Development and Evaluation of a Collision Avoidance System for Supervisory Control of a Micro Aerial Vehicle

by

Kimberly F. Jackson

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Author . . . .
Department of Aeronautics and Astronautics
May 2, 2012

Certified by . . . .
Mary L. Cummings
Associate Professor of Aeronautics and Astronautics
Thesis Supervisor

Accepted by . . . .
Eytan H. Modiano
Professor of Aeronautics and Astronautics
Chair, Graduate Program Committee

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Abstract

Recent technological advances have enabled Unmanned Aerial Vehicles (UAVs) and Micro Aerial Vehicles (MAVs) to become increasingly prevalent in a variety of domains. From military surveillance to disaster relief to search-and-rescue tasks, these systems have the capacity to assist in difficult or dangerous tasks and to potentially save lives. To enable operation by minimally trained personnel, the control interfaces require increased usability in order to maintain safety and mission effectiveness. In particular, as these systems are used in the real world, the operator must be able to navigate around obstacles in unknown and unstructured environments.

In order to address this problem, the Collision and Obstacle Detection and Alerting (CODA) display was designed and integrated into a smartphone-based MAV control interface. The CODA display uses a combination of visual and haptic alerts to warn the operator of potential obstacles in the environment to help the operator navigate more effectively and avoid collisions. To assess the usability of this system, a within-subjects experiment was conducted in which participants used the mobile interface to pilot a MAV both with and without the assistance of the CODA display. The task consisted of navigating though a simulated indoor environment and locating visual targets. Metrics for the two conditions examined performance, control strategies, and subjective feedback from each participant.

Overall, the addition of the CODA display resulted in higher performance, lowering the crash rate and decreasing the amount of time required to complete the tasks. Despite increasing the complexity of the interface, adding the CODA display did not significantly impact usability, and participants preferred operating the MAV with the CODA display. These results demonstrate that the CODA display provides the basis for an effective alerting tool to assist with MAV operation for exploring unknown environments. Future work should explore expansion to three-dimensional sensing and alerting capabilities as well as validation in an outdoor environment.

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Chapter 1

Introduction

1.1 Micro Aerial Vehicles

Recent advances in Unmanned Aerial Vehicle (UAV) technology have resulted in widespread field use in both military and civil domains. In particular, interest in Micro Aerial Vehicles (MAVs) has risen sharply in the past few years due to the promises of smaller, cheaper, and more portable systems. Although the term 'MAV' originally referred to a vehicle of less than six inches in length [2], the term can now refer to a broader range of small UAV systems, as shown in Figure 1-1.

For smaller, portable UAV systems (MAVs), the operator paradigm has shifted from one where a pilot (or team of operators) remotely controls every aspect of a vehicle's operation to one where the person on the ground can focus on using the system's capabilities to obtain local surveillance information. This setup allows the operator to obtain immediate and current information about his or her surroundings. The systems are ideal for local surveillance tasks, whether on the battlefield, in a disaster area, or for scientific observation. Recent commercial applications include wildfire monitoring, disaster area surveillance after hurricanes or tornados, and property damage assessment.

Figure 1-1: Example MAV systems, shown on a scale with relative size information. [3, 4]

In February of 2012, the United States Congress passed a mandate requiring unmanned aircraft to be integrated into the civil airspace no later than 2015 [5], so there is an anticipated increase in the use of these systems in the civilian sector. Organizations such as police forces, first responders, news agencies, and hobbyists have expressed interest in taking advantage of the capabilities MAVs offer.

For a MAV system to be effective in the field, the design needs to be tailored to the expected operating scenario. One scenario of interest for the MAV systems within the focus of this thesis is an Intelligence, Surveillance, and Reconnaissance (ISR) mission. Soldiers on the battlefield require immediate and current information about the environment in order to stay safe and accomplish higher level mission goals. To help a soldier accomplish the necessary missions, portable MAV systems are being developed that could be removed quickly from a pack, assembled, and launched to obtain immediate surveillance information about an area around a corner, over a hill, or in a building. The operator could then control the MAV from the field environment. For wide deployment, such systems should not require a time-consuming or extensive training course, which means that the interface must be intuitive and easy to learn. Because the operator may be in a dangerous area and may need to respond to threats in the vicinity, operating the MAV device should not significantly impair situational

awareness of the surroundings.

In such scenarios, *a priori* knowledge of the environment may not be available. If the locations of buildings, walls, or other obstacles in the environment are not known in advance, the operator may need to compensate while maneuvering the vehicle. This is also true in missions involving disaster assessment, as described in [6], where the landscape or structures may have changed, so pre-existing information may no longer be valid. Designing an appropriate interface for such scenarios is the focus of this thesis.

1.2   MAV Design Challenges

The widespread use of MAV systems will necessarily be limited unless a few key hurdles are overcome, namely improved usability to minimize operator training and improved ability to operate robustly in unstructured environments.

1.2.1   Improving Usability to Minimize Training

Developing intuitive interfaces for MAVs is essential to minimize the required training and knowledge for operation. In the military domain, extra training is costly and undesirable. In the civilian sector, the additional time or cost for training may make using the system infeasible. A local police force often cannot afford excess amounts of time and money for training costs, and there have already been documented cases of organizations failing to replace systems that were costly or too difficult to use. For example, in February 2010, a police force in England chose not to replace a UAV unit that crashed into a river, due to "certain technical and operational issues including staff training costs and the inability to use the UAV in all weather conditions" [7]. Until UAV systems can be used safely, effectively, and consistently, their operational practicality remains limited.

Improving the usability of unmanned systems and reducing need for operator train-

ing are areas of current research. A recent study demonstrated that by leveraging automation in the system, operators with only three minutes of training and practice could effectively use a MAV to accomplish visual surveillance tasks in both a controlled lab environment [8] and a more realistic outdoor field environment [9]. Additionally, in these instances, the operator could not see the vehicle during the flight and was able to find visual targets relying solely on the mobile interface. However, these tests occurred in a structured environment with no obstacles, and software boundaries were set up to prevent crashes and constrain the vehicle to the experiment area. In a real scenario, this may not be feasible, as the details of an environment may not be known in advance or the environment may contain dynamic obstacles that the operator would need to avoid.

1.2.2 Improving Collision Avoidance Capabilities for Unstructured Environments

Coupled with the problem of increasing usability is the need to operate effectively in unstructured and unknown environments. Current operational systems do not have the ability to detect objects in the environment, so they rely solely on operator skill to avoid collisions. For many applications that require operation in close quarters with structures, flights are limited to the operator's visual line-of-sight. However, the skill and attention required to maintain a safe standoff distance while correcting for wind deviations and avoiding obstacles can cause increased stress and pilot fatigue [6]. For these systems to successfully operate in crowded urban areas, unknown battlefield environments, or constrained indoor spaces, they must have the ability to cope with uncertainty and unexpected obstacles, especially since most of these operations must occur beyond the operator's line of sight. To allow for easy information gathering, even in uncertain environments, a collision avoidance system is essential for effective operation.

Although the necessary obstacle sensors are becoming smaller and more feasible for

MAV use, most current research in this area is focusing on how to accomplish autonomous obstacle detection and collision avoidance in the MAV system rather than how to present this information to the operator in an intuitive manner to facilitate spatial awareness. By integrating a collision avoidance display into the control interface, operators can form a more complete mental picture of the flight environment and pilot the vehicle more effectively. This additional capability could make the system more robust and easier for minimally trained operators to use in unknown environments. For example, military personnel may need to obtain local surveillance imagery of a person or area of interest without detailed maps of their environment, so collision avoidance would help in such unknown and potentially cluttered environments. As another example, MAVs could potentially assist with fault inspection for buildings or bridges that are hard for humans to reach. Such applications that require close proximity and careful navigation around existing structures provide motivation for better obstacle detection and avoidance capabilities to improve operator performance.

Because presenting more information increases the complexity of the display, the challenge lies in integrating this additional information about potential obstacles into the user's display without affecting the usability of the interface or increasing the operator's mental workload. Also, the addition of a collision notification and avoidance system should not drastically increase the required training. For most of these systems, the small form factor and portability of the system provides a key advantage, but this limits the display size and screen real estate available for the operator's interface. By presenting this information to operators in an intuitive, embedded way that does not increase mental workload, the system could improve the effectiveness of operators and lead to further adoption of MAVs and larger UAVs in a wider range of applications.

1.3   Preliminary Study of MAV Operators

In a previous study involving MAV operation by minimally trained operators [9], several observations were made that further motivate and guide the design of an obstacle alerting display.

1.3.1   Study Description

The purpose of the study was to assess the usability of an iPhone®-based MAV control interface in an outdoor field environment. Subjects with no experience with the interface completed navigation and visual search tasks in an open environment. Flights took place on an outdoor field, and two visual targets were placed on the edges of the field. For safety purposes, the vehicle was constrained to the field via software boundaries and a physical tether. Subjects were in a separate area and had to rely solely on the interface for information about the vehicle location and state. Subjects were given three minutes of training and practice with the system and had nine minutes to locate the specified targets and complete the observation tasks. Overall, the results were positive, with almost all subjects able to locate both targets, and full results can be found in [9].

1.3.2   Observations on MAV Operation

The study revealed that when a system has the ability to autonomously avoid obstacles and limit the motion of the vehicle, the operator may become frustrated if that information is not conveyed appropriately. Users need information when the system either is not able to respond or is intentionally altering the desired inputs. The flight area was an open field with an invisible software barrier to constrain the vehicle to the test area. Despite being told about the barrier in advance, subjects became annoyed when the system did not respond to intended inputs due to the constraints.

In addition, users had a poor sense of depth. While completing visual search tasks, subjects wanted to move as close as possible to each target to obtain the best viewing perspective. Had the software constraint boundary not limited the vehicle's motion, most subjects would likely have collided with the target, yet most were still primarily frustrated that the system would not respond to their intended inputs.

Finally, observations indicated that users need to be aware of objects outside of the field of view. Because a quadrotor MAV is capable of motion in any direction (not just in the forward direction), it is possible for the user to collide with an obstacle that they could not see. While completing the visual task of reading a sign, subjects would often move the vehicle side-to-side to align to the proper viewing angle. In a more constrained environment, this could be disastrous to the vehicle if obstructions are present outside the field of view presented to the users. These observations in an earlier study motivate the need for obstacle awareness and guide the design of the display.

1.4 Research Objectives

The purpose of this thesis is to explore how to display information about the environment to allow a user with minimal training to operate a small UAV effectively. Specifically, it presents the design and evaluation of an interface to alert an operator of potential obstacles in the flight path, addressing the challenges of operating in an unknown or unstructured environment while maintaining an intuitive interface. This was accomplished through two research objectives:

- **Objective 1: Design an alerting interface to assist an operator in preventing collisions in unknown environments.** The alerting interface was designed based on human factors-based alerting principles and intuitive interface design principles. Since the interface was integrated into an existing interface for MAV control based on a mobile device, these system constraints also influenced the design. Details of the design process and the resulting system

are discussed in Chapter 3.

- **Objective 2: Evaluate the effectiveness of the interface in improving operator performance during navigation and visual search tasks.** To evaluate the interface, a human-subjects experiment was performed in order to test a person's ability to maneuver and perform visual flight tasks using the mobile interface. This experiment took place in a simulation environment and aimed to answer the following questions:

  - Does an operator find the alerting system to be an intuitive, useful aid?

  - Does the alerting system affect an operator's ability to complete a visual search task in the following areas:

    * Task Performance, based on quantitative metrics for the specified mission

    * Situational Awareness, as indicated by perception of location in the environment and knowledge of location of other objects

    * Mental Workload, or the level of cognitive resources the operator needs to devote to the task

    * Subjective Perception, as indicated by changes in perceived ease of use or frustration level

The setup for the experiment is described in detail in Chapter 4, and a discussion of the results occurs in Chapter 5.

1.5   Thesis Organization

This thesis is organized into six chapters, as follows:

- Chapter 1, *Introduction*, describes the motivation for obstacle detection capabilities for Micro Air Vehicles.

- Chapter 2, *Background and Literature Review*, describes relevant background

research, including the current state-of-the-art in obstacle detection capabilities as well as an analysis of available alerting methods.

- Chapter 3, *Collision Avoidance System Design*, illustrates the design and development of the collision avoidance, the system created to evaluate the interface, and a pilot demonstration of the system in an outdoor environment.

- Chapter 4, *Usability Evaluation*, describes the setup of a usability experiment to assess the effectiveness of the collision avoidance display.

- Chapter 5, *Usability Evaluation Results and Discussion*, describes the results of the usability study, the implications, and the comparisons to outdoor pilot testing in a realistic environment.

- Chapter 6, *Conclusions and Future Work*, summarizes the findings and outlines areas of potential future study.

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Chapter 2

Background and Literature Review

With the rise in potential applications for UAV and MAV technologies, research into these systems has increased over the past decade. A number of new MAV systems have emerged in the past few years, and researchers in both academia and industry are pursuing the problems of building better systems that can help people accomplish an increasing number of tasks. Through this review, a gap in the literature was identified. Although Micro Aerial Vehicle (MAV) systems are becoming more common, available systems lack obstacle avoidance capabilities. In addition, even though the sensors and methods are starting to emerge, very little work has examined how to display this information to operators appropriately to allow for more effective navigation in unknown environments.

This chapter starts by discussing current MAV systems and their applications. It then explores the problem of collision avoidance and obstacle detection for MAVs, including available sensors and methods of detection as well as autonomous methods. Finally, available alerting methods are described, along with their pros and cons and examples from previous research or applications.

2.1 Current State of MAV Capabilities

Although UAVs and MAVs are not yet widely used in the commercial sector in the United States due to Federal Aviation Administration (FAA) regulations, limited use cases in non-military areas have occurred. One area of research has focused on using MAVs for visual search tasks in wilderness environments, including wildfire monitoring as well as search and rescue tasks [10, 11]. As part of this work, a cognitive task analysis was performed to determine appropriate mission setup, which resulted in the definition of a 3-man team for operating MAV systems for these surveillance or rescue missions [11]. However, the eventual goal is to leverage automation and reallocate tasks to create a system that can be operated effectively by one person.

2.1.1 Human Supervisory Control

Human Supervisory Control provides a way to leverage automation to promote more effective interaction between robot and operator [12]. Supervisory control differs from teleoperation in that the operator is not providing direct controls to the system. Instead, the operator gives a command to a computer, which has closed-loop control over the underlying system. This interaction is displayed in Figure 2-1, along with
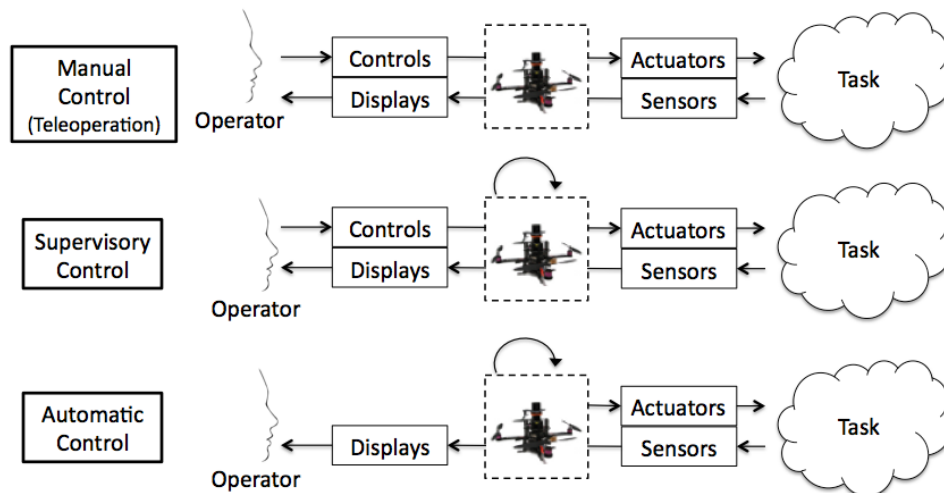
Figure 2-1: Levels of Automation, adapted from [12]

28

the system architecture for both manual and autonomous modes. Previous work with MAVs often falls in the teleoperation domain, as shown on the top of the figure, and it is not uncommon for a pilot to directly fly the MAV with a joystick-based remote controller (for example, [10, 11]). In a supervisory control framework, the operator might instead give the vehicle a desired waypoint on a map or a high level command such as 'land'. The automation would then be responsible for flying to the designated location or executing the 'land' procedure.

2.1.2 Systems in Use

Recently, several commercial MAVs have been developed to provide local surveillance imagery, with the goal of providing a system operable by a single person. Examples are shown in Figure 2-2. The operator gives commands through a tablet-based display rather than a traditional joystick interface. These systems operate in the domain of human supervisory control, rather than piloting the UAV directly, so the operator has high level control of the vehicle and can direct it to specified locations. However, these systems still rely primarily on the operator to prevent collisions, either by skilled piloting, correct waypoint inputs, or by restricting operation to clear, open areas or altitudes that provide clearance around all structures.

2.2 Motivation for Collision Avoidance Capabilities

Due to a combination of limited system capabilities and flight regulations, very little work has addressed collision avoidance for MAVs. In some applications, the need for collision avoidance is reduced by using different operational strategies. For example, wildfire monitoring can often assume high altitude operations above the tree line and can use existing terrain maps for path planning [11]. However, other proposed uses require operation near structures or trees, or in the so-called 'urban canyon', which

(a) Aeryon Scout [13]
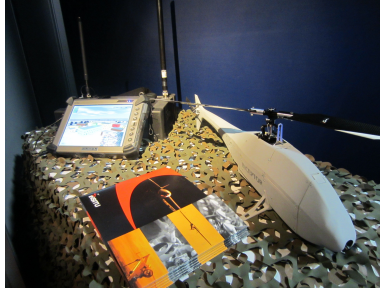
(b) Insitu Inceptor

(c) AeroVironment Qube [14]

Figure 2-2: Commercial UAV systems developed to accomplish local surveillance missions.

refers to cluttered urban or city environments with limited GPS availability due to obstructions from manmade structures. Although widespread use is not yet possible, several UAV and MAV systems have been used for damage assessment following natural disasters. For example, in an observational study of field use for disaster response after hurricane Katrina, "the emergent standoff distance for adequate imaging was for the MAV to be 2-5 meters from a structure [...] which poses significant control challenges" [6]. Particularly from a ground-based vantage point, it is difficult for the pilot to have good depth perception to get adequate viewing distances while maintaining a large enough margin to correct for deviations and prevent crashes. This is also an example of a situation where the system could benefit from an increase in on-board autonomy, such that the vehicle could automatically work to keep a minimum stand-off distance, leaving the pilot with more resources to do high-level navigation or monitor the payload. However, as previously mentioned, many systems lack the sensors or computational capabilities this framework would require.

2.3   Methods of Obstacle Sensing

The primary obstacle sensing challenges for MAVs are the size and weight limitations for distance sensors. In full-size aircraft, radar typically provides this capability, although laser rangefinders have been used to do detection for helicopters [15]. Ground robots generally rely on some combination of radar, lidar, and sonar, but ground systems do not have the same weight restrictions as MAV systems. Certain laser rangefinders, such as the Hokuyo shown in Figure 2-3, are becoming smaller and more useful for MAV applications. Scanning laser rangefinders give a relatively large amount of information in a compact platform, and have been successfully used in Simultaneous Localization and Mapping (SLAM) applications [16], where a robot can navigation through an unknown area while building a map of the environment. The recently developed flash LIDAR systems, which can provide 3D depth maps of an environment, have high potential as 3D sensors for UAVs [17], but at this point the form factor is still too large for a MAV. The rise of smaller, lighter, and more powerful computer processors has caused an increase in research into in vision-based obstacle detection, employing feature detection or optical flow techniques [18, 19]. Table 2.1 outlines some of the available distance sensors for robotics applications, along with their advantages and disadvantages.

Figure 2-3: Hokuyo UTM-30LX Scanning Laser Rangefinder [20]

Table 2.1: Available Distance Sensor Types, Adapted from [1]

Sensor	Pros	Cons
Radar	Long range, less sensitive to varied environmental conditions	Too large for MAV applications
LIDAR/Laser	High accuracy, high data rate	Affected by surface reflectivity, relatively large
Acoustic (Sonar)	Small form factor, Not surface dependent	Short range
Visual (Camera)	Passive sensor, often no additional sensors required	Requires high processing capabilities

2.4 Development of Autonomous Collision Avoidance Capabilities

The increasing availability of small distance sensors has spurred research in autonomous UAV flight. One particular area of interest is the 'urban canyon', where collision avoidance is a huge concern. Numerous demonstrations in the research community have shown that both fixed wing vehicles and helicopters can operate in cluttered environments and do automated obstacle detection. For example, single point laser rangefinders have been used on a small fixed wing vehicle for obstacle avoidance in highly dynamic flight environments [21]. Developments in MAV onboard processing capabilities have enabled autonomous obstacle detection and avoidance with the aid of SLAM algorithms using stereo vision with laser rangefinders [22] or RGB-D cameras [23], which provide a color image along with depth measurements.

With the promising results emerging from the research community, one might expect these capabilities to provide a clear benefit to field operators. However, although there has been significant work in autonomous collision avoidance, very little work has been done on collision avoidance for MAVs in the supervisory control domain. Completely autonomous systems avoid interacting with a human operator and do not display the environment state information to an operator. Helping operators make informed decisions will required designing an appropriate display for the user and

integrating proper alerts, notifications, and decision support tools to enable effective operation.

2.5 Alerting Methods

To support operator awareness, the interface must provide the appropriate obstacle information, particularly for operation beyond the operator's line of sight. Alerts are necessary to direct an operator's attention to a potentially dangerous situation so he or she can respond appropriately. Selection of the proper alerting method depends on many factors, including the types of information to be conveyed and the operating environment of the system. Typical alerting mechanisms include visual, auditory, and haptic alerts, although olfactory or gustatory alerts are also used rarely. This section describes visual, auditory, and haptic alerting systems, and then discusses some of the advantages and factors involved in combining alerting modes.

2.5.1 Visual Alerts

Visual alerts are appropriate for messages that may be long or complex or that need to be archived for later reference [24]. For maximum detectability, the alert should be within the operator's line of sight and should stand out against the background, through brightness, texture, and color, and issues of color-blindness need to be considered [25]. However, visual alerts are localized, in that an operator must be looking at the area of interest. Also, a visual alert will not be apparent in poor lighting conditions [24].

2.5.2 Auditory Alerts

Auditory alerts works well for information that is short, simple, and requires immediate attention [24]. Their omnidimensional nature means that an operator does not need to be looking at the display to be able to respond to the alert [24]. Addition-

ally, auditory alerts can be advantageous when lighting is a concern (darkness, screen glare). Auditory alerts are typically intrusive, so are well suited for critical alerts, but can be annoying if the alerts are too frequent [24]. The intensity of the alert should be loud enough to be detectable above any background noise but not high enough to be overly disruptive [25].

2.5.3   Haptic Alerts

Haptic displays present information to an operator through pressure, force, or vibration feedback. Of these methods, vibration is best suited for alerting because it maximizes detectability [25]. Haptic alerting systems need contact with the operator, which means that either the operator needs to be stationary or the device needs to be affixed to the person. The intensity of the vibration should be tailored to the region of the body [25], and must also be high enough to be discriminated from background or environmental factors [24]. For humans, most of the vibration-sensing receptors are skin-based, and the hands and the soles of the feet are the most sensitive areas [25].

2.5.4   Combining Alerting Modes

Different types of alerts are often used in conjunction to reinforce the information being presented. The multiple resource theory of information processing says that humans have separate pools of resources that can simultaneously be allocated to different modalities [26]. This means that if one channel is overloaded by the primary task, an alert in a different mode can still be processed. For example, when performing a visual search task on a map, the visual channel may become overloaded and the operator may be more likely to miss a visual alert indicator on the screen. In this case, an operator may be more likely to respond to an auditory alert. Additionally, redundant alerts in more than one mode can improve detection and processing times [27].

Given this arsenal of alerting mechanisms, the question then becomes which is most appropriate for the application.

2.6   Examples in Practice

Though little prior work exists in the specific application of obstacle alerting for MAV systems, there are a number of previous studies in mobile interfaces or ground robot control that can inform the design of an obstacle notification system. Input devices have included Personal Digital Assistants (PDAs), smartphone-like mobile devices, and electronic tablet displays. In a previous study where a mobile device was used to control a small UAV, a user experiment determined that subjects performed better when they had simultaneous access to both a map and a sensor display [28]. Subjects also preferred this layout and indicated that they had better situational awareness. Due to the limitations in screen size, it is not always possible to display these elements separately. Another study examining PDA-based control of ground robots examined perceived workload when comparing: 1) a visual display of the environment, 2) sensor display of the environment, and 3) an overlay of the sensor data on the visual display [29]. The study determined that workload was highest for the case with the sensor overlay. However, drawing the sensor overlay increased the lag for that condition, which likely influenced the results. Newer mobile devices with improved processing capabilities might partially mitigate this issue.

A number of previous studies have explored the use of haptic feedback for collision avoidance during UAV teleoperation [30, 31, 32]. Most of these focus on feedback during teleoperation, and the input device is a joystick. Efforts have explored using both active correction [31, 33] as well as varied stick stiffness [30, 32, 34] as the haptic feedback. While this has promise for larger systems, the joystick device required to give haptic feedback can weigh several pounds, making it impractical for portable field use with smaller systems. With a mobile device, the range of possible haptic input is limited to vibration feedback. One study explored the use of aural and haptic

vibration alerts during a UAV control mission. Although the setup was primarily for larger UAVs with a command console type display, many of the same principles apply. This study found that there was no difference between typical response time in controlled experiments in standard environments, noisy environments, or in a follow-on study for long term environments where vigilance is an issue [35, 36]. However, subjects noted a preference for the haptic feedback in noisy environments, due to the uniqueness of the alerting scheme amid the background noise of the environment. Given that the MAV systems of interest will be operating in a field environment where background noise may be present, a haptic vibration alert could be beneficial.

2.7   Summary

Although MAV collision avoidance capabilities have been improving significantly over the past decade, there is a significant need to develop alerting systems that will help operators interact with and use these systems effectively in real environments. The following chapter will describe the Collision and Obstacle Detection and Alerting (CODA) display, designed to notify operators of obstacles in the environment to allow for more effective navigation and task completion.

Chapter 3

Collision Avoidance System Design

To allow operators to use MAV systems more effectively in unstructured environments, the Collision and Obstacle Detection and Alerting (CODA) display was created. This chapter outlines the requirements that drove the design of the CODA display and the mechanisms chosen to provide alerting capabilities. Next, the chapter describes the integration of the CODA display into an existing iPhone®-based MAV control interface and outlines the hardware and simulation systems created to test the integrated display. Finally, the chapter details the setup and results for a demonstration of the system in an outdoor environment.

3.1   Requirements

From observations during prior work (Section 1.3.2) and factors pertaining to the expected operating environment, the following requirements for the collision notification system emerged:

- The display must warn the user of potential collisions in the vicinity, both within and outside the user's field of view.

- The display must show information about location and distance of potential

obstacles.

- The display must integrate effectively into an existing display on a mobile device, as described in Section 3.2.

Additionally, due to the current technological difficulties of detecting obstacles in three dimensions, this first iteration of the display was limited to showing information about obstacles in the two-dimensional horizontal plane.

3.2 Description of Smartphone-based Control Interface

Previous research in the Humans and Automation Lab at MIT focused on how to design a MAV system that could be operated by an single person with minimal training. This work resulted in the Micro Aerial Vehicle Visualization of Unexplored Environments (MAV-VUE) interface, an iPhone®-based application that could be used to accomplish local surveillance tasks. For a full description, the reader should refer to [8], but an overview of the interface and its functionality is presented here.

The MAV-VUE interface has two modes of control. The first is a traditional *waypoint control* interface, shown in Figure 3-1, which allows for high-level control of the vehicle. Users place waypoints at desired locations by double-tapping on the screen with one finger, and the MAV autonomously traverses to these locations in the order of creation. This high level of automation allows for a low pilot workload while the vehicle travels to the area of interest, as the operator is free to attend to other tasks as necessary. The Vertical Altitude Velocity Indicator (VAVI), on the bottom of the screen, displays the current altitude of the vehicle numerically along with an indicator showing relative vertical velocity [37]. The inset camera view (in the top right corner) allows the operator to view the camera image during this flight, but no additional inputs are necessary.
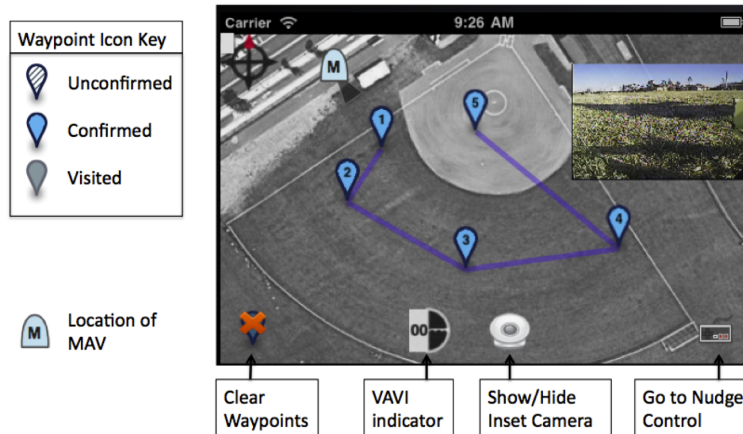
Figure 3-1: Annotated Waypoint Control Interface Diagram

The second mode of control, called *nudge control*, allows for more fine-tuned position inputs once the vehicle reaches an area of interest. Figure 3-2 shows an example of the interface. This mode, which is the focus for the CODA display, allows an operator to explore a possibly unknown area, relying solely on visual feedback from the device and without having to view the vehicle itself. The user can interact with the system and give flight controls through natural gesture inputs that, from the user's perspective, control the view provided by the vehicle. In order to command the vehicle, the user must press the 'dead-man switch', which causes the controls to become active. A 'dead-man' switch is a type of fail-safe that requires constant user input to remain active, which prevents unintentional control commands from affecting the system. While holding the dead-man switch, translational commands are given by tilting the device in the desired direction of motion, with the degree of tilt corresponding to the magnitude of the input. The small red dot in the navigation circle moves in relation to the tilt angle; if the device is level, the dot will be in the center. Rotation commands require a one-fingered swiping motion around the circle in the center of the display. Altitude commands involve a pinching motion, where the magnitude of the resulting command is proportional to the size of the pinching input. In all three cases, the interface provides visual feedback that the desired inputs have been received.
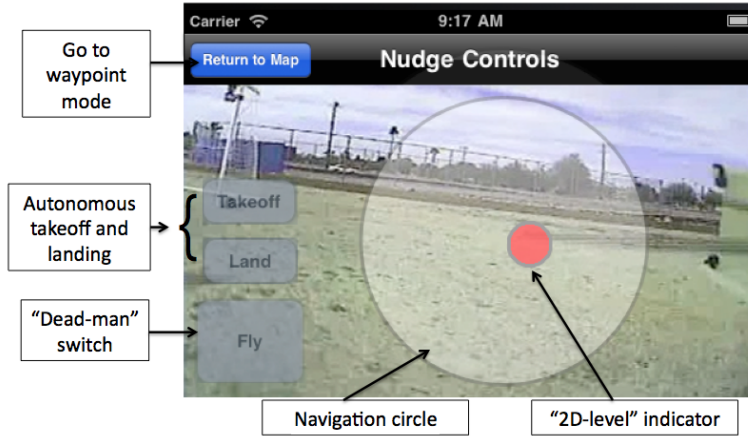
Figure 3-2: Annotated Nudge Control Interface Diagram

3.3   CODA Display Design

To address each of the requirements in Section 3.1, the Collision and Obstacle Detection and Alerting (CODA) display was developed. The steps of the design process included selecting the appropriate alerting modalities and designing each alerting mechanism, with several iterations of each step. The display was integrated with the *nudge control* mode in the MAV-VUE interface, in which operators have more direct control over the vehicle and could benefit from indications of the objects in the surrounding environment. Although the focus of this project is on *nudge control* mode, future work could explore how to most effectively display obstacle information in *waypoint control* mode.

3.3.1   Choice of Alerting Mechanisms

As discussed in Section 2.5, selection of the proper alerting method depends on many factors, including the types of information to be conveyed and the operating environment of the system. For this application, two main factors contributed to the design: the anticipated environment and the capabilities of the hardware platform.

As described in Section 1.1, MAV systems can be applied to tasks in a wide variety of

environments, including wilderness search-and-rescue, exploration of disaster areas, and video surveillance of crowded areas. These applications cover a range of indoor and outdoor environments, with varied terrain and lighting conditions. An operator needs access to a visual display to show the video feed from the vehicle along with any sensor information related to the task (infrared readings, radiation levels, etc.). However, visual displays can have trouble in lighting conditions and require the operator to be looking at the display, which may not be the case if the operator has other tasks to perform. Due to these factors, the system should not rely solely on visual alerts. Supplemental auditory alerts may not be noticeable if the environment is noisy, and alternatively, if an operator is using the system to gain surveillance information, additional noise may be undesirable. On both ends of this spectrum, auditory alerts may not be effective or may even be harmful to the goals of the mission.

This research targets a hand-held mobile device, or "smartphone" as the intended hardware platform for controlling the MAV due to its portability, functionality, and commercial availability. The typical alerting capabilities of a mobile device (as of 2012) are displayed in Table 3.1. The mobile interface is primarily a screen-based display, and previous work with MAV control has only taken advantage of the visual capabilities [8]. The screen is 2-inches by 3-inches, so screen real estate is limited. The system has audio capabilities, and can play a number of built-in alert tones along with an unlimited number of sound files. The only haptic alerting mechanism consists of vibration feedback.

Table 3.1: Mobile Device Alerting Capabilities and Limitations

Alerting Mode	Capabilities	Limitations
Visual	Screen-based display (text, pictures, color)	Limited screen space
Auditory	Alert tones, Sound files	Not salient in noisy environments, or intrusive if stealth is required (unless using headset)
Haptic	Vibration	Limited functionality and customization options

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Due to the combination of expected environmental conditions and capabilities of current mobile devices, it was determined not to use auditory alerts in the system. Auditory alerts may not be practical in noisy environments or may be undesirable during stealth operations. Also, such systems possess very small speakers and limited volume capabilities, unless used with a headset. Although a headset eliminates most of the problems of auditory alerts, it increases the necessary amount of equipment and could have other effects on situational awareness, so investigations have been left to future work. Instead, the system was designed to have both visual and haptic feedback. These specific components are discussed in the following sections.

3.3.2   CODA Visual Alert Design

The main challenge of the visual component of the alerting system was incorporating an alert indicator into the limited screen real estate, where the primary function is controlling the MAV.

It was assumed that the system would be equipped with one or more distance sensors that could provide information about objects in a two-dimensional plane. Some distance sensors, such as a laser rangefinder, can return many distance measurements every second, which would provide an overload of information if displayed to the user directly. To simplify the information presented to the operator, the alert system had three stages, as shown in Figure 3-3. The salience of the alert increases with response to distance, and the thresholds are set up such that the system's alert increases in discrete steps, rather than gradually, as shown by the graph in Figure 3-4. Obstacles are shown to the operator via an arc-shaped indicator, as shown in the top row of Figure 3-5. Each indicator consists of a triangle and two arcs. The triangle represents the location of the obstacle, and the arcs help make the indicators more noticeable. To make the difference between levels more conspicuous, the alerting levels are dual-coded, so the indicators increase in both size and in opacity as the level of the alert increases. Additionally, this causes the more critical indicators to stand out and min-

imizes the clutter onscreen from less important indicators. Due to the limited screen size, the indicators were overlaid on the camera image instead of creating a separate display on the side, as that would have required shrinking the camera image.
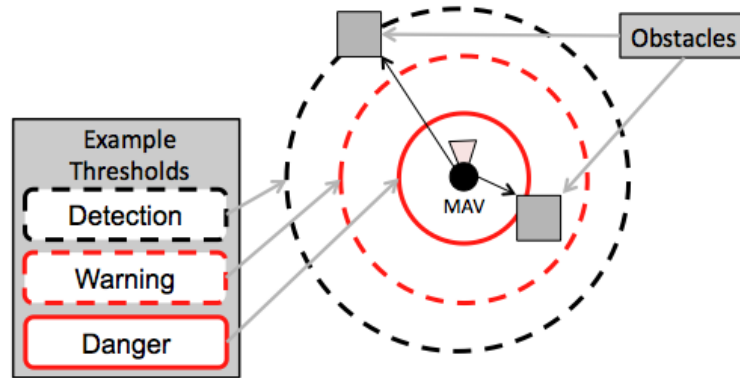
Figure 3-3: Diagram of 3-level Alerting System, with three thresholds corresponding to distance of obstacle from the vehicle. The diagram shows the MAV in an environment with two obstacles within the alerting thresholds.
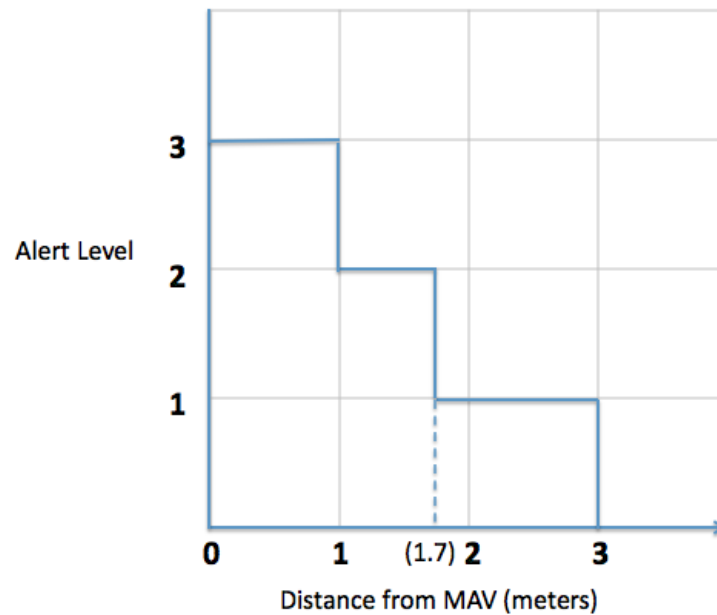
Figure 3-4: Graph of alerting threshold function, where alert level is based on obstacle distance from the MAV.

Keeping the indicators inside the navigation circle places the CODA display in a
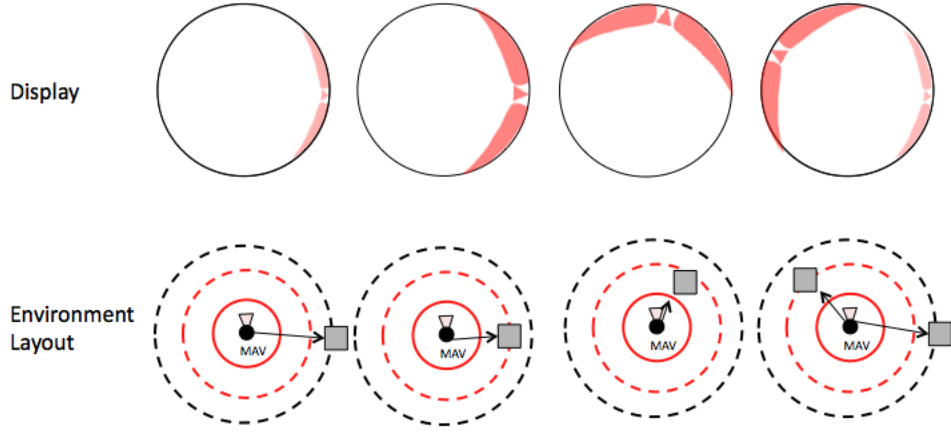
Figure 3-5: Examples of alerting indicators for various environmental configurations.

consistent frame of reference with the control inputs. The navigation circle, which shows the feedback from the tilting, rotating, and pinching control inputs, essentially provides a 'top-down' view of the system. The video stream, however, represents a forward facing view. The CODA interface assumes obstacle information coming from the sensors represents objects in the horizontal plane of the vehicle. As an example, imagine a vehicle in an environment free of obstacles except for obstacle directly in front of it. From the user's perspective, this obstacle would be in the middle of the camera frame. If the obstacle is within the alerting threshold, the CODA system would alert the operator to this with one visual indicator. By aligning the indicator with the navigation circle, the operator can see the obstacle is in front, and by tilting the interface to move the vehicle forward (which would move the navigation ball towards the indicator), a collision occurs. If this indicator were instead aligned with the top of the screen (and therefore the top of the image), the operator could incorrectly assume that the indicator referred to an object above the vehicle.

Figure 3-6 shows the levels of the alerting system as incorporated into the existing MAV-VUE interface. Frame 1 shows the interface when no indicators are triggered, meaning no obstacles are inside the alerting thresholds. In Frame 2, the vehicle has moved closer to the wall on the right, triggering the first alert level. Frames 3 and 4 represent the second and third alert levels, respectively, as the vehicle gets closer

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to the wall. As shown, the indicators become both larger and more opaque as the distance to the wall decreases.
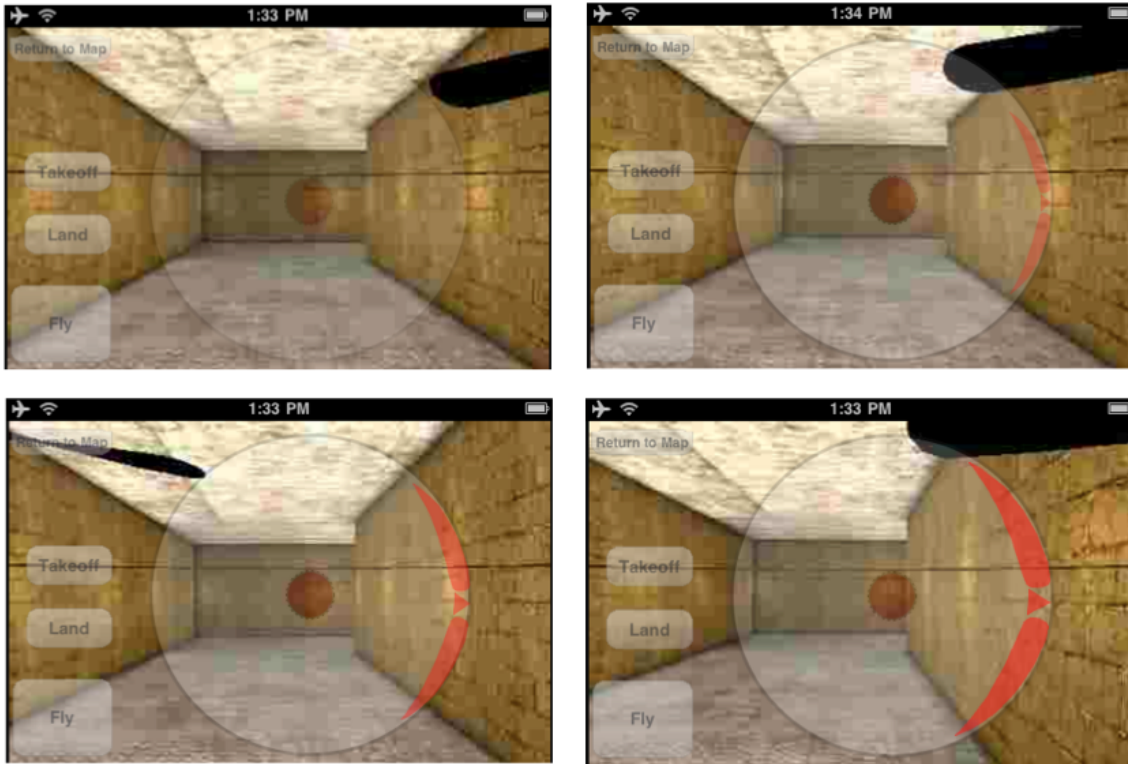
Figure 3-6: Examples of collision alerting interface, illustrating the change in indicator level as vehicle approaches the wall on the right.

3.3.3 CODA Haptic Alert Design

The initial design consisted solely of visual indicators, but pilot users often did not notice the change in the alert levels. To supplement the visual display, haptic feedback was used to increase the salience of critical alerts. Dual coding the alerts in this manner allows the operator to respond to the haptic feedback even if he or she is not looking at the display.

When designing a haptic alert based on vibration, there are several factors to consider, including:

- Intensity: How strong is the vibration?

- Duration: For how long does the vibration occur?

- Pattern: Are there repetitions in the vibration? At what intervals?

- Frequency: How many times is the vibration repeated?

- Thresholds: What triggers the vibration event?

For this application, the hardware capabilities of the iPhone® limited the possible functionality of the alerting mechanism. The current development kit at the time this system was implemented (iOS4), only contained support for a single vibration alert of fixed intensity and a duration of 1.5 seconds. The only customizable options available were when to trigger the alert and how many times to repeat it. In the future, other variations could be investigated.

While different repetitions could have been employed for the different alert levels, users during pilot testing described the alert as "startling" and disruptive to operation. As a result, it was most effective to incorporate a single vibration at the onset of the highest alert level, where disrupting the current course of action is necessary to avoid a collision. The vibration occurs simultaneously with the appearance of the largest visual display indicator (Frame 4 in Figure 3-6).

3.3.4 Summary of Display Design

In summary, the CODA display consists of a combined visual and haptic alerting system to increase the operator's awareness of potential hazards in the environment. The three alerting levels simplify the information presented to the operator. The visual indicators dual-code each level using size and opacity, and a vibration accompanies the highest alert level for added saliency. Additionally, the indicators integrate with existing controls, so the operator can continue to focus on controlling the vehicle while also getting supplemental obstacle information. The next section details the steps taken to integrate the CODA display into the MAV-VUE interface.

3.4 Development of Collision Detection System

For the CODA display to provide obstacle information to the operator, the MAV system must be equipped with distance sensors that can provide the appropriate inputs. In order to test the effectiveness of the display, two such systems were implemented. The first consisted of a quadrotor vehicle augmented with distance sensors. The second consisted of a simulation environment that was constructed for rapid prototyping and usability testing.

For both of the following setups, the MAV-VUE application ran on an iPhone® 4G, with a screen resolution of 480 by 320 pixels. The iPhone® interfaced with a server program which ran on a laptop and allowed much of the computation to be offloaded from the mobile device. The laptop used was an Apple MacBook® running Mac OS X 10.6, with 2 GB of RAM. Wireless communication between the iPhone® and the MacBook® occurred via a wireless router.

3.4.1 Hardware Platform

In previous research, the MAV-VUE platform interfaced with the Ascending Technologies (AscTec) Hummingbird, a commercially available quadrotor helicopter platform [8]. The Hummingbird does not have built-in distance sensing capabilities and lacks the payload capacity to add additional sensors. To develop a system with obstacle sensing capabilities, the AscTec Hummingbird was replaced by the AscTec Pelican, a larger quadrotor vehicle that can carry up to 500 grams of payload beyond its built-in autopilot, Inertial Measurement Unit (IMU), and GPS sensors. A Hokuyo UTM-30X laser scanner was added to the Pelican to enable distance sensing capabilities, as shown in Figure 3-7. The Hokuyo UTM-30X uses a rotating single point laser to sweep out an arc in the horizontal plane. It has a 270-degree field of view (FOV) and a maximum range of 30 meters.

Figure 3-8 illustrates the system setup. The quadrotor MAV communicates with

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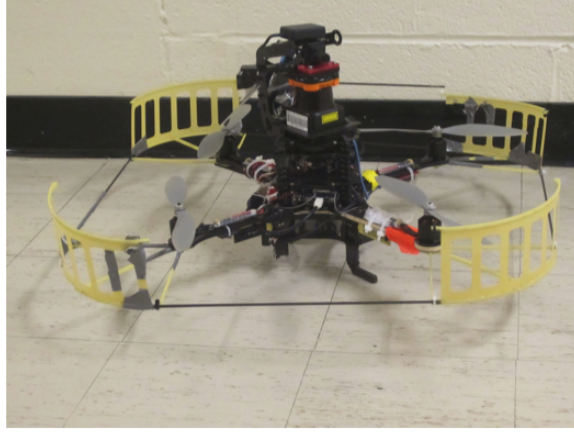
Figure 3-7: AscTec Pelican with Integrated LIDAR Sensor

a server program running on the MacBook®, via an XBee® 2.4 Ghz radio. The quadrotor's onboard computer has an Atom™ processor board. Onboard computation, communication, and processing occurs using the Robot Operating System (ROS) framework [38]. ROS is used to collect data from the Hokuyo laser scanner and the AscTec autopilot, to send controls to the autopilot, and to transmit and receive data through the XBee® serial interface. An onboard camera was mounted on top of the quadrotor, facing forward. A 2.4GHz analog video transmitter was used to send the video feed to the ground-based receiver, where the analog video feed was converted to discrete JPEG frames by an external video capture card attached to the server computer and then sent to the iPhone® via UDP.
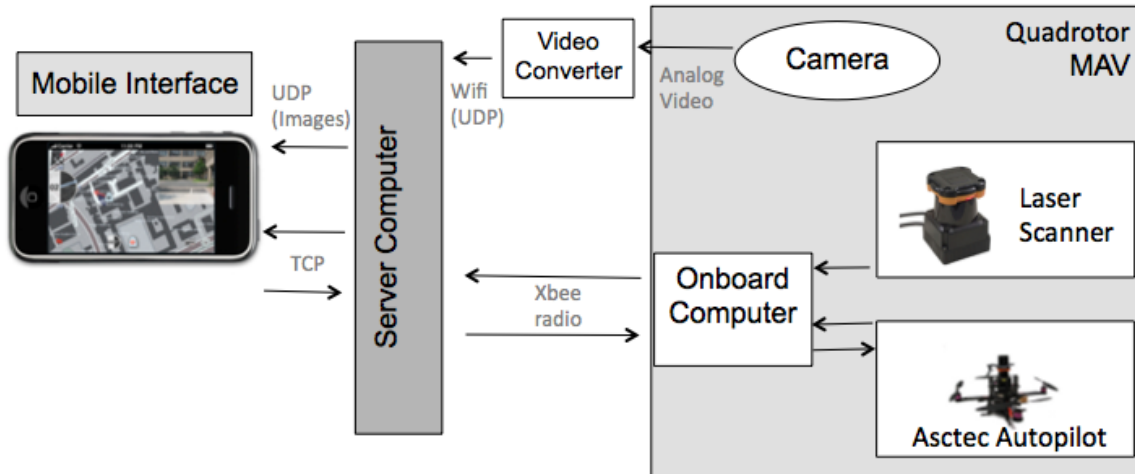
Figure 3-8: Hardware System Diagram

3.4.2 Simulation Environment

Developing a simulation system promoted efficient prototyping and testing of the interface. The simulation was configured to mimic the capabilities of the hardware platform as closely as possible. Unified System for Automation and Robot Simulation (USARSim) provided a suitable simulation environment with built-in vehicle and sensor configurations [39]. The platform is built on the Unreal Tournament Engine and has been previously used in the RoboCup Urban Search and Rescue Challenge. Figure 3-9 shows an example screenshot of the simulated indoor environment. The vehicle used in the simulation was the AirRobot®, an existing robot in the USARSim program that is modeled after a real system developed by AirRobot Gmbh & Co. The AirRobot® is a quadrotor vehicle with a diameter of 1 meter (see Figure 3-10). The predefined settings file includes the robot structure, a forward-facing camera, and a ground-truth sensor. In order to mimic the capabilities of the Pelican-based hardware platform (see Section 3.4.1), the existing settings file was augmented with a range scanner with range and resolution properties identical to the Hokuyo UTM-30X.

Figure 3-9: Example screenshot of simulation environment

Figure 3-11 illustrates the system setup for the simulation environment. The simulation engine ran on a Dell desktop computer running Windows® XP. The USARSim
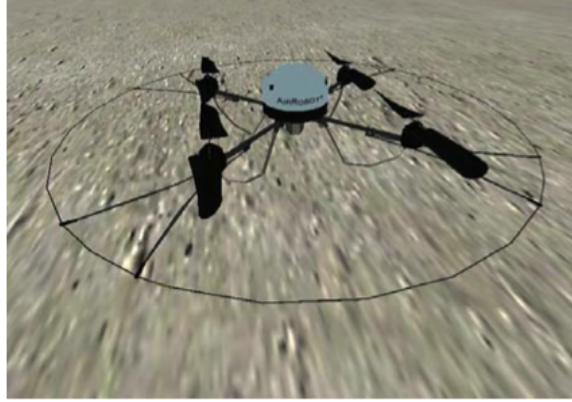
Figure 3-10: Simulated Quadrotor Vehicle

version used was compatible with Unreal® Tournament 2004. Screenshots from the simulation were sent over the network as low-quality JPEG images. Communication between USARSim and MAVServer occurred via local wired ethernet with network communications routed through through a wired/wireless router.
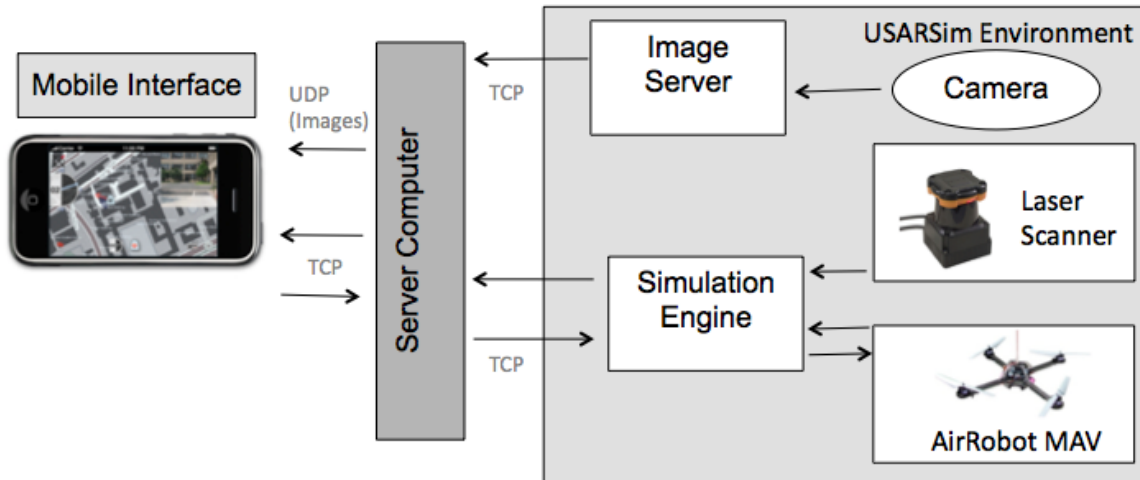
Figure 3-11: Simulation System Diagram

3.5   Proof of Concept Demonstration in Outdoor Environment

To begin to assess feasibility in a real-world, outdoor scenario, a proof-of-concept demonstration was performed. The purpose was to demonstrate functionality in a

field environment with obstacles, so a small course was set up on an outdoor athletic field and participants were given a simple navigation task. The hardware system used in this experiment is described in Section 3.4.1.

3.5.1 Demonstration Tasks

Two participants were given a simple navigation task that involved maneuvering through an outdoor corridor. They were instructed to take off, navigate down the corridor, turn to the left, and land the MAV. Subjects were located on an adjacent field to the flight area and could not see the vehicle during the task. The user relied on the iPhone® interface for feedback about the environment during the flight. Figure 3-12 shows an example of the interface in the outdoor test.
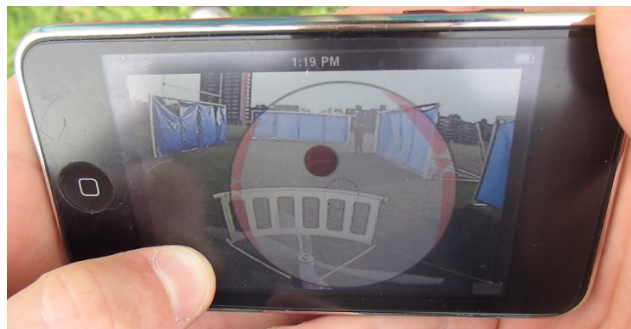
Figure 3-12: Example of Interface used in Outdoor Environment.

3.5.2 Demonstration Environment Setup

Figure 3-13 shows a photo of the environment, and the layout is shown in Figure 3-14. Obstacles were constructed using soccer goals with plastic tarps to create a solid reflecting surface for the LIDAR sensors. Although the system has obstacle sensing capabilities, "no-fly zones" were implemented in the software (see Figure 3-14) to prevent damage to the vehicle. These zones were calibrated at the beginning of each test session using the GPS locations of the obstacles since these locations are liable to drift over time.

Figure 3-13: Outdoor testing environment, with MAV stationed at the takeoff location.
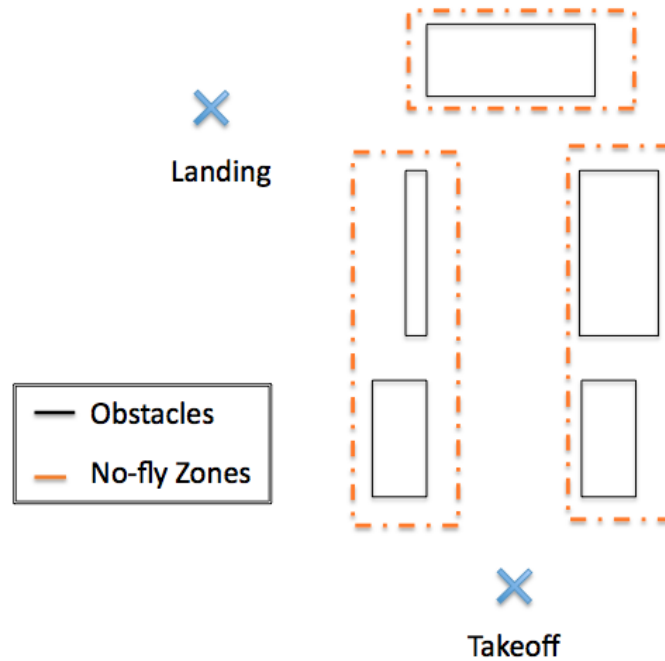
Figure 3-14: Outdoor field layout for proof-of-concept demonstration.
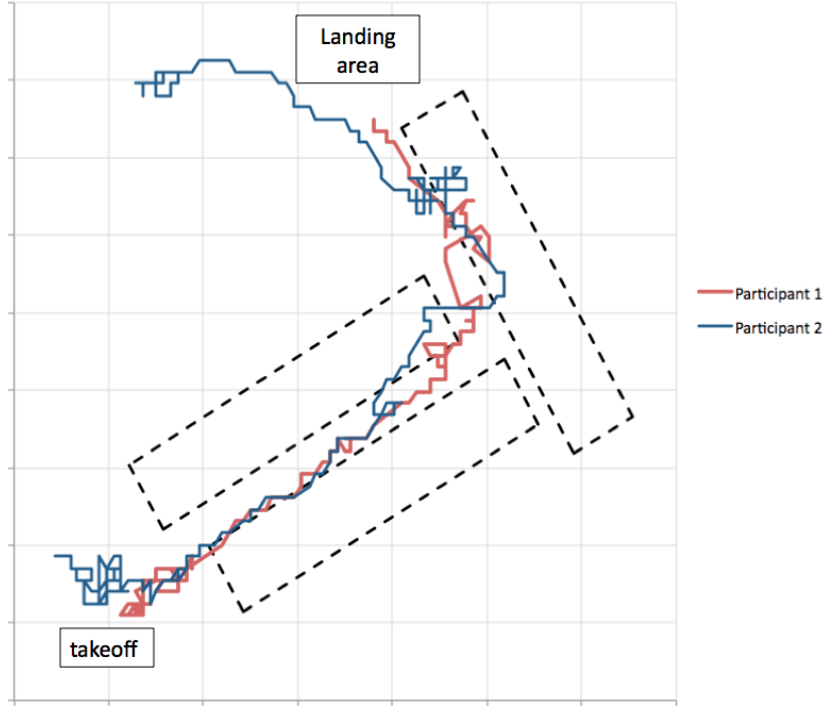
Figure 3-15: Flight paths from outdoor pilot testing with two participants in the outdoor environment.

3.5.3   Demonstration Results

Both users successfully completed the navigation task in the outdoor environment. During the flights, obstacle data was successfully transmitted from the onboard LIDAR to the CODA interface in real time, via the ground station, with all components running in full operational mode. The CODA interface successfully represented the obstacles in the mobile display so that the user could take advantage this information during operation. The lag experienced ranged from 0.25 to 0.75 seconds for the control inputs and from 0.5 to 1.5 seconds for the video and CODA display.

As shown by the flight paths in Figure 3-15, both participants were able to navigate through the corridor and turn the corner, although both did drift into the 'no-fly zones' on multiple occasions. The zones included a buffer around the actual obstacle, and no actual collisions occurred in either case.

3.5.4 Discussion of Demonstration Results

While the task was shown to be possible, numerous system improvements are necessary in order to make this system robust enough to run a usability study. In particular, several environmental factors made the task more challenging than expected. The Pelican relied on GPS for position control, and GPS accuracy alone is not sufficient for maneuvering around buildings and structures. With the MAV, we saw position drift of two to four meters, which increased if the windspeed was greater than 8 mph. Given the scale of the course, this could easily cause the system to drift into an obstacle. Additionally, the "no-fly zones" were calibrated using GPS, and the locations would drift over the course of the test flight. This had two effects: 1) The obstacles would no longer be within the zones, causing potential collisions, and 2) The drift would cause 'obstacles' where a clear path existed. These preliminary results showed that significant further development is needed to increase robustness and improve repeatability of the setup in order to isolate usability problems of the interface from technology and system limitations. This thesis focuses on the problem of assessing usability of the CODA interface, leaving the system development to future work.

3.6   Summary

Developing a collision avoidance display to assist a MAV requires understanding the expected operating environment as well as the capabilities and limits of the system. For the MAV systems of interest to this work, the purpose is to perform local ISR tasks with the capability to operate in both indoor and outdoor environments. To assist in operation in unknown environments, the CODA display was developed, and this display was then integrated into the iPhone®-based MAV-VUE control interface to aid in collision avoidance. The chosen design for the CODA display integrates a combination of visual on-screen indicators and haptic vibration feedback to present information about objects in the environment in a simplified manner. Two platforms were then developed to interface with and test the alerting display: A simulation

environment to be used for prototyping and usability assessment, and a hardware-based platform to be used for pilot testing in an outdoor field environment. Finally, a pilot demonstration was performed to test the hardware system in an outdoor environment. Although the system functionality was confirmed, several system issues were uncovered. The following chapter describes the setup for a usability experiment, conducted using the simulation platform, which aims to show whether the CODA display has an effect on MAV operation.

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Chapter 4

Usability Evaluation

In order to test the effectiveness and usability of the Collision and Obstacle Detection and Alerting (CODA) display, a usability study was conducted using the simulated MAV system described in Section 3.2. The experiment involved navigating a simulated MAV through a simple indoor course. The objectives of this experiment were to assess whether the addition of the CODA display would improve performance and examine how the display impacted user experience. Eighteen participants who had no previous experience with the interface were recruited from the MIT student population. Participants were required to have normal or corrected vision and were screened for colorblindness.

4.1   Experimental Setup

The experimental factor was the presence of the CODA interface. In the control condition, participants interacted with the vehicle via the original MAV-VUE interface [8] without the CODA display. In the experimental condition, participants used the CODA display integrated with the MAV-VUE system. The experiment was within-subjects, with each participant completing the visual search tasks for both conditions. The setup was also counterbalanced, with half of the participants completing the con-

trol condition first and half completing the experimental condition first.

4.2   Task Scenario

As laid out in Chapter 3, the intended purpose of the MAV system is to allow an operator to complete local Intelligence, Surveillance, and Reconnaissance (ISR) tasks. To assess the usability of the system for this type of mission, experimental tasks were constructed which consisted of locating and observing visual targets in the simulation environment. For each condition, the participant had to complete two visual search tasks, each of which involved locating a sign on the wall of the environment and reading the word on the sign aloud to the experimenter (see Figure 4-1). The layouts were the same for each experiment condition, and the targets were similar, but each had a unique word. Figure 4-2 displays the layout for the practice and test courses with dimensions. The maps given to the participants for both the practice course and the test courses are shown in Figure 4-3. Participants were instructed to visit the

Figure 4-1: Example target for the visual task.

tasks in the specified order. As indicated by Figure 4-3, the map labeling varied slight for each task. Although the target indicators were in the same general area on the map, participants were told that the targets might not be in exactly the same place in both trials. Additionally, the words printed on the visual targets were different

in each condition so that the participants could not rely on memory when reading the targets. If a participant crashed into a wall, the vehicle would be reset at the 'save-point' location corresponding to the most recently crossed threshold (see Figure 4-2). The thresholds and 'save-points' were manually placed in roughly even spacing, just before areas that were likely to cause crashes (i.e. turning a corner, entering or exiting the room). Due to the time necessary to reset the simulator, the restart process took approximately three seconds. Once restarted, the participant needed to take off, reorient themselves, and continue on the mission.

4.3   Metrics

The dependent variables analyzed can be separated into several categories: performance metrics, control strategy metrics, spatial abilities, and qualitative metrics.

4.3.1   Performance Metrics

- **Number of Collisions:** The primary performance metric was the number of times the participant crashed into a wall. Each time a collision occurred, the system took three seconds to restart and place the simulated quadrotor back at the most recent reset point, after which the participant could continue with the task. Figure 4-2 shows the course map with reset points indicated.

- **Task Completion Time:** Overall task completion time measured the time from initial takeoff to final landing after viewing both targets. For participants who did not complete both tasks, completion time was capped at seven minutes (the maximum allotted time), and these participants were not included in the final analysis. Task completion time did not include the server reset time after each crash.

- **Sub-Task Completion Times:** In addition to overall completion time, two interval metrics were examined. The first was the total time required to enter
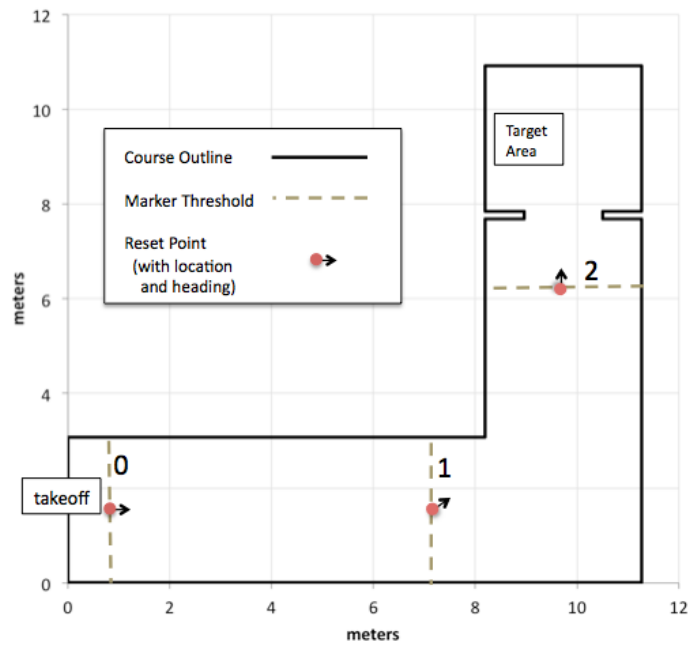
(a) Practice Course
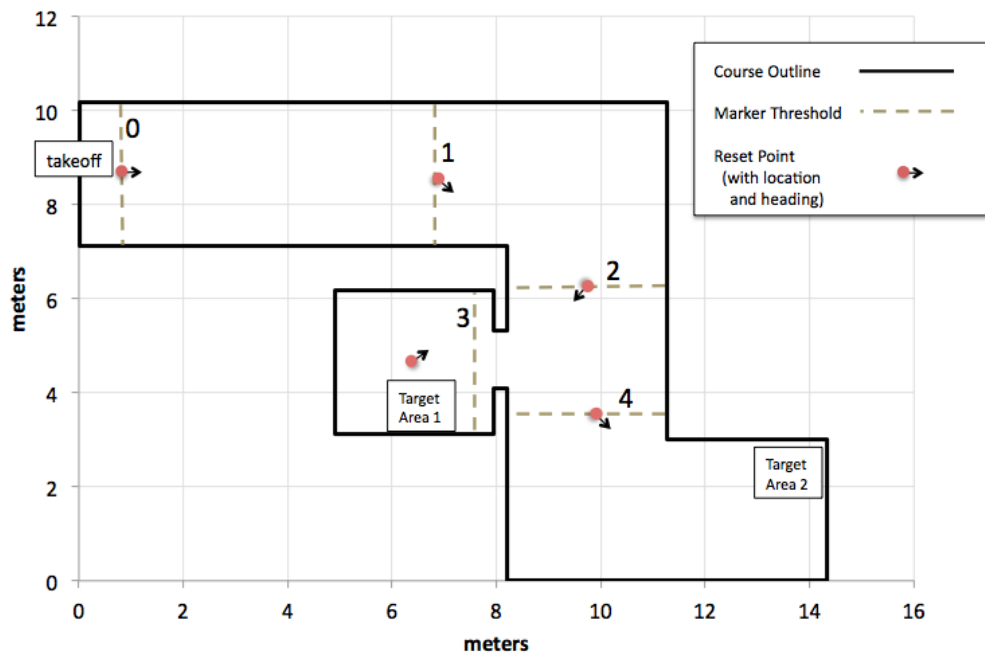
(b) Flight Task Course

Figure 4-2: Course diagrams for practice and test flights, with dimensions and labeled marker thresholds. The thresholds acted as "save-points" as the user traversed the course.

(a) Practice Course

(b) Flight Task Course 1

(c) Flight Task Course 2
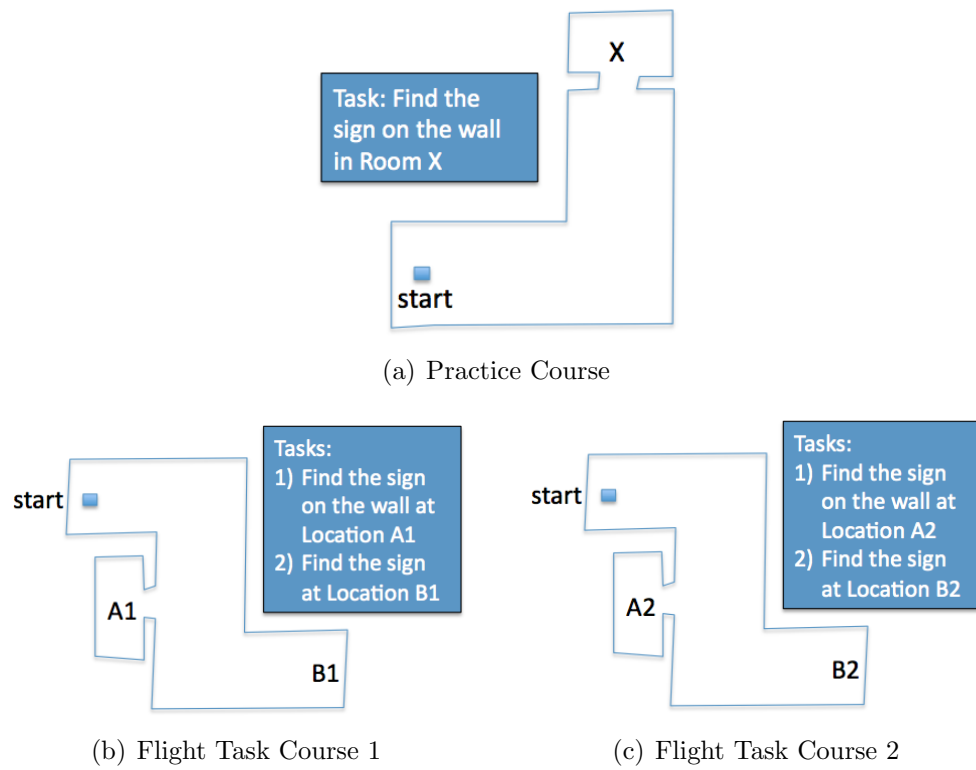
Figure 4-3: Maps for Practice and Test Flights, as given to the participants.

the room, which was measured as the difference between crossing the threshold at marker 2 and reaching marker 3 (see Figure 4-2). Because participants were instructed to fly down the hallway and enter the room, this increment represented the period beginning at the approach to the door and ended when the participant had successfully entered the room. This time interval included the cumulative time for multiple attempts, if applicable, but did not include the approximately three-second reset period after each crash. The second time interval examined was the time to pass through the doorway on the final (successful) attempt.

4.3.2   Control Strategy Metrics

The nudge control inputs for each participant were recorded. This data reveals information about how hard the participants had to work to control the system as well as any underlying control strategies that emerged.

- **Number of nudge controls:** The total number of nudge control inputs for the participant to complete the tasks in each condition was recorded. This provides a proxy measure for workload, measuring how many commands were required to complete the specified task.

- **Magnitude of nudge controls:** Descriptive statistics were recorded for the nudge control commands given by each participant in each experimental condition. Although the participant perceives nudge control commands as velocity inputs, each command actually send a waypoint to the vehicle, so the magnitude is measured as the distance between the current location and the commanded waypoint. The magnitude and variation of the control inputs could reveal how the presence of the CODA display affected user actions and control strategies.

- **Total path length:** Path length included the cumulative path traveled from initial takeoff to final landing, including segments generated by multiple attempts after crashing.

- **Location of crashes:** The location of each crash was recorded to examine which areas of the course were most difficult to maneuver.

4.3.3   Spatial Abilities

The following two pencil-and-paper tests were administered to each participant in order to correlate existing spatial abilities with performance on the experimental task.

- **Mental Rotation Test**

  The Mental Rotation Test (MRT) [40] measures spatial visualization capabilities by asking participants to compare three-dimensional rotations of an object. The version used in this research is a reconstructed version, since the original version has been lost due to deterioration of the existing copies [41]. The test is scored by number of correct answers, so a higher score on the MRT represents higher performance.

- **Perspective-Taking/Spatial Orientation Test**

  The Perspective-Taking/Spatial Orientation Test (PTSOT) [42, 43] measures perspective-taking abilities by asking participants to visualize themselves in a given reference frame. The test is scored by adding together the error in each answer, so a lower score on the PTSOT represents higher performance.

4.3.4   Qualitative Measures

- **Subjective feedback:** Subjective feedback was collected using a survey administered at the end of each trial (see Appendix C). The survey consisted of questions regarding frustration, understanding of the interface and controls, and perceived difficulty of the task. In addition, the experimenter conducted a verbal interview at the conclusion of both flight tasks. Field notes were also taken throughout the experiment.

4.4 Procedure

The experiment ran between 50 to 75 minutes for each participant, depending on how long the participant took to complete the flight tasks. Participants began by completing a consent form and a preliminary demographic survey (see Appendix A). The flight portion of the experiment then progressed as follows:

1. The participant was briefed on the interface and the functions of each of the controls. The experimenter then demonstrated how to use each of the controls by interacting with the simulation in the practice course. This demonstration phase took approximately three minutes.

2. The participant was allotted three minutes to fly through the practice course and test out each of the controls. Participants were also instructed to crash into a wall in order to see the system reset behavior. A time of three minutes was selected to mirror the practice time given with earlier versions of the MAV-VUE interface [8, 9]. Participants could ask questions during this stage.

3. For the first test flight, the participant had seven minutes to find two visual targets in the real course. During pilot testing, participants completed the course in around six minutes. Seven minutes was selected to give participants enough time while also putting a deadline as incentive to finish quickly. During this test portion, the experimenter did not answer any questions or give any advice.

4. The experimenter explained the CODA display through a paper handout (see Appendix B) and demonstrated the behavior of the CODA display by interacting with the simulator in the practice course.

5. The participant again had three minutes in the practice course to test out the controls and get experience using the system with the CODA display. Par-

ticipants were encouraged to approach obstacles to observe how the indicators would change in different situations. Participants were again instructed to intentionally cause a collision to observe the indicators and the reset behavior.

6. For the second test flight, the participant had seven minutes in the real course to complete both visual tasks with the assistance of the collision notification indicators.

As mentioned previously, the task ordering was counterbalanced between participants to account for possible learning effects. For half of the participants, steps 4-6 would come before steps 1-3.

Following the completion of each experiment condition, the participant was asked to fill out an evaluation survey (see Appendix C). Once the participant had completed both conditions, the experimenter conducted a brief verbal interview to get general subjective feedback from the participant. The questions from the interview are available in Appendix D. Finally, the participants completed the two spatial tests: the Perceptive-Taking Spatial Orientation Test (PTSOT) and the Mental Rotation Test (MRT). The tests were completed at the end of the session to reduce the risk of task performance impacts based on perceived performance on the spatial tests.

4.5   Data Collection

The telemetry data from each flight as well as each participant's command inputs were logged to text files on the MacBook® computer. All of the simulated onboard video frames were recorded to the MacBook® and saved as time-stamped JPEG image files to allow post-flight reconstruction of the participant's perspective. An external video camera recorded the participant's interactions with the device. The participant completed the spatial tests and the usability questionnaires on paper. The experimenter took notes during testing and during the post-flight interview to record observations and additional comments from each participant.

4.6   Summary

This chapter describes the usability experiment conducted to examine the effectiveness of the CODA display. A within-subjects experiment was conducted in order to examine the effect of the CODA display on a range of performance metrics, control strategies, and subjective experience. The next chapter describes the results of this experiment and their implications for collision interface design for MAV systems.

Chapter 5

Usability Evaluation Results and Discussion

In order to evaluate the usability and effectiveness of the CODA display, a mission involving two visual search tasks was set up in a simulated environment. This chapter presents the results of the experiment described in Chapter 4. Unless otherwise stated, an α value of 0.05 is used for determining significance in all statistical tests.

5.1 Subject Population

For this experiment, 18 participants were recruited from the MIT undergraduate population. Of the 18 participants, six had to be excluded from the quantitative data analysis for technical reasons. Two of these encountered logging issues, and four encountered bugs in the simulation.

The 12 participants used in the analysis were between the ages of 18-23 (M=19 yrs, SD=1.5 yrs). Self-reported video game usage varied from 1-4 (on a 5-point scale) and self-reported iPhone® use varied from 1 to 5 (on a 5-point scale). Descriptive statistics for participant demographic information are presented in Appendix E.

5.2 Analysis of Primary Performance Metrics

The following section describes the analysis of the performance metrics. Descriptive statistics summarizing these metrics can be found in Appendix F.

5.2.1 Task Completion

A primary metric of interest was task completion, or how many participants could complete the mission in the allotted time in each experimental condition. Of the twelve remaining participants, seven completed the full mission in the allotted time for both trials. A significant difference in video game experience was found between the participants who were able to complete the tasks and those who were not, $t(10)=2.22$, $p=0.050$. This matched results in previous work [8] that suggests that video game experience can be used to predict performance in MAV control.

Table 5.1 displays the task completion results for the 12 participants, separated by experimental condition.

Table 5.1: Task Completion by Experiment Condition

Tasks	Control Condition	With CODA Display
Completed both visual tasks	9	8
Only completed first task	0	2
Did not complete either task	3	2

Overall, there were no significant differences between the experiment conditions. Eight participants performed the same in both experiment conditions. Of these, seven were successful in both trials, and only one participant could not complete either task in either trial. One participant performed better with the CODA display, finding both targets compared to none in the control condition. Two participants performed better in the control condition.

Table 5.2 displays the results separated by trial number. Three of the participants

who missed one or more targets improved during their second trial, finding more or all of the targets. However, one participant's performance actually decreased, and he did not find either target during the second trial (the control condition), despite having found both targets on the first run (with the CODA display). Overall, there is not a notable difference between the two trials.

Table 5.2: Task Completion by Trial Number

Tasks	Trial 1		Trial 2	
	Control	With CODA	Control	With CODA
Completed both visual tasks	4	4	5	4
Only completed first task	0	1	0	1
Did not complete either task	2	1	1	1

5.2.2   Collision Avoidance

The ability to navigate a course without hitting obstacles is key to completing a mission successfully. In the simulation, participants were alerted to an impending collision but were not prevented from actually hitting the wall. When the CODA display was added to the interface, the hypothesis was that fewer crashes would occur, since the CODA display provided extra warning. Figure 5-1 shows that the mean number of crashes was lower when the CODA display was present. Based on a paired-sample t-test, there was a marginally significant difference in the number of crashes between the condition with the CODA display (M=1.7, SD=2.0) and the control case (M=2.8, SD=2.4), t(11)=-1.167, p=0.089. This metric was calculated for all twelve participants, not only those who completed the full mission.

Given that additional practice could improve flying skills and lower the probability of crashing, it is important to examine whether a learning effect was present between the first and second trial. However, based on a paired t-test, there was no significant learning effect on the number of crashes.

Because a collision in a real-world system could be devastating to mission completion (more so than in simulation), it is useful to examine the number of participants who
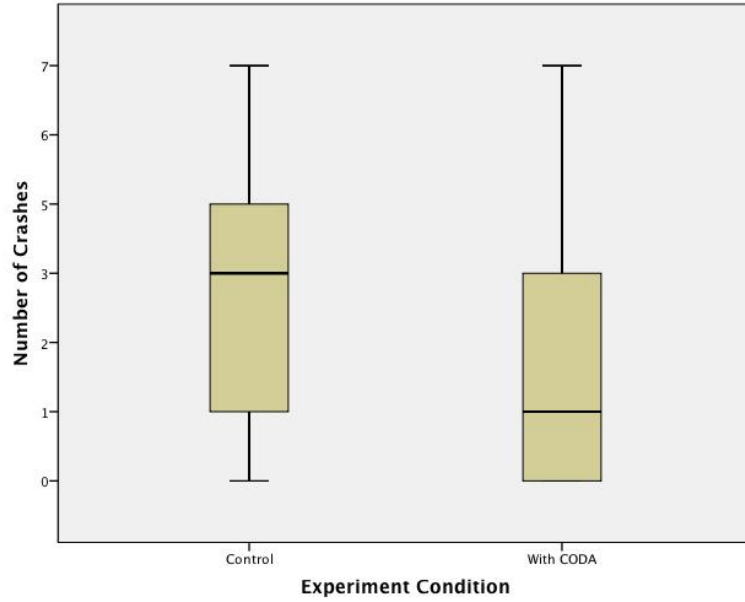
**Figure 5-1:** Boxplots comparing distribution of number of crashes for each experiment condition.

did not crash at all. With the CODA display, four of the thirteen participants did not crash, compared to only two in the control condition. Only one participant managed to complete the mission in both experiment conditions without crashing.
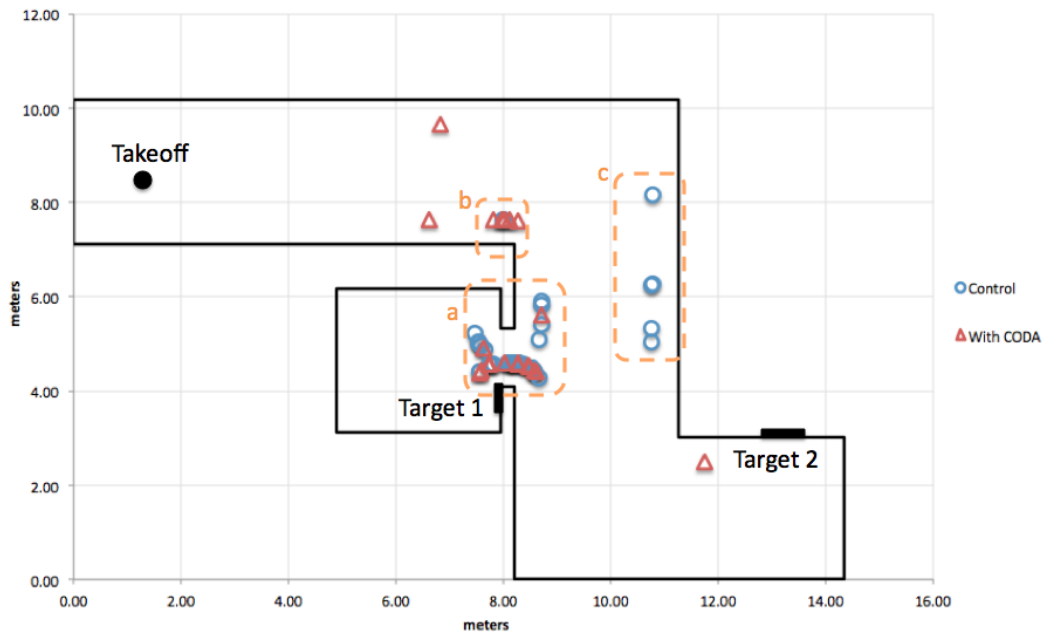
Figure 5-2: Map of the course with crash locations displayed for each experiment condition.

Table 5.3: Number of Crashes by Area, separated by Experiment
Condition
(Areas indicated in Figure 5-2)

Area	Control	With CODA
a	28	13
b	1	5
c	5	0

Figure 5-2 displays a map of the course with an overlay of the crash locations aggregated over all participants for both experiment conditions. This plot reveals that many of the crashes were clustered in a few distinct areas. Unsurprisingly, most of the crashes occurred at the doorframe as participants were attempting to enter the room where the first target was located. Crashes in this first area seemed to occur at relatively equal frequencies for each condition. A second cluster of crashes occurred at the first corner; however, all of the crashes in the second area for the condition with the CODA display are from a single participant. The third area of interest is near the wall directly across from the doorway. Participants in the control condition, without the CODA display, crashed several times by this wall. In these cases, the participants collided with the wall while moving backwards or sideways, so it's a clear indication that the CODA display helped decreased collisions with obstacles out of the operator's view.

5.2.3   Mission Completion Time

For the participants who were able to complete the full mission, one of the primary performance metrics was the total mission completion time. It was hypothesized that the CODA display would help participants complete the course in a shorter amount of time. Figure 5-3 shows a decrease in mean completion time with the addition of the CODA display. A paired t-test revealed a marginally significant difference in the mean time between the condition with the CODA display (M=241 s, SD=72 s) and the control condition (M=312 s, SD=109 s), $t(6)$=-2.147, p=0.075. There was no significant learning effect found between the two trials.
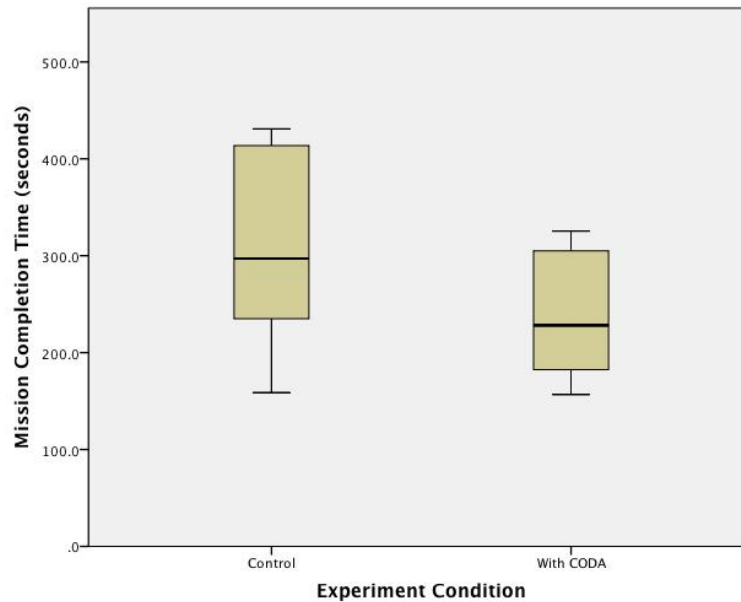
Figure 5-3: Boxplots comparing distribution of mission completion times for each experiment condition.

For the participants who were able to complete the full mission, additional analysis was performed on the portion of the flight where the participant entered the room with the first target. For each participant, two metrics were examined. The first metric was the time required to enter the room, which included the time required for multiple attempts, if applicable. The other metrics measured the time required to enter the door on the final (successful) attempt.

The hypothesis was that the presence of the CODA display would increase the time required to pass through the door on a single attempt, as it would provide the operator with more information and cause the operator to act more cautiously. However, it was also expected to decrease the total amount of time required to enter the room, by reducing a combination of the number of attempts and the time for each attempt. Figure 5-4 shows the comparison between the time to pass through the door on the successful attempt for each experimental condition. A paired t-test showed no significant difference between the two experiment cases, $t(6)=-0.221$, $p=0.833$. There was also no significant learning effect.
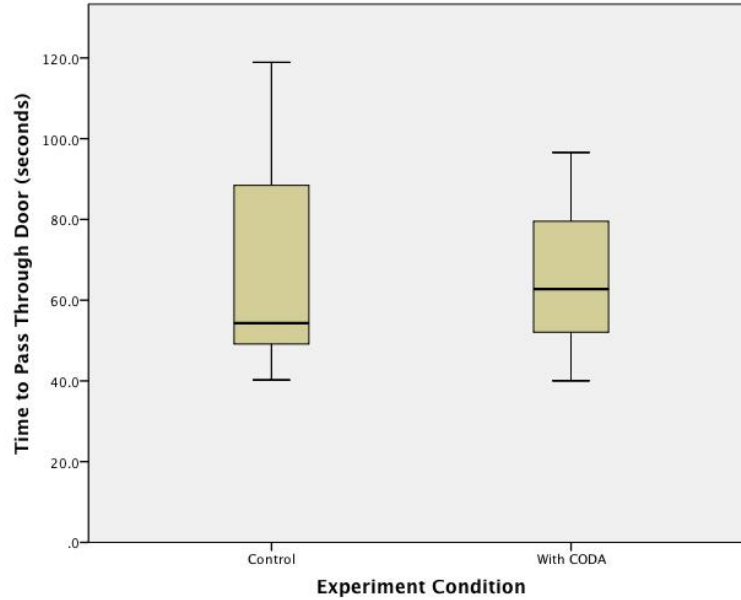
Figure 5-4: Boxplots comparing time to pass through the door for
each experiment condition.

Figure 5-5 shows the comparison between total time required to enter the room for
the two experiment conditions. Again, a paired t-test confirmed that there was no
significant difference between the means of the two cases, t(6)=-1.566, p=.168. There
was also no significant learning effect between the first and second trial. However,
there does appear to be a reduction in the variance when the CODA display is present,
which was confirmed by Levene's test of Equal Variances (F=77.429, p<.001). Exam-
ining the data more closely, two of the participants had a very large reduction with
the CODA display (a decrease of an order of magnitude), but for the others, the times
were on the same order of magnitude for both cases. This would suggest that the
CODA display had a large positive effect for participants who have significant trouble
with the system, but not as much effect for those who are reasonably proficient.

5.2.4 Total Path Length

For the participants who were able to complete the full mission, the total path length
traveled to complete the course was analyzed. The initial hypothesis was that the
presence of the CODA display would affect the path length, because participants

73
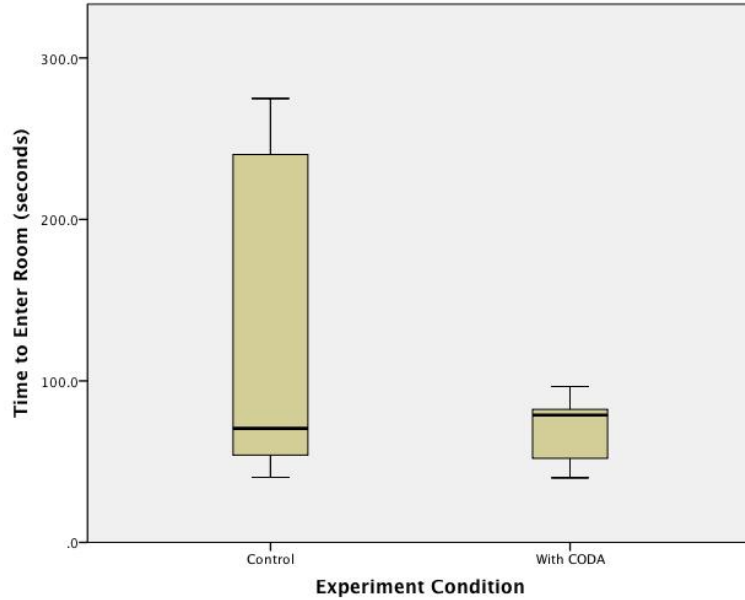
Figure 5-5: Boxplots comparing total time to enter the room for each experiment condition.

would not "cut corners" and would take a path that stayed further away from obstacles since they would be more aware of them. Figure 5-6 shows a reduction in the mean path length with the CODA display, and a paired t-test confirmed that there was a significant difference between the means of the two conditions, $t(6)=-2.272$, $p=0.048$. There was not a significant learning effect between the two trials.

5.3 Analysis of Control Strategy Metrics

5.3.1 Nudge Control Count

For the eight participants who completed the full mission within the allotted time, the number of nudge controls required to complete the mission were compared for the two experiment conditions. The initial hypothesis was that the CODA display would decrease the number of control inputs required to complete the tasks by allowing operators to navigate more efficiently.

Figure 5-7 shows the distribution of nudge control counts for the control condition and
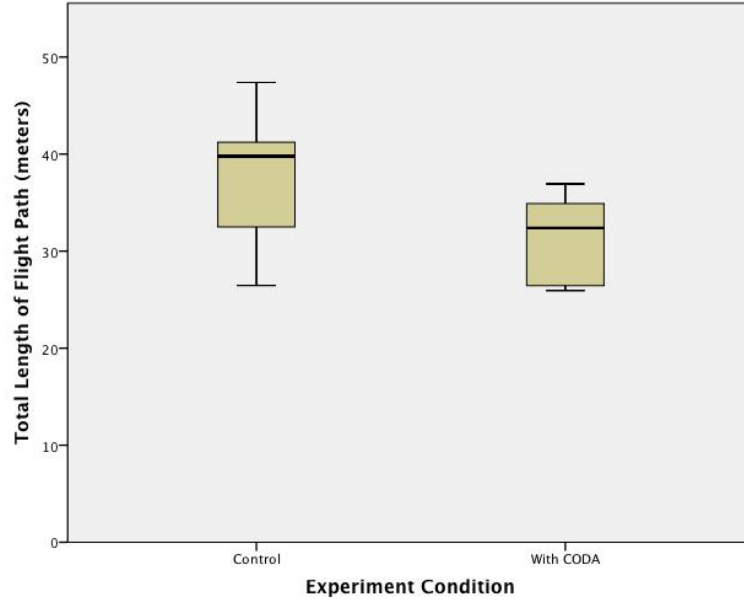
Figure 5-6: Boxplots comparing total path length for each experiment condition.
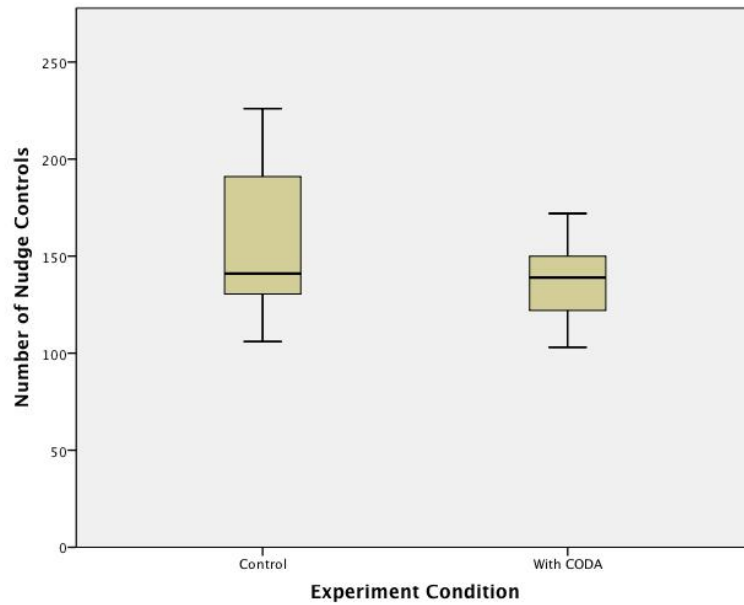
Figure 5-7: Boxplots comparing nudge control count for each experiment condition.

the condition with the CODA display. A paired t-test shows the difference between the cases is not statistically significant. However, there was a marginally significant learning effect present, as indicated by a paired t-test between the trials, t(6)=2.243, p=0.066. Figure 5-8 illustrates the comparison of number of controls for each trial number.
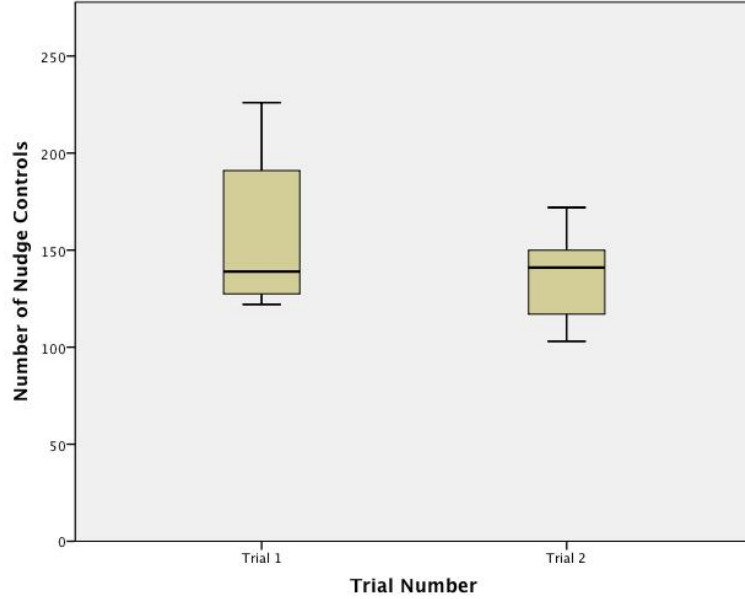
Figure 5-8: Boxplots comparing nudge control count for trial 1 and trial 2.

5.3.2 Nudge Control Magnitude

In previous work [8, 9], correlations existed between mean and standard deviation of nudge control commands and performance metrics, which led to the conclusion that smaller, more consistent inputs correlated with higher task performance. In this study, the hypothesis was that this correlation would still exist, and additionally, that the addition of the CODA display might cause a notable difference in control strategy. For this experiment, the presence of the CODA display did not significantly affect the magnitude of the nudge controls (t(11)=.726, p=0.483) but there was a marginally significant effect on the standard deviation of nudge control inputs (t(11)=2.070, p=0.07).

One major difference between this and previous studies with the MAV-VUE system [8, 9] which might help to explain this result is the role of nudge control in the experimental task. In previous work, the nudge control was used to do fine-level control in the area of interest, whereas in this study, the nudge control was used both for navigating through the environment and also for fine level control to pass through the doorway and observe the visual target. Additionally, the simulation environment was much more controlled than the previous work with real vehicles. Although the simulation was set up to drift around the controlled position, the amount of drift was within a 0.25 meter radius of the commanded location, which was still far less than the one to two meters seen in the outdoor environment. This meant that participants did not have to compensate for as much unintentional motion of the vehicle.

In addition to comparing the control strategy between experimental conditions, further analysis explored correlations between the nudge control inputs and the performance metrics. The correlation analysis was completed for participants who completed the full mission in both experiment conditions. Correlations were performed on a per-participant basis, using the individual participant's mean and standard deviation. Full correlation results are found in Table 5.4. Significant correlations (indicated by the shaded cells) existed between mean nudge control magnitude and number of crashes. This results is similar to the results found in previous work [9], where control magnitudes correlated to higher performance in terms of number of controls required to complete the task.

5.4 Spatial Abilities

In previous work, performance on the spatial orientation tests related to performance in the flight task [8]. In this experiment, the hypothesis was that similar relations would exist in both experimental conditions.

An independent-sample T Test was used to compare the spatial test scores for the participants who completed both tasks within the allotted time and those who did

Table 5.4: Correlations between Nudge Control Mean and St. Dev.
and Performance Metrics

Control Condition		Nudge Mean	Nudge SD	N
Number of Crashes	Spearman ρ	-.828	-.432	12
	Sig. (2-tailed)	.001	.161	
Mission Completion Time	Spearman ρ	-.536	-.321	7
	Sig. (2-tailed)	.215	.482	
Time to Enter Door	Spearman ρ	-.607	-.071	7
	Sig. (2-tailed)	.102	.911	
With CODA Display				
Number of Crashes	Spearman ρ	-.615	.184	12
	Sig. (2-tailed)	.033	.568	
Mission Completion Time	Spearman ρ	-.536	-.536	7
	Sig. (2-tailed)	.215	.215	
Time to Enter Door	Spearman ρ	-.036	-.250	7
	Sig. (2-tailed)	.939	.589	

not. No significant difference existed between these two groups (see Appendix F).

In addition, analysis was performed to examine correlations between the spatial test scores and the performance metrics. Table 5.5 shows the correlations of interest, with the shaded cells representing significant correlations. The only significant correlations are positive correlations between PTSOT score and number of crashes for both experimental conditions. The correlation of performance with PTSOT score matches the results found in previous research [9] that show that PTSOT scores can be a predictor of performance.

5.5 Subjective Measures

At the completion of each run, each participant completed a survey consisting of Likert-scale questions for multiple categories relating to usability and preferences (see Appendix C). Categories consisted of user confidence, perceived difficulty of the task, awareness of obstacle proximity, perceived performance, frustration, time pressure, and understanding of the interface.

Table 5.5: Correlations between Performance Metrics and Spatial Abilities

Control Condition		MRT	PTSOT	N
Mission Completion Time	Pearson Correlation	.523	.541	7
	Sig. (2-tailed)	.229	.210	
Total Path Length	Pearson Correlation	.378	.523	7
	Sig. (2-tailed)	.403	.229	
Number of Nudge Controls	Pearson Correlation	.717	.643	7
	Sig. (2-tailed)	.070	.119	
Number of Crashes	Pearson Correlation	-.072	.571	12
	Sig. (2-tailed)	.825	.052	
With CODA Display				
Mission Completion Time	Pearson Correlation	.162	.234	7
	Sig. (2-tailed)	.728	.613	
Total Path Length	Pearson Correlation	.234	.595	7
	Sig. (2-tailed)	.613	.159	
Number of Nudge Controls	Pearson Correlation	.344	.618	7
	Sig. (2-tailed)	.451	.139	
Number of Crashes	Pearson Correlation	-.490	.798	12
	Sig. (2-tailed)	.106	.002	

Analysis was performed to determine whether any of these factors were significantly affected by the introduction of the CODA display. Because the data comes from Likert-scale questions, a Wilcoxon Signed-rank test was used to assess differences between the response to each question for each experimental condition. The only significant effects occurred in the questions relating to proximity awareness. The Wilcoxon Signed-rank test showed a significant increase in awareness when the CODA display was present both while entering the room (Z=-2.126, p=0.033) and a marginally significant increase when locating the target (Z=-1.725, p=0.084). There was also a marginally significant increase in awareness while traveling down the straight hallway (Z=-1.667, p=0.096). For full results, see Table G.2 in Appendix G.

The post-experiment interviews revealed that participants felt confident using the system to complete the mission. Nine of twelve said they felt they were able to effectively control the MAV, and all but one said that they felt they would be able to use the system in an unknown environment (without a provided map). All but

one participant said they preferred the condition with the CODA display, if given a choice. Three participants commented on the shape of the alert, remarking that that the triangle portion of the indicator made sense, but that the "arms" got in the way as they took up too much space and made the indicator feel less precise. One participant suggested that the indicators be shaped such that there is an outline that "fills up", to establish a baseline and make the relative levels clearer.

Participants had a mixed reaction to the vibration feedback. The majority appreciated having the extra vibration alert, although there were some criticisms. The most common criticism was that after the initial alert, there was not enough information to determine how to act next. One participant suggested having the intensity or frequency increase as the alert level increased, which had been considered in the initial alerting design, but was a limitation of the mobile device used in this experiment. A few participants stated that the alert was startling, and from observations, most participants seemed startled on the first occurrence of the vibration in the practice session. Most participants reacted to the to the alert by stopping before considering the next action and then moving on. However, participants would typically tend to ignore the vibration alert at certain points in the course once they were used to it, mainly while passing through the door where the alert would be triggered regardless of the path.

During the debriefing interview, participants were asked which parts of the course they found the CODA display most and least helpful, and the results are shown in Table 5.6. Note that column sums are not equal because some participants chose multiple options or did not provide an answer.

Table 5.6: List of Areas where participants found the CODA display
to be Helpful or Not Helpful.

Helpful	# of Participants	Not Helpful	# of Participants
Doorway	11	Straight Hallway	6
Corner	8	Doorway	3
In Room	1	In room	2

Participants primarily relied on the alerting interface in two areas of the course. First, participants found the CODA display useful when turning a corner. The camera had only a 60-degree field-of-view, so participants cannot see directly to the side of the vehicle. Without the CODA display, participants would often turn too soon and have to maneuver sideways before going down the next hallway. Second, they used it when entering the room to help them center on the opening before attempting to pass through the door. These areas match with the areas shown in Figure 5-2 where most crashes occurred.

However, participants did not like the CODA display in cases where it provided too much information or when information was deemed unnecessary. Three participants did not like the CODA display when entering the doorway. Because of the small opening, the alert remained at the highest level and did not provide useful information, so the participants just had to "ignore it and go for it". Six participants said it was not useful on the straight hallway, claiming that information was not necessary. Two said that the CODA display was least helpful in the room, when there were clearly walls on all sides.

The majority of the participants (9 of 12) remarked that lag was a problem. The simulator was designed to have lag that mimicked the lags seen in outdoor testing (see Section 3.5.3), although the lag in the simulation environment was typically more consistent. The framerate was set at 7 frames per second. This is lower than in previous studies [8, 9], but the noise from signal interference that occurred in the outdoor studies was not present. Although participants found the lag to be an annoyance, the task performance indicates that most were able to overcome or adjust to the lag.

5.6   Summary

This chapter discusses the results of a usability experiment involving MAV control in a simulated environment. The purpose of the experiment was to evaluate the effect

of the CODA display on an operator's ability to perform a surveillance task.

Overall, the CODA display resulted in higher performance in some of the quantitative metrics explored. Fewer crashes and shorter completion times were observed when the display was present. For one of the sub-task time metrics, the time required to enter the room, the CODA display did not provide a notable average improvement but its presence helped reduce variability across all participants. More importantly, the CODA display did not cause any decreases in performance, indicating that more information can successfully be integrated into the small display area. In addition, participants tended to prefer having the additional information that the CODA display provided and felt it was overall helpful as they completed the course.

Subjective feedback after the experiment revealed that participants understood the interface well. With only three minutes of training, the added CODA display did not significantly impact the usability of the system, despite CODA taking up more of the limited visual space. Correlations were observed between the spatial ability test scores (PTSOT) and task performance (specifically, number of crashes), which matches earlier conclusions that such tests could be used to predict performance and guide training. From these results, there are areas of the display that can be improved, based on participant feedback. For example, further investigation should examine how to set the alerting thresholds and explore whether they should be dynamic in order to provide more useful information in all parts of the course. These results demonstrate that the CODA display provides the basis for an effective alerting tool to assist with MAV operation in unknown environments.

Chapter 6

Conclusions and Future Work

Despite the increased prevalence of UAV and MAV systems in a range of domains, most existing systems are difficult to use and require extensive operator training. They also do not provide any collision avoidance capabilities, relying on operator skill to avoid accidents. In order for MAV systems to safely and robustly operate in the anticipated range of environments, from battlefields to police monitoring to disaster response, they must be able to operate in environments with unknown layouts or unexpected obstacles. This research was motivated by the need to develop systems that can give operators useful information about obstacles in the environment and warn of potential collisions, without substantially increasing the required training or mental workload.

6.1   Research Objectives

This thesis addressed two research objectives:

- Objective 1: Design an alerting interface to assist an operator in preventing collisions in unknown environments.

- Objective 2: Evaluate the effectiveness of the interface in improving operator

performance during navigation and visual search tasks.

The Collision and Obstacle Detection and Avoidance (CODA) display was developed to accomplish the first objective. Chapter 3 described the design process and the choices that resulted in the final display. To fulfill the second objective, an experiment was conducted to assess the usability and effectiveness of the CODA display when integrated with an smartphone-based MAV control system. For the experiment, subjects completed visual search and navigation tasks in a simulation environment, as described in Chapter 4.

The addition of the CODA display resulted in improved mission performance. Additionally, subjects felt that the information provided by the interface was beneficial to their task. The performance improvements and subjective feedback demonstrate that the CODA display was able to successfully integrate additional information into the display to benefit the operator without decreasing usability.

6.2 Future Work

Although the CODA display provided an effective alerting tool for this experiment, further study is required before this interface can be reliably fielded in a realistic environment. The following is a list of areas that could benefit from further investigation or development:

- The CODA display focused on how to display obstacle information from a two-dimensional sensor. Future work could explore how to incorporate three-dimensional information about the environment. This also should include altitude information, to detect height above ground as well as clearance to overhead obstacles.

- This design focused on improving the *nudge control* mode of the MAV-VUE interface, and further work should explore how obstacle information would be best integrated into a map-based mode like the *waypoint control* interface.

- As discussed in Chapter 3, the vibration capabilities of the chosen mobile device limited the possible design space for haptic alerting. For example, newer platforms (such as iOS 5) have the ability to assign custom vibrations.

- The alerting thresholds, described in Chapter 3, are based solely on distance from an object. Variations could be explored where the thresholds are dynamic and also incorporate information about the current velocity.

- As discussed in Chapter 5, the presence of the CODA display normalized operator performance on some of the metrics. Further studies should continue to explore how such an interface can be used to 'level the playing field' and allow for more consistent performance between operators.

- Although functionality in an outdoor environment was shown to be feasible, the experiment was completed in simulation, so usability in a real environment should be validated.

- In this study operators could collide with walls. In field use, the system would likely include built-in autonomous collision avoidance capabilities to further assist the operator. Thus, the effects of integration with collision avoidance algorithms should be explored.

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Appendix A

Pre-Experiment Demographic Survey

Subjects completed the following survey at the beginning of the experiment.

MAV-VUE Simulation Study Pre-experiment Survey

Subject ID:_____

Age:_____

Gender: M   F

Occupation:_____

if student, (circle one):   Undergrad   Masters   PhD
year of graduation:_____

Military experience (circle one):   No   Yes
If yes, which branch:_____Years of service:_____

Give an overall rating of your past two nights of sleep. (circle one)
Poor   Fair   Good   Great

How much experience do you have with video games? (circle one)
Never play games   Play games once a month   Weekly gamer   Frequent gamer   Extreme gamer

Types of games played:

How much experience do you have with RC helicopters/airplanes or unmanned vehicles? (circle one)
Never Used   Previously Used   Used Monthly   Used Weekly

Have you used an iPhone, iPod Touch, iPad or other touch-based device before? (circle one): Yes   No
If Yes, what is your comfort level with using one? (1 is little, 5 is most comfortable)

1   2   3   4   5

Are you far-sighted/unable to see read text as it moves closer to you? (circle one)   Yes   No
If Yes, are you currently wearing corrective contacts or glasses? (circle one)   Yes   No

Are you red/green color blind? (circle one)   Yes   No

What applications do you think are appropriate for Unmanned Aerial Vehicles (UAVs)?

Appendix B

CODA Display Descriptive Diagram

Description of Obstacle Alerting Interface

3 Alert Levels corresponding to the relative distance to the obstacle:

When you enter the highest alert level, the iPhone will also vibrate.

Farther away ←——————————→ closer

Location on the circle corresponds to direction to the obstacle relative to the current field of view

Obstacle is in front and to the left   Obstacle is to the right

Notes:

- The obstacle sensor only has a range of 270 degrees
  (It won't sense obstacles directly behind the vehicle.)

- The vibration is part of the alerting system, It is NOT an indication that you've hit an obstacle.

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Appendix C

Post-Experiment Survey

Subjects completed the following survey after completing the flight tasks for each experiment condition.

MAV-VUE Simulation Study Survey

Subject ID: _____   Trial Number: _____

For each question, check one box per row.

1) How confident were you while navigating the MAV?

	No Confidence	Minimal Confidence	Somewhat Confident	Mostly Confident	Absolutely Confident
Overall					
In a straight line					
Around corners					
Through a narrow doorway					

2) How difficult was it to navigate the MAV?

	Not hard at all	Slightly hard	Somewhat hard	Fairly hard	Very hard
Overall					
In a straight line					
Around corners					
Through a narrow doorway					

3) Do you feel like you were aware of your proximity to obstacles in the environment?

	Not aware	Slightly aware	Somewhat aware	Mostly aware	Absolutely aware
Overall					
In the straight hallway					
While turning corners					
While approaching the doorway					
While entering the room					
While locating the sign in the room					

4) How well did you feel you performed on the following aspects of the task? (check only one box per row)

	Very poor	Poor	Satisfactory	Good	Excellent
Controlling the MAV using nudge controls					
Avoiding walls and obstacles					
Locating and reading the sign					

5) Frustration

	Not at all	Minimally frustrated	Somewhat frustrated	Moderately frustrated	Very Frustrated
How frustrated were you during the task?					

6) Time

	Not at all	Only a little	Neutral	Moderately rushed	Very rushed
During the task did you feel rushed or like you wouldn't be able to finish in time?					

7) Please indicate how well you understood each of the following parts of the application:

	Poorly Understood	Somewhat Understood	Well Understood	Did Not Use
Moving the helicopter				
Rotating the helicopter				
Changing Altitude				

Appendix D

Post-Experiment Interview Questions

1. Were you able to effectively control the simulated MAV with the device? Explain.

2. Did the MAV do anything you did not expect it to do?

3. Do you have any comments about the alerting interface?

4. Do you think the alerting interface was helpful? Confusing?

5. During which part of the course, if any, was the alerting interface most helpful?

6. During which part of the course, if any, was the alerting interface least helpful, most distracting, or most confusing?

7. Do you feel that you could use the interface to have the MAV explore an unknown environment? (i.e. if we didn't give you a map)

8. Overall Feedback? Any other comments or suggestions?

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Appendix E

Subject Demographic Information

Table E.1: Subject Demographic Information based on Pre-Experiment Survey

Category	N	Minimum	Maximum	Mean	Median	Std. Dev.
Age	12	18	23	18.83	19.00	1.47
Amount of Sleep	12	1	4	2.58	2.50	1.00
Video Game Experience	12	1	3	1.92	2.00	0.79
Remote Control Experience	12	1	2	1.42	1.00	0.52
iPhone Experience	12	1	5	3.92	4.00	1.31

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Appendix F

Experiment Metrics

F.1 Descriptive Statistics

Table F.1: Descriptive Statistics for Performance Metrics

Metric	Condition	N	Mean	Median	Std. Dev.
Completion Time	Without	7	312.00	297.13	109.16
	With	7	240.76	228.27	71.53
Path Length	Without	7	37.30	39.78	7.20
	With	7	31.14	32.38	4.76
Time to	Without	7	69.81	54.32	30.93
Pass Through Door	With	7	66.08	62.76	19.93
Time to	Without	7	139.17	70.55	106.62
Enter Room	With	7	69.19	78.87	21.00
Nudge Control Count	Without	7	159.43	141.00	45.23
	With	7	136.86	139.00	23.26
Number of Crashes	Without	12	2.83	2.5	2.41
	With	12	1.67	1.0	2.02

Table F.2: Spatial Reasoning Test Scores

Spatial Test	N	Minimum	Maximum	Mean	Median	Std. Dev.
MRT	12	1.0	18.0	11.92	13.5	5.37
PTSOT	12	9.8	49.6	18.90	15.7	10.81

F.2 Correlations between Subject Demographics and Performance

Table F.3: Comparison of Subject Demographics based on Task Completion

	t	df	Significance
Age	0.06	10	0.95
Remote Control Experience	0.09	10	0.93
Video Game Experience	2.22	10	0.05
iPhone Experience	-0.18	10	0.86
PTSOT Score	-0.96	10	0.36
MRT Score	1.44	10	0.18

Appendix G

Post-Experiment Survey Summary

Table G.1: Descriptive Statistics of Post-Experiment Survey Results

Question	Condition	N	Minimum	Maximum	Mean	Median	Std. Deviation
1a	Without	12	2	4	3.17	3.0	0.84
	With	12	2	5	3.25	3.0	1.14
1b	Without	12	3	5	4.00	4.0	0.74
	With	12	3	5	3.92	4.0	0.67
1c	Without	12	1	4	3.08	4.0	1.08
	With	12	1	5	2.92	3.0	1.08
1d	Without	11	1	4	2.36	2.5	0.92
	With	12	1	5	2.17	2.0	1.19
2a	Without	12	1	4	2.92	3.0	1.08
	With	12	2	4	3.00	3.0	0.95
2b	Without	12	1	3	1.50	1.0	0.80
	With	12	1	3	1.42	1.0	0.67
2c	Without	12	1	5	3.00	3.0	1.28
	With	12	1	5	3.00	3.0	1.21
2d	Without	11	3	5	3.91	4.0	0.83
	With	12	2	5	4.08	5.0	1.17
3a	Without	12	2	5	3.50	4.0	0.91
	With	12	2	5	2.92	2.0	1.08
3b	Without	12	3	5	4.33	4.0	0.65
	With	12	3	5	4.08	4.0	0.79
3c	Without	12	1	5	3.33	3.0	1.23
	With	12	1	5	2.92	3.0	1.17
3d	Without	11	1	5	3.00	3.0	1.18
	With	12	1	5	2.50	2.0	1.38
3e	Without	11	1	5	2.82	2.5	1.33
	With	12	1	4	2.17	2.0	1.19
3f	Without	11	2	5	3.55	3.5	1.44
	With	11	1	5	2.64	2.5	1.21
4a	Without	12	1	5	3.00	3.0	1.04
	With	12	1	5	2.92	3.0	1.38
4b	Without	12	1	5	2.58	2.0	1.24
	With	12	1	4	2.33	2.0	1.16
4c	Without	12	1	5	3.00	3.0	1.28
	With	12	1	5	3.08	3.0	1.31
5	Without	12	1	4	2.42	2.0	0.79
	With	12	1	4	2.58	2.0	1.17
6	Without	12	1	5	2.08	2.0	1.31
	With	12	1	5	2.42	2.0	1.38
7a	Without	12	2	3	2.92	3.0	0.29
	With	12	2	3	2.92	3.0	0.29
7b	Without	12	1	3	2.83	3.0	0.58
	With	12	2	3	2.92	3.0	0.29
7c	Without	12	1	4	3.00	3.0	0.74
	With	12	2	4	3.17	3.0	0.58

Table G.2: Pairwise Comparisons (Wilcoxon Signed-Rank Test) of Post-Experiment Survey Results

Question	Z	Asymp. Sig. (2-tailed)
1a	-0.35	0.73
1b	-0.45	0.66
1c	-0.51	0.61
1d	-0.19	0.85
2a	-0.58	0.56
2b	-0.38	0.71
2c	0.00	1.00
2d	-0.63	0.53
3a	-1.28	0.20
3b	-1.34	0.18
3c	-1.22	0.22
3d	-1.41	0.16
3e	-2.13	0.03
3f	-1.73	0.08
4a	-0.28	0.78
4b	-0.91	0.37
4c	-0.38	0.71
5	-1.00	0.32
6	-1.23	0.22
7a	0.00	1.00
7b	-1.00	0.32
7c	-1.41	0.16

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