The impact of skill-based training across different levels of autonomy for drone inspection tasks

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Thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science in the Department of Computer Science
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ABSTRACT

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Abstract

Given their low operating costs and flight capabilities, Unmanned Aircraft Vehicles(UAVs), especially small size UAVs, have a wide range of applications, from civilian rescue missions to military surveillance. Easy control from a highly automated system has made these compact UAVs particularly efficient and effective devices by alleviating human operator workload. However, whether or not automation can lead to increased performance is not just a matter of system design but requires operators' thorough understanding of the behavior of the system. Then, a question arises: which type of training and level of automation can help UAV operators perform the best?

To address this problem, an experiment was designed and conducted to compare the differences in performance between 3 groups of UAV operators. For this experiment, 2 different interfaces were first developed - Manual Control, which represents low LOA interface, and Supervisory Control, which represents high LOA interface - and people were recruited and randomly divided into 3 groups. Group 1 was trained using Manual Control, and Group 3 was trained using Supervisory Control while Group 2 was trained using both Manual and Supervisory Control. Participants then flew a drone in the Test Mission stage to compare performance.

The results of the experiment were rather surprising. Although group 3 outperformed group 1, as expected, the poor performance of group 2 was unexpected and gave us new perspectives on additional training. That is, additional training could

lead not just to a mere surplus of extra skills but also a degradation of existing skills. An extended work using a more mathematical approach should allow for a more precise, quantitative description on the relation between extra training and performance.

Contents

List of Tables

List of Figures

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1

Introduction

Unmanned Aircraft Vehicle (UAV), commonly known as drone, refers to a flying object without a human pilot aboard. UAV markets are getting bigger, reflecting their popularity and increased demand in commerce. Among various sizes of UAVs, the most popular class are small-size UAVs, because of the ease of control with a highly automated system. However, if these drones are to be truly useful, human operators need to know and understand the interaction between operators and UAVs, so that they can realize the full potential of system.

1.1 Unmanned Aircraft System

According to a report by the Federal Aviation Administration (FAA)[21], the number of small-sized Unmanned Aircraft System (UAS) is expected to increase to 7 million in 2020, up from 2.5 million in 2016, as shown in Figure 1.1. Here, UAS refers to a system that consists of UAV, ground-based controller, and communication links that connect them.

The continuous growth of the UAV market indicates the growing demand and interest in drones. Having started as reinforcer to military force, UAVs have become
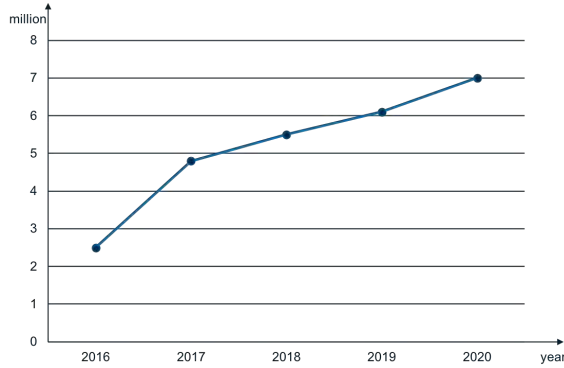
FIGURE 1.1: Sales Forecast(in units)

widely popular, with their use diversified and extended to commercial use. The current trend of popularity in UAV markets is the result of advances in different fields such as material science, mechanical engineering, telecommunication, and computer science. Lured by its promising future, as advanced technology enabled easier and simpler operation of drones using portable smart devices, many companies started joining the UAV market. The increased competition between companies has lowered the price of UAV down to the reasonable levels, satisfying consumer demand, especially in commercial market.

Figure 1.2 shows UAVs of different sizes. UAVs come in various sizes depending on the proposed use. Large UAVs that are as large as piloted aircraft or fighter planes are mainly used to perform military missions, such as combat operations or Intelligence, Surveillance, and Reconnaissance (ISR) missions. An example of this class is Global Hawk by NASA, shown in Figure 1.2a. Global Hawk is an unmanned aircraft for high-altitude, long-duration earth science missions; it has a wingspan of more than 116 feet, a height of 15 feet, a length of 44 feet and weighs 14,950 pounds. The aircraft's large size enables it to carry the large payloads required for long flight and guarantees stable flying, even at higher altitude. These properties make it suitable for monitoring and observing remote areas on earth for extended periods

2
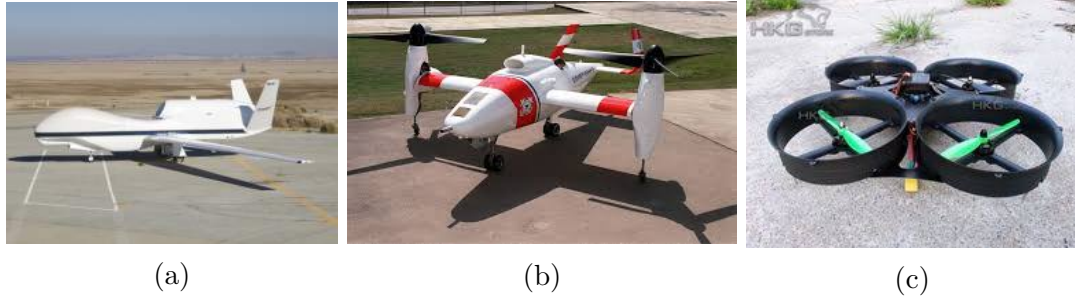
Figure 1.2: Various Sizes of UAV

of time without interruption, which is infeasible with piloted aircraft. Figure 1.2b is
a picture of Eagle Eye by Bell. Eagle Eye, developed for conducting ISR missions
in land-based or sea-based environments, has a wingspan of 24 feet, a height of 6
feet, a length of 18 feet, and weighs 1,300 pounds. Barely as large as or similar to a
human in size, this type of middle-sized aircraft is much faster and easier to control.
Although they might be inadequate for adventurous flight in extreme conditions,
because of soft airframe and light body, they are still strong enough to carry a number
of instruments for practical use. Aircraft of this class have various applications,
from agriculture to monitoring, remote sensing, filming and wildlife preservation.
At one extreme on the size spectrum are small UAVs, like Cyberquad Mini, as
shown in Figure 1.2c. Cyberquad Mini is designed for tactical ISR missions and has
dimensions of 0.65inch^2 and a weight of 1.76 pounds. Aircraft of this type boast easy
portability and provide the simplest modes of control which require only minimal
pilot training. Their small bodies are optimized for local ISR missions, thanks to
stealth and flexibility in movement, but limit the payload capacity, operation time
and range. It is this class that accounts for the largest share of the market by
attracting many hobbyists and private consumers.

A Ground Control Station (GCS) is an interface running on a ground-based com-
puter that controls and monitors a UAV from a remote distance. This system makes

FIGURE 1.3: Various Sizes of GCS

FIGURE 1.4: Examples of GCS Interface

the control of UAV easier and more effective than conventional manned aircraft. Depending on the size, complexity and number of drones under control, the scale ranges from a hand-held device to a command center equipped with a number of screens(Figure 1.3). Still, there are common, unique features that exist across the different scales.

The most distinguishing common feature of GCS compared to conventional cockpit is its augmented eagle-eye view on the operational area. Figure 1.4 shows examples of GCS software interface. Other than manually-operated joysticks and various instrumentation as in the manned aircraft, this third person perspective on the sur-

4

roundings greatly helps to increase the situational awareness (SA). The geographic information on the area augmented with visual representations of additional information provides better insight into planning the optimized strategy for mission. Removed from cockpit, UAV operators might be less sensible and reactive to local changes and anomalies, but they can gain eventual efficiency thanks to the well-calculated plan using this broad perspective view.

Also, a GCS offers a macroscopic mode of control. Generally, setting waypoints on a map is a way to control the vehicle using GCS without having to give detailed instructions on the flight control. This waypoint feature buys a significant amount of time to human operators if we consider that the pilots in usual manned aircraft are usually heavily involved in piloting. In manned aircraft, piloting requires a consistent attention and continuous action because pilots are consistently required to read various indicators and instrumentations, followed by instantaneous actions that decide the physical movement of the aircraft. With GCS, however, UAV operators are free from worrying about fine-grained control relevant to piloting because it autonomously manages overall flight control. It keeps gathering information on the movement and status of the aircraft, then autonomously make decision required for piloting to guarantee stable aviation through waypoints. The feature allows operators to focus more on strategic decision and analysis task on the data streamed from the aircraft. It further increases efficiency in completing a mission because operators can spare their attention to communication with other UAV operators, which facilitates the sharing of SA (as a form of distributed SA) and collaborative operations between UAVs.

1.2   Small UAV

Small UAVs have been successfully proving their usefulness and the promising future at workplace as replacements of their manned equivalents. Substantially cheaper and

5

relatively less dangerous to operate, these compact drones are currently being used and expected to be used in various fields. Above all things, one of the most important features of small UAVs that make them preferred in these application fields is their easy control represented by autonomous operation. There are 2 essential components that make autonomous operation available for these UAVs - Inertial Measurement Unit (IMU) and Global Navigational Satellite Systems (GNSS). An IMU is an onboard device of UAVs that plays a crucial role in drones' flight control system. It works by continually estimating drones' angular rates and linear acceleration using gyroscopes and accelerometers. The data stream from this device are integrated to calculate any forces moving against the drone and then sent to the motor Electronic Speed Controllers (ESC), which is responsible for varying the speed of rotors for multi-rotor UAVs (a typical type of small UAVs) to compensate them. The constant adjustments in rotor movements directed by an IMU realize the smooth and stable autonomous flight of these vehicles without requiring an operator's continual involvement. Next, GNSS refers to satellite navigation systems that provide geo-spatial information on the receiver's location, represented by United States' Global Positioning System (GPS) and Russia's Global Navigation Satellite System (GLONASS). GNSS sends and displays the information to the operator on the current location (longitude, latitude and altitude) of the drone in relation to the operator so that the operator can set waypoints using a GCS to perform a mission. GNSS uses a satellite constellation, a group of satellites working together to give an accurate, seamless, fail-safe coverage, which makes the operation easier and safer.

Given their compact size, the low operational costs and the flight capabilities, the applications of small UAVs include, but are not limited to,

- Wildlife conservation via searching for and monitoring endangered animals

- Disaster area surveillance after hurricanes or tornados

- Increased productivity in agriculture through monitoring and crop dusting

- Aiding rescue missions such as tracking lost hikers

- Bridge/ Antenna/ Skyscraper inspections

- Aerial photography

With such growing use and anticipated benefits of small UAVs, Congress has passed Public Law 112-95. Section 332 of Public Law 112-95 requires that the Secretary of Transportation seek for the ways to incorporate the administration over the operation of small UAVs into the national airspace system(NAS). The FAA, upon the request, has been proposing and amending the relevant regulations regarding the operation and certificate requirements of non-recreational small UAV operators. As specified Part 107 of the Federal Aviation Regulations, a small UAV is officially defined as unmanned aircraft weighing less than 55 pounds with no limitation on appearance specifications, consistent with the statutory definition in Pubic Law 112-95, section 331.

As a part of officially qualifying any potential UAV operators, the FAA issues a certificate to the applicants who meet the specified eligibility requirements. However, the FAA does not propose any specific training, flight experience, or demonstration of proficiency in order to be eligible for a certificate as a small UAV remote pilot other than basic biological, linguistic requirements and passing a FAA-approved aeronautical knowledge test. One thing to note is that, in the procedure of remote pilot certificate acquisition, there is no formal step to test hands-on experience or actual piloting proficiency that addresses the unique properties and sensitiveness of UAV operation using a real drone. This comes in handy for applicants because the process makes the certificate acquisition easier, but at the same time, it might produce immature, unexperienced operators.

Small UAVs are expected to bring a huge sets of benefits by replacing risky manned flights or comparable manned operations in dangerous jobs that could potentially lead to fatalities and injuries. Furthermore, because of its reduced weight, they do not have the potential of inflicting significant damage to persons and property on the ground even in the event of an accident. These benefits originate from the unmanned, remote, and autonomous nature of (small) UAV operation. Considering UAV operation in relation to the operating environment, however, these properties can also act as a negative factor at the same time and thus pose its own unique safety issues different from manned aircraft.

First, because UAV operators are physically separated from the aircraft during flight, remote pilots do not have the instant first-person perspective sight, sensory cues and agility as expected in manned-aircraft pilots. Pilots in a manned-aircraft cockpit are able to use humans-sensory cues from sight, hearing, and smell, as complements to machine-managed instrumentations. This acts as additional safety measures in case of machine failures. Also, the proximity of pilot to the aircraft under control greatly increases agility in reacting to any changes in the aircraft and surroundings. However, UAV operators cannot inherently possess the same abilities as manned-aircraft pilots because they are less sensitive to the surroundings of the vehicle due to the physical discrepancy between the operator and the aircraft.

Also, since UAVs are operated from a remote distance, there is a chance that the operator may lose control of the aircraft due to the connection failure between GCS and the aircraft. This may result from a system failure, flying beyond the signal range, bad weather or signal interruption. The sole reliance of the operation on the wireless communication makes the system subject to changes in the conditions of the surrounding environment, and precludes the operator from taking extra, direct measure on drifting drones through physical manipulation in emergency situations.

Finally, the capability of automated UAV operation renders the operators less re-

sponsible for the operation. Coupled with the fact that operators are free from danger, this can result in aggressive operation, which holds an increased chance of crash into other manned aircraft or people on the ground that could lead to catastrophic results. There are no UAVs that provide functions of perfect collision avoidance system and automatic perception of every potential threats. If the operator is not attentive and prepared for the surrounding changes and obstacles, the automation of operation can be the source of potential danger.

1.3 Problem Statement

The applications of UAVs have benefitted from the capabilities introduced by increasing level of autonomy. As technology advances, UAVs are getting more able to act as an independent, autonomous machine that does not have to wait for the operator's approval for every single action. The increasing autonomy does not only help to reduce workload imposed to operator, but also make the operation task (and thereby operator training) easier. Thus, it seems important to be able to exploit the benefits of the advances of technology as much as possible. At the same time, however, it should be noted that contemporary UAVs are not AI robots with intelligence comparable to humans. They are imperfect and not creative. They require strategic instructions from human operators, and need to be consistently instilled with the operator's intention toward the given mission.

Given the situation, it is clear that finding an optimal scheme of the cooperation between human operators and UAVs is critical to maximize the performance of UAS. Although proper system design is also an important factor, what is more important is for human operators to have complete understanding of the given automated system, as the cooperation is realized as a form of human operators' interaction with the system. Then, this raises a question: how much training would be the best choice for them to have "complete" understanding of the system considering its associated

training cost and potential impact on human operator's performance for the given system interface and is this choice of training affected by the level of UAV onboard autonomy?

1.4   Research Objectives

The goal of this thesis is to give a general guideline to those who are also trying to seek for an answer to the question posed in Section 1.3. This goal is described in detail as the following research objectives.

- Objective : **Evaluate the effect of training, or a lack thereof, for drone operators with different levels of autonomy.** For this purpose, 2 different controlling interfaces are developed, named Manual Control and Supervisory Control, respectively. These are representative interfaces of 2 different levels of autonomy. Manual Control represents a system with low level of autonomy, while Supervisory Control represents a system with high level of autonomy. Then, an experiment is conducted to test the proposed objective using various performance measures. In the experiment, recruited people are divided into 3 groups of equal sizes, where one group is trained and tested using only Manual Control interface, another is trained and tested using only Supervisory Control interface, and the other is trained using both Manual and Supervisory Control but tested using Supervisory Control.

1.5   Thesis Organization

This thesis is organized into the following 5 chapters:

- Chapter 1, *Introduction*, provides an overview of UAS, the motivations and the objectives of this thesis.

10

- Chapter 2, *Background*, describes concepts and background related to UAV operation automation.

- Chapter 3, *Experiment Design*, describes the testbed and the procedure of an experiment to test and compare performance between UAV operators who were trained with different programs.

- Chapter 4, *Results*, defines performance metrics to be considered in analysis and addresses the results of the experiment based on the defined metrics.

- Chapter 5, *Discussion and Conclusions*, discusses the results of the experiment, its implication and limitation to real world applications, with a possible future work area.

2

Background

Ever since computers were invented, they have aided human operators in many application domains with its exceptional computation power. As computers evolve, they have taken bigger roles in the integrated system of human and computer. With more highly automated system available, system designers have wider options available in choosing the degree of automation. In UAV operation, a choice of proper automation scheme among various alternatives directly determines the performance of the associated system, as automation has both benefits and compensating costs. However, if a system offers too much flexibility in its automation scheme, human operators can get confused, leading to poor performance of the system.

2.1 Levels of Automation

As technical developments in both software and hardware constantly improve the capabilities of computers, they have become more and more able to perform jobs that used to be considered as human jobs. Automation, in this context, can be defined as the computer's full or partial replacement of a function previously carried out by the human operator [15]. The question that naturally follows this definition is what

Table 2.1: Fitts List [9]

Humans appear to surpass present-day machines in respect to the following:	Present-day machines appear to surpass humans in respect to the following:
1. Ability to detect a small amount of visual or acoustic energy.	1. Ability to respond quickly to control signals and to apply great force smoothly and precisely.
2. Ability to perceive patterns of light or sound.	2. Ability to perform repetitive, routine tasks.
3. Ability to improvise and use flexible procedures.	3. Ability to store information briefly and then to erase it completely.
4. Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time.	4. Ability to reason deductively, including computational ability.
5. Ability to reason inductively.	5. Ability to handle highly complex operations, i.e. to do many different things at once.
6. Ability to exercise judgment	

functions are to be automated and to what extent, which are matters of automated system design. While choosing a proper design is a crucial factor that determines the overall performance of the system, it is not an easy task and requires a preliminary understanding of the capabilities and limitations of human and computer. The first attempt can be traced back to 1951, when Fitts tried to reveal and state the relative strengths of human and computer, which is also referred to as MABA-MABA ('Men are better at, Machines are better at') (Table 2.1). As the relevant study matures, function allocation is increasingly recognized as a process of finding a proper combination scheme of integrated system that generates much better synergic performance than either by itself, rather than merely replacing each other's place just like zero-sum game. In this trend, several function allocation models were proposed including Levels of Automation (LOA) [2][15][10]. Generally putting 2 extremes of fully man-

Table 2.2: Levels of Automation in Decision Selection Stage [15]

Level	Automation Description
10	The computer decides everything and acts autonomously, ignoring the human.
9	informs the human only if it, the computer, decides to.
8	informs the human only if asked, or
7	executes automatically, then necessarily informs humans, and
6	allows the human a restricted time to veto before automatic execution, or
5	executes that suggestion if the human approves, or
4	suggests one alternative, and
3	narrows the selection down to a few, or
2	The computer offers a complete set of decision/action alternatives, or
1	The computer offers no assistance: human must take all decision and actions.

ual and fully automated systems in both ends, LOA partitions and describes different levels of automation within the spectrum. In the literature, different models of LOA have been proposed and exist depending on the different aspects of automation that respective authors want to look at, including the one shown in Table 2.2. Specifically, the given LOA taxonomy mainly refers to automation in the perspective of decision selection. At the very bottom of the scale is complete manual operation, where the computer offers no assistance to the human operator. As the levels increase, the computer plays a more active role in the system, leaving the human less involved in the system. At the top of the scale is complete automation, where the computer autonomously makes decisions without human interaction.

One of the important aspects of LOA framework is that it addresses and highlights the interactive nature between human and computer rather than focuses on the complete division of labor between them. Also, as is implicated in the description of LOA, it is not task-centric. Instead, LOA describes how each divided sub-stage of the given task can be implemented with one of the levels of automation. For example,

the above LOA scale was presented with a 4-stage model of information processing that consists of information acquisition, information analysis, decision selection and action implementation stages [15]. The seemingly inadequate simplicity of single-dimensional scale is supplemented with the introduction and individual application of LOA to each stage of information processing, in order to cover the complexity and immensity of the class of general tasks. Specifically, the given LOA scale is tailored to decision selection stage, but similar LOA scales, with some modifications, can be applied to different stages, according to the functional characteristics of each stage. Then, for a given task, different combinations of levels at each stage can be employed. In the task of holding an election for an organization, for example, the ballot papers are collected manually from eligible voters (low level automation in acquisition stage), the results are counted by computer (high level automation in analysis stage), the winners are automatically decided according to the results (high level automation in decision selection stage), and then the inauguration takes place, including moving offices and the handover of the former officer's business (moderate level of automation in action implementation stage) [20].

Choosing a proper automation design is a complex task that requires thorough consideration of numerous evaluative criteria. These criteria involve performance measures on the human component, such as mental workload, automation reliability, and the system's expected costs and benefits from possible choices of decision/action implementations [15]. What makes things more complicated is that there is no one definite way of evaluating these criteria and incorporating them into a single equation. It is not as simple as solving one optimization problem in mathematical optimization theory. The evaluation on such criteria is not objective and is up to individual subjective interpretation. There is no formal definition that limits and expresses these ideas with objectively quantifiable numbers, and even if we can find one, it is mostly based on empirical observations that are prone to biased sampling, imprecise mea-

surements, and overgeneralization from the limited number of samples. Furthermore, the actual dimension of these criteria, or, "independent variables" in mathematical terms, is so huge that it is almost impossible to find an optimal automation scheme, which is often referred to as "the curse of dimensionality". There are so many hidden variables that need consideration, which is practically impossible, that they are duly summarized in the name of (hyper-)parameters to limit our interest in a reduced dimension. Combined together, however, they are hard to estimate by themselves and make the entire optimization problem much more complicated. This is the main reason why choosing automation level is considered art beyond science [20], where macroscopic decision on the automation scheme is made on a heuristic and empirical basis first. Given these difficulties, discussion regarding automation is often preferred in a more constrained, area-specific domain in the perspective of practicality and feasibility.

2.2   UAV automation

The advances in technology have made the increased level of automation available in UAV operation and thus broaden available options with regard to choosing level of automation. In the domain of aviation, automation is started as a means of alleviating the human pilot's workload on repetitive tasks that often require constant involvement in the cognition, decision, and action routine. In UAV operation, the meaning of automation remains similar as in manned aircraft, reducing the workload imposed on human operators, while also bringing additional values to UAV that make it a unique and useful apparatus.

The trend in increased automation has been for human operators to assume the role of supervisor of automation, which is also known as Human Supervisory Control (HSC). More specifically, HSC is the process by which a human operator intermittently interacts with a computer, receiving feedback from and providing commands
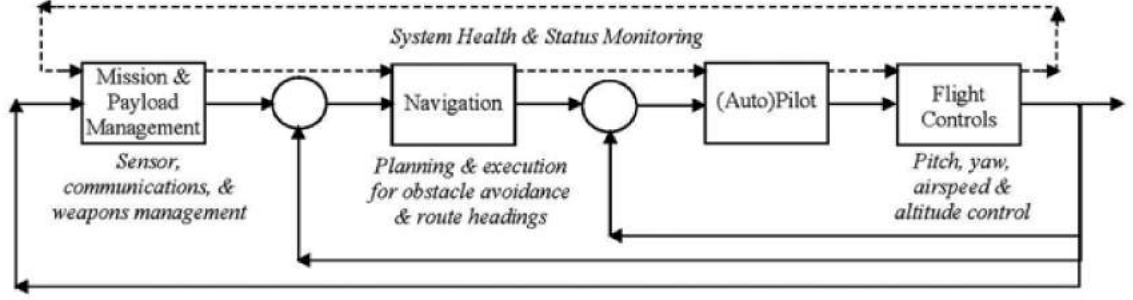
FIGURE 2.1: Hierarchical Control Loops for a Single UAV [5]

to a controlled process or task environment, which is connected to that computer through actuators and sensors [19]. HSC in single UAV operation can be illustrated using the diagram shown in Figure 2.1 [5]. The diagram shows that the tasks of UAV operation can be represented by the two parallel loops - one for the nested chain of hierarchical sub-loops on the lower side and the other for the system health & status monitoring on the upper side. Each loop is the pictorial representation of ordinary feedback-action routine in the respective control loop. If the human operator is required to be engaged in a certain loop for assistance or instruction, he sends commands to the computer through input devices, such as joysticks or buttons; the computer then carries out the requested command and displays the resulting status after its execution. The process continues until the system reaches the step where it requires the operator's next interruption. In this setting, the way the operator interacts with the computer is decided by the choice of level of automation. If the automation is designed in the framework similar to level 2 in LOA table (Table 2.2), the computer offers only a variety of action alternatives in response to the changes in the system (perceived by the system through acquisition and analysis phase, which can also be automated in a manner discussed in the previous section) but does not automatically decide a choice. On the other hand, if the automation scheme is built on the basis of level 6 framework, then the computer will only wait for the human

operator's interruption within a limited time frame; otherwise, it will automatically make a choice. Thus, as LOA implemented in each loop increases, the frequency of the operator's intermittent involvement in each loop decreases.

The hierarchical structure of sub-loops in the nested chain describes the dependencies between relevant tasks. For example, it is intended to imply that if the innermost loop, which represents the basic flight and motion control of UAV fails, the outer loops such as the navigation (path planning) loop will automatically fail. The flight control loop is therefore the most critical and radical component that is directly related to the safety and stable flight of UAV. However, the mission & payload management loop cannot be neglected, if the operator wants to perform a mission. Since the mental resources of the human operator are limited in capacity and subject to rapid decrement in performance if overloaded with many tasks, it is practically impossible to be constantly involved in every single loop at every instant. Given this situation, the meaning of HSC is to allow the operator to sit back and monitor the whole system (system health & status monitoring) while interacting with one of the sub-loops in the nested chain at the same time only if requested by the system or needed in case of emergency. As a result, it helps the human operator to not be too distracted and exhausted by low level tasks that are simple and repetitive, such as flight control (which is relatively easy to automate) and be able to shift his attention to high level tasks that require expertise-driven steps of operation, such as mission management (which is not often easy to automate) so that he can reorient himself toward the mission. This shift of low-level, fine-grained control to high-level supervisory control contributes to reducing operator workload, as it relieves the operator from wasting mental resources on low-level control loops. This helps the operator to appropriately allocate his attention by his choice across the loops in a way that he thinks maximizes system performance. Specifically, the operator can spare his cognitive resources and selectively focus on the mission management loop which has

more to do with mission accomplishment, increasing performance in carrying out the mission.

There are some recent studies that show the framework of HSC indeed brings the expected effect of attention switching. In the study by Chen and Joyner [3], an experiment was conducted where subjects took the combined position of gunner and operator piloting UGV. As a gunner, subjects were required to detect and fire upon targets through video feed. As an operator, subjects were required to operate UGV, where automation levels were set to 3 different levels (fully autonomous, semi-autonomous, and fully manual) for different groups. In addition to these tasks, subjects were also told to perform a communication task. Results showed that operators' performance on the gunner's job increased as the level of automation with piloting increased, because they could more focus on the gunner's job. Furthermore, Ruff et al [17] found that the UAV operator's perceived workload (based on participant's subjective ratings on a Likert-scale type question) in target acquisition task was decreased, when they were working with systems that exhibit higher LOA (management-by-consent, management-by-exception) than lower LOA (manual control).

The reduction in workload for the operator, not just in terms of physical amount of but in terms of perceived amount of work, allows room for extra work, contributing to the increase in the operator's ability to multitask. It is one of the important factors that makes UAVs versatile, as a human operator does not have to remain just seated in front of GCS and constantly monitor UAV. For example, in ISR-type mission, the human operator can fly UAV to scout unexplored surrounding environment to obtain geographic information, while he himself is simultaneously conducting an independent mission that can be assisted from the information gained from UAV scout [12]. Further, the disengagement from compulsory involvement with system may determine the safety and even the survival of operators who are

working in hazardous environments, such as dismounted soldiers and archaeologists, because they can still reserve sensory attention for their own security. It even allows the operator to manage multiple UAVs simultaneously, by coordinating plans of respective UAVs at the same time [6].

When it comes to building an efficient and healthy UAV system, implementing highly automated control is not always the best solution, however, because unexpected issues - such as vigilance, reliability, or complacency - might affect operators' performance on their supervisory role [7]. The benefits from increased automation are often offset by comparable side-effects of these kinds. Indeed, there are many researchers who have empirically shown that intermediate levels of automation can be advantageous over 2 extreme modes of automation, depending on the types of given tasks [17][13][16][4][24][8][1][14][23]. The goal of automation should be thus to increase overall efficiency of the integrated system and its durability by appropriately balancing expected benefits and these limitations.

2.3   Mode Confusion

In the domain of aviation, mode confusion refers to a phenomenon that when operating systems that have many different modes of operation and require dynamic interaction with different modes, pilots confused about which modes they are actually in and thus make inappropriate requests or responses to the systems. Mode confusion is a major concern and there have been many aircraft accidents involving mode confusion [22]. Mode confusion occurs when the system is in a different mode than that assumed by its operator [18]; from the perspective of psychology, it occurs when operators have a poor mental model of the system. More detailed discussion on the mode confusion using mathematical representation can be found in the Appendix E.

There are some researchers who are working on the analysis of mode confusion,

mostly in the more comprehensive domain of aviation. According to some relevant research on the cause of the phenomenon, it is claimed that mode confusion can usually result from inappropriate interface design, lack of appropriate feedback, and pilot inexperience with the respective mode [11] that leads to the formation of a poor mental model of system.

2.4 Summary

Technical advances have made available highly automated UAV systems. Although it is true that UAV automation can bring a lot of benefits to human operators, it can also be a source of disaster, if human operators are not properly trained with the appropriate program and prepared to use the system. The following chapter will describe an experiment designed to test the relation between training, increased autonomy, and UAV operator performance.

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Experiment Design

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An experiment was conducted to compare the difference in performance between UAV operators who use two extreme modes of control, that is, Manual Control (low LOA control) and Supervisory Control (high LOA control). For this purpose, two different interfaces that represent each extreme were developed. A representative drone operation environment was built to test these interfaces, and a total of 38 people were recruited for the experiment. Participants were randomly divided into 3 groups and each group completed different training programs. Group 1 was trained using Manual Control, and Group 3 was trained using Supervisory Control, while Group 2 was trained using both Manual and Supervisory Control. Participants then flew drones in their test mission stage for performance analysis.

3.1 Application Interface

3.1.1 Manual Control

Manual Control gives an operator full control over a drone by allowing fine-grained maneuver. Figure 3.1 shows the Manual Control interface. An operator can easily check the drone's current battery status by looking at the battery gauge located in
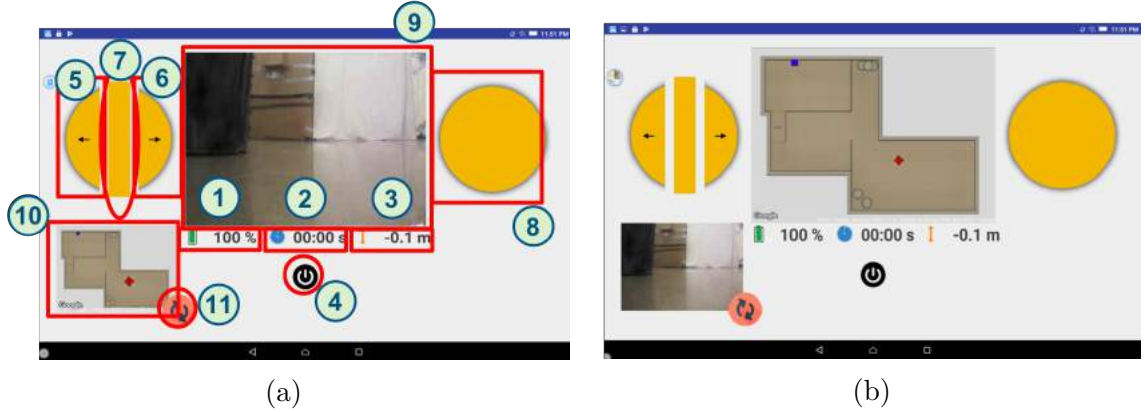
FIGURE 3.1: Manual Control Application Interface

the middle of the screen (the red box 1 in Figure 3.1a), so that the operator can keep track of the drone's health during navigation and allow the operator to report to experimenters immediately should the battery run out. Next to the gauge is the panel displaying flight time since takeoff, allowing an operator to keep his/her record in mind (box 2). Altitude indicator, placed next to the flight time panel, provides the true height of the drone's current position from a specific ground reference level (not sea level, box 3). It gives numerical information on the drone's height, which greatly helps when crossing certain types of obstacles, like bars and tunnels.

An operator controls a drone by using 2 joysticks located next to the main camera window. The right joystick (box 8) is responsible for lateral movement, without altering the current altitude. The direction of movement is not just limited to straight-line or diagonal movement, but reflects the drone's flexible movement. It adds much more freedom, when it comes to control, because an operator does not always have to align the drone's heading with the direction it is actually headed for. The middle bar in the left joystick (box 7) changes altitude, and 2 buttons marked with respective arrows (boxes 5 and 6) cause the drone to rotate in the corresponding direction.

23
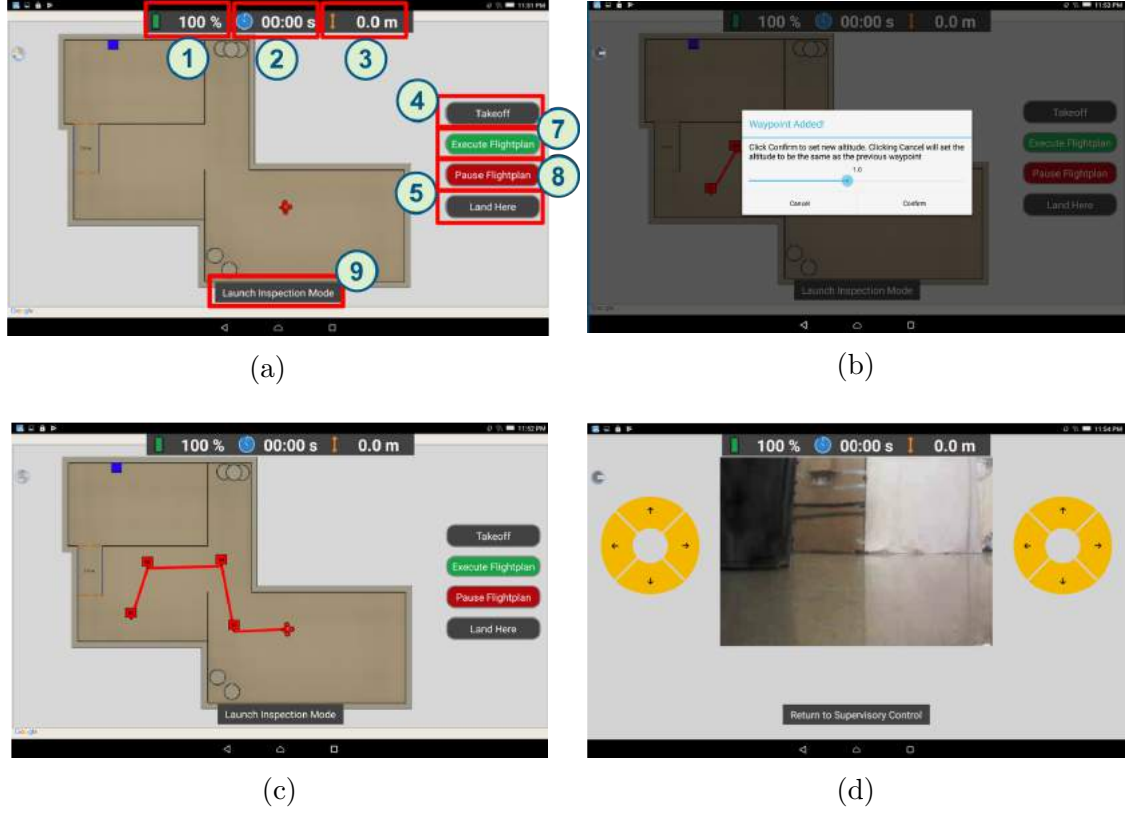
FIGURE 3.2: Supervisory Control Application Interface

An operator can get information on the surroundings through live camera stream (box 9), and can also check the current position of the drone in the mini-map placed at the bottom left corner of the screen (box 10). The position is marked by red drone icon and updated live. The main camera and mini-map frames can be swapped for the operator's convenience, using the swap button (box 11). The resulting configuration after window switching is shown in Figure 3.1b.

3.1.2 Supervisory Control

In Supervisory Control, an operator does not have to worry about micro control. Instead, an operator sets waypoints and executes the customized flight plan represented by waypoints. Figure 3.2 shows the Supervisory Control interface. First, an

operator can monitor battery status, flight time, and altitude through the relevant panels positioned at the top of the screen (boxes 1,2, and 3 in Figure 3.2a). On a map that occupies the entire screen, an operator can see the basic layout of the environment and known obstacles, and can create a waypoint by tapping and holding a finger at the desired spot. Along with the position of a waypoint, an operator can also specify the altitude of a waypoint (Figure 3.2b). Once the waypoints have been set as in Figure 3.2c, pressing the Execute Flight Plan button (box 7 in Figure 3.2a) will cause the drone to fly through the waypoints autonomously and sequentially (in the order of creation), as indicated by the path on the map. The drone moves in a straight line, considering the difference in altitude and position between 2 adjacent waypoints, and it pauses and hovers temporarily (about 1s) over each waypoint, until it resumes navigation to the next waypoint, in order to eliminate the momentum of moving forward when turning around.

Since Supervisory Control does not offer the feature of avoiding obstacles autonomously and only directs the drone through waypoints in a straight line, it is entirely the operator's responsibility to avoid any obstacles by setting proper waypoints. An operator can force the drone to pause at any time during navigation, using the Pause Flight Plan button (box 8), and change/remove the existing waypoints. Supervisory Control also allows the operator to check the surroundings through the camera by switching to Inspection Mode, using the Launch Inspection Mode button (box 9). The resulting screen is shown in Figure 3.2d.

Inspection Mode is similar to Manual Control in terms of function and how it works, but it has a different purpose. It is intended to work with the camera installed onboard drone; its main purpose is checking surroundings, not maneuvering the drone. For this reason, unlike Manual Control, Inspection Mode does not provide a mini-map, where an operator can check the location of the drone relative to the environment. Actually, an operator can control the drone manually using Inspection
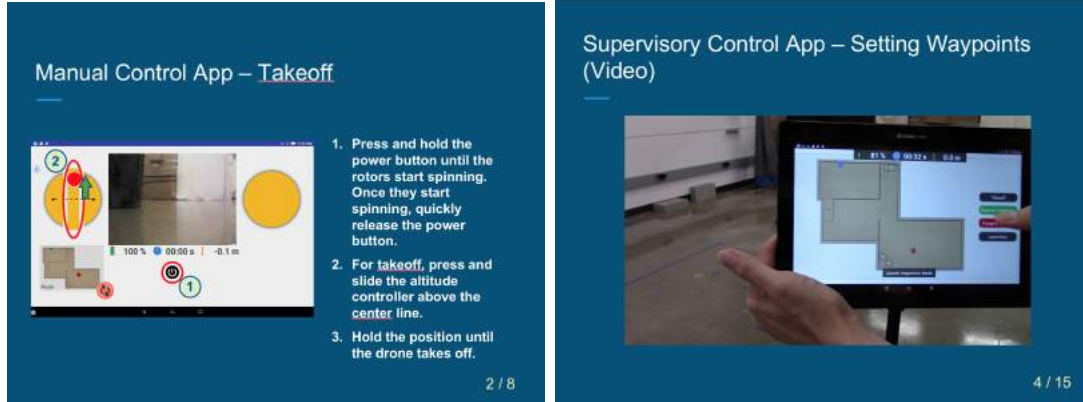
FIGURE 3.3: PowerPoint Slides For Training Program

Mode, but the drone's speed is much slower compared to Manual Control, and the direction of lateral movement is limited (only allowed to move in 4 directions; forward, backward, left, and right) so it is much harder to navigate using Inspection Mode than Manual Control. Operators can freely switch back and forth between Navigation Mode and Inspection Mode at anytime during flight and mix the use of them. For example, operators can interrupt and enter Inspection Mode while drones are executing a flightplan. Upon pressing the Inspection Mode button, drones will stop and hover at the position where the button is pressed, as if they are not doing anything. If the same button is pressed again, drones will resume executing the flightplan.

3.2   Training Program

3.2.1   Basic Training Modules

The training program consisted of 6 basic training modules + Checkride module. The first basic training module briefly explained basic concepts and knowledge about drones. Module 2 introduced the interface of the corresponding application, which was different according to which group a participant belonged. Module 3 explained how to take off and land a drone. Module 4 taught how to navigate a drone. Module
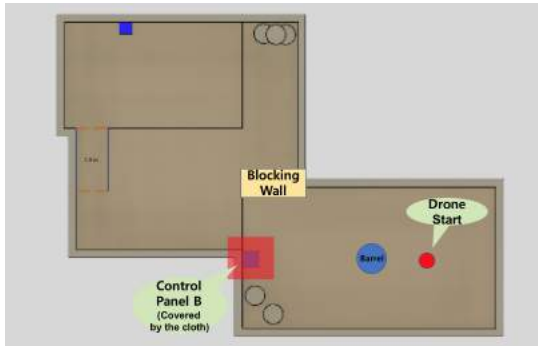
FIGURE 3.4: Module 3 Settings
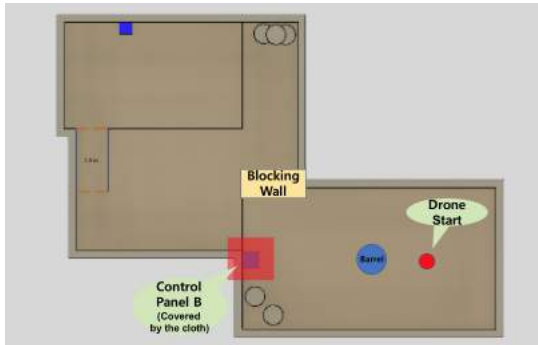
FIGURE 3.5: Module 4 Settings
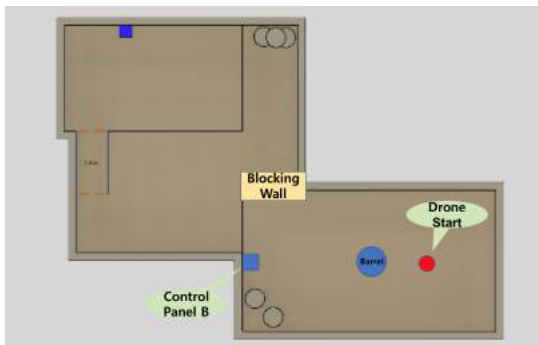
FIGURE 3.6: Module 5 Settings

5 explained how to control the camera installed on a drone. Module 6 introduced and explained possible emergency scenarios and provided general advice and tips on emergency handling in situations that are likely to occur during operation.

Each of these first 6 modules contained self-paced learning parts, where participants were given PowerPoint slides to study (Figure 3.3). All module slides can be found at http://hal.pratt.duke.edu/training-modules. In the slides, short video clips were included to facilitate training on how to operate an actual drone, so that they could get the sense of how it works in relation to the actual movement of a drone. Following the PowerPoint slides session, they were given multiple choice quizzes [Appendix D], to help them self-review the materials before moving on to the next module. Also, each one of Modules 3 - 5 (and also the Checkride; explained in the next section) included a hands-on practice part, where participants were given opportunities to practice actual control skills, based on what they learned from PowerPoint slides. The environmental settings for the flight training part of these modules are as shown in Figures 3.4, 3.5, 3.6. Their simple settings were intended to serve the purpose of each module while guaranteeing that participants were not confused and distracted by other objects. The complete schedule for training is shown in Table 3.1. The only difference (but one which is important) in the training programs between the 3 groups was that, while Groups 1 and 3 only learned about how to manipulate Manual Control and Supervisory Control, respectively, Group 2 learned both applications.

3.2.2 Checkride

The last module of the training program is the Checkride, the final flight practice. Unlike the previous basic modules focusing on a specific aspect of drone control, participants in this module were asked to complete a full mission in a miniature version of the test environment (which is explained in the next section). The Checkride

28

Table 3.1: Training Program

Module		Topic	Contents
Basic Training Modules	1	Basic Aerodynamics of Quadrotor UAVs	Powerpoint Slides Quizzes
	2	Control App Interface	Powerpoint Slides Quizzes
	3	How to Take Off & Land	Powerpoint Slides Quizzes Hands-on Training
	4	How to Navigate Quadrotor UAVs	Powerpoint Slides Quizzes Hands-on Training
	5	Camera Operation	Powerpoint Slides Quizzes Hands-on Training
	6	Guildelines for Safety and Emergency Handling	Powerpoint Slides Quizzes
Checkride		Actual Operation Practice	Hands-on Training

environment was not the same as the test environment, but was designed to train participants in preparation for types of obstacles they might encounter during the Test Mission. Also, this module prepared participants for the tasks they wouldl have to do during the Test Mission.

Figure 3.7 shows the Checkride settings. In the Checkride, operators were asked to fly the drone to reach Control Panel A, read signs on the control panel (Figure 3.8) (reading signs means examining the shapes and colors of the figures on the panel), and then safely fly the drone back to the designated spot while avoiding obstacles. For training, they were not allowed to fly over the barrels or PVC gates, which is obviously the easiest solution to avoid obstacles. Also, they were not allowed to proceed until they reported correct information on the panel (shapes and colors of figures). Participants were given a maximum of 3 chances to complete the mission.
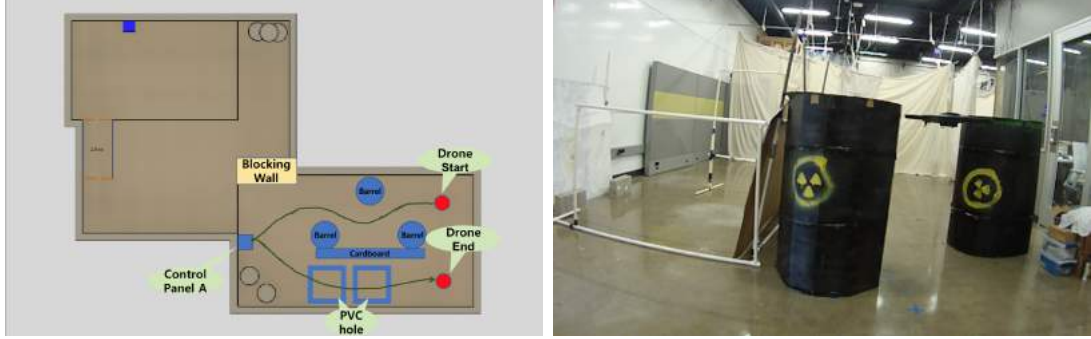
FIGURE 3.7: Environment Settings For the Checkride
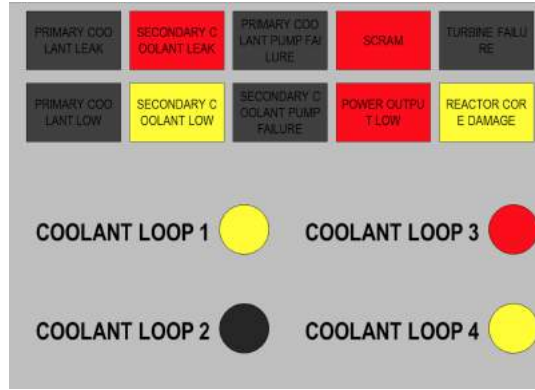
FIGURE 3.8: Control Panel

3.3 Test Mission

The Test Mission environment was designed to represent a typical drone operation environment, where a human operator flies the drone into a building for local ISR-type mission. The environmental settings for the Test Mission are shown in Figures 3.9a and 3.10. Figure 3.9a is a detailed map of the environmental space. Figure 3.10a is a picture of Room A, where the drone takes off and lands. Figure 3.10b is a picture of Room B, which leads to the Shaft. Figure 3.10c is a picture of the entrance of the Shaft, the hardest part to pass through - because of its limited space. Figure 3.10d is a picture of Door B, which leads to the hallway. Figure 3.10e is a picture of Control
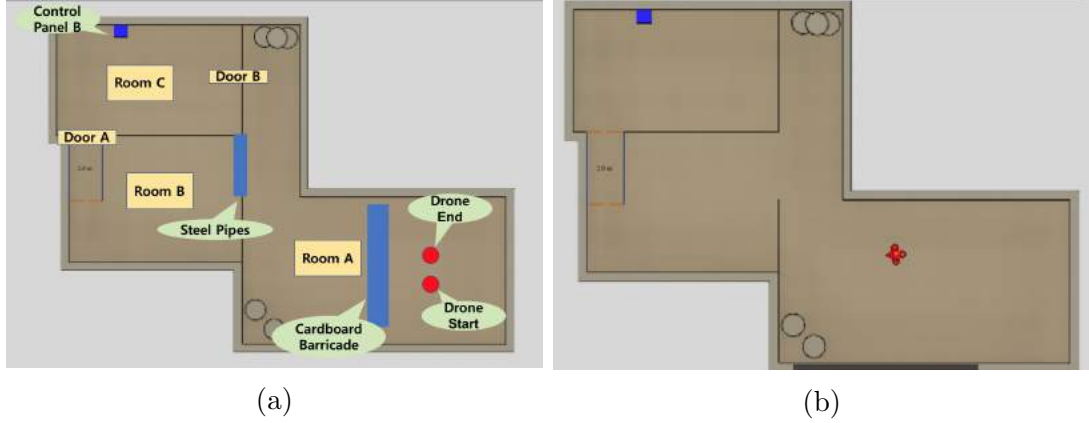
FIGURE 3.9: Environment Settings For Test Mission

Panel B, which is the target during the Test Mission. Figure 3.10f is a picture of the hallway which connects Rooms A, B and C.

In the Test Mission, participants were given exactly the same type of mission they were given in the Checkride. Participants were asked to fly the drone to reach Control Panel B, read signs on the control panel, and then safely fly the drone back to the original starting point. However, in the Test Mission, they were given only one opportunity to complete the mission.

Before beginning the Test Mission, participants were first briefed about the assumed task scenario of the Test Mission.

A nuclear reactor has been partially destroyed due to an earthquake, and it is unclear how compromised the containment of radioactive material has become. The building needs to be examined to determine the extent of the damage, but due to the risk of sending humans into this environment, a UAV will be sent instead. Now, you are assumed the task of sending a UAV into the building to reach a control panel, and to read key information on the status of the reactor on this panel. Then, fly the UAV safely back to the takeoff location for recovery of the vehicle.

31

(a)

(b)

(c)

(d)

(e)

(f)

FIGURE 3.10: Environment Settings for the Test Mission

Given the situation, some changes in the layout of environmental space were implemented to reflect a more realistic scenario. First there were static changes; since the space was assumed to be damaged, it is possible that some changes might have occurred in the space before the operator sent a UAV. This is why obstacles like the cardboard barricade and the steel pipes did not appear on the map of controlling interface provided to operators (Figure 3.9b); they had no way to access updated information on the status of the environment after damage, so a detailed, complete map like Figure 3.9a was not given to them.

Second, there were dynamic changes. These changes were to represent a situation where changes in the environmental space occurred while operators were performing the mission. At the start of Test Mission, participants did not know the existence and the exact location of Door B (which was physically blocked at the start of the mission), as it did not appear on their map (Figure 3.9b). To their knowledge, Door A of Shaft was the only viable and obvious path that led to the room where the target (Control Panel B) was. As soon as they reached Control Panel B, however, Door A was blocked and Door B was opened (with the help of an experimenter's manual operation), making Door B the only available evacuation path out of Room C. These door changes represented possible changes in the layout of a building in a real mission where the unexpected collapse of building structures forces operators to improvise and change their original plan under uncertain environment conditions. Figures 3.11 and 3.12 show the pictures of Doors A and Door B before and after change. Changes were signaled to participants through the sound of a loud, audible explosion, so that they could easily appreciate the changes. Participants were notified during mission briefing about the explosion sound and its implication so that, whenever hearing the sound, they could be prepared for the changes and start finding a new path. This notice was to prevent participants from being too panicked; otherwise, with no

FIGURE 3.11: Picture of Door A Before and After Explosion

FIGURE 3.12: Picture of Door B Before and After Explosion

warning, it would have been much harder for them to guess the real meaning of the sound.

Expected flight paths before the environmental changes and after the changes are shown in Figures 3.13a and Figure 3.13b, respectively.

3.4 Procedure

3.4.1 Participants

Subjects were recruited on the Duke campus through recruitment emails and flyers, but were not limited to students. Only those over 18 with 20/20 or corrected to normal vision (i.e., with glasses or contact lenses), and with no neurological disorders, seizure disorders, head injury or any physical impairments that would prevent them
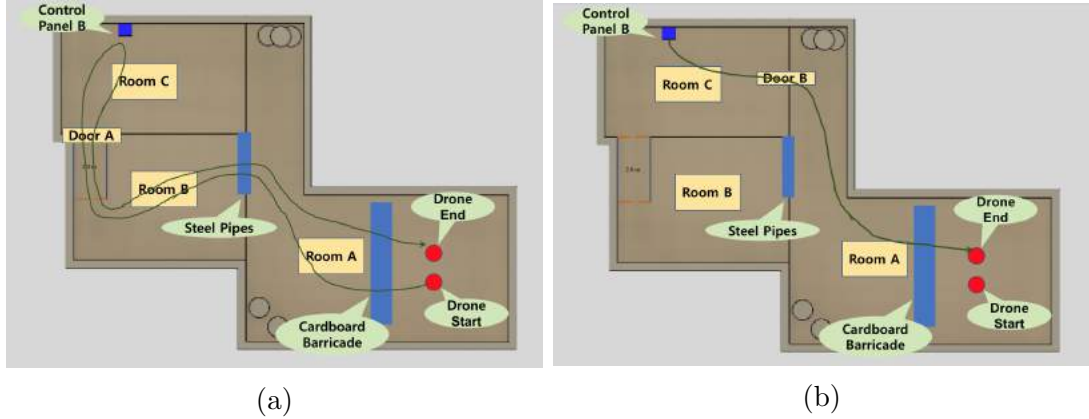
$\textsc{Figure}$ 3.13: Expected Flight Paths Before and After Explosion

from using a conventional computer input device were accepted as participants. As a result, a total of 38 people were recruited.

3.4.2 Timeline

Through a scheduling website, recruited subjects scheduled a time at their convenience. They were then randomly assigned to one of 3 groups, along with 2 experimenters, referred to as experimenter A and B. Experimenter A was mainly in charge of interaction with participants - guiding them through the experiment, giving instructions in each training module and Test Mission, and answering any questions. Experimenter B was responsible for system management - drone setup, battery change, repair in case of breakdown, and preparation of different environment settings between training modules, Checkride and Test Mission.

Each participant ran through the experiment individually with 2 assigned experimenters. Participants were first asked to sign a printed Consent form, IRB Personal Data Disclosure Form (for monetary compensation) and then asked to complete a preliminary demographic survey [Appendix A] using a desktop which asked about experiences with computer games, tablet computers, remote controlling devices, and

Table 3.2: Timeline & Time Allotment(mins) for Group 1

Experimenter gave an overview of experiment to participants			2
Subject signed forms(Consent form & IRB Personal Data Disclosure Form)			3
Subject filled out a demographic survey			3
Training	Module 1	Powerpoint Slides(Manual Control) Quizzes(Manual Control)	7
	Module 2	Powerpoint Slides(Manual Control) Quizzes(Manual Control)	7
	Module 3	Powerpoint Slides(Manual Control) Quizzes(Manual Control) Hands-on Training(Manual Control)	20
	Module 4	Powerpoint Slides(Manual Control) Quizzes(Manual Control) Hands-on Training(Manual Control)	20
	Module 5	Powerpoint Slides(Manual Control) Quizzes(Manual Control) Hands-on Training(Manual Control)	20
	Module 6	Powerpoint Slides(Manual Control) Quizzes(Manual Control)	7
	Checkride	Hands-on Training(Manual Control)	20
Subject flew the Test Mission(Manual Control)			20
Subject filled out a Post Experiment Survey			5
Experimenter gave a debriefing on subject's performance			2

drone operation. After completing a survey, participants proceeded to start the training program, as explained in Section 3.2. Participants then flew the Test Mission. At the conclusion of the test, participants were asked to fill out the post-experiment survey after the Test Mission. Finally, participants were debriefed about their performance in the Test Mission by Experimenter A and were paid ($40, $50, and $25 for Groups 1, 2, and 3 respectively. The amount reflects the estimated average runtime). Table 3.2 summarizes the timeline for Group 1 along with associated time allotment (Group 3 had a similar schedule). Table 3.3 shows the timeline for Group 2.

To minimize potential bias of different experimenters, all instructions were documented [Appendix B], that is, all experimenters were instructed to read aloud written

Table 3.3: Timeline & Time Allotment(mins) for Group 2

Experimenter gave an overview of experiment to participants			2
Subject signed forms(Consent form & IRB Personal Data Disclosure Form)			3
Subject filled out a demographic survey			3
Training	Module 1	Powerpoint Slides(Manual & Supervisory Control) Quizzes(Manual & Supervisory Control)	7
	Module 2	Powerpoint Slides(Manual & Supervisory Control) Quizzes(Manual & Supervisory Control)	10
	Module 3	Powerpoint Slides(Manual & Supervisory Control) Quizzes(Manual & Supervisory Control) Hands-on Training(Manual Control) Hands-on Training(Supervisory Control)	25
	Module 4	Powerpoint Slides(Manual & Supervisory Control) Quizzes(Manual & Supervisory Control) Hands-on Training(Manual Control) Hands-on Training(Supervisory Control)	25
	Module 5	Powerpoint Slides(Manual & Supervisory Control) Quizzes(Manual & Supervisory Control) Hands-on Training(Manual Control) Hands-on Training(Supervisory Control)	25
	Module 6	Powerpoint Slides(Manual & Supervisory Control) Quizzes(Manual & Supervisory Control)	7
	Checkride	Hands-on Training(Manual Control) Hands-on Training(Supervisory Control)	25
Subject flew the Test Mission(Supervisory Control)			20
Subject filled out a Post Experiment Survey			5
Experimenter gave a debriefing on subject's performance			2

scripts, and to follow exactly the same experiment procedure and timeline which was documented in detail as a to do list. Although experimenters were allowed to answer questions, they refrained from giving additional, voluntary comments or lectures of any kind. To ensure uniformity, each experimenter went through at least 3 practice experiments, to train themselves and become acquainted with the experiment procedure.

(a)   (b)
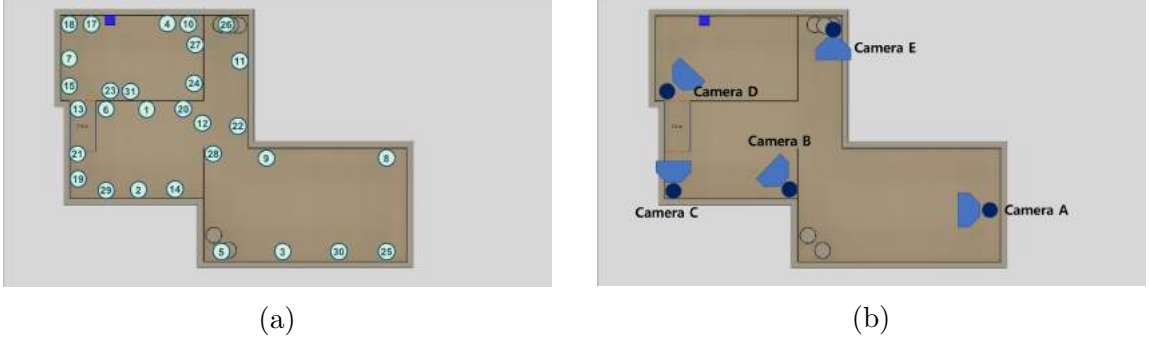
FIGURE 3.14: Camera Configuration

3.4.3 Apparatus

A tablet computer (Lenovo Tab 2 A10-70, 1920 × 1080 pixels) was used as hand-held device for the display of interfaces and control of drones by participants. The type of the UAV used in the experiment is a Parrot AR 2.0 UAV, and open-source software Paparazzi was used to customize the drone's settings. To track the drone's location, 26 Vicon Vero cameras and 4 Vicon Vantage cameras (for better coverage than Vero cameras to open areas) were installed in the experiment environment as replacements for GPS. The VICON camera configuration is as shown in Figure 3.14a. To guarantee their accuracy, the cameras were calibrated for every 4-5 experiments. In addition to VICON cameras, 5 digital recording cameras were placed as shown in Figure 3.14b to record the drone's movement.

3.4.4 Data Collection

Demographic and Post-Experiment survey [Appendix C] data were collected electronically through Qualtrics. At the end of each experiment, Experimenter A filled out an Experimenter Report and submitted it to Qualtrics as well. The Experiment report is a summary of what happened during the experiment, including crash report and information on the Experimenters. Participant interactions with a controlling

38

device were recorded as a form of tablet screen capture using DU recorder application. Drone's movements were recorded using 5 video cameras placed as depicted in Figure 3.14b. Also, the drone's exact location at every instant were logged to a CSV file consisting of x, y, z coordinates relative to VICON system calibration.

3.5 Summary

This chapter describes the experiment design of an experiment organized to examine the difference in performance between 3 different UAV operator groups who were trained with 3 different programs. The experiment was conducted and data from 38 participants were collected as a result. The next chapter presents the results obtained from the experiment.

4

Results

After conducting an experiment described in the previous chapter, data were collected to study and compare Test Mission performance between 3 groups. During the Test Mission, subjects in Group 1 used Manual Control, while subjects in Group2 2 and 3 used Supervisory Control. Out of 38 subjects, 4 were excluded from analysis for either poor quality of data or failure in data retrieval. The performance of the 3 groups were compared to each other, based on the data label and the defined performance metrics. For any statistical test incurred, a significance level $\alpha = 0.05$ is used throughout this chapter.

4.1 Performance Metrics

1. Pass vs. Fail

   If a participant completed the mission without any crash, the test was marked as Pass. If a participant crashed, experimenters immediately examined the reason using recorded video files. If the crash was clearly due to operator fault, the test was marked as Fail. If it was clear that the crash resulted from a system malfunction, such as battery runout or unstable connectivity of any

kind between devices, the participant was allowed to resume the test from the point of crash. In this case, the test was marked as either Pass or Fail, depending on the final result, but also asterisked for reference in analysis. If the reason for the crash was unclear at the time of experiment, the participant was allowed to resume the test from the point of crash, while being asterisked.

2. Mission Completion Time

   Measured total completion time elapsed from take off at starting point until landing at the landing point. This metric assesses the operator's overall ability to navigate a drone, while passing through various courses of different levels.

3. Time Taken From Start To Shaft

   Measured time elapsed from take off at the starting point until entry into Shaft in Room B. This metric assesses the operator's ability to control the drone in an known environment, where space is wide open with few obstacles that are not hard to avoid.

4. Time Taken To Pass through Shaft

   Measured time elapsed to pass through Shaft in Room B. This metric assesses the operator's ability to control the drone in a tight, limited space, where the virtues of caution, patience and endurance are required. This is because the passage through Shaft is relatively narrow compared to the drone's size, and the drone's random, unstable movements due to the wind created by its own rotors and reflected from the walls of Shaft make the control even harder.

5. Time Taken From Explosion To Finish

   Measured time elapsed from the moment of explosion until landing at the landing point. This metric assesses the operator's ability to make decisions under uncertainty, as operators had to find and explore another evacuation

Table 4.1: Data Label

	Group 1	Group 2	Group 3
Complete	10	8	8
Broken	1	1	0
Partial	1	3	2
Total	12	12	10

route that did not appear on the map when they were not sure which way would be the right way.

4.2   Data Label

Out of 38 recruited subjects, 4 of them were completely excluded from analysis. For 2 of them, data were not collected successfully because of the Experimenter's fault. The other 2 subjects were excluded because they showed significantly poor performance compared to others. Neither of them could not make it through the very first obstacle (the cardboard barricade) in Room A, while others successfully passed through the second obstacle (the steel pipes) and at least made it to the Shaft. So their data were labeled as outliers and filtered out.

As a result, only data from 34 subjects were used for analysis (12 / 12 / 10 for Group 1, 2, and 3, respectively). For reliable discussion of the results from data analysis, data were labeled as either "Broken", "Partial", or "Complete" for easy and appropriate use of data. Broken data is data where the drone landed prematurely due to battery depletion, so participant had to pause and resume flight after replacing the battery. In this case, the subject's performance was estimated by adding 2 separate records, while appropriately taking out time unnecessarily spent on landing, takeoff and re-orienting before and after battery change. Partial data is data where the subject's performance might have been affected by external factors (other

than battery issue) that were not intended and unexpected. One example was the case where Door B did not operate in a timely manner, so that it delayed subject's performance. The other cases were caused by system error that caused the drone to malfunction and had nothing to do with the subject's actions. Finally, Complete data is data where the subject did not suffer any kind of noticeable issues during the Test Mission that could have prevented normal operation. Table 4.1 summarizes the number of data for each label.

For analysis purposes, all of these data were selectively chosen and used wherever appropriate. For example, when considering "Mission Completion Time", only complete data were used. However, when dealing with "Time Taken From Start To Shaft", some partial and broken data were also included in analysis (in addition to complete data) because those data were not corrupted and thus valid at least up to the point where the drone reached Shaft. By doing so, we could maximize use of our collected data while making the results as reliable as possible.

4.3   Subject Population

All 34 valid subjects used in analysis were between the ages of 21 and 41, with an average of 25.53 years (sd = 3.70 yrs). Out of 34 subjects, 31 were students (29 graduates, 2 undergraduates), with 27 males and 7 females. Among 34 subjects, 11 people reported experience in UAV operation such as quad-copter and model aircraft, and all of them reported to have used a joystick controller as a control device, which is different from the touchscreen controller used for the experiment. Self-estimated hours of drone experience were merely 1.95 hrs on average (with sd = 1.46 hrs) and most of them tended to feel less confident when asked about their comfort level with flying drones (average = 2.36 on a 5-point likert scale, 1 implying Not Comfortable and 5 implying Very Comfortable). Table 4.2 shows the summary statistics on these metrics.

Table 4.2: Subject Population

	Age (yrs)	Drone Experience (hrs)	Comfort Level with Drone (5-point likert scale)
Average	25.53	1.95	2.36
Minimum	21	0.5	2
Median	25	1	2
Maximum	41	5	4
Standard Deviation	3.70	1.45	0.67
Sample Size	34	11	11

Table 4.3: Success Rate

	Group 1	Group 2	Group 3
Pass	5	3	6
Fail	5	5	2
Total (Complete)	10	8	8

4.4 Performance Comparison

4.4.1 Pass and Fail

Table 4.3 shows the number of Pass and Fail for each group. Group 3 was the most successful in terms of the success rate ($6/8 = 0.75$), followed by Group 1 ($5/10 = 0.5$) and Group 2 ($3/8 = 0.38$). However, the generalized Fisher exact (Fisher-Freeman-Halton) test yields the p-value of $p = 0.3017$ on the Pass/Fail ratio between groups, which indicates that statistically, there is no significant difference in the success rate. Among 12 crashes, 8 crashes occurred near Shaft as shown in Figure 4.1. In Figure 4.1, red arrows indicate the drone's movement at the moment of crash, and numbers are subjects' IDs. Examining their screen recording, all 8 subjects had a hard time aligning their drones to the 40 inch-wide entrance of the Shaft, due to the delay in video stream and wobble caused by reflected winds from its rotors.

(a) Group 1

(b) Group 2

(c) Group 3
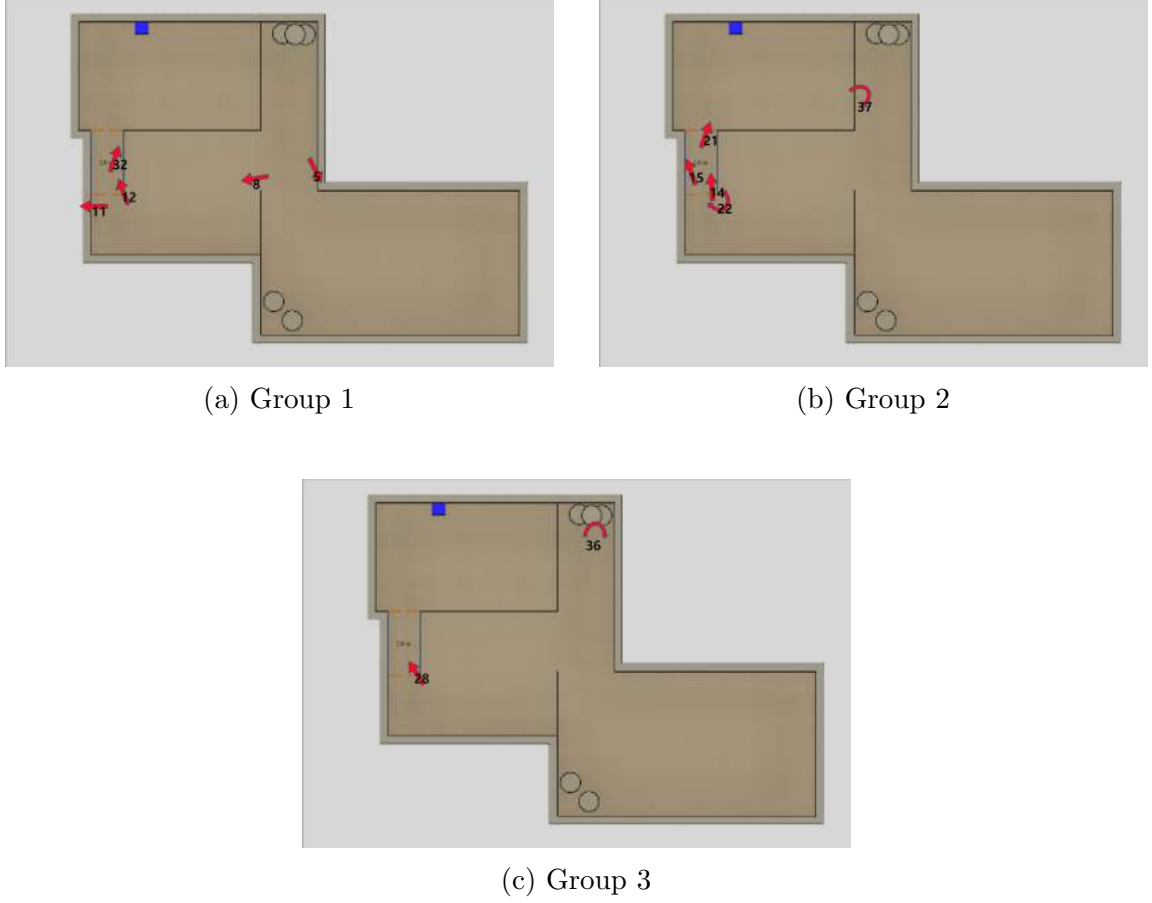
FIGURE 4.1: Crash Points

4.4.2 Mission Completion Time

Table 4.4 shows the summary statistics on completion time for those who succeeded in the Test Mission and were labeled as Complete data. Based on one-way ANOVA test, there was no significant difference in the completion time ($p = 0.7438$). The best performers from the 3 groups showed similar performance in terms of completion time (5:22, 5:23, 5:27 for Group 1, 2, and 3, respectively), while the worst performers did not (10:05, 10:00, 8:06 for Group 1, 2, and 3, respectively); the worst performer in Group 3 showed much better performance than those in other groups. Actually, the performance by subjects in Group 3 was more consistent (sd = 1:05) than other

Table 4.4: Completion Time (mm:ss)

	Group 1	Group 2	Group 3
Average	7:49	7:21	6:58
Minimum	5:22	5:23	5:27
Median	8:13	6:42	7:10
Maximum	10:05	10:00	8:06
Standard Deviation	2:10	2:22	1:05
Sample Size	5	3	6

Table 4.5: Performance of the Experienced Operators
(Completion)

	Group 1	Group 2	Group 3
Pass	1 (10:05)	1 (10:00)	2 (8:00) (8:06)
Fail	2	2	1
Total (Complete)	3	3	3

groups (sd = 2:10, 2:22 for Groups 1 and 2, respectively). Interestingly, it turned out that those who said that they had previous drone experience showed the worst performance in each group. Table 4.5 shows the results of these experienced operators who were labeled as Complete only. In Group 1, all 3 experienced operators (out of 10 complete data) ended up either Fail or being the worst performer (10:05) in the group. In Group 2, all 3 experienced operators (out of 8 complete data) were either Fail or being the worst performer (10:00) in the group. Especially, the worst performer in Group 2 did considerably worse (10:00) than others who passed the Test Mission in the same group (6:42, 5:23). Similarly, in Group 3, all 3 experienced operators (out of 8 complete data) were either Fail or being the worst performers (8:00, 8:06) in the group.

Table 4.6: Time From Start To Shaft (sec)

	Group 1	Group 2	Group 3
Average	189.82	205.89	153.11
Minimum	95	93	54
Median	165	168	145
Maximum	307	368	264
Standard Deviation	62.29	101.12	69.13
Sample Size	11	9	9

Table 4.7: Performance of the Experienced Operators
(Start To Shaft)

	Group 1		Group 2		Group 3	
Pass	4	(161) (307) (161) (119)	3	(168) (368) (270)	3	(203) (122) (54)
Fail	0		0		0	
Total (Complete + Broken)	4		3		3	

4.4.3 Time Taken From Start To Shaft

Table 4.6 shows the summary statistics on the time elapsed from start to the Shaft. For this metric, there was no statistical evidence found to support the difference between groups using one-way ANOVA ($p = 0.3526$). While the average record for each group tells that Group 2 was the worst, the poor performance came from the 2 subjects (358 sec, 368 sec) who noticeably underperformed the others in the same group. On the other hand, in Group 3, there were 2 subjects (54 sec, 64 sec) who showed remarkably better performance than the others in the same group. One of them (54 sec, the fastest for this metric) was an experienced operator, but he ended up finishing the Test Mission with the worst performance (completion time = 8:06) in the group. The other (64 sec, the second fastest for this metric) recorded the

Table 4.8: Shaft Passage Time (sec)

	Group 1	Group 2	Group 3
Average	83.63	73.00	61.88
Minimum	29	29	23
Median	74.5	60.5	55.5
Maximum	168	176	122
Standard Deviation	50.89	53.62	30.46
Sample Size	8	6	8

Table 4.9: Performance of the Experienced Operators
(Shaft Passage)

	Group 1		Group 2		Group 3	
Pass	3	(29)(81)(84)	1	(55)	2	(88)(122)
Fail		1		2		1
Total (Complete + Broken)		4		3		3

second best performance (completion time = 5:56) in the group. Table 4.7 shows the results of the experienced operators for this metric.

4.4.4 Time Taken To Pass Through Shaft

Table 4.8 shows the summary statistics on Shaft passage time. For this metric, no statistically significant evidence was found between groups based on one-way ANOVA ($p = 0.6376$). On average, Group 3 was the fastest (61.88 sec) to get through the Shaft, followed by Group 2 (73.00 sec) and Group 1 (83.625 sec). After examining the screen recording of each subject in Groups 2 and 3 who used the same application (Supervisory Control) in the Test Mission, it was found that the increased time by Group 2 came from the mixed use of Supervisory Control and Inspection Mode. In Group 2, 3 out of 6 subjects used Supervisory Control and Inspection Mode

Table 4.10: Time Taken From Explosion To Finish (sec)

	Group 1	Group 2	Group 3
Average	153.00	150.75	154.33
Minimum	93	107	124
Median	157	152	139
Maximum	219	192	253
Standard Deviation	50.82	46.03	49.30
Sample Size	5	4	6

Table 4.11: Performance of the Experienced Operators
(Explosion To Finish)

	Group 1	Group 2	Group 3
Pass	1 (182)	1 (192)	2 (146) (253)
Fail	2	2	1
Total (Complete)	3	3	3

interchangeably. The remaining 3 subjects used Inspection Mode only while in the Shaft. On the other hand, in Group 3, only 1 out of 8 subjects used both Supervisory Control and Inspection Mode at the same time. The remaining 7 subjects used only Inspection Mode while in the Shaft. Table 4.9 shows the results of the experienced operators for this metric.

4.4.5 Time Taken From Explosion To Finish

Table 4.10 shows the summary statistics on the time elapsed from explosion to end. For this metric, there was no statistical difference in groups. Table 4.11 shows the results of the experienced operators for this metric. After examining tablet recording data, it was found that most people in Groups 2 and 3, more cautious after the explosion sound, relied more on Inspection Mode after explosion than before the entry into the Shaft (Start to the Shaft), which can be observed from Tables 4.12

Table 4.12: Percentage of time spent on Inspection Mode
(Start to Shaft, %)

	Group 2	Group 3
Average	56.21	71.50
Minimum	32.86	16.67
Median	51.90	74.48
Maximum	87.10	99.18
Standard Deviation	19.52	28.46
Sample Size	9	9

Table 4.13: Percentage of time spent on Inspection Mode
(Shaft Passage, %)

	Group 2	Group 3
Average	70.50	91.75
Minimum	14.29	34
Median	80.97	100
Maximum	100	100
Standard Deviation	35.80	23.33
Sample Size	6	8

Table 4.14: Percentage of time spent on Inspection Mode
(Explosion To Finish, %)

	Group 2	Group 3
Average	76.13	88.01
Minimum	26.10	64
Median	89.22	93.68
Maximum	100	100
Standard Deviation	33.79	15.07
Sample Size	4	6

and 4.14.

Tables 4.12, 4.13 and 4.14 show the summary statistics on the percentage of time operators in group 2 and 3 spent in using Inspection Mode for each metric.

For example, if an operator took 219 seconds from start to the Shaft while using Inspection Mode for 67 seconds, his percentage was calculated by $67/219 \times 100 = 69.41(\%)$. Overall, they spent more time in using Inspection Mode, because they had to use it by default to check and investigate the surroundings (which acted as a fixed cost). On average, people in group 2 and group 3 spent more time on Inspection Mode after Explosion than before the Shaft. Also, people in group 3 used the Inspection Mode more than group 2 on average. More specifically, more people in group 3 (7 out of 8 subjects) showed 100% use of Inspection Mode in the Shaft, while only half of people (3 out of 6 subjects) in group 2 showed 100% use of Inspection Mode in the Shaft.

4.5   Summary

This chapter presents the results of a drone operation experiment that was designed to compare different performance between 3 groups. The next chapter examines the implications of the results in greater detail in relation to our research objective declared in Section 1.4, while addressing the limitations of the experiment and suggesting a direction for the next step in future work.

5

Conclusions

The difference in performance between Group 1 and Group 3 was expected and not surprising. However, the fact that Group 2 underperformed Group 3 raised question about effect of additional training. The results forced us to change our prejudice and claim that additional training is not only more costly, but it could even be detrimental to operator performance. Caution should be exercised in generalizing from the results of the experiment, but an extended work using a more mathematical approach could be helpful in drawing a meaningful conclusion from these empirical results obtained under limited conditions.

5.1   Implications of Results

If Group 2 is taken out, the results were quite as expected. For all metrics considered, Group 3 was mostly better than Group 1, except for the record in Time Taken From Explosion To Finish (see Tables 4.3, 4.4, 4.6, 4.8). This was clearly due to the advantage of high LOA system, because people in Group 3 had an additional option of using waypoint function which helped them do better. People in Group 1, who only had Manual Control option, might have suffered from mental and physical

fatigue from continuous involvement with fine-grained control. Most of them seemed to care about small random movements while the drone was hovering at a fixed point, erroneously thinking that they were doing something wrong with control, which was not true. Then they tried to react to every unexpected behavior of drone, by adjusting their control to compensate for the unexpected disposition, which quite significantly delayed their flight. This was not the case with Group 3, mainly because most people in Group 3 seemed not to care too much about wobbling of the drone or were not even able to recognize the existence of such movements even when the drone was not in the middle of navigation and staying still for inspection of surroundings. For group 3, direct flight control was not their main job, causing them to less focus on the perception of drone's small random movements and believe that the system would not fail unless they did something wrong. It is worth noting that one of the participants who failed in Group 3 was a heavy user of Inspection Mode. He did not use waypoint function at all and entirely relied on Inspection Mode throughout the whole course until he crashed, which might have caused a similar amount of mental fatigue in him as with Group 1 operators. In summary, using high LOA system made Group 3 do better by alleviating their overall workload and fatigue.

What was perplexing though were the results of Group 2. Theoretically, people in Group 2 should have shown the best performance, or at least similar performance to those in Group 3, because they were trained with both Manual Control and Supervisory Control and used the same Supervisory Control in the Test Mission as Group 3. However, the hypothesis was contradicted by the poor performance of Group 2. First of all, its success rate (3/8) was even worse than Group 1 (5/10). Most failures came from crashes near the Shaft. However, the fact that people in Group 3 who also used Supervisory Control were not in trouble when passing through the Shaft suggests the poor performance of Group 2 should be interpreted differently. What is interesting is their performance in Time From Start To Shaft.

According to this metric, Group 3 showed the best average performance (153.11 sec), while Group 2 (205.89 sec) was the worst. After examining their interaction patterns with the controller through tablet recording data, it was found that most people in Group 2 were trying to do fine-grained control, even when they were using waypoint function of Supervisory Control. In other words, they were doing near-manual control using the waypoint function. This could be observed through their constant change/removal of the existing waypoints, which happened more frequently than with people in Group 3. It seemed like they were obsessed with pinpointing the exact spots they wanted to set waypoints when it was not necessary at all. It appeared that they were unnecessarily more worried and even distrustful about the stability and accuracy of the waypoint function than Group 3, even though they had the same amount of training with Supervisory Control as Group 3. They kept trying to set waypoints right in the middle, between obstacles and walls, so as to minimize the chance of crash as much as possible. Whatever the true reason was, their frequent changes in existing flight plan significantly slowed down their pace and even led some to failure.

What is also interesting is the difference in strategy used by people in Group 2 and Group 3 when passing through the Shaft. Comparing the average Time Taken To Pass Through Shaft, Group 3 was the best (61.88 sec), followed by Group 2 (73 sec) and Group 1 (83.63 sec). The reason of the slower record by Group 2 was the mixed use of Supervisory Control and Inspection Mode. As mentioned in Section 4.4.4, more people in Group 2 chose to use Supervisory Control and Inspection Mode interchangeably (3 out of 6) than people in Group 3 (1 out of 8). However, after examining the best performers' flight patterns of Group 2 and Group 3, it turned out that using only Inspection Mode was the best strategy to pass through the Shaft, because the structure was too narrow and hazardous to use waypoint function safely. Using Inspection Mode only through the course helped them minimize the

overhead coming from constantly changing the mode between Supervisory Mode and Inspection Mode. In contrast, they could gain little benefit from using Supervisory Mode because they had to keep setting just one or two waypoints cautiously and executing the flight plan again so that they would not fail in the narrow structure of the Shaft. So, it could be said that half of the people in Group 2 failed to choose an optimal strategy that was best suited to the structure.

From these different flight patterns between Group 2 and Group 3 and their association with differences in performance, we concluded that the additional training given to Group 2 had somehow negatively impacted their performance. More specifically, their extra knowledge and skill in Manual Control might have made them less skillful in Supervisory Control by forming a poor mental model. It could be argued that the way the people in Group 2 were trained could have been detrimental to them. As it can be seen from the Table 3.3, they were trained in a serial manner; they completed one module at a time with both Manual and Supervisory Control interfaces. It could have been different for them if they were trained in parallel by differentiating the combined training program into 2 separate programs for Manual and Supervisory Control interfaces just like how aircraft pilots are normally trained. This might have helped them better differentiate mental models for Manual and Supervisory Control interfaces and not be confused about them, at the cost of increasing the whole training time due to the duplicated materials. But, at least it could be claimed that the results should be attributed to the poorly formed mental models of two different interfaces, the effect called mode confusion. Another observation that supports this idea was that Group 3 showed relatively consistent performance in terms of Completion Time (sd=1:05) compared to Group 2 (sd =2:22). Not only were their time records consistent, but their flight strategies were similar to each other, meaning they had more solid and consistent understanding of the interface. The idea could be further supported by the poor performance of experienced opera-

tors, as is described in Section 4.4.2. The heavy user of Inspection Mode in group 3 mentioned earlier in this section was also an experienced user. Those who had drone experience might have suffered from confusion between what they remembered from past experience with the use of other drones and what they learned through training in this experiment (which is called negative transfer of training). All of the experienced users said that they used a real joystick controller, which is totally different from our tablet controller. Therefore, we concluded that all of these mixed experiences with different interfaces must have led to the formation of poor mental models of Supervisory Control.

5.2   Limitations And Future Work

Caution should be exercised in interpreting and generalizing the results. First, the sample size was not big enough to make any broad generalizations. We had to label many data as "partial" or "broken" and thus lost many "complete" data because of either system failure or Experimenter fault. As a result, we had too few "complete" data. Second, the sample pool was biased. Most subjects were graduate students in their twenties. Out of 34 student subjects, 32 said that their majors were engineering-based (computer science, engineering management, biomedical engineering, mechanical engineering, and electrical engineering). The 2 exceptions were sociology and neurobiology. Most of the subjects were people who were familiar with electronics, mechanics, and space perception. As a result, the samples were skewed. Next, it should be noted that this was an indoor experiment. So, results may have been different if weather effects played a role in the drone's movement and distracted operator's attention.

As extended work, it would be worth conducting a similar experiment using the parallel training program as pointed out in the previous section, to see if the serial training was the main cause of the skill degradation. Also, changing the environment

for the experiment from the indoor settings to outdoor would be helpful in generalizing and interpreting the empirical results in relation to the actual drone operation environment where there are a lot more uncertainty, especially caused by random weather effect of wind, dust and moist. In the outdoor settings, the increased uncertainty is highly expected to affect the performance of UAV operators, but the study on whether or not it would affect differently across the operators with different training would be useful in examining the effect of training under increased uncertainty settings. The ISR-type mission task could be replaced by more complex task (such as target shooting and delivery) that requires more attention and workload in order to see how increased level of mission task would affect differently.

For future work, a good research topic would be to directly evaluate the different mental models between UAV operators. More specifically, first evaluate mental models that are formed in different UAV operators who are trained with different training programs (possibly using the method discussed in the Appendix E) and use the evaluation as the comparison criteria instead of other indirect criteria such as mission completion time. The direct comparison through mental models could serve as a more compelling method in discussing the results as opposed to the use of completion time, for example, which is not guaranteed to well-represent the quality of the mental model and thus an operator's overall understanding of the interface. Eventually, it could enable a more mathematical, quantitative discussion on the performance comparison between operators under different conditions.

Appendix A

Demographic Survey

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<u>Demographic Survey</u> : Please answer to the following questions.

Q1. Please select your assigned subject number.

[⬍]

Default Question Block

Q2. Date of Birth (mm/dd/yyyy) :

[   ]

Q3. Gender :

Male

Female

Q4. What is your visual acuity?

Normal vision (20/20)

Corrected vision (20/20)

Other (please explain):
[   ]

Q5. Do you have any type of color blindness?

Yes, type :
[   ]

No

Not sure

Q6. Have you ever had the following conditions? (Check all that apply)

Neurological disorders

Seizure disorders

Head injuries

Physical impairment on one or both hands

None of the above

Block 2

Q7. Are you a student?

Yes

No

Q7-1. You are

Undergraduate

Graduate

PhD

Q7-2. What is your major?

_____

Q7-3. Expected year of graduation (yyyy) :

_____

Q7-1. What is your occupation?

Block 3

Q8. How often do you play computer games?

Rarely   A few times a   Once a week   A few times a week   Daily
                    month

Q9. Types of games played (Check all that apply) :

First Person Shooter   Action / Adventure

Third Person Shooter   Survival Horror

Role Playing   Beat em ups

Sports   Simulation

Educational   Real Time Strategy

Puzzle   None of the above

Q10. Rate your comfort level with remote controlling devices :

Not Comfortable   Very Comfortable

Q11. Rate your comfort level with using tablet computers :

Not Comfortable   Very Comfortable

Q12. Have you previously flown any sort of drone or Unmanned Aerial Vehicle (e.g. quadcopter, model aircraft)?

Yes

No

Q12-1. What types of drone or UAV have you flown?

Q12-2. Estimate how many hours you have spent flying drones :

Q12-3. What type of controller did you use in flying drones?

Joystick Controller

Touchscreen Controller (e.g. phone, tablet)

Other :

Q12-4. Rate your comfort level with flying drones :

Not Comfortable

Very Comfortable

Appendix B

Instructions for Experiment

	Subject Status	To do	
		Researcher A	Researcher B

Step 0	Not Available	1. Print & prepare the following documents:
		  A. Consent Form
		  B. IRB Personal Data Disclosure Form
		
		2. Prepare the following apparatus / devices:
		  A. Drone B & C.
		  B. Fully charged 6 Batteries(A~F) for drones.
		  C. Fully charged 5 Video Recording Cameras(A~E) with SD card inserted.
		    Place them in the designated places with turned off.
		  D. Fully charged Tablet.
		  E. Fully charged iPad.
		  F. Wireless Stick C, plugged into the Desktop B.
		  G. Door trigger, battery disconnected.
		  H. Check the VICON Cameras are calibrated and working good.
		    (no need to recalibrate the cameras unless there is an issue).
		    PLEASE REPORT ANY ISSUE ASSOCIATED WITH THE VICON SYSTEM IMMEDIATELY ONCE YOU SEE ANY.
		  I. Working pen (will be used to sign the consent form).
		
		3. Check the following experimental settings:
		  A. Make sure Door C closed, Door B is open. Using Door trigger, check whether they do work automatically (make sure all of the batteries are still working).
		  B. Leave Door B and Door C open, with batteries disconnected.
		  C. Control Panel A and B attached to the wall firmly.
		
		4. Check the Speaker connected to a Desktop A is working.
		
		5. Please read "Cautions" document carefully before the experiment.	

Step 1	**(Training room)**
	Enter the training room
		1. Remember to carry **iPad** always with you.
		
		2. Open up this **checklist.docx** file.
		
		3. Check the pre-assigned subject number (1 ~ 36) in the **schedule.xlsx** file on our shared Box.
		
		4. Meet the subject at **North 130.**
		  A. Do not ask for any unnecessary information (including name, phone number) or questions.
		  B. **Do not explain about anything related to the experiment yet.** Just say "I will explain it later once we get to the experimental space."
		
		5. Lead the subject to the **Training Room**
		  A. **Do not use the direct path to the Training Room; use the path outside.**
		
		6. Have the subject be seated in front of the **Desktop C**
			1. Close the **Door C**, with battery disconnected.
			
			2. Put the **Blocking Cloth Wall** (to separate the practice room) in place before the subject comes in.
			
			3. Put 3 **Steel pipes** across the doorway of the **Door A.**

Step 2	**(Training room)** Be given an overview	1. Read out the overview(script) on the experiment. 2. Then, unlock the screen saver of the **Desktop C**. The password is **HAL@134**	1. Put the warning signs on the **Door D** and **Door E. (IMPORTANT!)** 2. Switch on the power strip for the **VICON Cameras** to turn them on. . 3. Execute the VICON tracker in the **Desktop A.**

				4. Check whether all the **VICON Cameras** are calibrated and working good. 5. Should any **VICON Camera** display [X] mark in the VICON tracker, reboot the cameras in trouble (no need to reboot all the cameras). 6. Make sure the status of all the **VICON Cameras** are displaying [▶].

Step 3		**(Training room)**
		Fill out the forms
			1. Give the prepared working pen & one hard copy of **Consent Form** to the subject. Fill out the **Consent Form.**
			
			2. Once completing the **Consent Form,** collect the form. Hold it in hand.
			
			3. Fill out the **IRB data disclosure form.**
			4. Then, open up the **link.docx** file in the **Desktop C** (under the "drone_project" folder) and follow the link for **Demographic Survey.**
			
			5. Fill out **Demographic Survey**.
			
			6. While filling out **Demographic Survey**, give the completed **Consent Form** to the **Researcher B.**
				1. Once receiving the completed **Consent Form**, take the picture of the second page of the form (where the subject's sign is) using **Tablet**.
				
				2. Connect the **Tablet** to **Desktop A** using USB cable and export the saved picture. Rename the picture using the name convention "XX_consentform" where XX is the 2 digit (possibly 0-leading) subject number. For example,
				  A. If the subject number is 7:
				    save it as "07_consentform"
				  B. If the subject number is 31:
				    save it as "31_consentform"
				
				3. Create a new folder for the subject under the "drone_project/data" folder in the **Desktop B** and save the picture file under the created folder.

Step 4	Module1	**(Training)** Slide	1. Open up the training slide for **Module 1**. 2. Be ready and prepared for the questions from the subject.	1. Prepare the Module 3 environment(map). 2. Have the following items ready: A. **Drone B & C.**

		A. Questions are allowed, but do not try to give an additional lecture. B. Answer passively to the questions.	B. Fully charged 6 Batteries. C. Fully charged 5 Video Recording Cameras with SD card inserted. D. Fully charged Tablet
	(Training) Written test	1. Follow the proper Written Test Question link in the link.docx file according to the subject's group (1 ~ 3) 2. If the subject got a wrong answer, explain briefly using the answer sheet(answer).	3. Have Drone B ready for flight. A. Insert a battery to Drone B. B. Connect a desktop B to Drone B using Wi-Fi. C. Upload drone software through Paparazzi. D. Open up the control app in the Tablet. E. Check whether the video feed is working. F. Check whether the drone's position is correctly initialized. 4. Place Drone B at the starting position.
Module2	**(Training)** Slide	1. Open up the training slide for **Module 2**. 2. Be ready and prepared for the questions from the subject.	
	(Training) Written test	1. Wait until the subject completes the Written Test Question for **Module 2.** 2. Check the answer. If the subject got a wrong answer, explain briefly using the answer sheet	
Module3	**(Training)** Slide	1. Open up the training slide for **Module 3**. 2. Be ready and prepared for the questions from the subject.	
	(Training) Written test	1. Hold the Tablet in hand. 2. Close all the apps in the Tablet. (the reason is because to prevent confliction between apps and for better performance). 3. Wait until the subject completes the Written Test Question for **Module 3.** 4. Check the answer. If the subject got a wrong answer, explain briefly using the answer sheet	
	(Control) Hands-on	1. Lead the subject to the **Subject Spot** in the **Control Room**. 2. Start the screen capture app. 3. Start the control app. 4. Give the Tablet to the subject.	1. Start VICON tracker recording. 2. Start recording Video Recording Camera A. 3. Start training. 4. Be prepared for any emergency situations during flight.

			5. Have the subject read the instruction for **Module 3**. 6. Start training.	5. If drone malfunctions / is physically broken, replace the drone by another and fix the broken drone.
	Module4	**(Training)** Slide	1. Get back the **Tablet.** 2. Give the **Tablet** to **Researcher B.** 3. Go back to the **Training Room.** 4. Open up the training slide for **Module 4**. 5. Be ready and prepare for the questions from the subject.	1. Stop recording **Video Recording Camera A.** 2. Stop **VICON tracker** recording. 3. Turn off the control app. 4. Stop recording the screen capture. 5. Take out the battery from the **Drone B.** 6. Charge the used battery.

		(Training) Written test	1. Hold the **Tablet** in hand.
			2. Close all the apps in the **Tablet.**
			3. Wait until the subject completes the **Written Test Question** for **Module 4.**
			4. Collect the **Written Test Question** for **Module 4** and hand it over to **Researcher B**.
				7. Prepare the Module 4 environment(map)
				8. Move Barrel into place.
				9. Have **Drone B** ready for flight.
				  A. Insert a battery to **Drone B.**
				  B. Connect a desktop B to **Drone B** through Wi-Fi.
				  C. Upload drone software through Paparazzi.
				  D. Connect **Tablet** to **Drone B** using Wi-Fi.
				  E. Open up the control app.
				  F. Check whether video feed is working.
				  G. Check whether the drone itself is working.

		(Control) Hands-on	1. Lead the subject to the **Subject Spot** in the **Control Room**. 2. Start the screen capture app. 3. Start the control app. 4. Give the **Tablet** to the subject. 5. Give the instruction to do for **Module 4**. 6. Start training.	1. Start **VICON tracker** recording. 2. Start recording **Video Recording Camera A.** 3. Start training. 4. Be prepared for any emergency situations during flight. 5. If drone malfunctions / is physically broken, replace the drone by another and fix the broken drone.
	Module5	**(Training)** Slide	1. Get back the **Tablet.** 2. Hand over the **Tablet** to **Researcher B.** 3. Open up the training slide for **Module 5**.	1. Stop recording **Video Recording Camera A.** 2. Stop **VICON tracker** recording. 3. Turn off the control app.

			4. Be ready and prepare for the questions from the subject.	4. Turn off the screen capture app. 5. Disassemble the battery in the **Drone B.**

		(Training)
		Written test
			1. Hold the **Tablet** in hand.
			2. Close all the apps in the **Tablet.**
			3. Wait until the subject completes the **Written Test Question** for **Module 5.**
			4. Collect the **Written Test Question** for **Module 5** and hand it over to **Researcher B**.
				6. Charge the used battery.
				7. Prepare the Module 5 environment(map)
				8. Turn the control panel cover over.
				9. Have **Drone B** ready for flight.
				   A. Insert a battery to **Drone B.**
				   B. Connect a desktop B to **Drone B** using **Wireless stick.**
				   C. Upload drone software through Paparazzi.
				   D. Connect **Tablet** to **Drone B** using Wi-Fi.
				   E. Open up the control app.
				   F. Check whether video feed is working.
				   G. Check whether the drone itself is working.

		(Control) Hands-on	1. Lead the subject to the **Subject Spot** in the **Control Room**. 2. Start the screen capture app. 3. Start the control app. 4. Give the **Tablet** to the subject. 5. Give the instruction to do for **Module 5**. 6. Start training.	1. Start **VICON tracker** recording. 2. Start recording **Video Recording Camera A.** 3. Start training. 4. Be prepared for any emergency situations during flight. 5. If drone malfunctions / is physically broken, replace the drone by another and fix the broken drone.
	Module6	**(Training)** Slide	1. Get back the **Tablet.** 2. Hand over the **Tablet** to **Researcher B.** 3. Open up the training slide for **Module 6**. 4. Be ready and prepare for the questions from the subject.	1. Stop recording **Video Recording Camera A.** 2. Stop **VICON tracker** recording. 3. Turn off the control app. 4. Turn off the screen capture app. 5. Disassemble the battery in the **Drone B.**
		(Training) Written test	1. Hold the **Tablet** in hand. 2. Close all the apps in the **Tablet.** 3. Wait until the subject completes the **Written Test Question** for **Module 6.**	6. Charge the used battery. 7. Prepare **Checkride** environment(map) 8. Have **Drone B** ready for flight. A. Insert a battery to **Drone B.**

			4. Collect the Written Test Question for **Module 6** and hand it over to **Researcher B**.	B. Connect a desktop B to Drone B using **Wireless stick.** C. Upload drone software through Paparazzi. D. Connect Tablet to Drone B using Wi-Fi. E. Open up the control app. F. Check whether video feed is working. 9. Check whether the drone itself is working.
Step 5	**(Control room)** Checkride		1. Lead the subject to the **Subject Spot** in the **Control Room**. 2. Give the instruction to do for checkride. 3. Start the screen capture app. 4. Start the control app. 5. Give the Tablet to the subject. 6. Start training.	1. Start VICON tracker recording. 2. Start recording Video Recording Camera A. 3. Start training. 4. Be prepared for any emergency situations during flight. 5. If drone malfunctions / is physically broken, replace the drone by another and fix the broken drone.
Step 6	**(Control room)** Learn about the test mission		1. Get back the Tablet. 2. Turn off the control app. 3. Turn off the screen capture app. 4. Give a brief explanation about the mission, including the obstacles, the target, goal and features of the geography of the map, stopping condition(reaching to the designated spot), and possible cases where the subject should fail the mission.	1. Stop recording Video Recording Camera A. 2. Stop VICON tracker recording. 3. Disassemble the battery in the Drone B. 4. Charge the used battery. 5. Have Drone C ready for flight. A. Insert a battery to Drone C. B. Connect a desktop B to Drone C using **Wireless stick.** C. Upload drone software through Paparazzi. D. Connect Tablet to Drone C using Wi-Fi. E. Open up the control app. F. Check whether video feed is working. 6. Check whether the drone itself is working. 7. Prepare the **Test Mission** environment(map) A. Three barrels and one of them is fallen on the ground. B. Dangling wires between Door A and Door C.

			C. Rubbles in the corner of practicing room. D. Barrels next to the wall in practice room. 8. Connect the batteries for the **Door B** and **Door C.** 9. Connect the battery for **Door trigger.** 10.Hand over the **Door trigger** to the **researcher A** 11.Set the speaker volume of the **Desktop A** to be 70.
Step 7	**(Control room)** Start the test mission	1. Start the screen capture app. 2. Start the control app. 3. Give the **Tablet** to the subject**.** 4. Start the test mission. 5. Right after the sound, close the **Door B** and open the **Door C** using the **Door trigger.** 6. Then, tell the subject that: *"There was an explosion with a thundering noise. The path you used for the entrance to the control panel room has been blocked, and you have to find another way out of the room."* 7. Stop the test mission if: A. The subject completed the mission. B. The subject failed the mission. C. The subjected requested stop. 8. Get back the **Tablet.** 9. Hand over the **Tablet** to the **Researcher B**.	1. Start **VICON tracker** recording. 2. Start recording **5 Video Recording Camera.** 3. Start the test mission. 4. After the drone passed through the tunnel, send the sound alert(play explosion.wav file in desktop A). 5. Be prepared for any emergency situations during flight. 6. If drone malfunctions because of the reason not caused by the subject, replace the drone by another and restart the mission. 7. Right after the drone entered the room C, play the blasting sound file. 8. After **Door B** closed and the **Door C** open, manually check whether the both doors operated properly. 9. After getting back the **Tablet** from the **Researcher A**, turn off the control app. 10.Turn off the screen capture app.
Step 8	**(Training room)** Post Experiment Survey	1. Lead the subject to the **Training Room.** 2. Give the **Post Experiment Survey** to the subject. 3. Wait until the subject completes the form.	1. Stop recording & turn off **5 Video Recording Camera.** 2. Stop **VICON tracker** recording.

		4. Collect the **Post Experiment Survey** and hand it over to **Researcher B.**	3. Disconnect the batteries for the **Door B** and **Door C.**
Step 9	**(Practice room)** End the experiment	1. The subject is given a debrief(script) based on his/her performance during the test.	4. Disconnect the battery for the **Door trigger.** 5. Disassemble the battery in the **Drone C.**
Step 10	Not Available	1. Put **Steel pipes** at **Door A** back on the ground. 2. Fill out the **Experiment Report**(link) 3. Clean up the entire room.	6. Export & save **VICON tracker** video into the data folder in desktop A. 7. Export & save **5 Video Recording Camera** video into the data folder in desktop A. 8. Export & save screen capture video from the **Tablet** into the data folder in desktop A. 9. Turn off **VICON Cameras.** 10. Charge the **5 Video Recording Camera.** 11. Charge **8 Batteries** for drone. 12. Clean up the entire room.

Appendix C

Post Experiment Survey

.

Post-Experiment Survey : Please answer to the following questions.

Q1. Please select your assigned subject number.

[⬍]

Block 1

Q2. How difficult was it to understand the training slide materials?
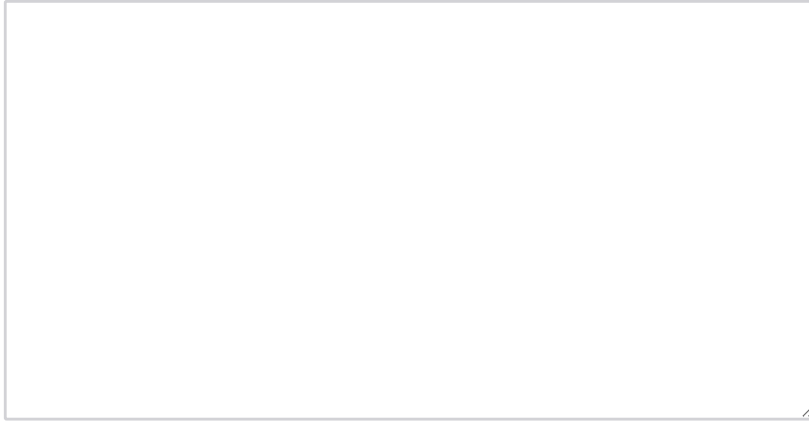
    Very Difficult   Very Easy

Q2-1. What parts / aspects of the training slides were difficult to understand?

[   ]

Q3. How much did you find the training slides helpful to prepare yourself for the test?

Not Helpful   Very Helpful

Q3-1. Why do you think the slides were not helpful?
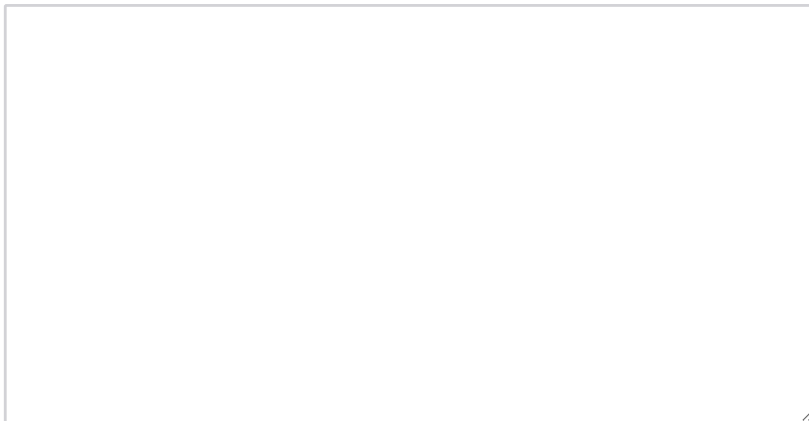
Block 2

Q4. How much did you find the hands-on training helpful to prepare yourself for the test?

Not Helpful   Very Helpful

Q4-1. Why do you think the hands-on training were not helpful?
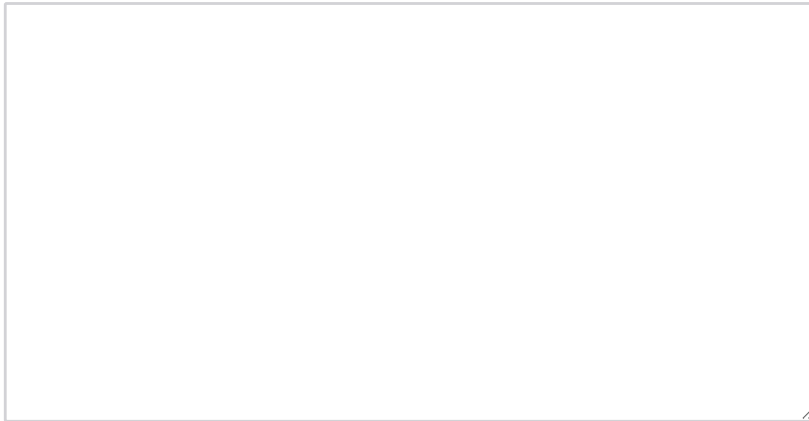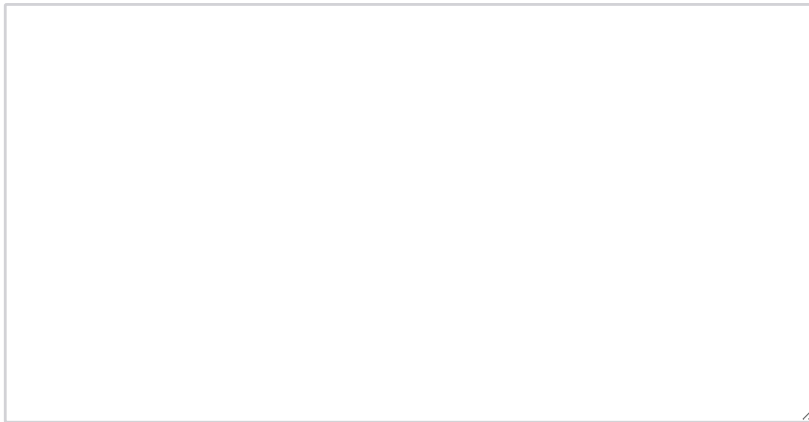

Q5. How difficult was it to complete the final test mission?

Very Difficult   Very Easy

Q6. What aspect / part of the final mission did you find the most difficult?

Q7. How did you determine a new egress path when evacuating the control panel room?
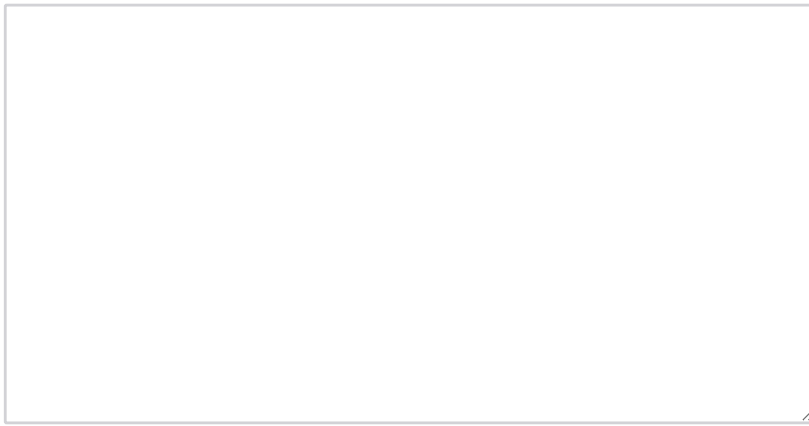
Block 3

Q8. How difficult was it to control the UAV overall?

Very Difficult   Very Easy

Q9. What features of drone or control app do you think made the operation of the UAV difficult (or easy)?

```
```
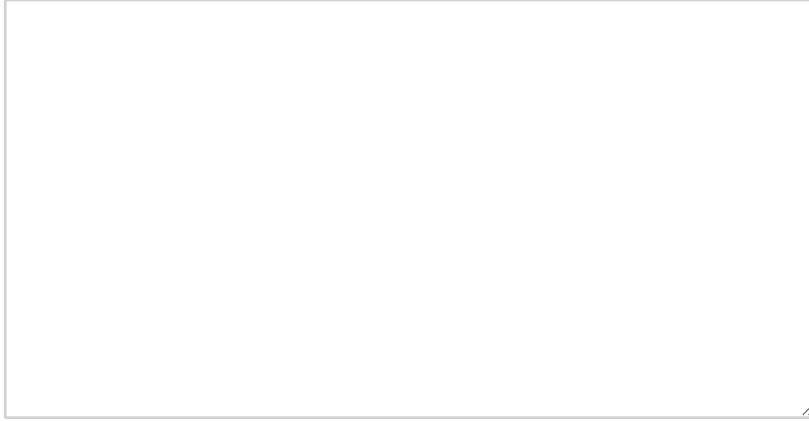
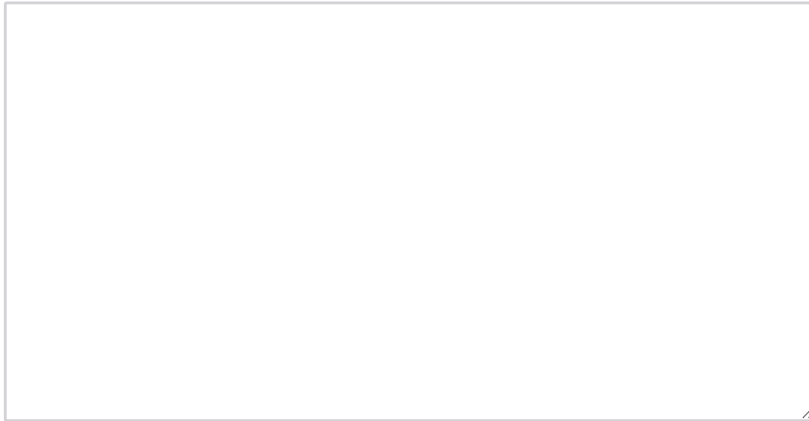*Q10.* How stressed did you feel during the experiments overall?

Extremely Stressed   Not Stressed

Q10-1. What features / aspects of drone or control app made you feel stressed?

Q11. Any other comments :

Appendix D

Subject Number

Quizzes

Q1. Please select your assigned subject number.

[⬍]

Module 1: Basic Aerodynamics of Quadrotor UAVs

. **Module 1: Basic Aerodynamics of Quadrotor UAVs**

Q1. Choose a feature that UAV does <u>not</u> have :

UAV can fly without a pilot on board.
UAV can take off and land vertically.
UAV is completely autonomous.
UAV needs power supply for operation.

Q2. Changing the altitude of a UAV means you are changing its :

Heading
Height above ground
Speed
Rotation

76

Block 11

*. Congratulations! You've got all the correct answers for Module 1.

Please go back to the slide material for Module 2 before proceeding to the written test for Module 2.

Module 2: App Interface - Manual

*. **Module 2: App Interface** - Manual

Q1. What does this tell us about?

Flight time since takeoff
Best record so far
Video stream delay
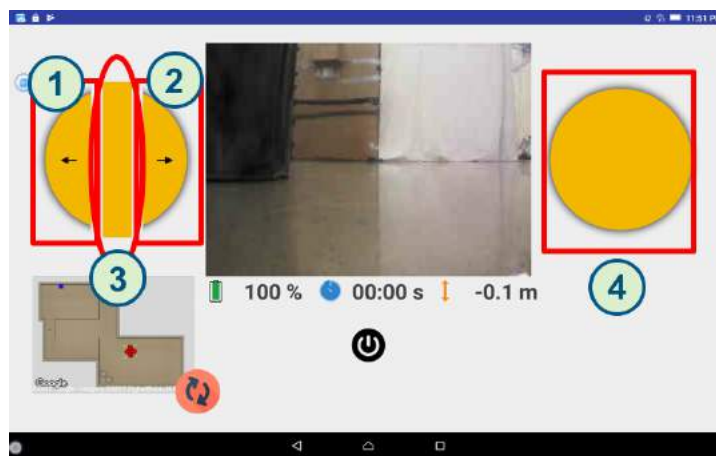Remaining time until the battery is used up

Q2. What does this tell us about?

Distance to the obstacle ahead
Drone's height above the ground

Estimated height of the obstacle ahead

Distance to the target

Q3. In the following image, which button is responsible for altitude control?

1
2
3
4

Q4. In the above image, which button do we need to control for going forward?

1
2
3

Block 12

. Congratulations! You've got all the correct answers for the manual mode section of Module 2.

Please proceed to the supervisory mode section of Module 2.

Module 2: App Interface - Supervisory

. **Module 2: App Interface** - Supervisory

Q1. What does this tell us about?

🕐 **00:00 s**

Flight time since takeoff

Best record so far

Video stream delay

Remaining time until the battery is used up

Q2. What does this tell us about?

↕ **0.0 m**

Distance to the obstacle ahead

Drone's height above the ground

Estimated height of the obstacle ahead

Distance to the target

Q3. In the following image, which button makes drone turn on the rotors?

1

2

3

4
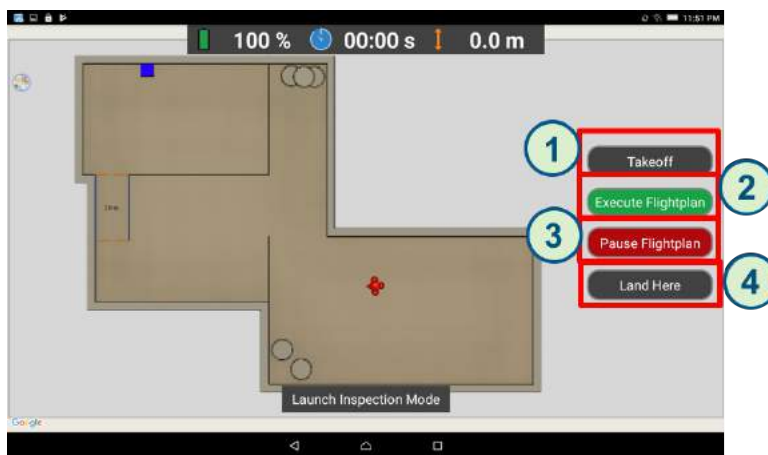
Q4. In the above image, which button makes drone turn off?

1

2

3

4

Block 14

. Congratulations! You've got all the correct answers for the supervisory mode section of Module 2.

Please go back to the slide material for Module 3 before proceeding to the written test for Module 3.

Module 3: Takeoff and Landing - Manual

. **Module 3: Takeoff and Landing** - Manual

Q1. In order to start drone(begin spinning rotors), the first thing you need

to do is :

Press and hold the power button

Turn on the camera

Increase the altitude of drone by controlling altitude controller

Switch to the inspection mode

Q2. For actual takeoff after starting drone, you need to :

Press and hold the power button

Turn on the camera

Press and slide the altitude controller above the center line

Switch to the inspection mode

Q3. In order to land drone at the current position, the first thing you need to do is :

Press the power button to turn off the power

Turn off the camera

Lower the altitude of drone by using the altitude controller

Switch to the inspection mode

Q4. After the drone touches the ground for landing, the drone will :

Return to the starting position automatically.

Turn off (stop rotors) automatically.

Remain turned on until the operator manually turns off the power.

Report its flight result to the operator.

Block 15

*. Congratulations! You've got all the correct answers for the manual mode section of Module 3.

Please proceed to the supervisory mode section of Module 3.

Module 3: Takeoff and Landing - Supervisory

*. <u>**Module 3: Takeoff and Landing**</u> - Supervisory

Q1. In order to start drone, the first thing you need to do is :

Set a waypoint near the starting point

Press the execute flight plan button

Click on the drone on the map

Press the takeoff button

Q2. For landing, all you need to do is:

Press and hold the pause flight plan button

Press the land here button

Press the pause flight plan button

Press and hold the takeoff button until it highlights the land here button

Block 16

. Congratulations! You've got all the correct answers for the supervisory mode section of Module 3.

Please go back to the slide material for Module 4 before proceeding to the written test for Module 4.

Module 4: Navigation - Manual

. **Module 4: Navigation** - Manual

Q1. While flying drone, suppose you found an obstacle ahead and wanted to pass by it by following the direction indicated by red line in the below

image. You need to :

Manipulate the altitude controller in the left joystick to increase altitude

Manipulate the altitude controller in the right joystick to increase altitude

Press and hold the right joystick to go over the obstacle ahead

Lightly tap on the right joystick to change heading

Q2. Suppose you want to change heading as shown in the following images. You need to :
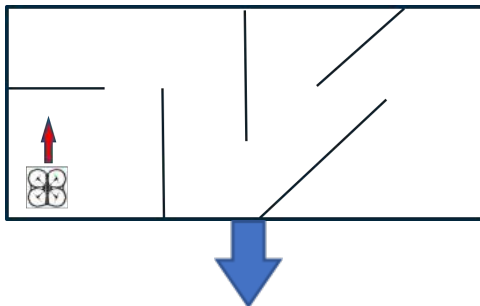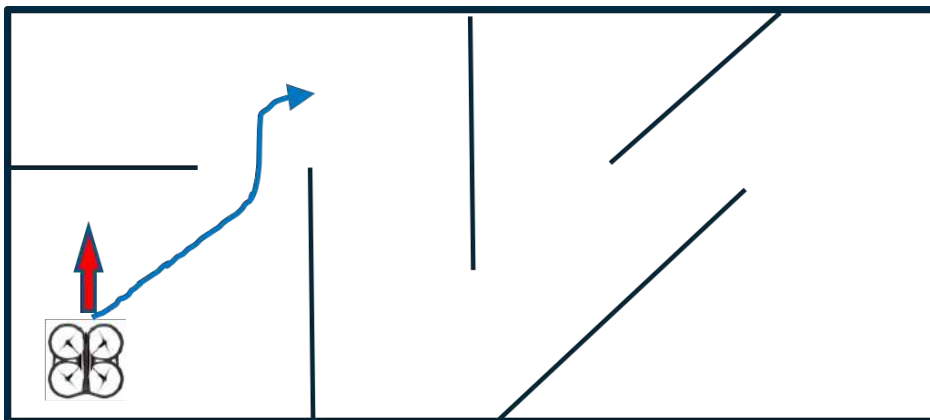
Tilt your tablet toward the desired direction to rotate the drone

Use rotation controller in the left joystick to rotate the drone

Spin the left joystick in the desired direction to rotate the drone

Spin the right joystick in the desired direction to rotate the drone

Q3. Suppose you want to avoid walls without rotating the drone in the following situation. The desired path you want to take is indicated by blue line. You have to :

Manipulate left joystick to pass by the walls

Manipulate right joystick to pass by the walls

Slide the drone symbol on the map over to the desired position directly to avoid walls.

Tilt your tablet toward the desired direction.

Block 17

. Congratulations! You've got all the correct answers for the manual mode section of Module 4.

Please proceed to the supervisory mode section of Module 4.

Module 4: Navigation - Supervisory

. **Module 4: Navigation** - Supervisory

Q1. How can you add a waypoint on the map?

Double click the desired position
Lightly tap on the desired position
Launch the inspection mode
Tap and hold at the desired position on the map

Q2. To start navigation, once you set up waypoints, you need to :

Hit the takeoff button
Slide the drone symbol on the map over to the desired position
Hit the Execute flight plan button
Click the drone to command flight

Q3. If you want to make changes to the current flight plan, first you need to :

Hit the Pause flight plan button
Hit the land here button
Click on the waypoints that you want to change
There is no way to change the current plan in mid-flight.

Q4. To adjust an existing waypoint, you need to :

Click on it and hit the pause flight plan button
Click and hold on it so that you can drag it to the new place you want.
Launch the inspection mode in order to manually control the waypoint
There is no way to change waypoints once they are set.

Block 18

*. Congratulations! You've got all the correct answers for the supervisory mode section of Module 4.

Please go back to the slide material for Module 5 before proceeding to the written test for Module 5.

Module 5: Camera Operation - Manual

*. **Module 5: Camera Operation** - Manual

Q1. Suppose you want to change the camera angle toward the direction indicated by red arrow in the below image. You need to control :
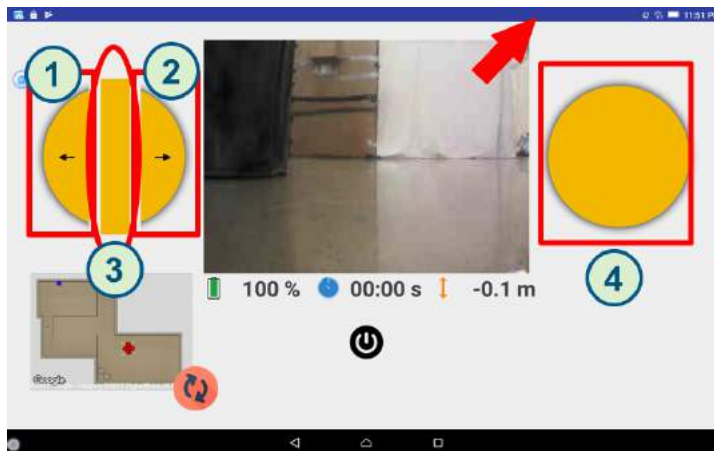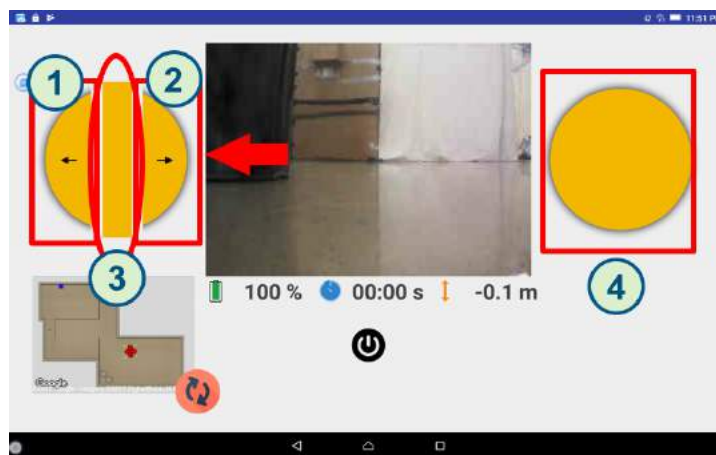

2 and 4

2 and 3

4

1 and 4

Q2. Suppose you want to change the camera angle toward the direction indicated by red arrow in the below image. You need to control :

1

3

4

1 and 4

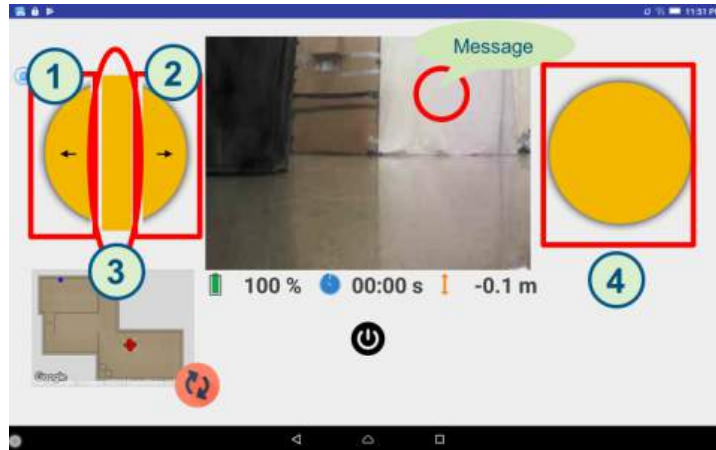*Q3.* Suppose you want to come closer to the wall ahead to read a message written on the wall. You need to control :

                                                           1

                                                           2

                                                           3

                                                           4

Q4. Suppose you want to swap the map screen and video feed in the following screen to maximize video feed. You need to :

Press and hold on the video feed

Magnify the video feed window using 2 fingers.

Hit the red Switch View button

Press and hold the center of the right joystick
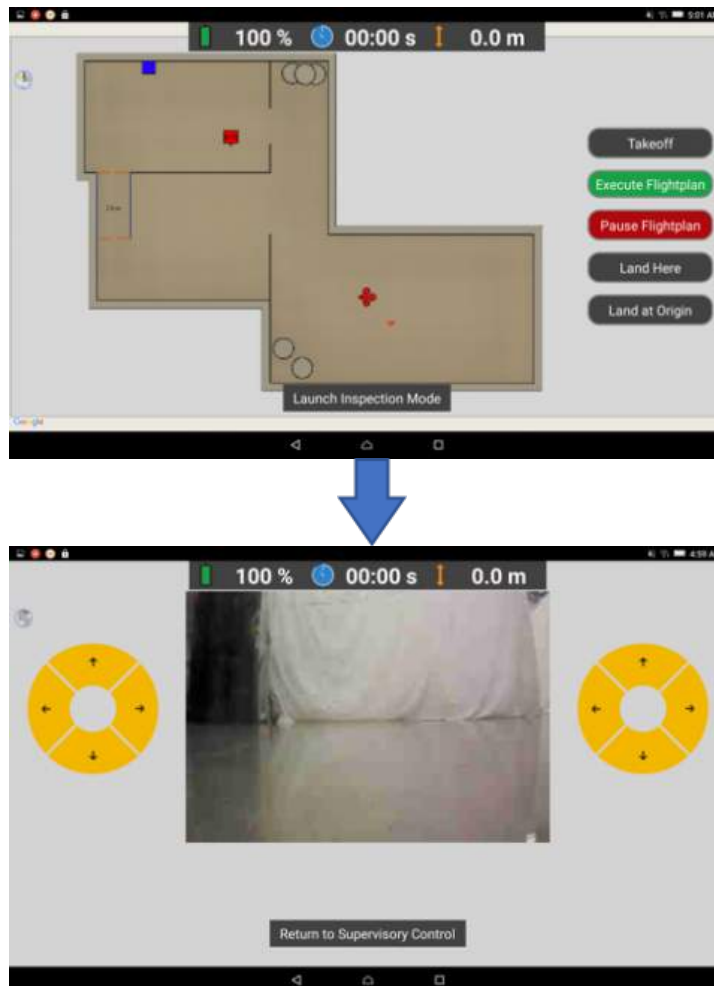
Block 19

. Congratulations! You've got all the correct answers for the manual mode section of Module 5.

Please proceed to the supervisory mode section of Module 5.

Module 5: Camera Operation - Supervisory

. **Module 5: Camera Operation** - Supervisory

Q1. In order to switch from supervisory mode to inspection mode as in the following images, you need to :
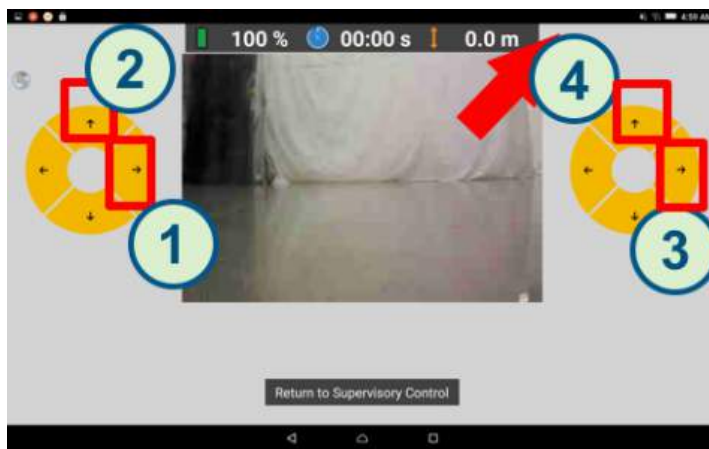

Press the takeoff button to start drone first.

Press and hold on the map in the middle of the screen.

Click on the drone symbol
Press Launch Inspection Mode button

Q2. Suppose you want to change the camera angle toward the direction indicated by red arrow in the below image while keeping the current position(but you can change the altitude). You need to control :
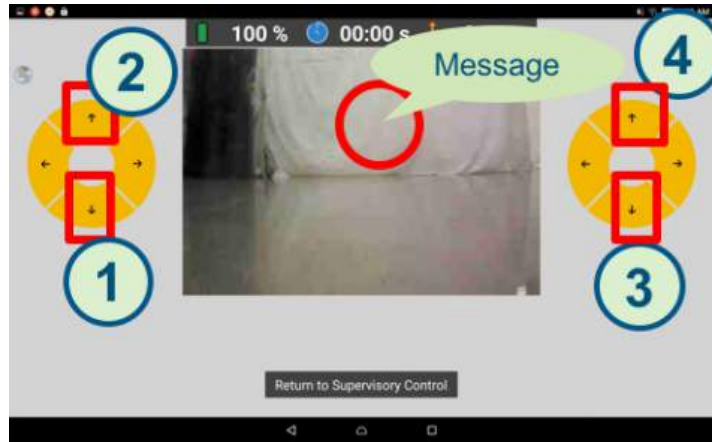

1 and 2
1 and 4
2 and 3
1 and 3

Q3. Suppose you want to change the camera angle toward the direction indicated by red arrow in the below image. You need to control :

1
2
3
4

Q4. Suppose you want to come closer to the wall ahead to read a message written on the wall. You need to control :

2

4

1 and 2

3 and 4

Block 20

. Congratulations! You've got all the correct answers for the supervisory mode section of Module 5.

Please go back to the slide material for Module 6 before proceeding to the written test for Module 6.

Module 6: Guidline for Safety and Emergency Handling

. **Module 6: Guidline for Safety and Emergency Handling**

Q1. All of the following situations might lead to malfunction of the drone or potential danger except for the case where :

Battery level is below 20%

Altitude is over than 5 m

Flight time indicates that it has been 4 minutes since takeoff

Video feed is not working

Q2. During flight, all of the following are highly recommended to do except for :

Using the video feed to look around the environment.

Attempting to pass through obstacles directly for a faster time.

Check battery status frequently

Asking for help from the supervisors in an unexpected emergency situation

Q3. If you wish to stop / pause your current flight trial for any reason, you need to:

Tell your supervisor

File a report regarding the incident afterwards

Control drone to crash into nearby walls to force the drone stop immediately in order to prevent potential dangers

You are not allowed to stop flight once you get started except for emergency situations

Block 13

. Congratulations! You've got all the correct answers for Module 6.

You have finished all the 6 training modules.

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Appendix E

Mental Models

Mode confusion discussed in the Section 2.3 can be mathematically formulated using a (finite) state machine model. Suppose there is a state machine $X := \langle \mathcal{S}, \mathcal{A}, \mathcal{M} \rangle$, which is a representative model of GCS that describes its behavior. For simplicity, assume X is deterministic, and initial and final state of the machine are ignored. Here, $\mathcal{S} := \{s_1, s_2, \cdots, s_n\}$ denotes a set of states , $\mathcal{M} := \{m_1, m_2, \cdots, m_r\}$ denotes a set of modes available for the system such that $m_k := \mathcal{S} \times \mathcal{A} \to \mathcal{S}, k = 1, \cdots, r$ are functions that trigger transition from one state to another in a deterministic way, and $\mathcal{A} := \{a_1, a_2, \cdots, a_m\}$ denotes a set of actions which, together with the choice of mode, determines the transition behavior of the system. There is one subtle point that needs further clarification in the description of mode; in a certain mode m_k(e.g, automatic control mode), certain action a_j(e.g., joystick control) may not work, in which case it is legitimately defined $m_k(s_i, a_j) := s_i$ for all $i = 1, \cdots, n$. And, m is naturally defined as maximum number of ways of giving commands to the system considering every possible mode.

Given these settings, it is worth further noting that a human operator's un-

derstanding of system behavior may be different from its actual behavior. This is because human operator's own perception $s_{i'}, m_{k'}, a_{j'}$ on the current status s_i, mode m_k and action a_j of the system is based on his subjective estimation of the current situation and prediction of the result from action. More specifically, let T_s, T_m, T_a be operator's mental models on the system parameters of state, mode, and action. It could be said that the mental model on mode is correct if $m'_k := T_m(m_k) \approx m_k$ where similarity relation is based on a certain reasonably justifiable measure (and similar definitions can be applied for T_s and T_a). That is, $m'_k \approx m_k$ if $m'(s_i, a_j) \approx m(s_i, a_j)$ for all $(s_i, a_j) \in \mathcal{S} \times \mathcal{A}$. Then, failing to have an incorrect mental model on mode and poor understanding on action with respect to the system's actual current mode in the context of environmental conditions can result in what is called mode confusion. For example, suppose the operator wants to move UAV forward by 10 inches. In "assisted control" mode m_1, the operator can relatively easily move the UAV from its current position $s_1 := (x_1, y_1) = (0, 0)$ to $s_2 := (x_2, y_2) = (0, 10)$ by pulling joystick in an upward direction for a few seconds a_1, yielding $m_1(s_1, a_1) \approx s_2$ under the measure of Euclidean distance (for simplicity, mental model T_s on state is assumed to be correct). However, suppose the operator is currently under "manual control" mode m_2 but he believes he is using m_1 mode. Then, even the same action a_1 might be able to yield a significantly different system state, for example, $s_3 := (10, 10)$, that is, $m_2(s_1, a_1) = s_3 \neq s_2$. This is because, the actual movement of UAV in the manual control mode m_2 can be greatly affected by various environmental conditions, including weather, for instance, and a strong westerly wind can guide and displace the UAV from its expected position s_2 to the actual resulting position s_3. Meanwhile, in the assisted control mode m_1, the UAV could reach the correct position s_2 even in the presence of the same strong wind because the system's "assistance" could play in offsetting the effect of the wind, through estimating intensity and direction, with an appropriate adjustment to the operator's input command.

The mathematical representation can be used for quantitative description on the mental models T_s, T_m, T_a, which are often discussed in a qualitative frame. If one wants to describe an operator's overall performance on a given system, a better approach would be to estimate these functions of mental models, which gives a comprehensive, numerical clue to the operator's understanding of the system, rather than compare the resulting performance of a mission such as flight time or number of success, which only considers a partial, biased information that is not guaranteed to well-represent the operator's "overall" performance.

Estimating the mental models can be done using regression. More precisely, the idea is to first set a target sequence of drone status(ex. drone's x, y, z coordinates in space) $s_1, s_2, \cdots, s_n$ and then ask operators to follow the sequence of positions exactly using whatever functions they can use within the given interface. Now, suppose mode m_1 and with an action a_i resulted in the position s_{i+1} from s_i; i.e., $m_1(s_i, a_i) = s_{i+1}$. Also, suppose operator's command input $a_i' := T_a(a_i)$ in response to the state s_i was $m_1(s_i, a_i') = s_{i+1}'$. Assuming invariance property of drone's position, we can say that $m_1(0, a_i) = s_{i+1} - s_i \implies a_i := m_1^{-1}(s_{i+1} - s_i)$ and similarly $a_i' := m_1^{-1}(s_{i+1}' - s_i)$ if we assume $|s_{i+1} - s_i|, |s\prime_{i+1} - s_i| < \delta$ are sufficiently small to be able to use Inverse Function Theorem in differential calculus. Since s_i, s_{i+1} and s_{i+1}' are directly measurable using proper distance measurements, m_1^{-1} is estimable with sufficient accuracy. This means that we can regress the function $a' = T_a(a)$ given sufficient set of data. Then, the use of the estimated mental models in describing human operators' performance can make it more reliable and justifiable the discussion on the performance comparison between operators because they do not just rely on a partial, summary description based on an arbitrarily chosen metric. Further, the estimated models can be used to predict operator's response to a given situation that is not present in the training data, which makes the results easily generalizable and extendible to different settings.

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