUSSION

This section interprets and discusses the results obtained from the 36 subject experimental study. First, the original hypotheses are revisited and discussed in the context of the experimental results. Next, an evaluative model for *Mission Specialist* aerial telemanipulation based on empirical findings from this study is presented, followed by interface considerations and recommendations. Finally, factors that could have influenced the results are discussed.

8.1 Hypotheses Discussion

8.1.1 Hypothesis 1

The mixed view interface condition will improve *Mission Specialist* performance when completing aerial telemanipulation tasks compared to the egocentric and exocentric conditions, measured by task completion time, task success rate, reversal rate, role empowerment, and stress indicators.

Data collected to measure performance included task completion time, task success rate, manipulator reversal rate, stress indicators, and post-assessment surveys. The manipulator-based measures of task performance, including number of manipulator commands and manipulator reversal rate, were not different for the mixed condition compared to other interface conditions, but additional data suggested that the mixed and exocentric conditions offered performance benefits over the egocentric condition.

8.1.1.1 Task Completion Time, Success Rate, and Overall Performance

Interface condition did not affect completion times for the probing task, grasping task, and the total task completion time, but the egocentric condition resulted in the slowest pushing task completion times. Additionally, the exocentric and mixed conditions resulted in higher task completion rates compared to the egocentric condition, and the mixed condition resulted in the highest average success rate. Only two participants out of 36 preferred the egocentric condition, which was consistent with poor egocentric performance results. Decreased task performance for the egocentric-only view was likely attributed to the "soda straw" effect (sometimes referred to as the "keyhole" effect), where operators have difficulty understanding and comprehending the remote environment due to a limited viewing angle [186, 195]. This effect leads to missed information and incomplete situation awareness of the vehicle and manipulator in the remote environment and may explain why the exocentric and mixed conditions, which provided a wide viewing angle and complete view of the manipulator, outperformed the egocentric condition.

8.1.1.2 Performance and Confidence and Comfort

On average, confidence and comfort levels were highest for the mixed condition and lowest for the egocentric condition, but this difference was not significant. Participants who reported higher levels of confidence and comfort (role empowerment) in controlling the manipulator tended to perform tasks faster than those who reported decreased levels of confidence and comfort for all conditions. In general, participants who reported higher levels of role empowerment used the manipulator less and issued verbal commands more frequently, which likely contributed to a correlation with improved task completion times. Interestingly, self-reported confidence and comfort in verbal communication with the *Pilot* did not change between interface conditions, but participants who reported higher levels of role empowerment had increased verbal command rates.

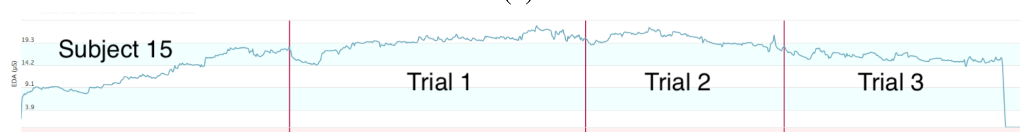
This discrepancy between confidence and comfort in verbal communication and the amount of actual verbal engagement with the *Pilot* may be confounded by response bias. Response bias is a potential issue with using self reported data from questions that deal with subjective measures (e.g., feelings) rather than factual data (e.g., age) [226]. For example, one instance of response bias occurred in this study when a subject failed to complete a majority of the tasks but reported their confidence and comfort levels to be a scale of five (on a five-point Likert scale), which was not reflective of their actual performance. These self-reported data should be used as a supplement to other performance data when making interface recommendations and not used as a primary decision-making metric.

8.1.1.3 Performance and Participant Stress

Results from this study showed that *Mission Specialists* had increased EDA responses during the experimental trials compared to their baseline data, but there was no change in EDA response between interface conditions. One interpretation of this may be that operating this technology for the first time in an experimental trial was sufficiently stressful to cause elevated levels such that the differences in interface conditions could not impact EDA response (i.e., the response to different stimulus might be less for a person who is already stressed). Additionally, these data suggest at the very least that none of the *Mission Specialist* interfaces created stressful conditions beyond participation in this study.

Participants had higher EDA response levels during the second trial compared to the first trial, independent of interface. This trend was likely due to *habituation*, which is the reduction in a psychophysiological response that occurs in reaction to repeated stimulus [227]. In this study, the magnitude of stress differentials from baseline values increased from trial one to trial two, then tapered off, and a trend of decreased EDA response during the third trial was present. Figure 8.1 includes two illustrations of habituation trends present in the EDA response data. This type of habituation is known as "short term" habituation that occurs during a single testing session [227] and increases in response to stimuli that are presented frequently and slowly, which was the exposure to the robot during multiple tasks.

(a)



(b)

Figure 8.1: Example EDA Response Levels for Two Example Subjects Across Three Subsequent Trials. The EDA Responses Were Greater in Trial 2 Compared to Trial 3 for All Participants, Which Was Likely Due to the Habituation Effect, or the Reduction in Psychophysiological Response In Reaction to Repeated Stimulus [227].

8.1.2 Hypothesis 2

***Mission Specialist* personality will positively influence performance if they are domineering or have an internal locus of control, and negatively affect performance if they are submissive or have an external locus of control, measured by personality assessment tools and task performance metrics.**

Mission Specialist participants operated as part of a human-robot team with the *Pilot*; therefore, personality traits related to locus of control, domineering, and submissiveness were hypothesized to affect human-robot team performance.

8.1.2.1 Submissiveness and Domineering Scales and Performance

The low-level traits of domineering and submissiveness were chosen because they identify with extroversion. Extroverts have been found to scale high in the domineering scale [228] while submissiveness has been associated with introversion [229]. Correlation analyses determined there were no significant relationships between submissiveness and domineering scales with trial-based task completion and success rate metrics, besides a significant correlation between total task completion time and domineering scales for the mixed condition.

In addition to performance, the extroversion or introversion of a participant could influence the level of verbal command usage, and participants with greater scales of extroversion were expected to feel more comfortable engaging with the *Pilot*; however, there were no significant correlations between domineering or submissiveness scales with verbal command data (note that increased verbal command rates correlated with faster task completion times). The standardized experimental protocols and limited allowable communications with the *Mission Specialist* may be reasons why relationships between extroversion, verbal command usage, and performance were not observed. Additionally, interacting with a small robot was far outside the norm for most participants, which may have affected their behavior compared to more natural settings.

8.1.2.2 Locus of Control and Performance

Locus of control was hypothesized to affect performance because it is a personal belief concept that has the potential to influence certain task completion outcomes. People with an internal locus of control may exert more effort during tasks to achieve success [220] and tend to achieve higher levels of success in the workplace [230], while people who identify with having an external locus of control are less persistent when completing tasks [221]. These trends have been observed in the literature, but no correlation between locus of control scale and task performance metrics were observed in this study. One reason for a lack of locus of control effects could be that this study was cross-sectional in nature, while many studies that observe locus of control beliefs with performance are longitudinal and take place over many weeks, months, or even years. Additionally, there is a subtle but significant difference in personal locus of control beliefs and the internal or external locus of the factors required for completing a task [231]. For example, a *Mission Specialist* might believe they will be successful at performing aerial telemanipulation because they have extensive experience playing first-person video games (an internal factor), or because they believe the *Pilot* is highly skilled (an external factor). These internal and external factors may be confounded with the independent perceived control over an outcome.

8.1.3 Hypothesis 3

Tasks that *Mission Specialists* rate as the most difficult to complete will be more stressful and result in lower overall task performance compared to tasks that were rated easier to complete, measured by EDA responses, task completion time, task success rate, verbal commands, and post assessment responses related to task preferences.

Participants may rate tasks to be more difficult if they have poor situation awareness and are unable to create an accurate mental model of the robot and task in a remote environment. The perception of task difficulty was hypothesized to negatively affect overall task performance if tasks were perceived to be more difficult, and post-assessment and performance data indicate that the pushing task was rated the most difficult to complete on average, and resulted in the worst overall task performance; however, there was no difference in EDA response between any of the tasks for all conditions, tasks with higher-rated difficulty do not necessarily result in higher levels of stress.

8.1.3.1 Post-Assessment Responses

A majority (64%) of participants reported that the pushing task was the hardest to complete for the mixed condition; however, only 39% rated the pushing task to be the most difficult for the exocentric condition, and 50% rated it most difficult for the egocentric condition. On average, a majority of participants either rated the grasping or probing task to be the easiest to complete. The higher percentages of pushing task difficulty ratings for the mixed and egocentric condition was likely due to the use of the egocentric camera view, which may have been suboptimal for the pushing task and created a blind spot if not used appropriately. Additionally, self-reported confidence and comfort levels were, on average, lower overall for the pushing task compared to the probing and grasping tasks. Participants confidence and comfort in operating the manipulator increased from trial 1 to trial 3; however, role empowerment did not increase between trials for the pushing task, despite performing multiple attempts.

8.1.3.2 Verbal Commands

The number of verbal commands given to the *Pilot* by the *Mission Specialist* was higher for the pushing task for both the mixed and egocentric conditions compared to the probing and grasping tasks, indicating that vehicle positioning and more frequent repositioning was required for successful task completion. Additionally, one-third of participants issued verbal commands to position the UAV forwards, then backwards, then forwards, in at least one repeating cycle, until the task was complete. This sequence of verbal commands resulted in multiple attempts at starting the task over, because the starting position of the UAV did not require backwards verbal commands to be issued. This verbal command pattern to reset the vehicle for a additional completion attempts occurred for only three participants during the probing task and four participants during the grasping task.

8.1.3.3 Task Completion Time and Success Rate

The pushing task was the most frequently missed task, comprising nearly 60% of the total number of missed tasks for all trials combined, and took longer to complete during the egocentric and mixed conditions compared to the probing and grasping tasks. Additionally, the eye tracking data showed that participants switched between views more frequently during the pushing task compared to any other task, which may indicate that either greater situation awareness by obtaining information from both camera streams was required, or that the egocentric camera view was visually simulating and diverted attention from the exocentric camera. Also, the pushing task results in slowest task completion times for the pushing task for the egocentric and mixed conditions. These task completion time and success rate results support hypothesis 3; the pushing task was, on average, rated to be the most difficult task, and resulted in the lowest over performance, including increased task completion times and decreased success rates.

8.2 Development of an Evaluative Model

A *Mission Specialist-Pilot* focused version of the Shared Roles Model describes telemanipulation in remote presence applications where the roles are split between the robot and human agents [34] (see Figure 8.2). Shared Roles frames teleoperation in the context of a joint cognitive system (JCS), where humans and machines can modify their behavior to reach a specific goal [232], and emphasizes the "what" and "why" of coagency between the humans and robots [34]. This framework takes advantage of the robot's semiautonomous capabilities, which include autonomous waypoint navigation and hovering, and the roles of the *Mission Specialist* to complete the telemanipulation. In this study, the *Pilot* roles included all aspects of navigation, including monitoring the robot's autonomous capabilities and manually refining the UAV position as necessary. The roles of the *Mission Specialist* included manually controlling the robotic manipulator and verbally directing the *Pilot* to refine vehicle position as necessary. Verbal communication links between the colocated *Pilot* and *Mission Specialist* provided a robust connection between these two roles necessary for completing telemanipulation using a semiautonomous platform. These roles were designed to represent the current state of aerial telemanipulation capabilities in unstructured, dynamic environments. While the Shared Roles Model provides an abstract framework for evaluating effects of autonomy on teleoperation applications, for a given set of autonomous capabilities and shared roles within an aerial telemanipulation system it is also useful to investigate the "how", including interfaces and environmental and personal factors.

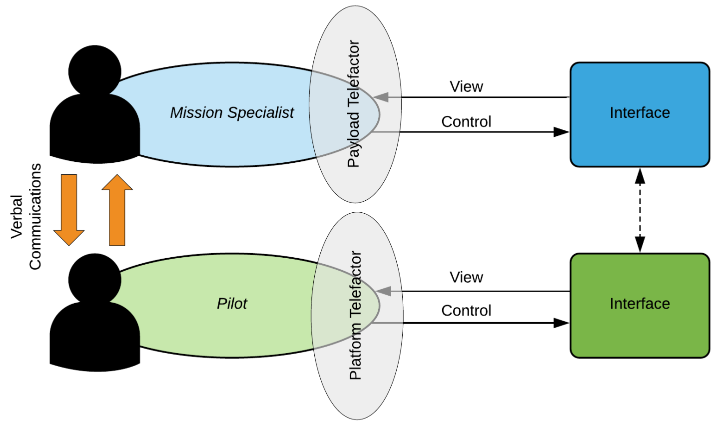


Figure 8.2: A *Mission Specialist-Pilot* Focused Version of the Shared Roles Model, Including the Verbal Communication Links, Role-Specific Interfaces, and Shared Roles of the *Mission Specialist* and *Pilot* with the Payload and Platform.

An evaluative model that explains the relationships between robot, personal, and environmental factors was hypothesized and evaluated to better understand how a *Mission Specialist* performs telemanipulation in this system. As shown in Figure 8.3, the components of this model were either varied (independent variable), measured, or held constant in this study. The measured dependent variables included stress indicators, reversal rate, verbal communication, and self-efficacy (confidence and comfort); these are intermediate dependent variables that ultimately led to direct measures of performance that informed this model: success rate and task completion times. The only dependent variable varied in this study was the interface type (egocentric, exocentric, mixed). All robot and environmental factors were held constant except for variables related to the tasks, including verbal overhead and task requirements. Verbal overhead is considered the amount of required verbal communication to complete a given task (i.e., the tasks were designed to require a minimal number of verbal commands for successful completion). The individual factors, including personality, prior experience, gender, and preference, were measured covariates. The factors that, on average, affected performance are included in bold, and the size of the font is a relative indicator of significance. Variables that did not influence the dependent variables at any level or were held constant are grayed out. This model provides a detailed framework, a complement to the abstraction of the Shared Roles Model, that can be used to determine the effects of changes in the system, environment, operators, and interfacing factors on performance.

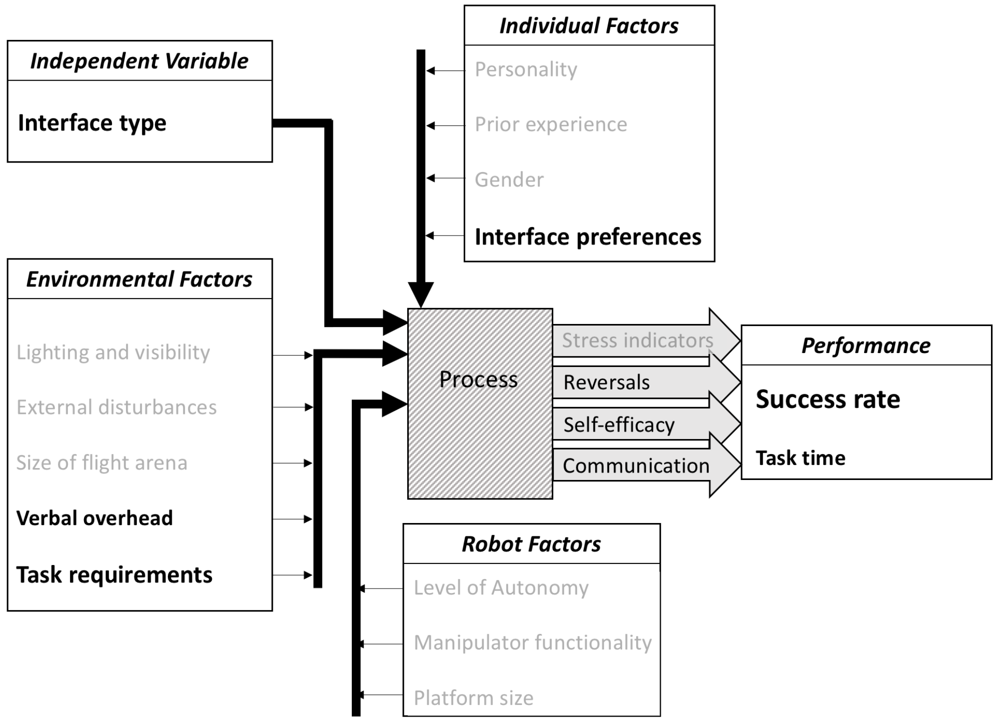


Figure 8.3: An Evaluative Model of Telemanipulation Performance, Incorporating Environmental, Robot, and Personal Factors, the Independent Variable and Dependent Variables. The Outputs are Primary Performance Variables that Informed the Development of this Model.

8.3 *Mission Specialist* Interface Recommendations and Considerations

8.3.1 Interface Recommendation Based on Experimental Results

Both the exocentric and mixed interface conditions offered performance improvements compared to the egocentric interface condition, including fewer missed tasked and higher task completion success rates. Additionally, on average participants completed fewer reversal rates with the manipulator and reported higher levels of role empowerment for the exocentric and mixed conditions. Participant preference also significantly affected performance; for participants who preferred the exocentric interface (69%), there was no performance difference between using the exocentric or mixed interface; however for participants who preferred the exocentric condition (25%), the exocentric condition resulted in faster task completion times. Based on the task performance results from this experimental study, the exocentric condition is recommended for a *Mission Specialist* interface to enable telemanipulation in a three-dimensional environment.

8.3.2 Tradeoffs Between Additional Information and Attentional Costs

One consideration of retaining both the egocentric and exocentric camera views in an interface are tradeoffs between increased levels of information and attentional deficits. The misuse of additional information is an interesting phenomenon that has been observed in the literature [178, 192, 233]. Attentional costs were not hypothesized to occur during this study as the mixed condition was not designed to be overly sensory-rich (e.g., mixed reality); however, data suggested that participants attention allocation when using the mixed interface was compromised if they did not use the multiple views effectively. One fourth of participants preferred the exocentric condition, and a major reason for their preference was distractedness during the mixed condition. All participants, regardless of interface preference, equally split their time between both views during the mixed condition, but having both views available did not improve task completion times for all participants. Additionally, there was a positive correlation between task completion time and view switching frequency, which suggests that the additional information was indeed used, but perhaps not effectively. Reasons for compromised attention may include attention switching, cognitive tunneling, and information integration [192].

Multiple view displays require users to switch their attention between views, detect changes in multiple views, and integrate information across different views [192], which introduce problems in attention allocation. Costs associated with integrating information between views are higher when those views do not present closely related information [234]; however, it is unlikely that information integration was the primary reason for compromised attention allocation in this study because the views were both from the perspective of the robot itself (as opposed to a situational 2D map combined with live feed from the robot).

Another potential reason for improper attention allocation is cognitive tunneling. Cognitive tunneling can cause display anchoring when one of the views is more information or sensory rich than the other, and users are "tunneled" into using one view thus ignoring information present in the other [178]. This cognitive tunneling effect may have occurred towards the egocentric view, and participants likely spent too much time focused on the egocentric display compared to the exocentric display, or used the egocentric display at inappropriate times. The movement of the egocentric camera mounted to the manipulator, compared to the fixed exocentric camera mounted to the UAV body frame, may have caused the egocentric view to be sensory rich. Additionally, the close-up view of the bright red target during the probing task may have also been a visual cue to change attention towards the egocentric camera, evidenced by higher view switching rates for the probing task.

It is difficult to determine the exact cognitive mechanisms that caused attentional issues, but the data indicated tradeoffs between performance improvements and attentional costs when adding information in the form of multiple views to the *Mission Specialist* interface [192]. These tradeoffs were taken into account in the following *Mission Specialist* interface recommendations.

8.3.3 Considerations for Future *Mission Specialist* Interfaces

It is well-known that human behavior is variable and stochastic, and people have different skill levels, preferences, and cognitive processes; therefore, interfaces should be flexible to accommodate these differences. A significant finding of this study was that interface preferences affect *Mission Specialist* performance for participants who preferred the exocentric condition, but did not affect performance for participants who preferred the mixed condition. Participants who preferred the exocentric condition performed tasks 50% faster during the exocentric trial compared to the mixed trial. Conversely, there was no difference in performance for participants who preferred the mixed condition between the mixed and exocentric trials. Also, participants with exocentric preferences reported being distracted during the mixed condition, but distraction was not reported by participants who preferred the mixed condition. These findings suggest that the egocentric view in the mixed condition was not always necessary, depending on the participant.

To accommodate these differences in preference, one avenue for exploration is creating interfaces with flexibility regarding the egocentric view display. For example, reducing the size of the egocentric view, such as in a picture-in-picture scheme, and adding the capability to dynamically expand and shrink or close and reopen the egocentric view as necessary give users the option to adjust the level of information. A picture-in-picture display would place emphasis on the exocentric view and minimize the cost of information access between related views by placing them in proper spatial proximity [234]. Also, if the size of the egocentric condition is reduced in a picture-in-picture display, users may deem it less important and pay less attention to it, using it as supplemental information rather than a primary information source. A single-touch gesture to expand and shrink the egocentric camera view would allow users to access that information when appropriate, for example, during tasks with higher levels of precision or UAV positioning. Note that it is recommended to include the egocentric condition in some capacity because 84% of participants used it to issue horizontal alignment commands, and 53% of participants used it for depth alignment commands.

This recommendation to create flexible and adjustable interfaces is not a new suggestion; however, it is often ignored. A majority of UAS interfaces have a single fixed camera location that the user can control using pan, zoom, and tilt commands, but the ability to adjust the window size, open additional views, or remove information from a cluttered interface is limited, and the decisions on what information to display and how to display it is left up to the designer. Although the ability to customize an interface might improve performance, one could argue that the additional responsibility of expanding and collapsing views would add to the overall attention and cognitive load requirements of the *Mission Specialist*. These recommendations and concerns should be formally evaluated in future experiments.

8.4 Potential Limitations and Factors that May Have Impacted Results

8.4.1 Robot Performance and Autonomy

One challenging aspect of using small UAVs for HRI studies is that they have higher degrees of freedom of movement compared to ground based vehicles or stationary manipulators, and this variance and uncertainty in positioning was exacerbated by the lab space used for these experiments. These experiments were conducted in an indoor laboratory, which was a near-ideal space for controlling unpredictable environmental factors such as wind, sun, and temperature, which would affect the performance of the robot in non-uniform ways between participants and cause confounds. Unfortunately, the size of the room was small enough such that non-negligible propeller wash effects from air flow within the lab space floors and walls were present. These effects were minimized through the use of a precise tracking system and real-time control, but at times the air dynamics in the room caused short, yet unpredictable, disturbances to UAV position. For this study, the robot acting the same way every time was important to maintain consistency, so use of the Vicon motion tracking system was critical.

A minor improvement would be made if this study were conducted in a large warehouse, but air effects would still be present because the UAV needs to approach a surface to perform manipulation. Additionally, due to the nature of quadrotor dynamics, developing a perfect system that is stable in all dynamic environments is difficult and also impractical for performing aerial telemanipulation outdoors. Using a physical system with small positioning disturbances for this study, as opposed to simulation environment, provided a better approximation of HRI during telemanipulation missions in real-world environments, which will always experience external disturbances such as wind, temperature, and mechanical variations in motors.

8.4.2 Novelty of the Robot

Another factor that could have influenced the results was participant's perceived novelty of the robot [210]. Thirty of the the participants reported having little to no robot experience or exposure, and the four participants who previously interacted with UAVs only used small, hobbyist platforms, so for many participants this study was their first formal interaction with a UAV. There was anecdotally a "neatness" factor visible when participants first entered the room, which was present during the practice flight. After the trials ended, some participants exclaimed about how "cool" the robot was, or that they had "fun" during this experiment. It is possible that the feelings of excitement and intrigue about the robot influenced their ability to treat the experiment as a serious mission and remain focused on task for the duration of all three trials. Formalizing the experimental protocols such that they left little room for experimentation with the robot mitigated the novelty effect during the experiments.

Additionally, it is possible that sampling bias occurred if participants were drawn to participate because of the novelty effect. Eliminating this sampling bias was difficult because targeted participants were people with little to no experience with UAVs, who are consequently more susceptible to experiencing the novelty effect. The practice flight, however, helped reduce this effect and get participants accustomed to the robot before they began the experimental trials.

CHAPTER 9
CONCLUSIONS AND FUTURE WORK

9.1 Conclusions

The primary research question that this dissertation addressed was: *What is the appropriate human-robot interface for a Mission Specialist role in a small unmanned aerial system to successfully perform telemanipulation tasks in a three dimensional environment?* This research answered the primary question by addressing three open sub-questions identified from the literature through an approach guided by the Shared Roles Model and human-robot interaction principles, including: i) what is the current state of human-robot interaction for a *Mission Specialist* role in small unmanned aerial system telemanipulation operations, ii) what display form and elements are necessary for remote physical interaction with a UAV, and iii) how do emotional and personality factors affect telemanipulation performance. Findings and three primary contributions are discussed first, followed by descriptions of suggested short-term and long-term future work.

9.1.1 Summary of Findings

This dissertation was an investigation of the appropriate human-robot interfacing for a *Mission Specialist* role performing aerial telemanipulation tasks. An initial review of literature suggested the following findings which were relevant to this work: i) there is a gap in focused HRI work for telemanipulating UAVs, ii) the current state of manipulating UAVs is autonomous operation in highly controlled, indoor environments, while autonomous manipulation outdoors remains a challenge, iii) the past 5-10 years have seen a trend of increased mobile tablet use for controlling unmanned systems, and iv) overall, the quality and type of visual display greatly affects operator performance. This review motivated the implementation of the Shared Roles Model and the design of the role functions to align with the current state of practice for manipulating UAVs. Additionally, the survey of telemanipulation interfaces motivated the use of a mobile tablet as the interface device and the implementation of high-resolution cameras mounted in two strategic locations on the UAV.

A 5 subject exploratory study and 36 subject experimental study were conducted to evaluate the effects of three interface conditions (egocentric, exocentric, mixed) and personality traits on *Mission Specialist* performance. The most significant finding of this work was that the interface preference of the operator affected performance for participants who preferred the exocentric condition and did not affect performance for participants who preferred the mixed condition. Participants who preferred the exocentric condition completed all tasks more than 50% faster when using the exocentric interface compared to the mixed interface. This result led to another finding that participants who preferred the exocentric condition were distracted by the egocentric view during the mixed condition, likely causing decreased performance. Eight out of the nine participants who preferred the exocentric condition reported feeling distracted when using the mixed interface, which was additionally supported by the eye tracking results. The mixed condition did not yield the best overall performance as hypothesized, nor were there differences in stress levels between interface conditions; however, both the mixed and exocentric conditions provided performance benefits over the egocentric condition, which had the lowest success rates. Finally, there were no effects of personality found on performance. Although personality was hypothesized to affect task performance, this finding was positive and indicated the interfaces and human-robot team were designed such that most participants were able to successfully verbally engage with the *Pilot* and complete a majority of the tasks.

9.1.2 Summary of Contributions

Contributions of this thesis include: i) conducting the first focused HRI study of aerial telemanipulation, ii) development of an evaluative model for telemanipulation performance, iii) creation of new recommendations for aerial telemanipulation interfacing, and iv) contribution of code, hardware designs, and system architectures to the open-source UAV community.

9.1.2.1 First Focused Study of Aerial Telemanipulation HRI

This work was the first focused human factors study of aerial telemanipulation HRI with a physical manipulating UAV platform. The implementation of the Shared Roles Model in this study enabled the *Mission Specialist* to focus on performing manipulation, while the *Pilot* role was responsible for navigating the UAV. These results are expected to remain valid even if the *Pilot* role is served by a sophisticated software agent in the future, as the responsibilities of the *Mission Specialist* remain the same as the team member with domain expertise responsible for manipulation. Broader impact contributions of this work include a better understanding of how these vehicles can be used in sampling and other missions by domain experts under operation of the Shared Roles Model. Primary stakeholders for adoption of this technology include researchers, practitioners, government agencies, and industries that currently use UAVs for visual inspection and have the policies and infrastructure in place to expand their usage of aerial vehicles.

9.1.2.2 Evaluative Model of Telemanipulation Performance

An evaluative model that explains the relationships between robot, personal, and environmental factors was hypothesized and evaluated to better understand how a *Mission Specialist* performs telemanipulation in this system. This model, which investigates the "how" for HRI, is a complement to the abstraction of the Shared Roles Model that addresses the "what" and "why" of coagency in a human-robot team. The literature and technology findings were not sufficient enough to determine the hidden cognitive effects of individual preferences in attention allocation. The ability to focus on the *Mission Specialist* role and understand the hidden dependencies that have been shown through this ethnographic evaluation and development of this model will provide an additional perspective to UAS HRI research and development of new UAV technologies.

9.1.2.3 New Recommendations for Aerial Telemanipulation Interfacing

The findings from this empirical study using this model were used to inform design recommendations for *Mission Specialist* telemanipulation interfaces, including the exocentric view being the recommended interface visualization. Additionally, the creation of dynamic interfaces with flexibility regarding the egocentric view display were identified as areas for further exploration to reduce attentional costs. The impacts on manipulating UAS from this work include guidelines for future software developers and system designers, and it is recommended that the supporting principles and recommendations for this dedicated *Mission Specialist* interface be a standard method of human-robot interaction for telemanipulating UAVs.

9.1.2.4 Development of an Open-Source Telemanipulating UAV Framework

This work contributes to the open-source community by providing code, hardware designs, and system architectures to enable the reproduction of the UAV telemanipulation system used in this study. This practical contribution will expedite the distribution and adoption of manipulating UAV technology by scientists, researchers, and other stakeholders. Domains that would benefit from access to this technology include civil, environmental, and agricultural engineering, search and rescue, and other domains where site accessibly is a prohibitive issue. Additionally, the foundation of the *Mission Specialist* interface developed in this study can be used immediately with any networked system, or can serve as groundwork for future unmanned system developers and engineers to inform future iterations of aerial manipulation interfaces.

9.2 Future Work

There are both short-term and long-term future research goals that can extend the work of this dissertation related to manipulating UAS. Short-term research goals include evaluating additional variations of the mixed interface, while long-term research goals include conducting HRI studies in dynamic environments and developing adaptive interfaces based on *Mission Specialist* use in real-time.

9.2.1 Short-Term Research Goals

The mixed interface developed in this dissertation included one configuration of the mixed interface condition. Based on the results from these studies, it is recommended to conduct empirical evaluations of additional mixed interface configurations with dynamic features, such as a picture-in-picture view or a collapsable and expandable egocentric view. In these future studies, it is also recommended to quantitatively measure situation awareness with the Situation Awareness Global Assessment Technique (SAGAT) and workload using the NASA-Task Load IndeX (NASA-TLX) to better quantify the cognitive load of the operator when using and adjusting multiple views.

Additionally, the evaluation of augmented reality that enhances depth representation in the egocentric interface is a recommended short-term research goal, as it has shown to improve performance for ground vehicles and stationary manipulators. Caution must be taken, however, when designing virtual elements in an interface because depth distances are underestimated worse in virtual environments compared to real camera views ([235], and depth misjudgment with a manipulating UAV could seriously compromise a mission or even lead to a crash.

9.2.2 Long-Term Research Goals

A long-term research goal is to conduct additional telemanipulation HRI experiments in outdoor, dynamic environments. While maintaining controlled and consistent experimental conditions in this study was necessary, it is also important to understand how the environment (e.g., sun, wind) and other uncertainties in dynamic environments affect the required HRI. Additionally, such experiments will enable the testing of real-world applications for manipulating UAVs, such as environmental sampling and nondestructive infrastructure testing. This research is long-term as it requires implementing more advanced vehicle control and stabilization techniques, as well as designing some type of encapsulation to prevent accidents.

A second long-term research goal is the development of adaptive interfacing. As a *Mission Specialist* uses and interacts with the mobile interface, an adaptive interface would change, remove, or highlight specific areas and information depending on the requirements of the user with potential goals of reducing workload and improving performance. This research area is new and requires advanced techniques in machine learning; therefore, a large number of additional experiments would need to be conducted to collect the amount of data necessary for training and implementation of an adaptive interface.

REFERENCES

[1] S. Young, J. Peschel, G. Penny, S. Thompson, and V. Srinivasan, "Robot-assisted measurement for hydrologic understanding in data sparse regions," *Water*, vol. 9, no. 7, 2017. [Online]. Available: http://www.mdpi.com/2073-4441/9/7/494

[2] A. Pires, H. I. Chaminé, J. C. Nunes, P. A. Borges, A. Garcia, E. Sarmento, M. Antunes, F. Salvado, and F. Rocha, "New mapping techniques on coastal volcanic rock platforms using UAV LiDAR surveys in Pico Island, Azores (Portugal)," in *Volcanic Rocks and Soils*. CRC Press, 2015, pp. 385–388.

[3] D. Gómez-Candón, A. Castro, and F. López-Granados, "Assessing the accuracy of mosaics from unmanned aerial vehicle (UAV) imagery for precision agriculture purposes in wheat." *Precision Agriculture*, vol. 15, no. 1, p. 44, 2014.

[4] E. Salami, C. Barrado, and E. Pastor, "UAV flight experiments applied to the remote sensing of vegetated areas," *Remote Sensing*, vol. 6, no. 11, pp. 11 051–11 081, 2014.

[5] I. Crocker, J. A. Maslanik, J. J. Adler, S. E. Palo, U. C. Herzfeld, and W. J. Emery, "A sensor package for ice surface observations using small unmanned aircraft systems," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 50, no. 4, pp. 1033–1047, 2012.

[6] K. Máthé and L. Buşoniu, "Vision and control for UAVs: A survey of general methods and of inexpensive platforms for infrastructure inspection," *Sensors*, vol. 15, no. 7, pp. 14 887–14 916, 2015.

[7] I. Sa, S. Hrabar, and P. Corke, "Inspection of pole-like structures using a vision-controlled VTOL UAV and shared autonomy," in *Proc. 2014 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*. Chicago, IL, USA: IEEE, Sept 2014, pp. 4819–4826.

[8] S. Montambault, J. Beaudry, K. Toussaint, and N. Pouliot, "On the application of VTOL UAVs to the inspection of power utility assets," in *Proc. 2010 1st Int. Conf. Applied Robotics for the Power Industry (CARPI)*. Montreal, QC, Canada: IEEE, Oct 2010, pp. 1–7.

[9] N. Metni and T. Hamel, "A UAV for bridge inspection: Visual servoing control law with orientation limits," *Automation in Construction*, vol. 17, no. 1, pp. 3 – 10, 2007.

[10] B. A. Duncan and R. R. Murphy, "Autonomous capabilities for small unmanned aerial systems conducting radiological response: Findings from a high-fidelity discovery experiment," *Journal of Field Robotics*, vol. 31, no. 4, pp. 522–536, 2016.

[11] M. A. Goodrich, B. S. Morse, C. Engh, J. L. Cooper, and J. A. Adams, "Towards using unmanned aerial vehicles (UAVs) in wilderness search and rescue: Lessons from field trials," *Interaction Studies*, vol. 10, no. 3, pp. 453–478, 2009.

[12] J. Willmann, F. Augugliaro, T. Cadalbert, R. D'Andrea, F. Gramazio, and M. Kohler, "Aerial robotic construction towards a new field of architectural research," *Int. J. Architectural Computing*, vol. 10, no. 3, pp. 439–459, 2012.

[13] Q. Lindsey, D. Mellinger, and V. Kumar, "Construction with quadrotor teams," *Autonomous Robots*, vol. 33, no. 3, pp. 323–336, 2012.

[14] J.-P. Ore, S. Elbaum, A. Burgin, B. Zhao, and C. Detweiler, "Autonomous aerial water sampling," in *Field and Service Robotics: Results of the 9th Int. Conf.*, Brisbane, Austrailia, 2015, pp. 137–151.

[15] L. Vacek, E. Atter, P. Rizo, B. Nam, R. Kortvelesy, D. Kaufman, J. Das, and V. Kumar, "sUAS for deployment and recovery of an environmental sensor probe," in *Proc. 2017 Int. Conf. Unmanned Aircraft Systems (ICUAS)*. Miami, FL, USA: IEEE, 2017, pp. 1022–1029.

[16] M. Fumagalli, R. Naldi, A. Macchelli, F. Forte, A. Q. L. Keemink, S. Stramigioli, R. Carloni, and L. Marconi, "Developing an aerial manipulator prototype: Physical interaction with the environment," *IEEE Robotics Automation Magazine*, vol. 21, no. 3, pp. 41–50, Sept 2014.

[17] W. Greenwood, H. Zhou, J. Lynch, and D. Zekkos, "UAV-Deployed impulsive source localization with sensor network," *Advances in Science and Technology*, vol. 101, pp. 104–111, 10 2016.

[18] M. Fanni and A. Khalifa, "A new 6-DOF quadrotor manipulation system: Design, kinematics, dynamics, and control," *IEEE/ASME Transactions on Mechatronics*, vol. 22, no. 3, pp. 1315–1326, June 2017.

[19] Y. Stergiopoulos, E. Kontouras, K. Gkountas, K. Giannousakis, and A. Tzes, "Modeling and control aspects of a UAV with an attached manipulator," in *Proc. 24th Mediterranean Conf. Control and Automation (MED)*. Athens, Greece: IEEE, 2016, pp. 653–658.

[20] C. Korpela, M. Orsag, M. Pekala, and P. Oh, "Dynamic stability of a mobile manipulating unmanned aerial vehicle," in *Proc. 2013 IEEE Int. Conf. Robotics Automation*. Karlsruhe, Germany: IEEE, 2013, pp. 4922–4927.

[21] C. M. Korpela, T. W. Danko, and P. Y. Oh, "Designing a system for mobile manipulation from an unmanned aerial vehicle," in *Proc. 2011 IEEE Conference on Technologies for Practical Robot Applications*. Woburn, MA, USA: IEEE, April 2011, pp. 109–114.

[22] P. Pounds, D. Bersak, and A. M. Dollar, "Stability of small-scale UAV helicopters and quadrotors with added payload mass under PID control," *Autonomous Robots*, vol. 33, no. 1-2, pp. 129–142, 2012.

[23] M. Orsag, C. Korpela, and P. Oh, "Modeling and control of MM-UAV: Mobile manipulating unmanned aerial vehicle," *Journal of Intelligent and Robot Systems*, vol. 65, no. 1-4, pp. 93–101, 2012.

[24] D. Mellinger, Q. Lindsey, M. Shomin, and V. Kumar, "Design, modeling, estimation and control for aerial grasping and manipulation," in *Proc. IEEE Int. Conf. Intelligent Robots and Systems (IROS)*. San Francisco, CA, USA: IEEE, 2011, pp. 2668–2673.

[25] V. Ghadiok, J. Goldin, and W. Ren, "Autonomous indoor aerial gripping using a quadrotor," in *Proc. 2011 IEEE Int. Conf. Intelligent Robots and Systems (IROS)*, San Francisco, CA, USA, 2011.

[26] K. Kondak, K. Krieger, A. Albu-Schaeffer, M. Schwarzbach, M. Laiacker, I. Maza, A. Rodriguez-Castano, and A. Ollero, "Closed-loop behavior of an autonomous helicopter equipped with a robotic arm for aerial manipulation tasks," *Int. J. Advanced Robotic Systems*, vol. 10, no. 2, p. 145, 2013.

[27] D. Katz, A. Venkatraman, M. Kazemi, J. A. Bagnell, and A. Stentz, "Perceiving, learning, and exploiting object affordances for autonomous pile manipulation," *Autonomous Robots*, vol. 37, no. 4, pp. 369–382, 2014.

[28] T. M. Howard, M. Pivtoraiko, R. A. Knepper, and A. Kelly, "Model-predictive motion planning: Several key developments for autonomous mobile robots," *IEEE Robotics & Automation Magazine*, vol. 21, no. 1, pp. 64–73, 2014.

[29] M. Naveau, M. Kudruss, O. Stasse, C. Kirches, K. Mombaur, and P. Souères, "A reactive walking pattern generator based on nonlinear model predictive control," *IEEE Robotics and Automation Letters*, vol. 2, no. 1, pp. 10–17, 2017.

[30] C. C. Kemp, A. Edsinger, and E. Torres-Jara, "Challenges for robot manipulation in human environments [Grand Challenges of Robotics]," *IEEE Robotics Automation Magazine*, vol. 14, no. 1, pp. 20–29, March 2007.

[31] C. M. Dellin, K. Strabala, G. C. Haynes, D. Stager, and S. S. Srinivasa, "Guided manipulation planning at the DARPA robotics challenge trials," in *Proc. 14th Int. Symp. Experimental Robotics*, M. A. Hsieh, O. Khatib, and V. Kumar, Eds. Marrakech, Morocco: Springer International Publishing, 2016, pp. 149–163.

[32] J. Y. C. Chen, E. Hass, and M. J. Barnes, "Human performance issues and user interface design for teleoperated robots," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 37, no. 6, pp. 1231–1245, 2007.

[33] N. Cooke and R. Chadwick, "Lessons learned from human-robotic interactions on the ground and in the air," in *Human-Robot Interactions in Future Military Operations*, F. Jentsch and M. Barnes, Eds. CRC Press, 2016, pp. 355–373.

[34] R. Murphy and J. Burke, "From remote tool to shared roles," *IEEE Robotics & Automation*, vol. 15, no. 4, pp. 39–49, 2008.

[35] H. Shim, B. H. Jun, P. M. Lee, H. Baek, and J. Lee, "Workspace control system of underwater tele-operated manipulators on an ROV," *Ocean Engineering*, vol. 37, no. 1112, pp. 1036–1047, 2010.

[36] P. M. Lee, C. M. Lee, B. H. Jun, H. T. Choi, J. H. Li, S. M. Kim, K. Kim, Y. K. Lim, S. I. Yang, S. W. Hong, S. C. Han, B. M. Gu, S. R. Lee, Y. W. Seo, T. Aoki, and A. Bowen, "System design and development of a deep-sea unmanned underwater vehicle HEMIRE for oceanographic research," in *Proc. 6th Int. Offshore and Polar Engineering Conf.* Los Angeles, CA, USA: ISOPE, 2006, pp. 205–212.

[37] G. Marani, S. K. Choi, and J. Yuh, "Underwater autonomous manipulation for intervention missions AUVs," *Ocean Engineering*, vol. 36, no. 1, pp. 15–23, 2009.

[38] S. Vozar and D. M. Tilbury, "Augmented reality user interface for mobile robots with manipulator arms: Development, testing, and qualitative analysis," in *Proc. ASME Int. Design Engineering Technical Conf. & Computers and Information in Engineering Conf. (IDETC/CIE)*. Chicago, IL, USA: ASME, 2012, pp. 1341–1350.

[39] M. Mast, Z. Materna, M. Ŝpanêl, F. Weisshardt, G. Arbeiter, M. Burmester, P. Smrẑ, and B. Graf, "Semi-autonomous domestic service robots: Evaluation of a user interface for remote manipulation and navigation with focus on effects of stereoscopic display," *International Journal of Social Robotics*, vol. 7, no. 2, pp. 183–202, 2015.

[40] B. Day, C. Bethel, R. Murphy, and J. Burke, "A depth sensing display for bomb disposal robots," in *Proc. 2008 IEEE Int. Workshop on Safety, Security and Rescue Robotics (ISSR)*. Sendai, Japan: IEEE, 2008, pp. 146–151.

[41] C. Parga, X. Li, and W. Yu, “Tele-manipulation of robot arm with smartphone,” in *Proc. 2013 6th Int. Symp. Resilient Control Systems (ISRCS)*. San Francisco, CA, USA: IEEE, 2013, pp. 60–65.

[42] K. Chintamani, A. Cao, R. D. Ellis, and A. K. Pandya, “Improved telemanipulator navigation during display-control misalignments using augmented reality cues,” *IEEE Transactions on Systems, Man, and Cybernetics, Part A (Systems and Humans)*, vol. 40, no. 1, pp. 29–39, 2010.

[43] J. Moore, K. C. Wolfe, M. S. Johannes, K. D. Katyal, M. P. Para, R. J. Murphy, J. Hatch, C. J. Taylor, R. J. Bamberger, and E. Tunstel, “Nested marsupial robotic system for search and sampling in increasingly constrained environments,” in *Proc. 2016 IEEE Int. Conf. Sys., Man, and Cybernetics (SMC)*. Budapest, Hungary: IEEE, Oct 2016, pp. 279–286.

[44] J. A. Atherton and M. A. Goodrich, “Supporting remote manipulation with an ecological augmented virtuality interface,” *Proc. 2009 Symp. on New Frontiers in Human-Robot Interaction/Artificial Intelligence and Simulation of Behaviour (AISB)*, 2009.

[45] J. Peschel and R. Murphy, “On the human-machine interaction of unmanned aerial system mission specialists,” *IEEE Transactions on Human-Machine Systems*, vol. 43, no. 1, 2013.

[46] R. Murphy, K. Pratt, and J. Burke, “Crew roles and operational protocols for rotary-wing micro-UAVs in close urban environments,” in *Proc. 3rd ACM/IEEE Int. Conf. Human-Robot Interaction*. Amsterdam, Netherlands: ACM, 2008, pp. 73–80.

[47] J. Peschel, B. Duncan, and R. Murphy, “Exploratory results for a mission specialist interface in micro unmanned aerial systems,” in *Proc. 2012 Int. Conf. Collaboration Technologies and Systems (CTS)*. Denver, CO, USA: IEEE, 2012, pp. 131–140.

[48] J. Peschel, “Mission specialist human-robot interaction in micro unmanned aerial systems,” Ph.D. dissertation, Texas A&M University, 2012.

[49] Department of Defense UAS Task Force, Airspace Integration Integrated Product Team, "Department of Defense unmanned aircraft system airspace integration plan, Version 2.0," United States Department of Defense, Tech. Rep. 1-7ABA52E, 2011.

[50] J. Peschel, "Towards physical object manipulation by small unmanned aerial systems," in *Proc. 2012 IEEE Int. Symp. on Safety, Security, and Rescue Robotics (SSRR)*. College Station, TX, USA: IEEE, 2012, pp. 1–6.

[51] P. Pounds and A. M. Dollar, "UAV rotorcraft in compliant contact: Stability analysis and simulation," in *Proc. 2011 IEEE Int. Conf. Intelligent Robots and Systems (IROS)*. San Francisco, CA, USA: IEEE, 2011, pp. 2660–2667.

[52] H. Tsukagoshi, M. Watanabe, T. Hamada, D. Ashlih, and R. Iizuka, "Aerial manipulator with perching and door-opening capability," in *Proc. 2015 IEEE Int. Conf. Robotics Automation*. Seattle, Washington: IEEE, 2015, pp. 4663–4668.

[53] L. Marconi, R. Naldi, A. Torre, J. Nikolic, C. Huerzeler, G. Caprari, E. Zwicker, B. Siciliano, V. Lippiello, R. Carloni, and S. Stramigioli, "Aerial service robots: An overview of the airobots activity," in *Proc. 2012 2nd Int. Conf. Applied Robotics for the Power Industry (CARPI)*. Zurich, Switzerland: IEEE, Sept 2012, pp. 76–77.

[54] L. Marconi, F. Basile, G. Caprari, R. Carloni, P. Chiacchio, C. Hurzeler, V. Lippiello, R. Naldi, J. Nikolic, B. Siciliano, S. Stramigioli, and E. Zwicker, "Aerial service robotics: The AIRobots perspective," in *Proc. 2012 2nd Int. Conf. Applied Robotics for the Power Industry (CARPI)*. Zurich, Switzerland: IEEE, Sept 2012, pp. 64–69.

[55] P. Pounds, D. Bersak, and A. M. Dollar, "Grasping from the air: Hovering capture and load stability," in *Proc. 2011 Int. Conf. Robotics and Automation (ICRA)*. Shanghai, China: IEEE, 2011, pp. 2491–2498.

[56] I.-W. Park, E. Wong, P. Piacenza, and M. Ciocarlie, “Developing a 3-DOF compliant perching arm for a free-flying robot on the international space station,” in *Proc. 2015 IEEE Int. Conf. Robotics Automation (ICRA)*. Seattle, WA, USA: IEEE, 2015.

[57] D. Mellinger, M. Shomin, and V. Kumar, “Control of quadrotors for robust perching and landing,” in *Proc. 2010 Int. Powered Lift Conf.* Philadelphia, PA, USA: AHS, 2010.

[58] J. Zerihan and X. Zhang, “Aerodynamics of a single element wing in ground effect,” *Journal of Aircraft*, vol. 37, no. 6, pp. 1058–1064, 2000.

[59] L. Marconi, F. Basile, G. Caprari, R. Carloni, P. Chiacchio, C. Hurzeler, V. Lippiello, R. Naldi, J. Nikolic, B. Siciliano, S. Stramigioli, and E. Zwicker, “Aerial service robotics: The AIRobots perspective,” in *Proc. 2012 2nd International Conf. on Applied Robotics for the Power Industry (CARPI)*. Zurich, Switzerland: IEEE, Sept 2012, pp. 64–69.

[60] G. A. Nixon, J. G. Wildenbeest, and D. A. Abbink, “Effective human-machine interfaces for aerial telemanipulation,” *Journal of Delft Haptics Lab*, vol. 1, no. 1, pp. 1–10, 2015.

[61] R. R. Murphy, S. Tadokoro, D. Nardi, A. Jacoff, P. Fiorini, H. Choset, and A. M. Erkmen, “Search and rescue robotics,” in *Springer Handbook of Robotics*. Springer, 2008, pp. 1151–1173.

[62] H. G. Nguyen and J. P. Bott, “Robotics for law enforcement: Applications beyond explosive ordnance disposal,” in *Enabling Technologies for Law Enforcement and Security*, vol. 4232, 2001, pp. 433–455.

[63] Q. Lindsey, D. Mellinger, and P. Kumar, “Construction of cubic structures with quadrotor teams,” in *Proc. Robotics: Science & Systems VII*, Los Angeles, CA, USA, 2011, pp. 177–184.

[64] J. Werfel, Y. Bar-Yam, D. Rus, and R. Nagpal, “Distributed construction by mobile robots with enhanced building blocks,” in *Proc. 2006 IEEE Int. Conf. Robotics and Automation (ICRA)*. Orlando, FL, USA: IEEE, 2006, pp. 2787–2794.

[65] L. A. Nguyen, M. Bualat, L. J. Edwards, L. Flueckiger, C. Neveu, K. Schwehr, M. D. Wagner, and E. Zbinden, “Virtual reality interfaces for visualization and control of remote vehicles,” *Autonomous Robots*, vol. 11, no. 1, pp. 59–68, 2001.

[66] D. Wettergreen, M. Bualat, D. Christian, K. Schwehr, H. Thomas, D. Tucker, and E. Zbinden, “Operating Nomad during the Atacama Desert Trek,” in *Field and Service Robotics*, A. Zelinsky, Ed. Springer London, 1998, pp. 82–89.

[67] A. Parness, M. Frost, N. Thatte, J. P. King, K. Witkoe, M. Nevarez, M. Garrett, H. Aghazarian, and B. Kennedy, “Gravity-independent rock-climbing robot and a sample acquisition tool with microspine grippers,” *J. of Field Robotics*, vol. 30, no. 6, pp. 897–915, 2013.

[68] M. Jadaliha and J. Choi, “Environmental monitoring using autonomous aquatic robots: Sampling algorithms and experiments,” *IEEE Transactions on Control Systems Technology*, vol. 21, no. 3, pp. 899–905, 2013.

[69] M. Dunbabin and L. Marques, “Robots for environmental monitoring: Significant advancements and applications,” *IEEE Robotics & Automation Magazine*, vol. 19, no. 1, pp. 24–39, 2012.

[70] D. R. McArthur, A. B. Chowdhury, and D. J. Cappelleri, “Design of the I-BoomCopter UAV for environmental interaction,” in *Proc. 2017 IEEE Int. Conf. Robotics Automation (ICRA)*. Singapore: IEEE, 2017, pp. 5209–5214.

[71] C. Korpela, M. Orsag, and P. Oh, “Towards valve turning using a dual-arm aerial manipulator,” in *Proc. 2014 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*. Chicago, IL: IEEE, 2014, pp. 3411–3416.

[72] T. W. Kim, G. Marani, and J. Yuh, “Underwater vehicle manipulators,” in *Springer Handbook of Ocean Engineering*, M. R. Dhanak and N. I. Xiros, Eds. Springer International Publishing, 2016, pp. 407–422.

[73] S. Vozar and D. M. Tilbury, “Improving UGV teleoperation performance using novel visualization techniques and manual interfaces,” in *Unmanned Systems Technology XIV*, vol. 8387, 2012, pp. 838 716–1–8.

[74] R. Marin, P. J. Sanz, P. Nebot, and R. Wirz, “A multimodal interface to control a robot arm via the web: A case study on remote programming,” *IEEE Trans. Ind. Electron.*, vol. 52, no. 6, pp. 1506–1520, Dec 2005.

[75] J. Aleotti, S. Caselli, and M. Reggiani, “Multimodal user interface for remote object exploration with sparse sensory data,” in *Proc. 11th IEEE Int. Workshop on Robot and Human Interactive Communication*. Berlin, Germany: IEEE, 2002, pp. 41–46.

[76] R. P. Khurshid, N. T. Fitter, E. A. Fedalei, and K. J. Kuchenbecker, “Effects of grip-force, contact, and acceleration feedback on a teleoperated pick-and-place task,” *IEEE Transactions on Haptics*, vol. 10, no. 1, pp. 40–53, Jan 2017.

[77] N. Y. Lii, Z. Chen, B. Pleintinger, C. H. Borst, G. Hirzinger, and A. Schiele, “Toward understanding the effects of visual- and force-feedback on robotic hand grasping performance for space teleoperation,” in *Proc. 2010 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*. Taipei, Taiwan: IEEE, Oct 2010, pp. 3745–3752.

[78] F. Schill, R. Mahony, P. Corke, and L. Cole, “Virtual force feedback teleoperation of the InsectBot using optic flow.” in *Proc. 2008 Australasian Conf. Robotics and Automation (ACRA)*, Canberra, Austrailia, 2008.

[79] K. Won, F. Tendick, S. Ellis, and L. Stark, “A comparison of position and rate control for telemanipulations with consideration of manipulator system dynamics,” *IEEE Journal on Robotics and Automation*, vol. 3, no. 5, pp. 426–436, 1987.

[80] A. H. Herdocia, A. Shademan, and M. Jägersand, “Unimodal asymmetric interface for teleoperation of mobile manipulators: A user study,” in *Proc. 2012 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*. Vilamoura, Algarve, Portugal: IEEE, 2012, pp. 5214–5219.

[81] T. L. Gibo, L. N. Verner, D. D. Yuh, and A. M. Okamura, “Design considerations and human-machine performance of moving virtual fixtures,” in *Proc. 2009 IEEE Int. Conf. Robotics and Automation (ICRA)*. Kobe, Japan: IEEE, 2009, pp. 671–676.

[82] R. Taylor, P. Jensen, L. Whitcomb, A. Barnes, R. Kumar, D. Stoianovici, P. Gupta, Z. Wang, E. Dejuan, and L. Kavoussi, “A steady-hand robotic system for microsurgical augmentation,” *International Journal of Robotics Research*, vol. 18, no. 12, pp. 1201–1210, 1999.

[83] G. Niemeyer, C. Preusche, and G. Hirzinger, “Telerobotics,” in *Springer Handbook of Robotics*. Springer, 2008, pp. 741–757.

[84] M. C. Yip, M. Tavakoli, and R. D. Howe, “Performance analysis of a haptic telemanipulation task under time delay,” *Advanced Robotics*, vol. 25, no. 5, pp. 651–673, 2011.

[85] S. E. Salcudean, M. Zhu, W.-H. Zhu, and K. Hashtrudi-Zaad, “Transparent bilateral teleoperation under position and rate control,” *Int. J. Robot. Res.*, vol. 19, no. 12, pp. 1185–1202, Dec 2000.

[86] J. Thomas, G. Loianno, J. Polin, K. Sreenath, and V. Kumar, “Toward autonomous avian-inspired grasping for micro aerial vehicles,” *Bioinspiration and Biomimetics*, vol. 9, no. 2, pp. 1–27, 2014.

[87] D. Mellinger, M. Shomin, N. Michael, and V. Kumar, “Cooperative grasping and transport using multiple quadrotors,” in *Distributed Autonomous Robotic Systems: The 10th Int. Symp.* Springer Berlin Heidelberg, 2013, pp. 545–558.

[88] K. Morton and L. Toro, “Development of a robust framework for an outdoor mobile manipulation UAV,” in *IEEE Aerospace*. IEEE, 2016, pp. 1–8.

[89] S. Kim, S. Choi, and H. J. Kim, “Aerial manipulation using a quadrotor with a two DOF robotic arm,” in *Proc. 2013 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*. Tokyo, Japan: IEEE, 2013, pp. 4990–4995.

[90] S. Kim, H. Seo, S. Choi, and H. J. Kim, “Vision-guided aerial manipulation using a multirotor with a robotic arm,” *IEEE/ASME Transactions on Mechatronics*, vol. 21, no. 4, pp. 1912–1923, Aug 2016.

[91] A. Dollar and R. Howe, “Joint coupling design of underactuated hands for unstructured environments.” *Int. J. Robotics Research*, vol. 30, no. 9, pp. 1157–1169, 2011.

[92] A. Suarez, A. E. Jimenez-Cano, V. M. Vega, G. Heredia, A. Rodrguez-Castao, and A. Ollero, "Lightweight and human-size dual arm aerial manipulator," in *Proc. 2017 Int. Conf. on Unmanned Aircraft Systems (ICUAS)*. Miami, FL, USA: IEEE, June 2017, pp. 1778–1784.

[93] A. Q. L. Keemink, M. Fumagalli, S. Stramigioli, and R. Carloni, "Mechanical design of a manipulation system for unmanned aerial vehicles," in *Proc. 2012 IEEE Int. Conf. on Robotics and Automation (ICRA)*. Minneapolis, MN, USA: IEEE, 2012, pp. 3147–3152.

[94] K. Kosuge, T. Itoh, and T. Fukuda, "Scaled telemanipulation with communication time delay," in *Proc. 1996 Int. Conf. Robotics and Automation (ICRA)*, vol. 3. Minneapolis, MN, USA: IEEE, 1996, pp. 2019–2024.

[95] L. Slutski, "Control Methods in the Systems 'Operator-Remote Manipulator'," in *Remote Manipulation Systems: Quality Evaluation and Improvement*, ser. Microprocessor-based and Intelligent Systems Engineering, S. Tzafestas, Ed. Kluwer Academic Publishers, 1998, vol. 17, pp. 59–117.

[96] S. Avgousti, E. G. Christoforou, A. S. Panayides, S. Voskarides, C. Novales, L. Nouaille, C. S. Pattichis, and P. Vieyres, "Medical telerobotic systems: Current status and future trends," *BioMedical Engineering OnLine*, vol. 15, p. 96, 2016.

[97] J. P. Ruurda, T. J. M. V. van Vroonhoven, and I. A. M. J. Broeders, "Robot-assisted surgical systems: A new era in laparoscopic surgery," *Annals of The Royal College of Surgeons of England*, vol. 84, no. 4, pp. 223–226, 2002.

[98] M. Hildebrandt, L. Christensen, J. Kerdels, J. Albiez, and F. Kirchner, "Realtime motion compensation for ROV-based tele-operated underwater manipulators," in *OCEANS-EUROPE*. Bremen, Germany: IEEE, 2009, pp. 1–6.

[99] B.-H. Jun, P. M. Lee, and J. Lee, "Manipulability analysis of underwater robotic arms on ROV and application to task-oriented joint configuration," in *2004 MTS/IEEE TECHNO-OCEAN*, vol. 3. Kobe, Japan: IEEE, Nov 2004, pp. 1548–1553.

[100] S. McMillan, D. E. Orin, and R. B. McGhee, "Efficient dynamic simulation of an underwater vehicle with a robotic manipulator," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 25, no. 8, pp. 1194–1206, 1995.

[101] Seamor Marine, "Seamor ROV Specifications," accessed: 2017-10-15. [Online]. Available: http:///seamor.com/products/

[102] R. R. Murphy, K. L. Dreger, S. Newsome, J. Rodocker, E. Steimle, T. Kimura, K. Makabe, F. Matsuno, S. Tadokoro, and K. Kon, "Use of remotely operated marine vehicles at Minamisanriku and Rikuzentakata Japan for disaster recovery," in *2011 IEEE Int. Symp. Safety, Security, and Rescue Robotics (ISSR)*. Kyoto, Japan: IEEE, Nov 2011, pp. 19–25.

[103] R. Clavel, "Device for the movement and positioning of an element in space." U.S. Patent 4 976 582, 1989.

[104] S. Martin and N. Hillier, "Characterization of the Novint Falcon haptic device for application as a robot manipulator," in *Proc. 2009 Australasian Conf. Robotics and Automation (ACRA)*, Sydney, Australia, 2009, pp. 1–9.

[105] D. Song, K. Goldberg, and N. Y. Chong, "Networked telerobots," in *Springer Handbook of Robotics*. Springer Berlin Heidelberg, 2008, pp. 759–771.

[106] I. Belousov, S. Chebukov, and V. Sazonov, "Web-based teleoperation of the robot interacting with fast moving objects," in *Proc. 2005 IEEE Int. Conf. Robotics and Automation (ICRA)*, IEEE. Barcelona, Spain: IEEE, 2005, pp. 673–678.

[107] A. K. Mishra and O. Meruvia-Pastor, "Robot arm manipulation using depth-sensing cameras and inverse kinematics," in *2014 Oceans - St. John's*. St. John's, NL, Canada: IEEE, 2014, pp. 1–6.

[108] T. L. Chen, M. Ciocarlie, S. Cousins, P. M. Grice, K. Hawkins, K. Hsiao, C. C. Kemp, C.-H. King, D. A. Lazewatsky, H. Nguyen et al., "Robots for humanity: A case study in assistive mobile manipulation," in *IEEE Robot. Autom. Mag., Special Issue Assistive Robotics*, vol. 20, no. 1, 2013.

[109] A. Speers, P. M. Forooshani, M. Dicke, and M. Jenkin, "Lightweight tablet devices for command and control of ROS-enabled robots," in *Proc. of 16th Int. Conf. Adv. Robot. (ICAR)*. Montevideo, Uruguay: IEEE, Nov 2013, pp. 1–6.

[110] Z. Materna, M. Spanel, M. Mast, V. Beran, F. Weisshardt, M. Burmester, and P. Smrz, "Teleoperating Assistive Robots: A Novel User Interface Relying on Semi-Autonomy and 3D Environment Mapping," *J. Robotics and Mechatronics*, vol. 29, no. 2, pp. 381–394, 2017.

[111] S. Vozar, "A framework for improving the speed and performance of teleoperated mobile manipulators," Ph.D. dissertation, The University of Michigan, 2013.

[112] C. S. Tzafestas, N. Palaiologou, and M. Alifragis, "Experimental evaluation and pilot assessment study of a virtual and remote laboratory on robotic manipulation," in *Proc. 2005 IEEE Int. Symp. Industrial Electronics (ISIE)*, vol. 4. Dubrovnik, Croatia: IEEE, June 2005, pp. 1677–1684.

[113] A. Nawab, K. Chintamani, D. Ellis, G. Auner, and A. Pandya, "Joystick mapped augmented reality cues for end-effector controlled tele-operated robots," in *Proc. 2007 IEEE Virtual Reality Conf.* Costa Mesa, CA, USA: IEEE, 2007, pp. 263–266.

[114] Y. P. Toh, S. Huang, J. Lin, M. Bajzek, G. Zeglin, and N. S. Pollard, "Dexterous telemanipulation with a multi-touch interface," in *Proc. 2012 12th IEEE-RAS Int. Conf. Humanoid Robots*. Osaka, Japan: IEEE, 2012, pp. 270–277.

[115] S. Hashimoto, A. Ishida, M. Inami, and T. Igarashi, "Touchme: An augmented reality based remote robot manipulation," in *Proc. 21st Int. Conf. Artificial Reality and Telexistence (ICAT)*, vol. 2, Osaka, Japan, 2011.

[116] D. A. Lopez, J. A. Frank, and V. Kapila, "Comparing interface elements on a tablet for intuitive teleoperation of a mobile manipulator," in *Proc. ASME 12th Biennial Conf. Engineering Systems Design and Analysis*, Copenhagen, Denmark, 2014, pp. 1–10.

[117] J. V. Draper, "Teleoperator hand controllers: A contextual human factors assessment," in *Environmental Restoration and Waste Management Program*. Oak Ridge National Laboratory, 1994.

[118] T. B. Sheridan, "Supervisory control of remote manipulators, vehicles, and dynamic processes: Experiments in command and display aiding," Engineering Psychology Group Office of Naval Research, Tech. Rep. DTIC ADA129678, 1983.

[119] T. B. Sheridan and W. L. Verplank, "Human and computer control of undersea teleoperators," Massachusetts Institute of Technology, Cambridge Man-Machine Systems Lab, Tech. Rep. ADA057655, 1978.

[120] O. Ben-Porat, M. Shoham, and J. Meyer, "Control design and task performance in endoscopic teleoperation," *Presence*, vol. 9, no. 3, pp. 256–267, Jun 2000.

[121] F. Lai, R. Howe, and P. Millman, "Frame mapping and dexterity for surgical task performance in robotic endoscopic surgery," in *Proc. 1999 ASME Dym. Sys. Contr. Div.*, Nashville, TN, USA, 1999.

[122] M. R. Endsley, "Design and evaluation for situation awareness enhancement," *Proc. 1988 Human Factors Society Annu. Meeting*, vol. 32, no. 2, pp. 97–101, 1988.

[123] E. You and K. Hauser, "Assisted teleoperation strategies for aggressively controlling a robot arm with 2d input," in *Proc. Robotics: Science and Systems*, Los Angeles, CA, USA, 2011.

[124] A. Singh, S. H. Seo, Y. Hashish, M. Nakane, J. E. Young, and A. Bunt, "An interface for remote robotic manipulator control that reduces task load and fatigue," in *Proc. 2013 IEEE Conf. Robot and Human Interactive Communication (RO-MAN)*. Gyeongju, South Korea: IEEE, Aug 2013, pp. 738–743.

[125] P. Hebert, J. Ma, J. Borders, A. Aydemir, M. Bajracharya, N. Hudson, K. Shankar, S. Karumanchi, B. Douillard, and J. Burdick, "Supervised remote robot with guided autonomy and teleoperation (SURROGATE): A framework for whole-body manipulation," in *Proc. 2015 IEEE Int. Conf. Robotics Automation (ICRA)*. Seattle, WA, USA: IEEE, May 2015, pp. 5509–5516.

[126] S. Payandeh and Z. Stanisic, "On application of virtual fixtures as an aid for telemanipulation and training," in *Proc. 10th Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS)*. Orlando, FL, USA: IEEE, 2002, pp. 18–23.

[127] T. Xia, S. Léonard, A. Deguet, L. Whitcomb, and P. Kazanzides, "Augmented reality environment with virtual fixtures for robotic telemanipulation in space," in *Proc. 2012 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*. Vilamoura, Algarve, Portugal: IEEE, 2012, pp. 5059–5064.

[128] S. E. Navarro, F. Heger, F. Putze, T. Beyl, T. Schultz, and B. Hein, "Telemanipulation with force-based display of proximity fields," in *Proc. 2015 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*. Hamburg, Germany: IEEE, 2015, pp. 4568–4574.

[129] C. P. Sayers, R. P. Paul, L. L. Whitcomb, and D. R. Yoerger, "Teleprogramming for subsea teleoperation using acoustic communication," *IEEE Journal of Oceanic Engineering*, vol. 23, no. 1, pp. 60–71, 1998.

[130] A. B. Kuang, S. Payandeh, Z. Bin, F. Henigman, and C. L. MacKenzie, "Assembling virtual fixtures for guidance in training environments," in *Proc. 12th Int. Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems*. Chicago, IL, USA: IEEE, 2004, pp. 367–374.

[131] F. Saito and T. Suehiro, "Toward telemanipulation via 2-D interface-concept and first result of "Titi"," in *Proc. IEEE 28th Annual Conf. Industrial Electronics Society (IECON)*, vol. 3. Sevilla, Spain: IEEE, 2002, pp. 2243–2248 vol.3.

[132] H. Chen, Y. Kakiuchi, M. Saito, K. Okada, and M. Inaba, "View-based multi-touch gesture interface for furniture manipulation robots," in *Advanced Robotics and its Social Impacts*, 2011, pp. 39–42.

[133] M. Bengel, K. Pfeiffer, B. Graf, A. Bubeck, and A. Verl, "Mobile robots for offshore inspection and manipulation," in *Proc. 2009 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*. St. Louis, MO, USA: IEEE, 2009, pp. 3317–3322.

[134] R. Jagacinski, D. Repperger, S. Ward, and M. Moran, "A test of Fitts' law with moving targets," *Human Factors*, vol. 22, pp. 225–233, 1980.

[135] R. Jagacinski, D. Repperger, M. Moran, S. Ward, and B. Glass, "Fitts' law and the microstructure of rapid discrete movements," *J. Exp. Psychol. Hum. Percept. Perform.*, vol. 6, pp. 309–320, 1980.

[136] B. Kantowitz and G. Elvers, "Fitts' law with an isometric controller: Effects of order of control and control-display gain." *J. Motor Behavior*, vol. 20, no. 1, pp. 53–66, 1988.

[137] W. Kim, F. Tendick, and L. Stark, "Visual enhancements in pick-and-place tasks: Human operators controlling a simulated cylindrical manipulator," *IEEE Journal on Robotics and Automation*, vol. 3, no. 5, pp. 418–425, October 1987.

[138] G. S. Gupta, S. C. Mukhopadhyay, C. H. Messom, and S. N. Demidenko, "Master-slave control of a teleoperated anthropomorphic robotic arm with gripping force sensing," *IEEE Trans. Instrum. Meas.*, vol. 55, no. 6, pp. 2136–2145, Dec 2006.

[139] D. A. Lawrence, "Stability and transparency in bilateral teleoperation," *IEEE Transactions on Robotics and Automation*, vol. 9, no. 5, pp. 624–637, 1993.

[140] L. J. Love and W. J. Book, "Force reflecting teleoperation with adaptive impedance control," *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, vol. 34, no. 1, pp. 159–165, 2004.

[141] P. Fischer, R. Daniel, and K. Siva, "Specification and design of input devices for teleoperation," in *Proc. 1990 IEEE Int. Conf. Robotics and Automation (ICRA)*. Cincinnati, OH, USA: IEEE, 1990, pp. 540–545.

[142] T. N. Judkins, D. Oleynikov, K. Narazaki, and N. Stergiou, “Robotic surgery and training: Electromyographic correlates of robotic laparoscopic training,” *Surgical Endoscopy And Other Interventional Techniques*, vol. 20, no. 5, pp. 824–829, 2006.

[143] K. S. Hale and K. M. Stanney, “Deriving haptic design guidelines from human physiological, psychophysical, and neurological foundations,” *IEEE Computer Graphics and Applications*, vol. 24, no. 2, pp. 33–39, 2004.

[144] V. Nitsch and B. Färber, “A meta-analysis of the effects of haptic interfaces on task performance with teleoperation systems,” *IEEE Transactions on Haptics*, vol. 6, no. 4, pp. 387–398, 2013.

[145] L. B. Rosenberg, “The use of virtual fixtures as perceptual overlays to enhance operator performance in remote environments,” Stanford University Center for Design Research, Tech. Rep. ADA292450, 1992.

[146] L. Ming and A. M. Okamura, “Recognition of operator motions for real-time assistance using virtual fixtures,” in *Proc. 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. Los Angeles, CA, USA: IEEE, 2003, pp. 125–131.

[147] J. J. Abbott, P. Marayong, and A. M. Okamura, “Haptic virtual fixtures for robot-assisted manipulation,” in *Robotics Research*, S. Thrun, R. Brooks, and H. Durrant-Whyte, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2007, pp. 49–64.

[148] A. M. Okamura, “Methods for haptic feedback in teleoperated robot-assisted surgery,” *The Industrial Robot*, vol. 31, no. 6, pp. 499–508, 2004.

[149] B. Weber and C. Eichberger, “The Benefits of Haptic Feedback in Telesurgery and Other Teleoperation Systems: A Meta-Analysis,” in *Int. Conf. Universal Access in Human-Computer Interaction (UAHCI)*. Los Angeles, CA, USA: Springer, 2015, pp. 394–405.

[150] T. Lam, M. Mulder, and M. van Paasen, “Haptic feedback in uninhabited aerial vehicle teleoperation with time delay,” *AIAA Journal of Guidance, Control, and Dynamics*, vol. 31, no. 6, pp. 1728–1739, 2008.

[151] L. B. Rosenberg, "Virtual fixtures as tools to enhance operator performance in telepresence environments," in *Telemanipulator Technology and Space Telerobotics*, vol. 2057, 1993, pp. 10–22.

[152] A. Bettini, S. Lang, A. Okamura, and G. Hager, "Vision assisted control for manipulation using virtual fixtures: Experiments at macro and micro scales," in *Proc. 2002 IEEE Int. Conf. on Robotics and Automation (ICRA)*, vol. 4. Washington, DC, USA: IEEE, 2002, pp. 3354–3361.

[153] S. A. Bowyer, B. L. Davies, and F. R. y Baena, "Active constraints/virtual fixtures: A survey," *IEEE Transactions on Robotics*, vol. 30, no. 1, pp. 138–157, 2014.

[154] F. Rydén, H. J. Chizeck, S. N. Kosari, H. King, and B. Hannaford, "Using kinect and a haptic interface for implementation of real-time virtual fixtures," in *Proc. 2nd Workshop on RGB-D: Advanced Reasoning with Depth Cameras (in conjunction with RSS 2011)*, Los Angeles, CA, USA, 2011.

[155] D. Aarno, S. Ekvall, and D. Kragic, "Adaptive virtual fixtures for machine-assisted teleoperation tasks," in *Proc. 2005 IEEE Int. Conf. Robotics and Automation (ICRA)*. Barcelona, Spain: IEEE, 2005, pp. 1139–1144.

[156] P. Milgram and F. Kishino, "A taxonomy of mixed reality visual displays," *IEICE Trans. Inf. Syst.*, vol. E77-D, no. 12, pp. 1321–1329, 1994.

[157] J. Carlson and R. R. Murphy, "How UGVs physically fail in the field," *Trans. Rob.*, vol. 21, no. 3, pp. 423–437, 2005.

[158] S. Thomas, "Design of a teleoperated rock sampling system," M.S. thesis, Virginia Polytechnic Institute and State University, 2011.

[159] S. A. Green, M. Billinghurst, X. Chen, and J. G. Chase, "Human-robot collaboration: A literature review and augmented reality approach in design," *International Journal of Advanced Robotic Systems*, vol. 5, no. 1, p. 1, 2008.

[160] B. H. Wilcox, T. Litwin, J. Biesiadecki, J. Matthews, M. Heverly, J. Morrison, J. Townsend, N. Ahmad, A. Sirota, and B. Cooper, "Athlete: A cargo handling and manipulation robot for the moon," *Journal of Field Robotics*, vol. 24, no. 5, pp. 421–434, 2007.

[161] A. Afaq, M. Ahmed, A. Kamal, U. Masood, M. Shahzaib, N. Rashid, M. Tiwana, J. Iqbal, and A. Awan, “Development of FPGA-based system for control of an unmanned ground vehicle with 5-DOF robotic arm,” in *Proc. 2015 15th Int. Conf. Control, Automation and Systems (ICCAS)*, Bremen, Germany, Oct 2015, pp. 724–729.

[162] B. Hine, C. Stoker, M. Sims, D. Rasmussen, P. Hontalas, T. Fong, J. Steele, D. Barch, D. Andersen, and E. Miles, “The application of telepresence and virtual reality to subsea exploration,” in *Proc. 2nd Workshop on Mobile Robots for Subsea Environments*, Monterey, CA, USA, 1994.

[163] Z. Ping, E. Shimizu, and M. Ito, “A teleoperating system for underwater manipulator to practice a time limit task,” in *Proc. 2003 IEEE Int. Symp. Intelligent Control*. Houston, TX, USA: IEEE, 2003, pp. 467–471.

[164] B. D. Conner, S. S. Snibbe, K. P. Herndon, D. C. Robbins, R. C. Zeleznik, and A. Van Dam, “Three-dimensional widgets,” in *Proc. 1992 Symp. Interactive 3D graphics*. San Diego, CA, USA: ACM, 1992, pp. 183–188.

[165] P. Milgram, S. Zhai, D. Drascic, and J. Grodski, “Applications of augmented reality for human-robot communication,” in *Proc. 1993 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*, vol. 3. Tokyo, Japan: IEEE, 1993, pp. 1467–1472.

[166] P. Milgram, S. Yin, and J. J. Grodski, “An augmented reality based teleoperation interface for unstructured environments,” in *Proc. American Nuclear Society (ANS) 7th Topical Meeting on Robotics and Remote Systems*, 1997, pp. 966–973.

[167] K. Ruffo and P. Milgram, “Effect of stereographic + stereovideo ’tether’ enhancement for a peg-in-hole task,” in *Proc. 1992 IEEE Int. Conf. Systems, Man and Cybernetics*. IEEE, 1992, pp. 1425–1430.

[168] D. Drascic and P. Milgram, “Perceptual issues in augmented reality,” in *Stereoscopic Displays and Virtual Reality Systems III*, vol. 2653. International Society for Optics and Photonics, 1996, pp. 123–135.

[169] D. Drascic and P. Milgram, “Positioning accuracy of a virtual stereographic pointer in a real stereoscopic video world,” in *Stereoscopic Displays and Applications II*, vol. 1457. International Society for Optics and Photonics, 1991, pp. 302–314.

[170] P. Milgram, A. Rastogi, and J. J. Grodski, “Telerobotic control using augmented reality,” in *Proc. 4th IEEE Int. Workshop Robot and Human Communication*. Tokyo, Japan: IEEE, 1995, pp. 21–29.

[171] A. Rastogi, “Design of an interface for teleoperation in unstructured environments using augmented reality displays.” Ph.D. dissertation, University of Toronto, 1997.

[172] C. Nielsen, “Using augmented virtuality to improve human-robot interactions.” Ph.D. dissertation, Brigham Young University, 2006.

[173] D. M. Lane, J. B. C. Davies, G. Casalino, G. Bartolini, G. Cannata, G. Veruggio, M. Canals, C. Smith, D. J. O’Brien, M. Pickett, G. Robinson, D. Jones, E. Scott, A. Ferrara, D. Angelleti, M. Coccoli, R. Bono, P. Virgili, R. Pallas, and E. Gracia, “AMADEUS: Advanced manipulation for deep underwater sampling,” *IEEE Robotics Automation Magazine*, vol. 4, no. 4, pp. 34–45, Dec 1997.

[174] J. P. McIntire, P. R. Havig, and E. E. Geiselman, “Stereoscopic 3D displays and human performance: A comprehensive review,” *Displays*, vol. 35, no. 1, pp. 18–26, 2014.

[175] D. Drascic, P. Milgram, and J. Grodski, “Learning effects in telemanipulation with monoscopic versus stereoscopic remote viewing,” in *Proc. IEEE Int. Conf. Systems, Man and Cybernetics*. Cambridge, MA, USA: IEEE, 1989, pp. 1244–1249 vol.3.

[176] J. V. Draper, S. Handel, C. C. Hood, and C. T. Kring, “Three experiments with stereoscopic television: When it works and why,” in *Proc. 1991 IEEE Int. Conf. Systems, Man, and Cybernetics*, vol. 2. Charlottesville, VA, USA: IEEE, 1991, pp. 1047–1052.

[177] A. Monferrer and D. Bonyuet, “Cooperative robot teleoperation through virtual reality interfaces,” in *Proc. 6th IEEE Int. Conf. Information Visualization*. Boston, MA, USA: IEEE, 2002, pp. 243–248.

[178] O. Olmos, C. D. Wickens, and A. Chudy, "Tactical displays for combat awareness: An examination of dimensionality and frame of reference concepts and the application of cognitive engineering," *International Journal of Aviation Psychology*, vol. 10, no. 3, pp. 247–271, 2000.

[179] L. C. Thomas and C. D. Wickens, "Visual displays and cognitive tunneling: Frames of reference effects on spatial judgments and change detection," in *Proc. 2001 Human Factors and Ergonomics Society Annu. Meeting*, vol. 45. SAGE Publications Sage CA: Los Angeles, CA, 2001, pp. 336–340.

[180] J. Casper and R. R. Murphy, "Human-robot interactions during the robot-assisted urban search and rescue response at the World Trade Center," *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, vol. 33, no. 3, pp. 367–385, 2003.

[181] M. Ferre, R. Aracil, and M. A. Sanchez-Uran, "Stereoscopic human interfaces," *IEEE Robotics & Automation Magazine*, vol. 15, no. 4, pp. 50–57, 2008.

[182] A. M. Pinto, P. Costa, A. P. Moreira, L. F. Rocha, G. Veiga, and E. Moreira, "Evaluation of depth sensors for robotic applications," in *Proc. 2015 IEEE Int. Conf. Autonomous Robot Systems and Competitions (ICARSC)*. Torres Vedras, Portugal: IEEE, 2015, pp. 139–143.

[183] S. Foix, G. Alenya, and C. Torras, "Lock-in time-of-flight (ToF) cameras: A survey," *IEEE Sensors Journal*, vol. 11, no. 9, pp. 1917–1926, 2011.

[184] Z. Jiejie, W. Liang, Y. Ruigang, and J. Davis, "Fusion of time-of-flight depth and stereo for high accuracy depth maps," in *Proc. 2008 IEEE Conf. Computer Vision and Pattern Recognition*. Anchorage, AK, USA: IEEE, 2008, pp. 1–8.

[185] J. L. Burke and R. R. Murphy, "Situation awareness and task performance in robot-assisted technical search: Bujold goes to Bridgeport," Center for Robot-Assisted Search and Rescue, Table, FL, USA, Tech. Rep. CRASAR-TR2004-23, 2004.

[186] J. Burke, R. Murphy, M. D. Coovert, and D. Riddle, "Moonlight in Miami: Field study of human-robot interaction in the context of an urban search and rescue disaster response training exercise," *Human Computer Interaction*, vol. 19, no. 1-2, pp. 85–116, 2004.

[187] R. R. Murphy and J. L. Burke, "Up from the rubble: Lessons learned about HRI from search and rescue," *Proc. 2005 Human Factors and Ergonomics Society Annu. Meeting*, vol. 49, no. 3, pp. 437–441, 2005.

[188] R. R. Murphy and S. Stover, "Field studies of safety security rescue technologies through training and response activities," in *Unmanned Systems Technology VIII*, vol. 6230. International Society for Optics and Photonics, 2006, p. 62300M.

[189] G. Hockey and R. John, "Changes in operator efficiency as a function of environmental stress, fatigue, and circadian rhythms." in *Handbook of Perception and Human Performance*, K. R. Boff, L. Kaufman, and J. P. Thomas, Eds. Wiley New York, 1986, vol. 2.

[190] J. L. Burke, "RSVP: An investigation of the effects of Remote Shared Visual Presence on team process and team performance in urban search and rescue teams," Ph.D. dissertation, University of South Florida, 2006.

[191] J. F. Thayer, F. Åhs, M. Fredrikson, J. J. Sollers III, and T. D. Wager, "A meta-analysis of heart rate variability and neuroimaging studies: Implications for heart rate variability as a marker of stress and health," *Neuroscience & Biobehavioral Reviews*, vol. 36, no. 2, pp. 747 – 756, 2012.

[192] L. C. Thomas and C. D. Wickens, "Effects of display frames of reference on spatial judgments and change detection," University of Illinois at Urbana-Champaign Savoy Aviation Research Lab, Tech. Rep. ARL-00-14/FED-LAB-00-4, 2000.

[193] B. G. Witmer and W. J. Sadowski Jr, "Nonvisually guided locomotion to a previously viewed target in real and virtual environments," *Human Factors*, vol. 40, no. 3, pp. 478–488, 1998.

[194] S. Lee Pazuchanics, "The effects of camera perspective and field of view on performance in teleoperated navigation," in *Proc. 2006 Human Factors and Ergonomics Society Annual Meeting*, vol. 50, no. 16. SAGE Publications Sage CA: Los Angeles, CA, 2006, pp. 1528–1532.

[195] D. D. Woods, J. Tittle, M. Feil, and A. Roesler, "Envisioning human-robot coordination in future operations," *IEEE Trans. on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 34, no. 2, pp. 210–218, May 2004.

[196] P. Darken, Rudolph, K. Kempster, and B. Peterson, "Effects of streaming video quality of service on spatial comprehension in a reconnaissance task," in *Proc. 2011 Interservice/Industry Training, Simulation and Education Conf. (I/ITSEC)*, Orlando, FL, USA, 2001, pp. 1–9.

[197] DJI Science and Technology Co., "DJI Matrice 100 User Manual v1.6 2016.03 ." [Online]. Available: https://dl.djicdn.com/downloads/m100/M100_User_Manual_EN.pdf

[198] M. Achtelik, "ROS vicon_bridge driver," 2010. [Online]. Available: https://github.com/ethz-asl/vicon_bridge

[199] S. Weiss, D. Scaramuzza, and R. Siegwart, "Monocular-SLAM–based navigation for autonomous micro helicopters in GPS-denied environments," *Journal of Field Robotics*, vol. 28, no. 6, pp. 854–874, 2011.

[200] T. Ogura, "rqt_ez_publisher," 2016. [Online]. Available: https://github.com/OTL/rqt_ez_publisher

[201] C. Powers, D. Mellinger, and V. Kumar, "Quadrotor kinematics and dynamics," in *Handbook of Unmanned Aerial Vehicles*. Springer, 2015, pp. 307–328.

[202] D. Chinarro, "System identification techniques," in *System Engineering Applied to Fuenmayor Karst Aquifer (San Julin de Banzo, Huesca) and Collins Glacier (King George Island, Antarctica)*, D. Chinarro, Ed. Springer International Publishing, 2014, pp. 11–51.

[203] I. Sa, M. Kamel, R. Khanna, M. Popovic, J. Nieto, and R. Siegwart, "Dynamic System Identification, and Control for a cost effective open-source VTOL MAV," *ArXiv e-prints*, Jan. 2017, arXiv1701.08623. [Online]. Available: http://adsabs.harvard.edu/abs/2017arXiv170108623S

[204] M. Kamel, R. Khanna, A. Vetrella, and I. Sa, "Dynamic system identification," 2017. [Online]. Available: https://github.com/ethz-asl/mav_dji_ros_interface

[205] MATLAB, *version 9.4.0.8 (R2018a)*. Natick, Massachusetts: The MathWorks Inc., 2018.

[206] M. Kamel, T. Stastny, K. Alexis, and R. Siegwart, *Model Predictive Control for Trajectory Tracking of Unmanned Aerial Vehicles Using Robot Operating System*. Cham: Springer International Publishing, 2017, pp. 3–39.

[207] embotech AG, "FORCES Pro," 2018. [Online]. Available: https://www.embotech.com/FORCES-Pro

[208] A. Ronacher, "Flask Web Development, v1.0," 2018. [Online]. Available: http://flask.pocoo.org/

[209] R. Teammco, "Streaming UDP Video," 2016. [Online]. Available: https://github.com/teammcr192/streaming-udp-video

[210] C. L. Bethel and R. R. Murphy, "Review of human studies methods in HRI and recommendations," *International Journal of Social Robotics*, vol. 2, no. 4, pp. 347–359, 2010.

[211] F. Faul, E. Erdfelder, A.-G. Lang, and A. Buchner, "G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences," *Behavior Research Methods*, vol. 39, no. 2, pp. 175–191, 2007.

[212] A. Steinfeld, T. Fong, D. Kaber, M. Lewis, J. Scholtz, A. Schultz, and M. A. Goodrich, "Common metrics for human-robot interaction," in *Proc. 2006 ACM Conf. Hum.-Robot Interact.*, Salt Lake City, Utah, USA, 2006, pp. 33–40.

[213] L. J. Simms, L. R. Goldberg, J. E. Roberts, D. Watson, J. Welte, and J. H. Rotterman, "Computerized adaptive assessment of personality disorder: Introducing the CAT–PD project," *Journal of Personality Assessment*, vol. 93, no. 4, pp. 380–389, 2011.

[214] L. R. Goldberg, "CAT-Personality Disorder Scales Static Form (CAT-PD-SF, v1.1, Simms, et al., 2011)." [Online]. Available: https://ipip.ori.org/newCAT-PD-SFv1.1ComparisonTable.html

[215] L. R. Goldberg, J. A. Johnson, H. W. Eber, R. Hogan, M. C. Ashton, C. R. Cloninger, and H. G. Gough, "The international personality item pool and the future of public-domain personality measures," *Journal of Research in Personality*, vol. 40, no. 1, pp. 84–96, 2006.

[216] J. B. Rotter, "Generalized expectancies for internal versus external control of reinforcement," *Psychological Monographs: General and Applied*, vol. 80, no. 1, p. 1, 1966.

[217] M. J. Findley and H. M. Cooper, "Locus of control and academic achievement: A literature review," *Journal of Personality and Social Psychology*, vol. 44, no. 2, p. 419, 1983.

[218] C. Jewitt, "An introduction to using video for research," *National Centre for Research Methods (NCRM) Working Paper*, 2012.

[219] Datavyu Team, "Datavyu: A Video Coding Tool." 2014, Databrary Project, New York University. [Online]. Available: http://datavyu.org

[220] E. J. Phares and J. T. Lamiell, "Relationship of internal-external control of defensive preferences," *Journal of Consulting and Clinical Psychology*, vol. 42, no. 6, p. 872, 1974.

[221] J. DuCette and S. Wolk, "Locus of control and extreme behavior," *Journal of Consulting and Clinical Psychology*, vol. 39, no. 2, p. 253, 1972.

[222] P. C. Duttweiler, "The internal control index: A newly developed measure of locus of control," *Educational and Psychological Measurement*, vol. 44, no. 2, pp. 209–221, 1984.

[223] S. S. Shapiro and M. B. Wilk, "An analysis of variance test for normality (complete samples)," *Biometrika*, vol. 52, no. 3/4, pp. 591–611, 1965.

[224] J. W. Mauchly, "Significance test for sphericity of a normal n-variate distribution," *The Annals of Mathematical Statistics*, vol. 11, no. 2, pp. 204–209, 1940. [Online]. Available: http://www.jstor.org/stable/2235878

[225] M. Friedman, "The use of ranks to avoid the assumption of normality implicit in the analysis of variance," *Journal of the American Statistical Association*, vol. 32, no. 200, pp. 675–701, 1937.

[226] J. Lazar, J. H. Feng, and H. Hochheiser, *Research Methods in Human-Computer Interaction*. West Sussex, United Kingdom: John Wiley & Sons Ltd, 2010.

[227] R. M. Stern, R. Morris, W. J. Ray, and K. S. Quigley, *Psychophysiological Recording*. Oxford, United Kingdom: Oxford University Press, 2001.

[228] A. Mehrabian, "Analysis of the big-five personality factors in terms of the PAD temperament model," *Australian Journal of Psychology*, vol. 48, no. 2, pp. 86–92, 1996.

[229] P. Gilbert and S. Allan, "Assertiveness, submissive behaviour and social comparison," *British Journal of Clinical Psychology*, vol. 33, no. 3, pp. 295–306, 1994.

[230] P. J. Andrisani and G. Nestel, "Internal-external control as contributor to and outcome of work experience," *Journal of Applied Psychology*, vol. 61, no. 2, p. 156, 1976.

[231] I. Ajzen, "Perceived behavioral control, self-efficacy, locus of control, and the theory of planned behavior: 1," *Journal of Applied Social Psychology*, vol. 32, no. 4, pp. 665–683, 2002.

[232] D. D. Woods and E. Hollnagel, *Joint cognitive systems: Patterns in cognitive systems engineering*. Boca Raton, FL: CRC Press, 2005.

[233] L. C. Thomas and C. D. Wickens, "Immersion and battlefield visualization: Frame of reference effects on navigation tasks and cognitive tunneling," in *Proc. 1999 Human Factors and Ergonomics Society Annual Meeting*, vol. 43, no. 3. SAGE Publications Sage CA: Los Angeles, CA, 1999, pp. 153–157.

[234] C. D. Wickens and C. M. Carswell, “The proximity compatibility principle: Its psychological foundation and relevance to display design,” *Human Factors*, vol. 37, no. 3, pp. 473–494, 1995.

[235] B. G. Witmer and P. B. Kline, “Judging perceived and traversed distance in virtual environments,” *Presence*, vol. 7, no. 2, pp. 144–167, 1998.

APPENDIX A

SYSTEM IDENTIFICATION MATLAB OUTPUT

Roll and Pitch System Identification

```
First order:

The roll model is estimated using experiment 1
and validated on data from experiment 2
The roll model fits the validation data
 with **77.6668** %
The pitch model is estimated using experiment 1
and validated on data from experiment 2
The pitch model fits the validation data
 with **75.4929** %
Roll estimated transfer function is:

ans =

  From input "roll_{cmd}" to output "roll":
    6.994
  ---------
  s + 5.548

Continuous-time transfer function.
roll tau=0.180, gain=1.260
Pitch estimated transfer function is:
```

```
ans =

  From input "pitch_{cmd}" to output "pitch":
    7.206
  ---------
  s + 5.718

Continuous-time transfer function.

pitch tau=0.175, gain=1.260

---------------------------------------------------

Second order:

The roll model is estimated using experiment 1
and validated on data from experiment 2
The roll model fits the validation data
 with **88.1578** %
The pitch model is estimated using experiment 1 and
validated on data from experiment 2
The pitch model fits the validation data
 with **85.3998** %
Roll estimated transfer function is:

ans =

  From input "roll_{cmd}" to output "roll":
        72.88
  ------------------
  s^2 + 8.613 s + 63

Continuous-time transfer function.
```

```
roll omega=7.937, gain=1.157 damping=0.543
Pitch estimated transfer function is:

ans =

  From input "pitch_{cmd}" to output "pitch":
          66.45
  ---------------------
  s^2 + 7.849 s + 58.71

Continuous-time transfer function.

pitch omega=7.662, gain=1.132 damping=0.512

---------------------------------------------------
```

Yaw Rate System Identification

```
First order:

The yawrate model is estimated using experiment 1
and validated on data from experiment 2
The yawrate model fits the validation data
 with **79.8866** %
yawrate estimated transfer function is:
ans =

  From input "yawrate_{cmd}" to output "yawrate":
    3.95
  ---------
  s + 3.765

Continuous-time transfer function.

yawrate gain=1.049, tau=0.266

---------------------------------------------------

Second order:

The yawrate model is estimated using experiment 1
 and validated on data from experiment 2
The yawrate model fits the validation data
 with **79.9876** %
yawrate estimated transfer function is:
```

```
ans =

  From input "yawrate_{cmd}" to output "yawrate":
          457.6
  ---------------------
  s^2 + 116.2 s + 437.2

Continuous-time transfer function.

yawrate omega=20.910, gain=1.046 damping=2.779

---------------------------------------------------
```

Vertical Velocity System Identification

```
First order:

Thrust estimated transfer function is:

ans =

  From input "thrust_{cmd}" to output "thrust":
    6.369
  ---------
  s + 2.532

Continuous-time transfer function.

thrust gain=2.515, tau=0.395
```

APPENDIX B

IRB APPROVAL LETTER AND DOCUMENTS

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 06/22/2018

To: Joshua Peschel

From: Office for Responsible Research

Title: **Human Robot Interaction for Aerial Manipulation Tasks by Ad-Hoc Users**

IRB ID: **18-060**

Submission Type: Modification **Review Type**: Expedited

Approval Date: 06/21/2018 **Date for Continuing Review: 02/19/2020**

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the **recruitment materials and informed consent documents that have the IRB approval stamp**.
- **Retain signed informed consent documents for 3 years after the close of the study,** when documented consent is required**.**
- **Obtain IRB approval prior to implementing any changes** to the study.
- **Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an eligible PI to remain open.
- **Immediately inform the IRB of** (1) **all serious and/or unexpected adverse experiences** involving risks to subjects or others; and (2) **any other unanticipated problems involving risks** to subjects or others.
- **Stop all human subjects research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Human subjects research activity can resume once IRB approval is re-established.
- **Submit an application for Continuing Review** at least three to four weeks prior to the **date for continuing review** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

IRB 03/2018

- Please be aware that IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g. student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

- Please be advised that your research study may be subject to **post-approval monitoring by Iowa State University's Office for Responsible Research**. In some cases, it may also be subject to formal audit or inspection by federal agencies and study sponsors.

- Upon completion of the project, transfer of IRB oversight to another IRB, or departure of the PI and/or Supervising Investigator, please initiate a Project Closure to officially close the project. For information on instances when a study may be closed, please refer to the IRB Study Closure Policy.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

CONSENT FORM

Introduction

This consent form describes the research study and helps you decide if you want to participate. It provides important information about what you will be asked to do during the study, about the risks and benefits of the study, and about your rights and responsibilities as a research participant. By signing this form, you are agreeing to participate in this study.

- You should read and understand the information in this document including the procedures, risks and potential benefits.
- If you have questions about anything in this form, you should ask the research team for more information before you agree to participate.
- Do not agree to participate in this study unless the research team has answered your questions and you decide that you want to be part of this study.

You have been asked to participate in a research study that examines the individual performance of a human interacting with a manipulating unmanned aerial vehicle (UAV). The purpose of this study is to evaluate a mobile tablet application we have developed that will allow you to view real-time video from a UAV and manipulate pre-determined objects. You were selected to be a possible participant because you either work or study in a field of interest. To be eligible for this study, you must meet *all* of the following inclusion criteria:

1. You are over the age of 18.
2. You study or work in the following: civil, agricultural, environmental, or related field of engineering or science.
3. You have limited or no experience in piloting unmanned aircraft.
4. You do not have a stainless steel skin allergy.

What will I be asked to do?

If you agree to participate in this study, you will be asked to 1) complete a pre-assessment background survey and short training meeting, 2) watch a video feed on a tablet and interact with the UAV manipulator payload via tablet device to perform pre-determined tasks when directed during three separate flights, and 3) complete a post-study survey. You may become ineligible for participation in this study based on your answers to the pre-assessment questionnaire. This study will take approximately 1-hour to complete.

Your participation will be video recorded with audio. Additionally, you be required to wear a wristwatch containing PPG and EDA sensors that measure heart rate and electrodermal response.

What are the risks involved in this study?

The risks associated with this study are minimal and are not greater than the risks ordinarily encountered in daily life.

What are the possible benefits of this study?

The possible benefits of participation are that you will gain experience working with a UAV in a laboratory exercise that uses cutting-edge robotics technology.

ISU IRB: 18-060-00
Approved Date: 06/21/2018
Expiration Date: 02/19/2020

Your participation is voluntary.
You may decide not to participate or to withdraw at any time without any penalty. Your choice of whether or not to participate will have no impact on you as a student/employee in any way.

Who will know about my participation in this research study?
Research records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available without your permission. However, it is possible that other people and offices responsible for making sure research is done safely and responsibly will see your information. This includes federal government regulatory agencies, auditing departments of Iowa State University, and the Institutional Review Board (a committee that reviews and approves human subject research studies) may inspect and/or copy study records for quality assurance and data analysis. These records may contain private information.

No identifiers linking you to this study will be included in any sort of report that might be published. Research records will be stored securely, and only Dr. Joshua Peschel, Ms. Sierra Young, and approved research assistants will have access to potentially identifiable records.

If you choose to participate in this study, you will be video recorded with audio. Any audio/video recordings will be stored securely and only Dr. Joshua Peschel, Ms. Sierra Young, and approved research assistants will have access to the potentially identifiable records (video/audio recordings). Any recordings will be kept for 3 years and then erased. *De-identified* information may be shared with other researchers or used for future research studies. Video recordings may be shared in presentations, but participant facial images will be blurred and audio will be distorted. We will not obtain additional informed consent from you before sharing the de-identified data.

Is there anything else I should consider?
The researchers can choose to end the experiment at any time.

Whom do I contact with questions about the research?
If you have questions regarding this study, you may contact Dr. Joshua Peschel, (515) 357-7448, peschel@iastate.edu

Whom do I contact about my rights as a research participant?
This research study has been reviewed by the Institutional Review Board at Iowa State University. For research-related problems or questions regarding your rights as a research participant, you can contact an IRB administrator at (515) 294-4566 or IRB@iastate.edu.

Signature
Please be sure you have read the above information, asked questions and received answers to your satisfaction. Your signature indicates that this research study has been explained to you, that your questions have been answered, and that you agree to take part in this study. This consent form is not a contract. It is a written explanation of what will happen during the study if you decide to participate. You will receive a signed and dated copy of this form.

ISU IRB: 18-060-00
Approved Date: 06/21/2018
Expiration Date: 02/19/2020

Signature of Participant:_______________________________Date: _________________

Printed Name: ____

Signature of Person Obtaining Consent:___________________Date: ________________

Printed Name: ____

ISU IRB: 18-060-00
Approved Date: 06/21/2018
Expiration Date: 02/19/2020

SAMPLE RECRUITMENT EMAIL

Greetings.

My name is Sierra Young, and I am a Visiting Scholar working with Dr. Joshua Peschel at Iowa State University. We are conducting a research study to examine human performance when operating a manipulating unmanned aerial vehicle (drone) under varying conditions. I am emailing to ask if you would like to participate in a ~1-hour study to test various tablet-based telemanipulation interfaces. Participation is completely voluntary, and your data will be anonymized, and the risks associated with this study are minimal.

If you are interested or have any questions, please contact Dr. Joshua Peschel (peschel@iastate.edu).

Thank you for your time.

(embed RECRUITMENT FLYER in the email)

Sierra Young
Graduate Research Assistant
Visiting Scholar at Iowa State University

VERBAL ANNOUNCEMENT SCRIPT

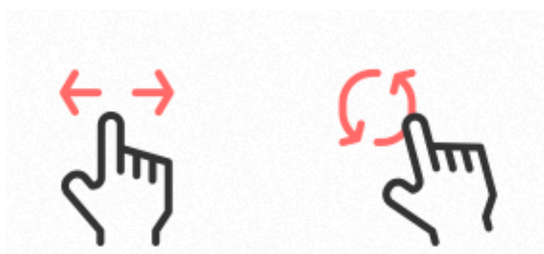
Welcome the prospective participant(s) and introduce yourself. State that you are speaking to the individual (or group) to solicit volunteers to participate in a study on the use of mobile touch-based devices for operating manipulator-equipped unmanned aerial systems. Tell them the purpose of the study is to evaluate a mobile tablet application we have developed that will enable participants to view real-time video from a UAV and perform manipulation on pre-determined objects using a tablet device, and that they were selected to be a possible participant because they either work or study in a related field of interest. Tell them they will be required to complete a pre-assessment survey and training meeting, operate the aerial system using a tablet interface, and complete post-assessment questionnaires. Determine whether or not the individual (or group) wishes to be considered as a prospective participant through obtaining verbal confirmation. If no, thank the individual (or group) and end the discussion. If yes, proceed to scheduling a time to complete the experimental procedures and/or give the prospective participants contact information to follow up for scheduling.

COMMAND PROTOCOLS

In all trials, participants should only use the following <u>verbal commands</u> to instruct the *Pilot*:

Vehicle Controls:
Turn Left___Degrees
Turn Right___Degrees
Move Up___centimeters (meters)
Move Down___ centimeters (meters)

In the study participants are instructed to control the UAV manipulator on the mobile tablet device by using the controls and gestures shown in Figure 1 below.



Swipe the switch to open and close the gripper

Rotate the dials to move the position of each motor

Fig. 1. Gestures Used During the Study for Touch-Based Control of the UAV Manipulator Payload.

CODING SCHEME FOR AUDIO/VIDEO RECORDINGS

Category Elements	**Elements**	**Definitions**
Sender-Recipient	1. Mission Specialist-Pilot 2. Pilot-Mission Specialist	Mission Specialist: responsible for controlling the remote manipulator Pilot: responsible for navigation and airworthiness of the vehicle
Form	1. Question 2. Instruction 3. Answer 4. Comment 5. Utterance	Request for information Direction for activity Response to question or instruction General statement related to the task General statement unrelated to the task
Content	1. Environment 2. Robot state 3. Robot situatedness 4. Information synthesis 5. Object 6. Manipulator 7. Planning 8. Off task	Conditions or characteristics in the task environment Robot system, parts, errors, sensor data, etc. Robot's location, position, or orientation in the remote environment Connections between current and prior observations or knowledge Pertaining to the object of interest in the manipulation task Pertaining to the manipulator, it's capabilities, etc. Task planning or strategy Unrelated or extraneous subject
Function	1. Report 2. Plan 3. Seek information 4. Clarify 5. Direct 6. Confirm 7. Convey uncertainty 8. Correct error	Sharing information about the robot, environment, or object Projecting future goals or steps to goals Asking for information Making previous comment more precise Tell a team member to conduct a specific action Arming previous statement/observation Expressing doubt, disorientation, or loss of confidence Correcting error made by self or others

BEFORE MISSION

Welcome the participants to the study. Introduce yourself and the other members of the research team. Issue a copy of the Consent Form. Read the information contained on the Consent Form aloud to the individual (or group). At the end of reading aloud, ask for any questions about the information that has been read. If the prospective participant(s) do not wish to participate, thank the individual (or group) and end the discussion. If yes, obtain signature(s) on the Consent Form(s) and continue on with this Mission Script.

Administer the pre-assessment questionnaire. Determine eligibility based on responses to the pre-assessment.

Obtain the baseline measurements with the EDA and PPG sensor instrumentation.

Allow the participant to practice with the interface for 5 minutes prior to the start of the mission; administer the Command Protocol sheet at this time.

Before beginning the first trial, say this:

You will be participating as part of an unmanned aerial system, which includes a human team and a small unmanned aerial vehicle equipped with a robotic manipulator, for the purposes of physically interacting with the environment. Your teams mission is to fly over predetermined stations to perform a series of physical and visual tasks.

Your role will be the Mission Specialist. Your responsibilities are to watch the live video feed from the unmanned aerial vehicle cameras on the Mission Specialist interface and operate the manipulator and answer questions when instructed to do so. The goal of the mission is to complete an entire set of given tasks within a single flight. The Pilot will navigate the vehicle between stations. You may verbally direct the Pilot to re-position the vehicle as needed to perform the task after arriving at a station. During the mission, you may refer to a quick reference sheet indicating commands you may give the Pilot for vehicle control.

We will be recording the mission activities on video, therefore please speak clearly and loud enough to be recorded. If you have any questions about how to operate the Mission Specialist interface, I can answer those for you. Do you have any questions before we start?

DURING THE MISSION

Because every participant must attempt to go through a similar set of tasks in the same amount of time, we have to constrain how you would most likely use a UAV in practice or what different models of UAVs can do. We would be happy to talk with you about UAVs after the experiments.

For this experiment, the Pilot will go to a series of pre-specified stations, and then you will try to complete a task using the manipulator. At each waypoint, the UAV will hover; however, you can tell the Pilot to turn the UAV turn left or right or move up and down as needed.

The goal is to complete all manipulation tasks during flight, with a maximum flight time of approximately 12 minutes. You will complete three flights, and during each flight you will use an interface with different visual information available.

For each flight:

Be sure the participant is seated in a chair facing away from the arena and is only viewing the robot and manipulator through the Mission Specialist interface.

We will now begin the flight.

Pilot moves vehicle to station 1.

We are now at Station 1. Please begin to complete the touching and probing task (describe the task detail here*). Remember to use the specific verbal commands to talk to the Pilot for vehicle control.

Observe when the task has been completed.

We have completed Task 1: now we are moving to Station 2.

Pilot moves vehicle to station 2.

We are now at Station 2. Please begin to complete the moving task (describe the task detail here*).

Observe when the task has been completed.

Now we are moving to Station 3.

Pilot moves vehicle to station 3.

We are now at Station 3. Please begin to complete the grasping task (describe the task detail here*).

Complete this protocol until all stations/tasks have been completed. At the end of the experiment when all tasks have been completed, OR when the flight time has nearly run out (battery approximately 10%), say:

We are done. We will return to land.

*The above sequence of mission instructions is repeated three times, once for each of the three interface conditions. There are also three separate sets of similar tasks, including object grasping, object placement, pushing, and probing-type tasks. The description (e.g., pick up the circular object on the table or move the red square will be modified and included accordingly in the above script depending on the trial.

AFTER THE MISSIONS

When the participant finishes the missions, thank them for participating and direct them back to exit the flight arena. Administer the post-assessment questionnaire at a desk in the laboratory.

IOWA STATE UNIVERSITY
Agricultural and Biosystems Engineering

ISU IRB: 18-060-00
Approved Date: 06/21/2018
Expiration Date: 02/19/2020

HUMAN-ROBOT INTERACTION STUDY SEEKS ADULT PARTICIPANTS IN ABE, CEE, OR RELATED FIELD

You may be eligible for this study if you:
- Are 18+ years old
- Have limited experience flying aircraft
- Are a student or professional in ABE, CEE, or related field of engineering or science

Dr. Joshua Peschel
is conducting a study to determine the effects of operational conditions on human-operated small, manipulating unmanned aerial vehicles

The study will last ~1 hour and includes:
- training + task-based trials with the robot
- recorded audio and video of each trial
- pre- and post-assessment questionnaires

Contact: Dr. Joshua Peschel 515-294-4814 or peschel@iastate.edu

APPENDIX C

PRE- AND POST-ASSESSMENTS

Pre Assessment

Please answer the following survey questions. All information is confidential and will be used for research purposes only.

Question 1: What is your age?
(a) Under 25-years
(b) 25-years to 34-years
(c) 35-years to 44-years
(d) 45-years to 54-years
(e) 55-years and older

Question 2: What is your gender?
(a) Male
(b) Female
(c) Non-binary / third gender
(d) Other

Question 3: What is your current occupation? _________________________

Question 4: What is your ethnicity/race? _____________________________

Question 5: Do you have a stainless steel skin allergy?
(a) Yes
(b) No

Question 6: Have you ever used a mobile touch-based device (e.g. Apple iPhone or iPad) before?
(a) Yes
(b) No

Question 7: If you answered Yes to Question 6, do you use any of the following mobile touch-based devices? If you answered No to Question 6, please skip to Question 11.

(a) Apple iPhone
(b) Apple iPad
(c) Android Smart Phone
(d) Android Tablet
(e) Other touch-based mobile device, please specify: ____________________

Question 8: If you answered Yes to Question 6, how long have you used mobile touch-based devices?

(a) 0- to 1-years
(b) 1- to 2-years
(c) 2- to 5-years
(d) 5- to 10-years
(e) More than 10-years

Question 9: If you answered Yes to Question 6, how often do you use mobile touch- based devices?

(a) Continuously throughout every day
(b) A few times per day
(c) A few times per week
(d) A few times per month
(e) A few times per year

Question 10: If you answered Yes to Question 6, in what context do you typically interact with mobile touch-based devices? This question can have more than one answer.

(a) I use it as my phone
(b) I use it to play games
(c) I use it to surf the Internet
(d) I use it to check email
(e) I do not own a device but I borrow from others

Question 11: Have you ever used a Tablet PC or other electronic pen-based device before?

(a) Yes
(b) No

Question 12: If you answered Yes to Question 11, how long have you used a Tablet PC or other electronic pen-based devices? If you answered No to Question 11, please skip to Question 15.

(a) 0- to 1-years
(b) 1- to 2-years
(c) 2- to 5-years
(d) 5- to 10-years
(e) More than 10-years

Question 13: If you answered Yes to Question 11, how often do you use a Tablet PC or other electronic pen-based devices?

(a) Continuously throughout every day
(b) A few times per day
(c) A few times per week
(d) A few times per month
(e) A few times per year

Question 14: If you answered Yes to Question 11, in what context do you typically interact with a Tablet PC or other electronic pen-based devices? This question can have more than one answer.

(a) I use it as my primary computer
(b) I use it to play games
(c) I use it to surf the Internet
(d) I use it to check email
(e) I do not own a device but I borrow from others

Question 15: How often do you play video games?

(a) Continuously throughout every day

(b) A few times per week

(c) A few times per month

(d) A few times per year

(e) I do not play video games

Question 16: If you do play video games, how often do you play first-person action games (e.g., Quake, HalfLife, etc.)?

(a) Continuously throughout every day

(b) A few times per week

(c) A few times per month

(d) A few times per year

(e) I do not play first-person simulation games

Question 17: Have you ever interacted with a robot before?

(a) Yes

(b) No

Question 18: If you answered Yes to Question 17, how often have you interacted with a robot before?

(a) Once

(b) Yearly

(c) Monthly

(d) Weekly

(e) Daily

Question 19: Have you ever owned a robot before?

(a) Yes

(b) No

Question 20: If you answered Yes to Question 19, please briefly describe the type(s) of robot(s) you have owned before.

Question 21: Have you ever flown RC helicopters or a plane?

(a) Yes

(b) No

Question 22: If you answered Yes to Question 21, please briefly describe the type(s) of RC helicopter(s) and/or plane(s) you have flown before. If you answered No to Question 21, please skip to Question 24.

Question 23: If you answered Yes to Question 21, how would you rate your flying expertise?

(a) Novice

(b) Below Average Expertise

(c) Average Expertise

(d) Above Average Expertise

(e) Expert

Question 24: Do you currently have a pilot's license?

(a) Yes

(b) No

Question 25: Have you ever controlled a robotic arm or manipulator remotely before (e.g., on a robot or through the Internet)?

(a) Yes

(b) No

Question 26: If you answered Yes to Question 25, please briefly describe the situation(s) in which you have controlled a robotic arm or manipulator remotely before.

Question 27: Have you ever participated in a robot-assisted data collection mission or exercise before?

(a) Yes

(b) No

Question 28: If you answered Yes to Question 27, please briefly list and/or describe your role and the type of robot (e.g., air, ground, water) in the situation(s) in which you have participated in a robot-assisted data collection mission before.

Question 29: Do you currently supervise one or more person(s) in a team or work environment?
(a) Yes
(b) No

Question 30: If you answered Yes to Question 29, please briefly list and/or describe your role(s) (function and command level; some examples may be: technical search team lead, transportation consulting reporting to DOT, etc.) and the type of supervision(s) you provide.

Question 31: Listed below are information and/or technology methods that can be used for decision-making. Circle the best choice that reflects your use of the information and/or technology method for decision-making in your current job.

Verbal Reports (e.g., telling someone the area is all clear)
(a) Never Use
(b) Below Average Use
(c) Average Use
(d) Above Average Use
(e) Always Use

Geographic Information on Paper Maps (e.g., topo maps)
(a) Never Use
(b) Below Average Use
(c) Average Use
(d) Above Average Use
(e) Always Use

Geographic Information on an Electronic Device (e.g., Google maps)
(a) Never Use
(b) Below Average Use
(c) Average Use
(d) Above Average Use
(e) Always Use

Digital Photographs and/or Video (e.g., digital cameras)
(a) Never Use
(b) Below Average Use
(c) Average Use
(d) Above Average Use
(e) Always Use

Commercial or Custom Apps on a Mobile Electronic Device (e.g., Apple iPhone, Android, etc.)
(a) Never Use
(b) Below Average Use; Please Specify Apps:____________________
(c) Average Use; Please Specify Apps:____________________
(d) Above Average Use; Please Specify Apps:____________________
(e) Always Use; Please Specify Apps:____________________

Question 32: Listed below are information and/or technology methods that can be used for decision-making. Circle the best choice that reflects your creation of the information and/or technology method for decision-making in your current job.

Verbal Reports (e.g., telling someone the area is all clear)
(a) Never Create
(b) Below Average Creation
(c) Average Creation
(d) Above Average Creation
(e) Always Create

Geographic Information on Paper Maps (e.g., topo maps)

(a) Never Create
(b) Below Average Creation
(c) Average Creation
(d) Above Average Creation
(e) Always Create

Geographic Information on an Electronic Device (e.g., Google maps)

(a) Never Create
(b) Below Average Creation
(c) Average Creation
(d) Above Average Creation
(e) Always Create

Digital Photographs and/or Video (e.g., digital cameras)

(a) Never Create
(b) Below Average Creation
(c) Average Creation
(d) Above Average Creation
(e) Always Create

Commercial or Custom Apps on a Mobile Electronic Device (e.g., Apple iPhone, Android, etc.)

(a) Never Create
(b) Below Average Create; Please Specify Apps:____________________
(c) Average Create; Please Specify Apps:____________________
(d) Above Average Create; Please Specify Apps:____________________
(e) Always Create; Please Specify Apps:____________________

Question 33: Listed below are information and/or technology methods that can be used for decision-making. If your job does not currently utilize one or more of the listed items, please circle which one(s) do you wish it did.

(a) Verbal Reports

(b) Geographic Information on Paper Maps

(c) Geographic Information on Electronic Devices

(d) Digital Photographs and/or Video

(e) Commercial or Custom Apps on a Mobile Electronic Device

(f) Other (please specify):___________________

Question 34: On the following pages, there are phrases describing peoples behaviors. Please use the rating scale below to describe how accurately each statement describes *you*. Describe yourself as you generally are now, not as you wish to be in the future. Describe yourself as you honestly see yourself, in relation to other people you know of the same sex as you are, and roughly your same age. So that you can describe yourself in an honest manner, your responses will be kept in absolute confidence. Please read each statement carefully and then circle the corresponding number that on the scale.

Response Options

1: Very Inaccurate

2: Moderately Inaccurate

3: Neither Inaccurate nor Accurate

4: Moderately Accurate

5: Very Accurate

Feel that others are out to get me.

1	2	3	4	5

Very Inaccurate Very Accurate

Boss people around.

1	2	3	4	5

Very Inaccurate Very Accurate

Am easily distracted.

1	2	3	4	5

Very Inaccurate Very Accurate

Am easily controlled by others in my life.

1	2	3	4	5

Very Inaccurate Very Accurate

Make careful choices.

1	2	3	4	5

Very Inaccurate Very Accurate

Like having authority over others.

1	2	3	4	5

Very Inaccurate Very Accurate

Am a law-abiding citizen.

1	2	3	4	5

Very Inaccurate Very Accurate

Let others take advantage of me.

1 2 3 4 5

Very Inaccurate Very Accurate

Have been told that my behavior often is bizarre.

1 2 3 4 5

Very Inaccurate Very Accurate

Insist that others do things my way.

1 2 3 4 5

Very Inaccurate Very Accurate

Demand perfection in others.

1 2 3 4 5

Very Inaccurate Very Accurate

Let myself be pushed around.

1 2 3 4 5

Very Inaccurate Very Accurate

Get jealous easily.

1 2 3 4 5

Very Inaccurate Very Accurate

Make demands on others.

1 2 3 4 5

Very Inaccurate Very Accurate

Have fixed opinions.

1 2 3 4 5

Very Inaccurate Very Accurate

Prefer that others make the major decisions in my life.

1 2 3 4 5

Very Inaccurate Very Accurate

Boss people around.

1 2 3 4 5

Very Inaccurate Very Accurate

Love dangerous situations.

1 2 3 4 5

Very Inaccurate Very Accurate

Let myself be directed by others.

1 2 3 4 5

Very Inaccurate Very Accurate

Say inappropriate things.

1 2 3 4 5

Very Inaccurate Very Accurate

Am known as a controlling person.

1 2 3 4 5

Very Inaccurate Very Accurate

Do not feel close to people.

1 2 3 4 5

Very Inaccurate Very Accurate

Need others to help run my life.

1 2 3 4 5

Very Inaccurate Very Accurate

Question 35: Please read each statement. Where there is a blank, decide what your normal or usual attitude, feeling, or behavior would be:

Response Options:
A: Rarely (less than 10% of the time)
B: Occasionally (about 30% of the time)
C: Sometimes (about half the time)
D: Frequently (about 70% of the time)
E: Usually (more than 90% of the time)

Of course, there are always unusual situations in which this would not be the case, but think of what you would do or feel in most normal situations.

Circle the letter that describes your usual attitude or behavior.

When faced with a problem I try to ___________________forget it.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ___________________ need frequent encouragement from others for me to keep working at a difficult task.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ___________________ like jobs where I can make decisions and be responsible for my own work.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ___________________ change my opinion when someone I admire disagrees with me.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

If I want something I ___________________ work hard to get it.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ___________________ prefer to learn the facts about something from someone else rather than have to dig them out myself.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I will ___________________accept jobs that require me to supervise others.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ___________________have a hard time saying no when someone tries to sell me something I don't want.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ___________________ like to have a say in any decisions made by any group Im in.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ___________________ consider the different sides of an issue before making any decisions.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

What other people think ___________________ has a great influence on my behavior.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

Whenever something good happens to me I ___________________ feel it is because Ive earned it.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ___________________ enjoy being in a position of leadership.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ___________________ need someone else to praise my work before I am satisfied with what Ive done.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I am ___________________ sure enough of my opinions to try and influence others.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

When something is going to affect me I ___________________ learn as much about it as I can.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ___________________ decide to do things on the spur of the moment.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

For me, knowing I've done something well is ___________________ more important than being praised by someone else.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ___________________ let other peoples demands keep me from doing things I want to do.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ____________________ stick to my opinions when someone disagrees with me.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ____________________ do what I feel like doing not what other people think I ought to do.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ____________________ get discouraged when doing something that takes a long time to achieve results.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

When part of a group I ____________________ prefer to let other people make all the decisions.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

When I have a problem I ____________________follow the advice of friends or relatives.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ____________________ enjoy trying to do difficult tasks more than I enjoy trying to do easy tasks.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

I ____________________ prefer situations where I can depend on someone elses ability rather than just my own.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

Having someone important tell me I did a good job is ___________________ more important to me than feeling I've done a good job.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

When I'm involved in something I ___________________ try to find out all I can about what is going on even when someone else is in charge.

A	B	C	D	E
Very Rarely	Occasionally	Sometimes	Frequently	Usually

Post Assessment 1

Please answer the following survey questions for the *egocentric condition*. All information is confidential and will be used for research purposes only.

Question 1: How confident did you feel in your individual ability to control the manipulator with the touch interface?

(a) Not confident at all
(b) Somewhat not confident
(c) Neutral
(d) Somewhat confident
(e) Very confident

Question 2: How comfortable did you feel in your individual ability to control the manipulator with the touch interface?

(a) Not comfortable at all
(b) Somewhat not comfortable
(c) Neutral
(d) Somewhat comfortable
(e) Very comfortable

Question 3: How confident did you feel in your team's ability to perform the 'touching/probing' task?
(a) Not confident at all
(b) Somewhat not confident
(c) Neutral
(d) Somewhat confident
(e) Very confident

Question 4: How comfortable did you feel in your team's ability to perform the 'touching/probing' task?
(a) Not comfortable at all
(b) Somewhat not comfortable
(c) Neutral
(d) Somewhat comfortable
(e) Very comfortable

Question 5: How confident did you feel in your ability to instruct the *Pilot* to accurately control the vehicle?
(a) Not confident at all
(b) Somewhat not confident
(c) Neutral
(d) Somewhat confident
(e) Very confident

Question 6: How comfortable did you feel in your ability to instruct the *Pilot* to accurately control the vehicle?
(a) Not comfortable at all
(b) Somewhat not comfortable
(c) Neutral
(d) Somewhat comfortable
(e) Very comfortable

Question 7: How confident did you feel in your team's ability to perform the 'pushing' task?
(a) Not confident at all
(b) Somewhat not confident
(c) Neutral
(d) Somewhat confident
(e) Very confident

Question 8: How comfortable did you feel in your team's ability to perform the 'pushing' task?
(a) Not comfortable at all
(b) Somewhat not comfortable
(c) Neutral
(d) Somewhat comfortable
(e) Very comfortable

Question 9: The amount of information presented to you in the *Mission Specialist* interface was:
(a) Not adequate at all
(b) Somewhat not adequate
(c) Neutral
(d) Somewhat adequate
(e) Very adequate

Question 10: If you felt that the information in the *Mission Specialist* interface was not or somewhat not adequate, please list the reasons below.

Question 11: How confident did you feel in your team's ability to perform the 'grasping' task?
(a) Not confident at all
(b) Somewhat not confident
(c) Neutral
(d) Somewhat confident
(e) Very confident

Question 12: How comfortable did you feel in your team's ability to perform the 'grasping' task?
(a) Not comfortable at all
(b) Somewhat not comfortable
(c) Neutral
(d) Somewhat comfortable
(e) Very comfortable

Question 13: The amount of time given to you to complete all tasks was:
(a) Not adequate at all
(b) Somewhat not adequate
(c) Neutral
(d) Somewhat adequate
(e) Very adequate

Question 14: Please choose the task that you felt was the most difficult to complete.
(a) The 'touching/probing' task
(b) The 'pushing' task
(c) The 'grasping' task

Question 15: Please choose the task that you felt was the easiest to complete.
(a) The 'touching/probing' task
(b) The 'pushing' task
(c) The 'grasping' task

Post Assessment 2

Please answer the following survey questions for the *exocentric interface condition*. All information is confidential and will be used for research purposes only.

Question 1: How confident did you feel in your individual ability to control the manipulator with the touch interface?

(a) Not confident at all
(b) Somewhat not confident
(c) Neutral
(d) Somewhat confident
(e) Very confident

Question 2: How comfortable did you feel in your individual ability to control the manipulator with the touch interface?

(a) Not comfortable at all
(b) Somewhat not comfortable
(c) Neutral
(d) Somewhat comfortable
(e) Very comfortable

Question 3: How confident did you feel in your team's ability to perform the 'touching/probing' task?

(a) Not confident at all
(b) Somewhat not confident
(c) Neutral
(d) Somewhat confident
(e) Very confident

Question 4: How comfortable did you feel in your team's ability to perform the 'touching/probing' task?

(a) Not comfortable at all
(b) Somewhat not comfortable
(c) Neutral
(d) Somewhat comfortable
(e) Very comfortable

Question 5: How confident did you feel in your ability to instruct the *Pilot* to accurately control the vehicle?

(a) Not confident at all

(b) Somewhat not confident

(c) Neutral

(d) Somewhat confident

(e) Very confident

Question 6: How comfortable did you feel in your ability to instruct the *Pilot* to accurately control the vehicle?

(a) Not comfortable at all

(b) Somewhat not comfortable

(c) Neutral

(d) Somewhat comfortable

(e) Very comfortable

Question 7: How confident did you feel in your team's ability to perform the 'pushing' task?

(a) Not confident at all

(b) Somewhat not confident

(c) Neutral

(d) Somewhat confident

(e) Very confident

Question 8: How comfortable did you feel in your team's ability to perform the 'pushing' task?

(a) Not comfortable at all

(b) Somewhat not comfortable

(c) Neutral

(d) Somewhat comfortable

(e) Very comfortable

Question 9: The amount of information presented to you in the *Mission Specialist* interface was:

(a) Not adequate at all

(b) Somewhat not adequate

(c) Neutral

(d) Somewhat adequate

(e) Very adequate

Question 10: If you felt that the information in the *Mission Specialist* interface was not or somewhat not adequate, please list the reasons below.

Question 11: How confident did you feel in your team's ability to perform the 'grasping' task?

(a) Not confident at all

(b) Somewhat not confident

(c) Neutral

(d) Somewhat confident

(e) Very confident

Question 12: How comfortable did you feel in your team's ability to perform the 'grasping' task?

(a) Not comfortable at all

(b) Somewhat not comfortable

(c) Neutral

(d) Somewhat comfortable

(e) Very comfortable

Question 13: The amount of time given to you to complete all tasks was:

(a) Not adequate at all

(b) Somewhat not adequate

(c) Neutral

(d) Somewhat adequate

(e) Very adequate

Question 14: Please choose the task that you felt was the most difficult to complete.
(a) The ‘touching/probing’ task
(b) The ‘pushing’ task
(c) The ‘grasping‘ task

Question 15: Please choose the task that you felt was the easiest to complete.
(a) The ‘touching/probing’ task
(b) The ‘pushing’ task
(c) The ‘grasping‘ task

Post Assessment 3

Please answer the following survey questions for the *mixed condition*. All information is confidential and will be used for research purposes only.

Question 1: How confident did you feel in your individual ability to control the manipulator with the touch interface?
(a) Not confident at all
(b) Somewhat not confident
(c) Neutral
(d) Somewhat confident
(e) Very confident

Question 2: How comfortable did you feel in your individual ability to control the manipulator with the touch interface?
(a) Not comfortable at all
(b) Somewhat not comfortable
(c) Neutral
(d) Somewhat comfortable
(e) Very comfortable

Question 3: How confident did you feel in your team's ability to perform the 'touching/probing' task?

(a) Not confident at all

(b) Somewhat not confident

(c) Neutral

(d) Somewhat confident

(e) Very confident

Question 4: How comfortable did you feel in your team's ability to perform the 'touching/probing' task?

(a) Not comfortable at all

(b) Somewhat not comfortable

(c) Neutral

(d) Somewhat comfortable

(e) Very comfortable

Question 5: How confident did you feel in your ability to instruct the *Pilot* to accurately control the vehicle?

(a) Not confident at all

(b) Somewhat not confident

(c) Neutral

(d) Somewhat confident

(e) Very confident

Question 6: How comfortable did you feel in your ability to instruct the *Pilot* to accurately control the vehicle?

(a) Not comfortable at all

(b) Somewhat not comfortable

(c) Neutral

(d) Somewhat comfortable

(e) Very comfortable

Question 7: How confident did you feel in your team's ability to perform the 'pushing' task?

(a) Not confident at all

(b) Somewhat not confident

(c) Neutral

(d) Somewhat confident

(e) Very confident

Question 8: How comfortable did you feel in your team's ability to perform the 'pushing' task?

(a) Not comfortable at all

(b) Somewhat not comfortable

(c) Neutral

(d) Somewhat comfortable

(e) Very comfortable

Question 9: The amount of information presented to you in the *Mission Specialist* interface was:

(a) Not adequate at all

(b) Somewhat not adequate

(c) Neutral

(d) Somewhat adequate

(e) Very adequate

Question 10: If you felt that the information in the *Mission Specialist* interface was not or somewhat not adequate, please list the reasons below.

Question 11: How confident did you feel in your team's ability to perform the 'grasping' task?

(a) Not confident at all

(b) Somewhat not confident

(c) Neutral

(d) Somewhat confident

(e) Very confident

Question 12: How comfortable did you feel in your team's ability to perform the 'grasping' task?

(a) Not comfortable at all
(b) Somewhat not comfortable
(c) Neutral
(d) Somewhat comfortable
(e) Very comfortable

Question 13: The amount of time given to you to complete all tasks was:

(a) Not adequate at all
(b) Somewhat not adequate
(c) Neutral
(d) Somewhat adequate
(e) Very adequate

Question 14: Please choose the task that you felt was the most difficult to complete.

(a) The 'touching/probing' task
(b) The 'pushing' task
(c) The 'grasping' task

Question 15: Please choose the task that you felt was the easiest to complete.

(a) The 'touching/probing' task
(b) The 'pushing' task
(c) The 'grasping' task