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The Effects of Remotely Piloted Aircraft Command and Control Latency during Within-Visual-Range Air-To-Air Combat

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THE EFFECTS OF REMOTELY PILOTED AIRCRAFT COMMAND AND CONTROL LATENCY DURING WITHIN-VISUAL-RANGE AIR-TO-AIR COMBAT

By

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ABSTRACT

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The type of military missions conducted by remotely piloted aircraft continues to expand into all facets of operations including air-to-air combat. While future within-visual-range air-to-air combat will be piloted by artificial intelligence, remotely piloted aircraft will likely first see combat. The purpose of this study was to quantify the effect of latency on one-versus-one, within-visual-range air-to-air combat success during both high-speed and low-speed engagements. The research employed a repeated-measures experimental design to test the various hypothesis associated with command and control latency. Participants experienced in air-to-air combat were subjected to various latency inputs during one-versus-one simulated combat using a virtual-reality simulator and scored on the combat success of each engagement. This research was pursued in coordination with the Air Force Research Laboratory and the United States Air Force Warfare Center.

The dependent variable, combat score, was derived through post-simulation analysis and scored for each engagement. The independent variables included the input control latency (time) and the starting velocity of the engagement (high-speed and low-speed). The input latency included six different delays (0.0, 0.25, 0.50, 0.75, 1.0, and 1.25 seconds) between pilot input and simulator response. Each latency was repeated for a high-speed and low-speed engagement. A two-way repeated-measures analysis of variance was used to determine whether there was a statistically significant difference in means between the various treatments on combat success and determine if there was an interaction between latency and fight speed.

The results indicated that there was a statistically significant difference between combat success at the various latency levels and engagement velocity. There was a significant interaction effect between latency and engagement speed, indicating that the outcome was dependent on both variables. As the latency increased, a significant decrease in combat success occurred, decreasing from .539 with no latency, to .133 at 1.250 seconds of latency during high-speed combat. During low-speed combat, the combat success decreased from .659 with no latency, to .189 at 1.250 seconds of latency. The largest incremental decrease occurred between 1.00 and 1.25 seconds of latency for high-speed and between 0.75 and 1.00 at low-speed. The overall decrease in combat success during a high-speed engagement was less than during the low-speed engagements.

The results of this study quantified the decrease in combat success during within-visual range air-to-air combat and concluded that, when latency is encountered, a high-speed (two-circle) engagement is desired to minimize adverse latency effects. The research informs aircraft and communication designers of the decrease in expected combat success caused by latency. This simulation configuration can be utilized for future research leading to methods and tactics to decrease the effects of latency.

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CHAPTER I

INTRODUCTION

Since the advent of the fighter plane in WW-I, every western trained fighter pilot has learned the three axioms of air-to-air combat, *lose sight lose fight, maneuver in relation to the bandit, and energy versus nose position* (Boelcke, 1916; United States Navy [USN], 2016). These three central themes permeate visual air-to-air combat tactics and describe the importance of analyzing the adversary's current position and state, executing offensive and defensive maneuvers based on the bandit's plane of motion, and making continuous decisions about conserving or exploiting energy (United States Air Force [USAF], 2005). The common thread in these concepts is time. Losing sight of the bandit momentarily, maneuvering too early or late, or depleting energy at the wrong time all spell defeat in the dogfight (USN, 2016). Boyd (1977) codified these ideas in his Observe-Orient-Decide-Act (OODA) Loop Theory and described the desire to complete the loop faster than the adversary.

The military use of remotely piloted aircraft (RPA) continues to increase into principal facets of military aviation. The MQ-1 Predator and MQ-9 Reaper have proven the utility of unmanned aircraft systems (UAS) in combat and have amassed millions of flight hours (USAF, 2015a; USAF, 2015b). Since the first introduction of the MQ-1 to the Bosnian theater of operation in 1995, the main mission of the medium-altitude, long-endurance (MALE) RPAs is intelligence collection and ground attack (Trsek, 2007). In the Department of Defense (DoD) mission taxonomy, this includes Intelligence, Surveillance, and Reconnaissance (ISR), and Close Air Support (CAS; Department of Defense, 2014). Despite not being designed or tasked for air-to-air combat, U.S. RPAs have engaged in air-to-air combat, albeit on a very limited scale (Gertler, 2012). An inherent drawback of RPA is the latency of command and control (C2) transmissions (Trsek, 2007). While latency influences all teleoperations, the extent of the effect during within-visual-range (WVR) air-to-air combat has not been explored. In preparation for the use of RPAs and artificial intelligence (AI) in WVR combat, the effects of latency or missing sensor data during a dogfight must be understood.

Background Information

The military services are pursuing the follow-on to the F-35 Joint Strike Fighter and soliciting industry to examine the capabilities of the Next Generation Tactical Aircraft. The USAF request for information (RFI) to the aerospace industry specifies an aircraft to be fielded in 2030 with key technologies including unmanned and optionally manned capabilities (Purdy, 2012). The USAF stated that this aircraft, considered the 6th Generation Fighter, will be tasked with offensive and defensive counter-air missions (Purdy, 2012). Other countries are pursuing advanced UAS as well, presumably capable of air-to-air missions, as is evident with the Chinese experimental RPA named the Dark Sword (Bier & Madden, 2018; Mayer, 2015).

Air-to-air combat typically requires a fighter aircraft that is highly maneuverable, capable of transonic velocities, and able to sustain high acceleration loads (Mayer, 2015; Trsek, 2007). These attributes are especially important during WVR combat where two aircraft are entangled in a rapidly changing, highly dynamic fight, with each attempting to gain an advantage and employ ordnance (Shaw, 1985; USAF 2005). While there are reports of short skirmishes between U.S. RPAs and manned enemy fighters, U.S. RPAs were not suited for such an engagement and ultimately defeated (Gertler, 2012). Current MALE UAS do not possess the attributes required to succeed in this dynamic air combat environment (Gertler, 2012; Mayer 2015). However, advances in UAS technology will inevitably yield an aircraft suited for WVR combat (Mayer, 2015; Shin, Lee, Kim, & Shim, 2018; USAF, 2009). As these fighter-unmanned combat aerial vehicles (F-UCAV) become operational, the opportunity for a WVR engagement increases. The first of these engagements will likely be between an F-UCAV and a manned fighter aircraft in an area of responsibility (AOR) far from the ground control station (GCS). Trsek (2007) identified command and control delay as a major hurdle in F-UCAV air-to-air combat and concluded that "…it is presumptuous to assume that short-range engagements are a thing of the past" (p. 26).

Several UAS control architectures are in service, including: human-in-the-loop (e.g., MQ-9, MQ-1), human on-the-loop (e.g., RQ-4), and autonomous (Rorie & Fern, 2016). *Human-in-the-loop* refers to control systems that require direct human input (e.g., manipulating the throttle and stick), *human-on-the-loop* describes when the human performs a supervisory role, and *autonomous* when the unmanned system is given tasks to fulfill without human involvement. While autonomous combat vehicles are promising as the Defense Advanced Research Projects Agency (DARPA) simulation trials have showcased, both technological and ethical considerations will influence their use. Analysts believe the use of deadly force must come from human authority and not be delegated to an autonomous unmanned system (Purves, Jenkins, & Strawser, 2015). For these reasons, the first widely-produced air-to-air capable unmanned aircraft will likely be flown through teleoperation similar to current RPAs with a human-in-the-loop architecture.

The majority of combat missions employing MALE UAS occur thousands of miles from the GCS using terrestrial and satellite communications architecture (Zhang, Fricke, & Holzapfel, 2016). During these beyond-line-of-sight (BLOS) operations, the C2 signal from the GCS must travel through terrestrial networks, be uplinked to a satellite constellation, and then downlinked to the UAS, as illustrated in Figure 2. Telemetry data and sensor information travel the same path in reverse before reaching the pilot in the GCS. This communication pathway injects latency between the adversary's true position and what is displayed to the pilot. This same latency occurs between the pilot's input and the aircraft receiving the command. Typically, in BLOS operations, the one-way latency can be as low as 0.25 seconds and as high as 1.0 seconds (de Vries, 2005; B. Opp, personal communication, May 15, 2018). During completely autonomous AI operations, delayed, inaccurate, and jammed sensors will influence the fight similar to C2 latency. Boyd (1977) described the effect(s) of latency during the decision making process during air-to-air combat.

Theoretical Construct

Lynham (2002) described a theoretical construct as an "…informed conceptual framework that provides an initial understanding and explanation for the nature and dynamics of the issue, problem, or phenomenon that is the focus of the theory" (p. 231). Boyd (1977) developed the OODA Loop theoretical construct through analysis of air-to-air combat and conceived that victory could be achieved by operating at a faster decision-making tempo than the opponent. Boyd (1977) theorized that the goal should be to "…get inside adversary's Observation-Orientation-Decision-Action time cycle or loop" (p. 5). By accomplishing this, the pilot would be able to "Simultaneously compress own time and stretch-out adversary time to generate a favorable mismatch in time/ability…" (Boyd, 1977, p. 7). The temporal fight that Boyd describes underscores the need to minimize decision time and latency. Boyd (1977) emphasized that this could be accomplished in many ways, including: better awareness of the situation, faster decisions and actions, and superior aircraft performance. His theory led to arguably the most successful modern-day fighter aircraft (A-10, F-15, F-16, and F-18) and the rapid defeat of Iraq in the Gulf War (Pearson, 2017). The OODA Loop has been widely applied in military combat, sports, and business. Injecting a delay before observation, limiting sensory input for orientation, making decisions based on stale data, and initiating actions that do not immediately occur are all symptoms of C2 latency and studied in this research.

Chen, Haas, and Barnes (2007) described two performance issues in teleoperations: remote perception (observation) and remote manipulation (action). While these two sources of latency are described and inferred in several studies, they are commonly combined into a total latency neglecting the individual effects of perception and manipulation latencies and their possible interaction. Luck, McDermott, Allender, and Russell (2006) authored one of the few studies that included the two directions of latency as an independent variable. However, they did not find statistical significance to support their hypothesis that control would be better when the latency was injected between the operator and robot versus between the robot and operator (Luck et al., 2006).

The latency can be applied to Boyd's (1977) OODA Loop as delays in observing, difficulty orienting, latent decisions, and delaying the act phase. The delay between the transmitted video/telemetry of the RPA and its reaching the pilot corresponds to the Observe phase and the delay between the RPA pilot making a flight control input and the RPA receiving the command corresponds to the Act phase (remote manipulation) in the OODA Loop. The sum of these two latencies is the total feedback loop latency induced by command and control transmission. However, the effect of transmission latency while maneuvering against a changing target location adds another level of complexity.

The rapidly changing adversary position relative to the attacking aircraft adds uncertainty to the original target location, which may increase the effect of latency. For example, in a static environment, the total latency can be seen as the sum of the transmission latency (t) in each direction. If the delay is the same in each direction, the total latency is 2t. While this total latency can be interpreted as the total time between control manipulation and feedback (i.e., the feedback loop), it does not take into account the changing position of the adversary. As seen in Figure 1, if the position of the target is rapidly changing, the total time between the true position of the target

(Adversary True Position A) and when the pilot receives his/her reaction feedback (Aircraft Response Displayed in GCS) must be taken into account. In other words, while maneuvering in a static or slow-moving environment, the feedback loop remains congruent with the target location. If the target aircraft is rapidly maneuvering in an unpredictable manner, the feedback loop is no longer congruent with the target. In a static environment, the Adversary True Position A and the Adversary Position A Displayed in the GCS are the same; in a dynamic environment, they are vastly different since both the adversary and own position are changing rapidly. The time between when the adversary is at position A and when the pilot receives feedback to his/her control input to counter the adversary becomes 3t plus other inherent delays. As a result of the dynamic environment, the perceived total delay becomes two times the observational latency plus the action latency (3t). During WVR combat, closure rates often exceed 500 meters per second (m/s) while angular rates in excess of 190 degrees per second are commonly observed, further exacerbating the effect(s) of latency.

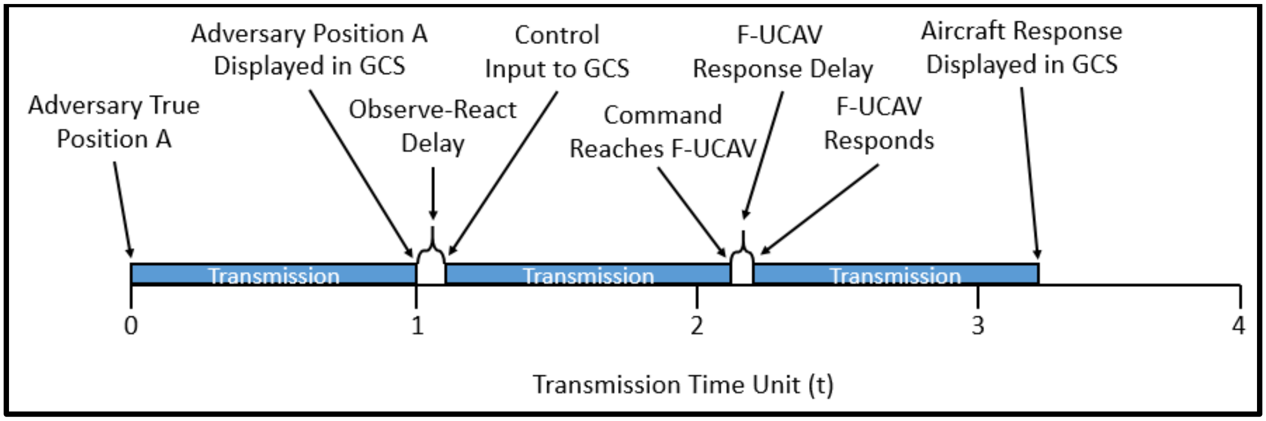


Figure 1. Command and Control timeline with dynamic, unpredictable target movement. The observe-react delay is assumed constant per individual pilot, and the F-UCAV response delay is assumed constant per aircraft type.

The review of relevant literature reveals a distinct gap: the effect of latency during highly dynamic maneuvering while both the vehicle and objective are rapidly changing parameters. This literature gap aligns with Boyd's (1977) OODA Loop Theory and forms the theoretical construct of this study and defines the independent variables. The results of this research add another dimension to the OODA Loop Theory by quantifying the effect of control-loop latency on air-to-air combat.

Statement of the Problem

With the combat use of UAS increasing in all facets of warfare, future UAS operations will include air-to-air combat whether piloted by a human or AI (Bier & Madden, 2018; Gertler, 2012; Mayer, 2015). In a letter of support for this study, Major General Gersten, Commander of the USAF Warfare Center (2018; see *Appendix A*) wrote,

> Encounters between remotely piloted aircraft and manned aircraft are becoming more common, but the level of combat degradation from transmission latency is not known. Quantifying the degradation in combat effectiveness will lay the foundation for mitigation strategies, tactics, and hardware/software design. (para. 1)

Future air-to-air combat will take place between unmanned systems as well as between F-UCAVs and manned fighters. During WVR maneuvering, each aircraft is maneuvering in relation to the other aircraft in four-dimensional space, and latency could be a substantial disadvantage. Future aerial combat needs to prepare for a multitude of platforms that are manned, remotely piloted, and autonomous. The problem is that the decrease in combat effectiveness due to latency effects during WVR combat is unknown yet critical for success in future air combat. Also unknown is whether these effects are the same for WVR combat entered at high-speed and low-speed which is essential in formulating strategies to counter the negative effects of latency in future combat.

Purpose Statement

The purpose of this study was to quantify the effect of latency on one-versus-one, within-visual-range air-to-air combat success during both high-speed and low-speed engagements. The research is foundational for future automated and manual programming decisions in highly dynamic environments when latency is involved. This dissertation quantified the influence of latency to formulate recommendations for the future unmanned aircraft demands, whether remotely piloted or autonomous. Quantifying the varying levels of latency will drive the technical requirements for future design of aircraft, communication, automation, and control architectures to minimize or eliminate the negative effects of latency. Additionally, the OODA Loop Theory gained depth by introducing the effects of unmanned systems latency to the theoretical literature.

Significance of the Study

Gersten (2018; see *Appendix A*) stated, “Research such as this is crucial to understanding the temporal environment that we [U.S. armed forces] face with unmanned systems” (para. 2). While this research investigated the effect of latency on manned aircraft, it is directly applicable to future F-UCAVs. Whether controlled remotely or autonomously, latency or inaccurate sensor data must be considered when developing aircraft, communication architectures, software, weapons, and tactics. Previous research discovered that latency influences the ability to perform precise maneuvers with unmanned aerial systems (Byrnes, 2014). In the case of WVR air-to-air combat, the effects have not been measured or quantified. The relationship between latency and projected combat success will inform hardware and software designers of the desired boundary in which to operate. It will indicate what latency levels are acceptable, when automation is required, and when latency effects must be overcome by other methods. The results add depth and breadth of characterization to Boyd’s OODA Loop (1977) theory in an untested domain. Findings from the study highlight how to increase the probability of combat success during WVR air-to-air combat. Follow-on research will include strategies to minimize the effects of latency.

As the aviation community moves toward more automation and unmanned systems, this dissertation informs designers of potential issues with latency whether from a teleoperation point of view or a fully autonomous system. Understanding these phenomena is germane to future remotely operated and autonomous air-to-air combat. Additionally, this dissertation explores the effects of latency in a highly dynamic environment that could apply to future space, undersea, or ground unmanned systems.

An autonomous system requires accurate sensor input to determine internal and external geometry. In a highly dynamic environment, the sensor data could be corrupted, delayed, spoofed, or inaccurate. These breaks in accurate sensor data are similar to a teleoperation transmission delay. In both cases (human operator or automated), the decision-making information (OODA Loop taxonomy) is delayed or inaccurate, causing the operator (or AI) to act on imperfect data. The results obtained from this dissertation research inform future engineers of the latency effects in applications such as sense and avoid, ground avoidance, and takeoff and landing operations in national and international applications. While this research explores the specific area of WVR air-to-air combat, the implications of the study are widespread in all aspects of aviation and unmanned systems.

Research Questions and Hypotheses

The research questions are focused on the effects of latency while executing the phases of Boyd’s (1977) OODA Loop Theory and comparing the results between high-speed and low-speed engagement entry conditions. The study focused on the control loop latency (input to feedback) in order to isolate the effects. The latency input through IV_1 can be seen as the delay from control manipulation to the aircraft movement plus the return delay.

RQ1: To what extent do different levels of command and control latency affect combat success during one-versus-one, WVR, air-to-air combat?

RQ2: To what extent does initial engagement speed affect combat success during one-versus-one, WVR, air-to-air combat?

RQ3: What is the possible interaction between command and control latency and engagement speed during one-versus-one, WVR, air-to-air combat?

There are three null hypotheses for this study and their accompanying alternatives, based on the statistical significance between the different experimental treatments.

$H_0$1: There is no significant decrease in combat success between fighter pilots experiencing no latency and those experiencing latency during one-versus-one, WVR combat.

$H_1$1: There is a significant decrease in combat success between fighter pilots experiencing no latency and those experiencing latency during one-versus-one, WVR combat.

$H_0$2: There is no significant decrease in combat success based on initial engagement speed during one-versus-one, WVR, air-to-air combat.

$H_1$2: There is a significant difference in combat success based on initial engagement speed, during one-versus-one, WVR, air-to-air combat.

$H_0$3: There is no significant interaction between command and control latency and engagement speed during one-versus-one WVR, air-to-air combat.

$H_1$3: There is a significant interaction between command and control latency and engagement speed during one-versus-one WVR, air-to-air combat.

Delimitations

There are several delimitations for this study, including: weapons employment, weapon capabilities, the simulated aircraft, and limiting the combat to one versus one. Weapons cueing and employment adds complexity to the experiment by introducing several confounding variables that could lead to incorrect conclusions. These variables include, but are not limited to, acceptable launch parameters (e.g., range, range rate, angle, angle rate, airspeed, and acceleration load), weapons seeker performance and errors, defensive countermeasure effects, weapons fuzing capability, and fragmentation patterns. Also, since missile capabilities vary, the weapon load itself could drastically alter the results by allowing several launches during the engagement. To isolate latency, weapons capabilities and employment were removed, although follow-on research could include weapons once the effect of latency is characterized.

The subject population of this dissertation included manned aircraft pilots with qualifications in fighter aircraft. The simulator utilized a generic cockpit setup similar to fighter aircraft. The aerodynamic performance parameters are set to a physics model designed to emulate an F-UCAV, based on performance criteria exceeding the capability of 5th Generation fighters such as the F-15, F-16, and F-18. Specifically, the simulated aircraft is capable of supersonic speed, acceleration loads 11.0 times gravity on the Z-axis (Gz), high thrust-to-weight ratio, digital flight controls, 60-degree maximum angle-of-attack, and an air-to-air radar.

Air-to-air combat is carried out with multiple aircraft working in concert toward a particular objective. This teamwork strives to increase firepower while providing defense in-depth and may result in a WVR engagement with multiple aircraft. In order to isolate the effects of latency on a single fight, only two aircraft were included in the experiment.

Limitations and Assumptions

This dissertation was limited by the use of simulation, a non-FAA certified simulator, unclassified performance data, and combining transmission latencies. The use of simulation allows the control of many confounding variables and precise treatment applications. The experiment could not be conducted during actual flight conditions due to access, cost, safety, and classification. Although the simulation is not officially certified by the FAA, DoD fighter simulators are internally certified by each service in a process that emphasizes the combat and performance realism of fighter combat (Everson, 2014). Subject matter experts (SME) in the weapons systems carry out the internal certification; the same SMEs that participated in the simulation field test. The software used in this experiment was developed by SMEs at the Fighter Collection (http://fighter-collection.com/cft/) and deemed accurate by the SMEs during the field test. The aircraft performance characteristics of this simulation were based on unclassified parameters. Finally, this study was limited by combining the individual delay segments into one total command-feedback delay.

While all phases of the OODA Loop are included in the execution of the simulated engagements, the Orient and Decide phases are assumed to be constant for each individual and the aircraft. There may be small variations between subjects, but due to their extensive training in the WVR arena, variations within subjects are assumed to be minimal. Additionally, the latency between the aircraft receiving a C2 input and reacting is constant since all the subjects used the same simulation system and software. Therefore, the total delay in the OODA Loop execution can be seen as Delay = Observe+Orient+Decide+Act where Observe+Act = IV_1 and Orient+Decide = Constant.

It was assumed that the projection delay from the time the telemetry and video signals arrive at the GCS and are subsequently displayed to the pilot is similar to the inherent delay in the simulation’s VR headset. Feldstein and Ellis (2020) performed tests on various VR systems and concluded that a 0.072 to 0.090 second latency should be expected. Considering that the simulation is operating at approximately 90 frames per second, this delay equates to 6 to 8 frames of video, similar to the delay for a standard computer monitor. Therefore, the VR headset latency is assumed to be equal to a normal flat-screen LCD display, such as used in a GCS.

Finally, each subject was assumed to put forth their best effort to achieve combat success. Given the population for this study was highly trained fighter pilots in the U.S. who routinely perform higher intensity flights and simulation, this assumption is not expected to be an issue.

Summary

The use of UAS is expanding into all military missions, including air-to-air combat. However, little is known about the effect of latency on WVR combat. While substantial research has studied the effect of command and control latency on unmanned ground vehicles (UGVs) and UAS in a static environment, none have explored the effect in highly dynamic environments such as during WVR air-to-air combat. This dissertation explored the latency effect during two different one-versus-one dogfight tactics to determine the effect of various levels of latency and whether there is a difference between fight tactics.

Boyd's (1977) OODA loop is the theoretical framework grounding this study. Of particular interest is the delay during the OODA loop process that is directly affected by latency. This experimental study manipulated latency (IV_1) and engagement entry speed (IV_2) in a simulated environment to determine the projected combat outcome (DV) and whether there is an interaction between the latency level and the velocity at which the fight occurs.

Definitions of Terms

Aspect Angle	The angular separation between the target's tail and the attacker's position.
Control Zone	A geometric area behind another aircraft where the range is 500-1,500 m and aspect angle equal or less than 50 degrees.
Dogfight	An air-to-air flight that occurs in the visual arena. Synonymous with WVR air-to-air combat.
High-Aspect	Aircraft meet heading opposite directions. Aspect angle equal to or greater than 150 degrees.
High-Speed	Engagement starting at 450 KTAS.
Latency	The time between signal transmission and reception.
Lift Vector	The orientation of lift force.
Low-Speed	Engagement starting at 250 KTAS.
Merge	The state of air-to-air combat when the friendly and target aircraft have arrived in the same visual arena, typically within 1 mile.
One-Circle	An air-to-air fight where the aircraft turn in opposite directions after passing the merge.
Two-Circle	An air-to-air flight where the aircraft turn in the same direction after passing the merge.
Velocity Vector	The current vector of the aircraft in direction and velocity.

List of Acronyms

AFRL	Air Force Research Laboratory
AOR	Area of Responsibility
AR	Augmented Reality
BFM	Basic Fighter Maneuvers
BLOS	Beyond Line of Sight
BVR	Beyond Visual Range
C2	Command and Control
CAS	Close Air Support
CS	Combat Score
CZ	Control Zone
DARPA	Defense Advanced Research Projects Agency
DCS	Digital Combat Simulator
DOD	Department of Defense
DV	Dependent Variable
ERAU	Embry-Riddle Aeronautical University
FAA	Federal Aviation Administration
FOV	Field of View
F-UCAV	Fighter-Unmanned Combat Aerial Vehicle
GCS	Ground Control Station
HALE	High Altitude Long Endurance
IAS	Indicated Air Speed
I/O	Input/Output
IRB	Institutional Review Board

ISR	Intelligence, Surveillance, and Reconnaissance
IV	Independent Variable
KIAS	Knots Indicated Air Speed
LOS	Line of Sight
MALE	Medium Altitude Long Endurance
MSL	Mean Sea Level
OODA	Observe-Orient-Decide-Act
PI	Primary Investigator
PIO	Pilot Induced Oscillation
RFI	Request for Information
RPA	Remotely Piloted Aircraft
SME	Subject Matter Expert
TAS	True Air Speed
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
URLLC	Ultra-Reliable Low Latency Communications
USAF	United States Air Force
USN	United States Navy
VR	Virtual Reality
WEZ	Weapons Engagement Zone
WIC	Weapons Instructor Course
WVR	Within Visual Range

CHAPTER II

REVIEW OF THE RELEVANT LITERATURE

The effects of latency on undersea, ground, and aerospace vehicles have been extensively studied. However, a distinct literature gap exists regarding latency effects in highly dynamic environments where precise control and reactions to other rapidly moving vehicles are required. Additionally, previous research has not investigated various tactics for WVR engagements with an RPA. As such, this review of relevant literature seeks to provide an overview of foundational literature and research in the areas of the OODA Loop, teleoperation latency, air-to-air combat, capabilities of current RPAs and their communication architectures, and inform the reader of pertinent research which identifies a specific range of expected latency. While research has shown a decrease in performance as latency increases, the magnitude of degradation has not been studied and generalized to characterize the effects during a dynamic WVR fight.

OODA Loop Theory

Boyd (1977) developed what is known as the OODA Loop theoretical framework through several iterations of tactical and strategic observation, experimentation, and analysis. The OODA Loop evolved over many years beginning with Boyd’s (1964) study on aerial attack. The ideas were refined in Boyd (1976) where he applied the concept of *rapid transients* (quicker decision and action) in a briefing on new air-to-air concepts. The first appearance of the entire OODA Loop came in Boyd (1977), where he described the OODA Loop as a concept for winning in a competitive world. Further refinement occurred with Boyd (1987), where the OODA Loop was discussed in terms of command and control. The OODA Loop has been the focus of many books, military strategies, aircraft designs, and air-to-air tactics. These OODA Loop concepts are foundational to this dissertation because they operationalize the concept of latency on overall performance and give context to the independent and dependent variables.

Latency

Human control of an unmanned system occurs through teleoperation. There are several difficulties with teleoperation including sensory deprivation and latency induced by signal transportation (Storms, Chen, & Tilbury, 2017). Chen et al. (2007) defined time delay or latency as "…the delay between input action and (visible) output response and is usually caused by transmitting information across a communications network" (p. 1236). Chen et al. (2007) highlight two performance issues during teleoperations: remote perception and remote manipulation. *Remote perception* limits the situational awareness of the operator while *remote manipulation* causes delay in the feedback loop further decreasing situational awareness and the ability to perform a task. Chen et al. (2007) concluded that robot-to-operator latency (orientation latency) was more critical than operator-to-robot (action latency). Several studies have investigated the effect of latency in various environments and vehicles.

Latency introduces a factor of uncertainty in the effectiveness of operating various systems (Garcia-Perez & Merino, 2017). For example, latency becomes a significant issue within the context of RPAs, as the latter may miss the target (in case of military drones) or be damaged in the process of landing if such delay is significant (Wang, Qi, & Li, 2017). However, latency is also a common issue within the context of teleoperation. According to Vozar and Tilbury (2014), modern robot systems that use wireless communication protocols have a higher latency rate when compared to surgical or industrial robots. In addition, mobile robots often have variable latency which makes it impossible for the operator to adjust. Understanding the nature of latency problems and how teleoperators interact with mobile robots can help develop solutions that will enhance teleoperation systems (Garcia-Perez & Merino, 2017; Taylor et al., 2017; Vozar & Tilbury, 2017).

Teleoperated robots. Mobile or teleoperated robots rely on wireless modes of communication in order to perform individual or collective tasks: formations, construction, exploration, or coverage. Depending on the type of application or task, the robots may be controlled by an operator or attain connectivity with the other robots (Taylor et al., 2017). Teleoperated robots currently expand human capabilities, both in Space and on the surface of the Earth (Garcia-Perez & Merino, 2017). According to Scholcover and Gillan (2018), teleoperated robots allow people to explore planets such as Mars and Venus. For example, on Venus, the average temperatures exceed 800° F which makes it impossible for astronauts to set foot on the ground, let alone explore it. Robotics, on the other hand, allow exploration of the surface of such planets from orbit – remotely (Scholcover & Gillan, 2018). In addition, robotics has become an important tool within manufacturing processes (car manufacturing) and surgical procedures (Scholcover & Gillan, 2018). Avgousti et al. (2018) note that robotics also allows surgeons to perform highly complex operations. For example, using remotely controlled robot arms allows surgeons to avoid minor tremors of hands which could potentially damage the patient`s blood vessels or other sensitive tissues and structures. The use of robotics allows for fine-tuning the surgeons' motions and maximizing the impact of the treatment to promote patients` recovery (Marano et al., 2015). One common characteristic of such robots is that both astronauts and surgeons can operate the machinery remotely, using visual clues as the main source of information. Depending on the distance between the operator and robot, and the specific design of the latter, the phenomenon of latency can be observed which interferes with the effectiveness of the teleoperations (Avgousti et al., 2018; Garcia-Perez & Merino, 2017; Mellinkoff et al., 2017).

Understanding the phenomenon of latency within teleoperating. Vozar and Tilbury (2014) argued that latency can be viewed as a significant problem in relation to remotely controlled robot performance. Regardless of the specific mechanism of how latency originates (sensing software or hardware issues, communications problems), the phenomenon negatively impacts how a human operator can achieve even the simplest remote tasks, not mentioning the highly complex missions such as Mars` surface exploration (Mellinkoff et al., 2017). In case a time delay is significant, the operator`s robot control strategy is usually switched to a methodology known as move-and-wait open-loop (Lupisella et al., 2018). This strategy is highly inefficient as it prevents the robot from conducting the tasks in a quick and efficient manner (Vozar & Tilbury, 2014). It is important to point out that to a certain degree, the issue of latency can be tolerable and does not significantly interfere with the actions of the operator. For example, robotic elements are now commonly used within cardiology to perform complex operations (Avgousti et al., 2018).

Time delay also introduces another challenge in teleoperations: while the operators are usually capable of adapting to a fixed (consistent) latency, variable latency introduces an element of unpredictability into the system and makes it nearly impossible to compensate for the time delay effect and predict, for the human operators, how the machine will respond/act (Garcia-Perez & Merino, 2017). According to Burns et al. (2018), latency is one of the key factors negatively impacting teleoperation performance as it skews remote manipulation of the robotics systems on Earth and in Space and modifies how the operators perceive the latter. Among some of the most common sources of latencies within teleoperations are network delays, processing delays, and sensory issues (Vozar & Tilbury, 2014). In addition to that, operators themselves and their cognitive and physical capabilities can be a potential source of time delay. Vozar and Tilbury (2014) pointed out that in case of the time delay of more than 1 second, the teleoperators have been shown to switch to the move-and-wait strategy to control the robots. The delays are relevant to the 3D robotic underwater navigation, 2D on-earth driving situations (Vozar et al., 2016), and even on Mars Space missions (Burns et al., 2018).

The researchers distinguish between the two types of latency: constant and variable (Lupisella et al., 2018). Variable latency has been demonstrated to be associated with decreased performance due to the inability of the operator to compensate. Another important aspect that has to be considered in the context of teleoperations is the directionality of the latency: robot-to-user or user-to-robot. Interestingly, latency has a more pronounced negative impact in the case of the robot-to-user direction (Garcia-Perez & Merino, 2017).

Latency becomes even a more significant issue when operating robots from a substantial distance. An extreme example of such a type of robotic operation is that of a Mars rover controlled from the surface of the Earth. The robots (rovers) are designed to be able to track a distance of up to 100 m across the rocky surface. Although the Martian day lasts 24 hours and 40 minutes, the Sun provides energy for the rovers only for a short period of 4 hours per day (around solar noon time). Therefore, the rover operators are faced with the challenging task of moving the rovers during the four-hour window and ensuring operations are effective in terms of research and exploration (Taylor et al., 2017). On average, due to the distance between Earth and Mars, a delay of 20 minutes emerges during communication. Therefore, operators of the rovers located on the surface of the Earth cannot rely on the visual signal to guide the robots. Such a significant delay (latency) can create potential risks and dangers for the rover exploitation: the operator simply would not have time to give a command to prevent the rover from falling off the cliff, etc. To date, the key strategy adopted to guide the rovers is sending the instructions directly to each robot on the surface of Mars at the beginning of each day. The package of information contains a detailed set of instructions concerning the direction and speed the rover should move (Taylor et al., 2017). The communicated sequence of commands also tells each rover the specific experiment or analysis to perform, and the specific location of the latter. According to Taylor et al. (2017):

> Projects with relay links (especially those that depend on other projects) need to design into the end-to-end ground system the capability to estimate the latency at each step in the process, again commensurate with the accuracy required in sol-by-sol activity planning. (p. 355)

This means that in case of complex projects which take place in remote locations, latency has to be accounted for to avoid distortion and failure of the entire mission.

According to Mellinkoff et al. (2017), low-latency surface robotics is the future of human missions on the various planets. Such remotely controlled operations involving robots will allow the conduct of complex scientific research within highly hostile environments (Taylor et al., 2017). The idea behind the use of low-latency robotics is to be able to combine practicality and endurance of a robotic mechanism with human precision and ingenuity. Such a novel approach is fundamentally different from what has been attempted before (using robotics or astronauts alone). As discussed before, the major limitation of using teleoperated robotics on Mars and other planets is that it dramatically limits situational awareness of the crew located on Earth (Gomez et al., 2016; Lester et al., 2017; Mellinkoff et al., 2017). According to Mellinkoff et al. (2017), currently, the round-trip latency in on-Mars operations ranges from 8.6 to 42 minutes, which makes the robotics operations considerably slower than those operated from a shorter distance. The Apollo missions demonstrated that physical human presence provides a number of advantages when exploring Space; however, such presence is both costly and highly risky. Therefore, remotely controlled robots will for a long time remain the key strategy to explore Mars, the Moon, and other distant objects (Taylor et al., 2017).

The lunar surface is also being explored with the help of remotely controlled robots (Taylor et al., 2017). According to Mellinkoff et al. (2017), the latency between the Earth control stations and the surface of the moon equals nearly 2.6 seconds when using satellite as a communication channel (the Earth-Moon L2 point). According to the existing evidence, humans have a so-called cognitive threshold that allows them to perceive a video with a round-trip latency which is close to 0.3-0.4 seconds or less, depending on an individual (Mellinkoff et al., 2017). Low-latency telerobotics is forecasted to change the nature of space operations by providing an improvement in precision and reactiveness of the rovers. To take full advantage of these first operations, telerobotics is expected to be paired with the use of a low-frequency radio to be placed on the Moon`s far side (Mellinkoff et al., 2017).

Developing such low-latency systems, however, requires significant financial investment as well as meeting certain technical parameters, including but not limited to: interface, light level during operations, bandwidth, etc. (Taylor et al., 2017). For example, currently, the maximum bandwidth available for communication between Earth and Moon (L2) is approximated at 4 Megabits per second (Mbps). However, it is important to realize that such bandwidth is nearly impossible to achieve during the variable line-of-sight between the robot (rover) and the communication antenna (Mellinkoff et al., 2017).

Botta et al. (2017) discuss an increased importance of the so-called Cloud robotics: a phenomenon when a group of robots can be simultaneously operated via wire-based or wireless networks by sending packages of data. This type of remote robotics controlling can help make robots perform operations from a greater distance (Lupisella et al., 2018). However, the side effects of the system design may cause significant issues. According to Botta et al. (2017), such network performance depends on the key three parameters: latency, bitrate, and loss. Bitrate corresponds to the number of bits which can be used to communicate information from the robot to the source. Loss corresponds to the packages of information which may never arrive from the source due to the different network interferences (Garcia-Perez & Merino, 2017). In case of the Cloud robotics, latency can be measured in terms of the time elapsed from the moment when the information package is sent to the destination and when it arrives. Such parameters depend on the physical distance between the receiver and sender, as well as on the network congestion and the adopted technology (Botta et al., 2017). Latency, under such circumstances, can be measured as two-way; in this case, it is referred to as Round Trip Latency (Botta et al., 2017).

Luck et al. (2006) explored the effect of constant and variable latency while employing various levels of automation in low-speed teleoperated robots. Latency was operationalized through duration, direction, and variability. Similar to other research, they found performance decreased with increased latency duration and variability, while higher levels of autonomy improved performance (Luck et al., 2006). The location of latency (i.e., where the latency was injected into the time loop) was unique in this proposed research. Luck et al. (2006) hypothesized that "…control would be better when the feedback returning from the robot was not delayed and the control signals going to the robot were delayed than when the feedback was delayed and the control signals were not delayed" (p. 204). The hypothesis that there would be a different effect on performance based on the direction of latency is of particular importance to this dissertation. While Luck et al. (2006) did not find a statistically significant difference in performance based on latency direction (possibly due to small sample size), the results could be very different in a highly dynamic environment where the target continually changes position at high-speed. Of note, Luck et al. (2006) employed a post-experiment questionnaire where participants reported that they perceived control to be more difficult when latency was robot to user.

Possible solutions to the problem of latency. According to Vozar and Tilbury (2014), the first approach to solving the problem is to understand which specific robot designs can help achieve maximum performance effectiveness. It is, therefore, often not possible (or practically feasible) to test the proposed technical designs with the help of human operators. To solve the problem, it is necessary to use a model of a human operator; such an approach allows testing of multiple designs quickly and is an approach commonly adopted within the automotive sector (Vozar et al., 2016). However, in the case of teleoperation, such a solution may not be applicable (Vozar & Tilbury, 2014). Vehicle operators rely on a wide range of sensory feedback, while teleoperators mostly use visual feedback (often limited) to obtain information about the vehicle.

Lupisella et al. (2018) discussed a number of solutions to the process of latency in the context of robot operations and gaming. According to Zhao et al. (2015), it is possible to adjust for the effects of the dead time by placing a matching size delay into the robot`s feedback loop. In order to do that, it is important to insert a module in the system which will predict and approximate the specific negative delay. The module has to approximate the delay value and have a forward model, while also providing instantaneous feedback about the command consequences to the operator. It has been stressed that such a design may be effective in case the delay interval can be predicted (non-variable; Ang et al., 2015). Such solutions are effective when there is a need to handle linear effects but may be inappropriate with the systems with non-linear effects (e.g., slippage of the wheels of the robot due to the surface).

According to Voigtländer et al. (2017), traditional approaches toward robotics teleoperations can be considered as inefficient, partially due to the high latency (300 ms). This is why the new, more efficient technology is developed to address this and other problems. Wireless communication between the operators and robots can be considered as the main issue within modern robotics science (Voigtländer et al., 2017). Currently, the 5th generation wireless systems are being tested in order to develop ultra-low latency solutions for robot communication. This type of technology is abbreviated and referred to as 5G, and it is expected that the new wireless 5G networks will become a global standard in 2020 (Garcia-Perez & Merino, 2017). The main problem with the current solutions such as 4G and LTE is that these means of communication allow for neither high volume data exchange nor ultra-low latency communication (Garcia-Perez & Merino, 2017). Apart from allowing to transfer larger volumes of data, 5G networks allow for the low latency communication. According to Voigtländer et al. (2017), a ping operation can be performed with a one-way trip of nearly 0.5 ms, or 1 ms for round-trip time. Such high-speed and efficiency allow operating robots in a more precise manner. According to the new 5G classification, the network requirements can be classified (grouped) into the following three categories: enhanced mobile broadband, ultra-reliable, low-latency communication (URLLC), and massive machine type communication (Voigtländer et al., 2017). This way a novel robotics system can consist of one or multiple machines, as well as one or more computation centers (units).

The time delay (latency) is a serious issue within the context of teleoperation when people have to control the motion and actions of the robots remotely. The stated researchers distinguished between the different types of latency. First of all, the scholars discuss variable and non-variable types of latency. The former is particularly problematic within the context of robotics and remote control because it makes it more difficult to develop algorithms that would compensate for the sudden changes in how fast the signal travels from the sender to the receiver. Using teleoperated robotics is an effective strategy when exploring the surface of Mars or the Moon; using robots allows to avoid highly cost- and effort-intense manned operations and helps conduct scientific research within highly hostile environments. However, due to the significant distance between the operators and the rovers, there is little opportunity for precise and real-time commands. According to the accumulating body of evidence, 5G technology is a promising solution to the problem of latency in robotics. It will not only allow to share and exchange bigger volumes of data when compared to the 4G standard but will also allow for the ultra-low latency communication. Decreasing latency through faster networks is one approach to solving the teleoperation issue. Another potential solution is the use of display augmentation and other control methodologies.

Several authors discussed control and display augmentation as a mitigation tool for latency effects including Byrnes (2014), Chen et al. (2007), Mayer (2015), Sheridan (2011), Storms et al. (2017), and Zhang et al. (2018). A potential solution is to project the position of the unmanned vehicle to an estimated position based on the current velocity vector and latency (i.e., extrapolating the position). This method yields a synthetically displayed position in reference to the environment. This method has shown promise with slow-moving vehicles in a static environment as it reduces the effect of the observational latency. However, it has not been applied in a dynamic, rapidly changing situation or with variable latency. As Chin et al. (2007) report, “disturbances in remote environment may make prediction model unreliable” (p. 1233). To reduce the effect of action latency, predictive control can be used along with a shared control scheme (Storms et al., 2017). In this control method, the operator continually designates a “go-to” position to which the vehicle then plans and proceeds via an automated route. This method has shown promise in a slow-moving environment with small and large latencies. However, similar to the projected position solution, it does not appear feasible in a highly dynamic environment.

An often-discussed solution to the teleoperation latency effect is autonomous operations where the vehicle is able to sense, decide, and maneuver in real-time based on programmed algorithms (Byrnes, 2014; Mayer, 2015). Research has shown that given accurate input data, simulated models can generate the maneuvers required to perform complex actions such as WVR air-to-air combat, albeit on a limited scale (McGrew et al., 2010; Shin et al., 2018). While these autonomous fighting machines are promising, they require a continuous input of precise aircraft and adversary parameters (position, range, range rate, velocity, acceleration, angle of attack, bearing to the adversary, etc.). Sensor suites with this capability which can cover the entire 360-degree view of an unmanned system and provide precise, real-time data are not currently available. Additionally, countermeasure systems can be employed to mislead the sensors. For example, electronic countermeasures (jamming) and metallic chaff bundles can cause radars to report erroneous data and lose “lock” on the target. Ejected flares and laser systems can cause optical and infrared tracking systems to lose the target. Towed decoys can spoof the sensors into tracking the wrong target, and miniature drones dropped from the adversary can confuse and disrupt radar and optical sensors.

Teleoperation latency parameters. Conklin (1957) performed some of the earliest research on control lag (latency) with an experiment designed to explore the effect of latency while attempting to track a target. The results highlighted the importance of valid track predictions during tracking exercises; the more random the path and the higher the latency, the lower the performance of the participant (Conklin, 1957). Conklin (1957) tested three different target movement schemes at four latency levels (0, 0.25, 1.0, 4.0, and 16.0 seconds). “The results supported the assumption that predictive behavior on the part of S [subject] is essential for skilled performance” (Conklin, 1957, p. 268).

Early research performed for NASA by Sheridan and Ferrell (1963) injected latency into manipulative tasks. Sheridan and Ferrell (1963) researched the effects of latency on remote manipulation and predicted that it would be a concern for the lunar project. While others had explored transmission delay, Sheridan and Ferrell (1963) were the first to propose mitigating strategies, quantify the effects, and create algorithms to predict the result. They concluded that an increase in task difficulty could only be compensated by increasing the time of the operation and designed an experiment to quantify the results. This was the first appearance of the “move and wait” strategy where subjects would make an input to the system, wait for feedback, then make the next move; a strategy seen today in remote surgery, underwater robotics, UAS, and space applications. Based on this strategy, Sheridan and Ferrell (1963) were able to accurately predict task completion times based on the roundtrip delay time. Interestingly, their experimental process used a single individual since they were interested in the change in time and accuracy to complete an event and not the subject’s ability. The researchers experimented with latency levels of 0.0, 1.0, 2.1, and 3.2 seconds while also varying the difficulty of the task (Sheridan & Farrell, 1963).

Sheridan published other papers on latency and teleoperation while at NASA before moving on to MIT. Sheridan (1978) published on the human/computer control of undersea teleoperation. This work defined supervisory control and sought solutions to teleoperation delay by including an autopilot type computer control system “on the loop.” In 1993, Sheridan published on teleoperation in space applications which serves as a compellation of strategies to overcome control delays. In 2011, Sheridan published a Rosetta Stone of control methodologies, levels of automation, and human factors.

Bulich, Klein, Watson, and Kitts (2004) explored the effects of delay on precisely piloting an undersea robot. They discovered that although performance suffered, basic maneuvers were still possible with roundtrip delays up to 1.5 seconds. Bulich et al. (2004) identified several negative consequences of latency including, “unnecessary vehicle motion, time it takes to complete maneuvers, and the significant increase in the level of pilot attention that is required” (p. 416). While the speed and complexity of the vehicle maneuvers in this study are not comparable to a WVR engagement, the research illustrates that C2 latency is an issue even for slow-moving unmanned systems.

The majority of research on teleoperation latency is carried out at very low velocities. Gorsich et al. (2018) recognized there was a gap of literature on teleoperation at “high” speed (greater than 25 mph) and designed a study to characterize latency effects. Their results indicated that as latency increased from 0.0 to 1.0 seconds, the error increased exponentially, while the average speed decreased exponentially. This remained consistent across multiple vehicle platforms and driving courses (Gorich et al., 2018).

Research to mitigate the decrease in performance associated with C2 latency is prevalent. Many of the studies employ a predictive algorithm and display along with combining teleoperation control with autonomous action (Chen et al., 2007). Storms, Chen, and Tilbury (2017) introduced a model employing predictive control in an attempt to mitigate the effects of latency for UGVs (unmanned ground vehicles). Their development of a shared control model demonstrated that the benefit was minor at low latency but increased with higher latency levels. Of note, their research limited the maximum roundtrip latency to 0.800 seconds which was determined to be near the maximum delay expected for ground vehicles.

The Department of Defense Handbook MIL-STD-1797A (1997) defines the flying qualities of piloted aircraft. Control delay from pilot initiation to aircraft response is defined in three levels of flight quality (FQ). To receive an FQ-1 rating (the highest rating), control delays must be less than 0.100 seconds, FQ-2 less than 0.200 seconds, and FQ-3 less than 0.250 seconds (Department of Defense, 1997). Zhang et al. (2016) described the consequences of latency as causing control overshoot leading to pilot induced oscillations (PIO), an issue MIL-STD-1797A (1997) sought to limit. Zhang et al.’s (2016) research attempted to reduce the effects of control latency in BLOS C2 by introducing a command director system. However, the adaptation strategy of move and wait was still required.

Dougherty, Hill, and Moore (2002) studied the effects of C2 latency on laser designation accuracy of ground targets with UAS. The research identified that the miss distance increased rapidly with higher levels of latency and target movement. Although the velocities studied (both UAS and ground vehicle) are significantly slower than in a WVR air-to-air fight, the outcome highlights the issue of latency in a dynamic environment (i.e., both the UAS and target are in motion). Additionally, and germane to this dissertation, Dougherty et al. (2002) identified that there is a lack of unclassified data relating to UAS C2 latency.

De Vries (2005) offered an extensive study of predicted LOS and BLOS latencies associated with UAS. Taking several influential factors into account including transceive and transport time, encryption and compression delays, error correction, synchronization, computations, and uplink/downlink delay, he concluded that the calculated maximum latency is 1.672 seconds (de Vries, 2005). However, he noted that this time could easily be exceeded due to other extraneous factors. Of note, this maximum time did not include trans-Atlantic transmission times associated with U.S. RPA operations.

Many of the studies revealed the use of the move and wait technique even when other mitigation strategies were introduced. This move and wait technique, witnessed by Sheridan and Ferrell (1963), appears in stark contrast to Boyd’s OODA Loop for success in air-to-air combat (McIntosh, 2011). While both of these models describe a closed-loop feedback system, Boyd’s emphasized the importance of rapidly transitioning to the next phase or even overlapping events to stay ahead of the enemy’s decision and maneuvering process (McIntosh, 2011). Boyd’s OODA Loop is the theoretical framework on which this dissertation is based.

RPA Command and Control

The C2 architecture for the MQ-9 is typical of a MALE UAS. An F-UCAV is expected to have a similar C2 design. The RPA is controlled either through direct line-of-sight (LOS) or beyond-line-of-sight through a satellite relay (USAF, 2009; Zhang et al., 2016). While the latency associated with LOS operation is negligible, the latency with BLOS depends on many variables (de Vries, 2005). Marshall, Barnhart, Shappee, and Most (2016) identified that for BLOS operations, “The drawback is that significant delay or latency of up to a number of seconds may be encountered” (p. 272). This corresponds to anecdotal evidence from experience in the MQ-9 indicating an observed latency of up to 2.5 seconds (B. Opp, personal communication, May 15, 2018).

Command and Control data links continue to evolve at a rapid pace in the areas of communication security, low probability of signal intercept, jamming resistance, and bandwidth (Fahlstrom & Gleason, 2012). However, the latency associated with transmitting a C2 signal across terrestrial networks, uplinking to a satellite, transferring to a satellite with a footprint covering the UAS, and transmitting to the UAS, is mainly physics-based (Zhang et al., 2016). Therefore, while latency may be reduced, it cannot be eliminated with current physics knowledge.

The latency between the pilot and aircraft is an inherent feature of an unmanned system. In the case of LOS operations, the latency is relatively short since the transmission time is due to the proximity of the transmitted signal and the aircraft (e.g., 90 miles). During BLOS operations, the transmission time can be considerably longer depending on the signal routing (de Vries, 2005).

A typical BLOS scenario involves operating in an AOR somewhere in the world with the GCS based thousands of miles away (de Vries, 2005). The C2 signal passes from the GCS through terrestrial communication nodes until it reaches a satellite uplink station where the signal is broadcast to the satellite. Depending on the location of the operation, the signal may be sent to another satellite before downlinking to the aircraft (see Figure 2). A hypothetical signal route is displayed in Figure 2. Likewise, the signal from the aircraft (video and telemetry) follows the reverse route back to the GCS. In this process, latency is induced through several factors.

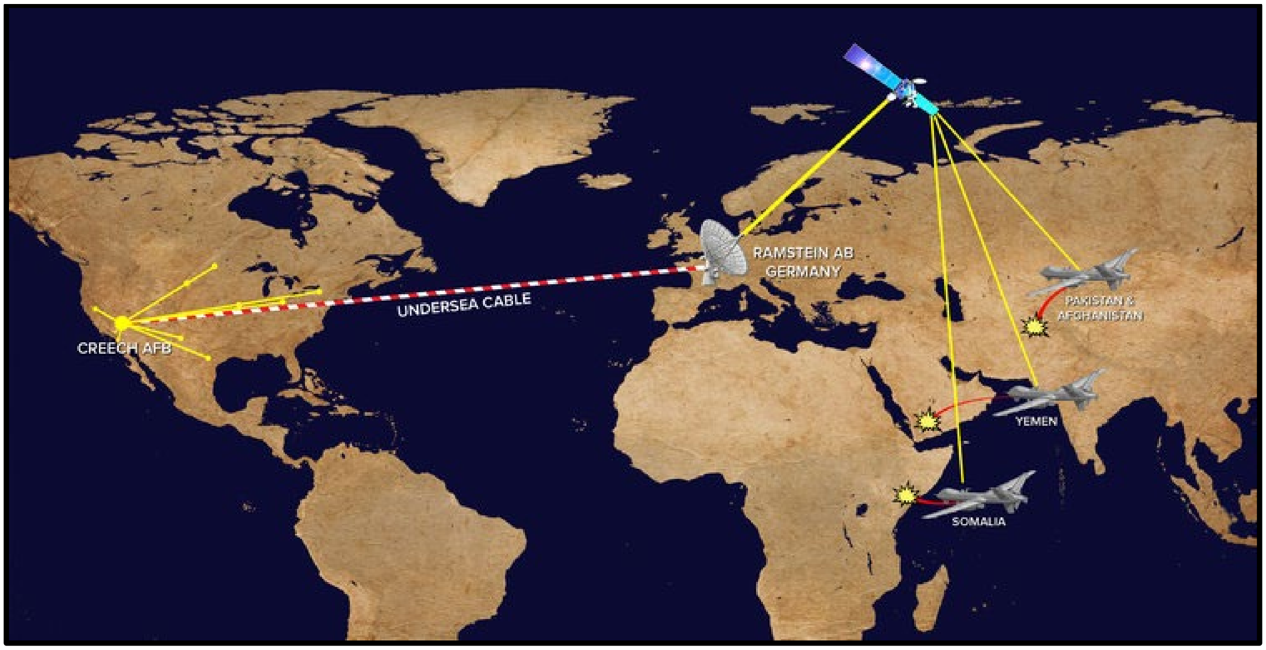


Figure 2. Hypothetical UAS satellite communications link. Adapted from Brownstein (2015).

RPA Capabilities

The performance of military UAS varies drastically from miniature aircraft such as the Wasp to high altitude long endurance (HALE) aircraft such as the RQ-4 (Thomas, 2017). While the MQ series of aircraft has performed admirably, their advertised performance numbers fall well short of fighter aircraft in the areas of speed and maneuverability. The MQ-9's maximum speed is 240 knots indicated airspeed (KIAS) while the new Predator C Avenger advertises 400 KTAS (Thomas, 2017). In comparison, the USAF list the F-16's maximum airspeed as 1,300 KTAS (USAF, 2015c). The maneuvering potential of an aircraft is governed by the minimum and maximum acceleration loads commonly referred to as "Gs," or the force due to acceleration on the z-axis (Newman, 2015). The MQ-9 is restricted to a maneuvering window of $0.0 \leq Gz \leq 2.2$, while most modern fighters have a window of at least $-3 \leq Gz \leq 9.0$ (personal communication, B. Opp, May 15, 2018; USAF, 2015c).

The future of air-to-air combat will undoubtedly include more capable drones than available today. Byrnes (2014) and Meyer (2015) note that current military UAS are designed for endurance while sacrificing speed and agility. Byrnes (2014) points out that machine piloted fighter aircraft can capitalize on Boyd's OODA Loop and provide unmatched lethality. Mayer (2015) contends that the next generation of military MALE UAS will move toward the ability to penetrate contested airspace partnered with either other unmanned systems or as a *loyal wingman* with manned fighter aircraft. Mayer (2015) predicts that militaries will continue to develop larger, faster, more maneuverable, and stealthy UAS that will fill a role at the tactical level of war. These aircraft will contain high levels of autonomy and be able to operate in contested airspace. However, for the near future (2025), RPAs such as the MQ-9 Reaper will still dominate the role of MALE UAS.

Air-to-Air Combat

The air-to-air combat environment is exceptionally dynamic, physically demanding (pilot and aircraft), and often unpredictable (Shaw, 1985; Trsek, 2007). The training required for a typical U.S. fighter pilot to become proficient in leading air-to-air missions spans several years and hundreds, if not thousands of flights (USAF, 2017). The USAF and USN advanced fighter training courses (Weapons Instructor Course [WIC], and Navy Strike Fighter Tactics Instructor Program [Top Gun], respectively) spend millions of dollars on developing air-to-air skills of a select group of pilots (Allen, 2016; USAF, 2016). The typical pilot chosen for these schools has acquired more than 750 hours of fighter time, equivalent to approximately three to five years of flying and is considered the best at their local units (USAF, 2016). However, the services still see the pilot's air-to-air skill as lacking and invest heavily in advancing their combat capability through WIC and Top Gun.

The high stakes, violent execution, and complex environment of air-to-air combat create an intense mental and physical challenge. The pilot must not only understand their own capability, capabilities of their aircraft, sensors, weapons, electronic attack, and countermeasures, but they must also understand the same of the threat aircraft and pilots (Shaw, 1985; USAF, 2005). They must assimilate this information and be able to orchestrate a coordinated attack in four-dimensions. In the case of a UAS pilot, based thousands of miles away, they must also deal with delayed C2 communications and limited situational awareness (Haider, 2014).

Beyond visual range. Air-to-air combat that occurs outside the expected visual range is defined as beyond visual range (BVR; USAF, 2005). The maximum range of a BVR engagement is based on missile range, while the commonly accepted range for the transition between BVR and the visual range is 10 nautical miles (USAF, 2005). The BVR arena is defined by medium and long-range missile tactics designed to destroy the target at long range by the most efficient means possible. While this is the preferred area of engagement for modern fighters, engagements often transition to WVR due to identification and weapons issues, radar jamming and countermeasures, deception tactics, enemy numbers, and degraded situational awareness (personal communication, M. Fessler, June 10, 2018; Trsek, 2007; USN, 2016).

Within visual range. Air-to-air combat that occurs inside the expected visual range is defined as within visual range (WVR) and known as a *dogfight* (Trsek, 2007; USN 2016). The range of a WVR engagement is approximately ten nautical miles or less. The WVR arena is defined by aggressive maneuvering and short-range weapons employment (Shaw, 1985, USN 2016). Typically, each aircraft approaches the fight in the transonic speed region (0.75 – 1.25 Mach) or approximately 500 nautical miles per hour (257 m/s) true airspeed (TAS), depending on altitude (USAF, 2005). Therefore, from the 10 nautical mile point to the merge takes approximately 36 seconds.

During a WVR engagement, both aircraft are attempting to achieve an acceptable weapons engagement zone (WEZ) to employ a missile or gun (Shaw, 1985; USAF, 2005). The WIC and Top Gun schools define this area as the Control Zone (CZ), an area behind the target aircraft approximately 500 - 1,500 m where an attack with either a missile or gun may commence (Shaw, 1985; USAF, 2005; USN, 2016). Although there is not an agreed upon angular definition of the CZ, a position where the attacker's angle-off and the targets aspect angle (see Figure 3 for angular definitions) are less than 30 degrees is considered the heart of the CZ (USAF, 2005). Figure 3 is a representation of the CZ, which is an offensive position with overlapping weapons engagement zones, generally leading to engagement success (USAF, 2005; USN, 2016). Successfully maneuvering the aircraft to arrive in this position is the dogfight objective and directly related to the dependent variable in this dissertation.

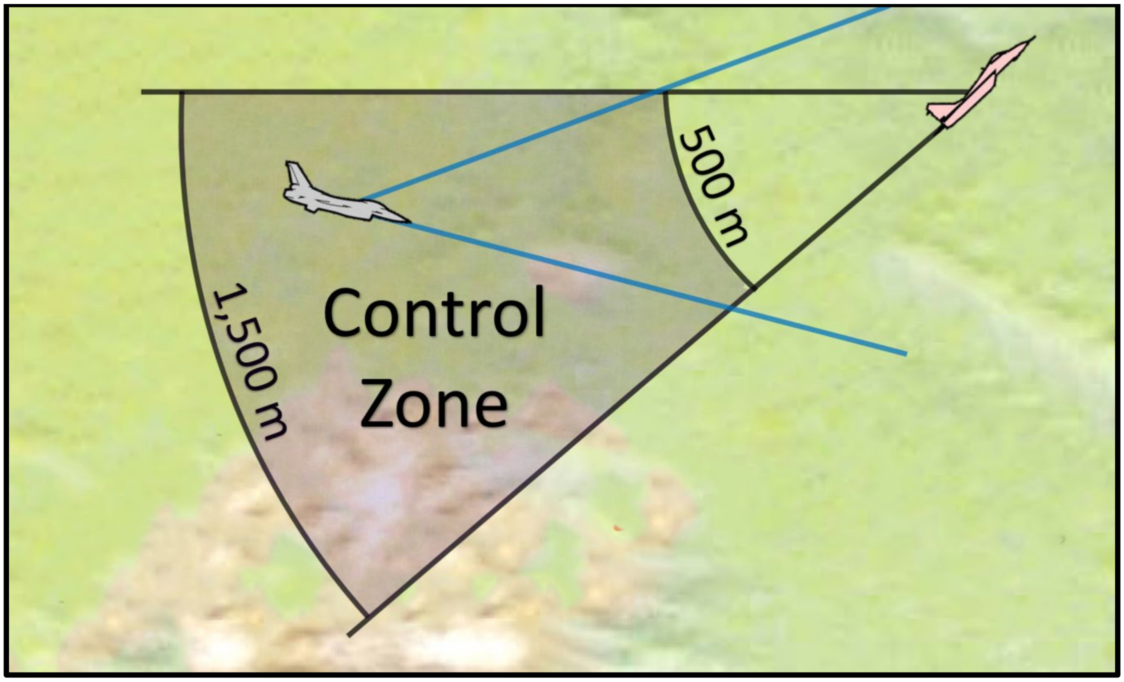


Figure 3. Depiction of the control zone as seen from above a turning fight.

There are typically three different categories of WVR combat (also defined as basic fighter maneuvers [BFM]): offensive, defensive, and high-aspect. An offensive situation occurs when the adversary aircraft is in front of the attacker, a defensive situation when the adversary is behind the attacker, and high-aspect when the two aircraft meet pointed in opposite directions (USAF, 2005; USN, 2016). These categories are transient and one, some, or all of the situations can be experienced during a dogfight. However, the majority of dogfights witnessed in modern WVR combat are considered high-aspect (Tresk, 2007). In a high-aspect dogfight, both the attacker and target approach each other head-on and pass at close quarters, usually inside of 1,000 ft at a point defined as the *merge* (USN, 2016). Once the merge occurs, both aircraft turn and maneuver in an attempt to achieve a weapons engagement zone (WEZ) from which to fire missiles or the gun. The high-aspect engagement is the simulated scenario for this dissertation.

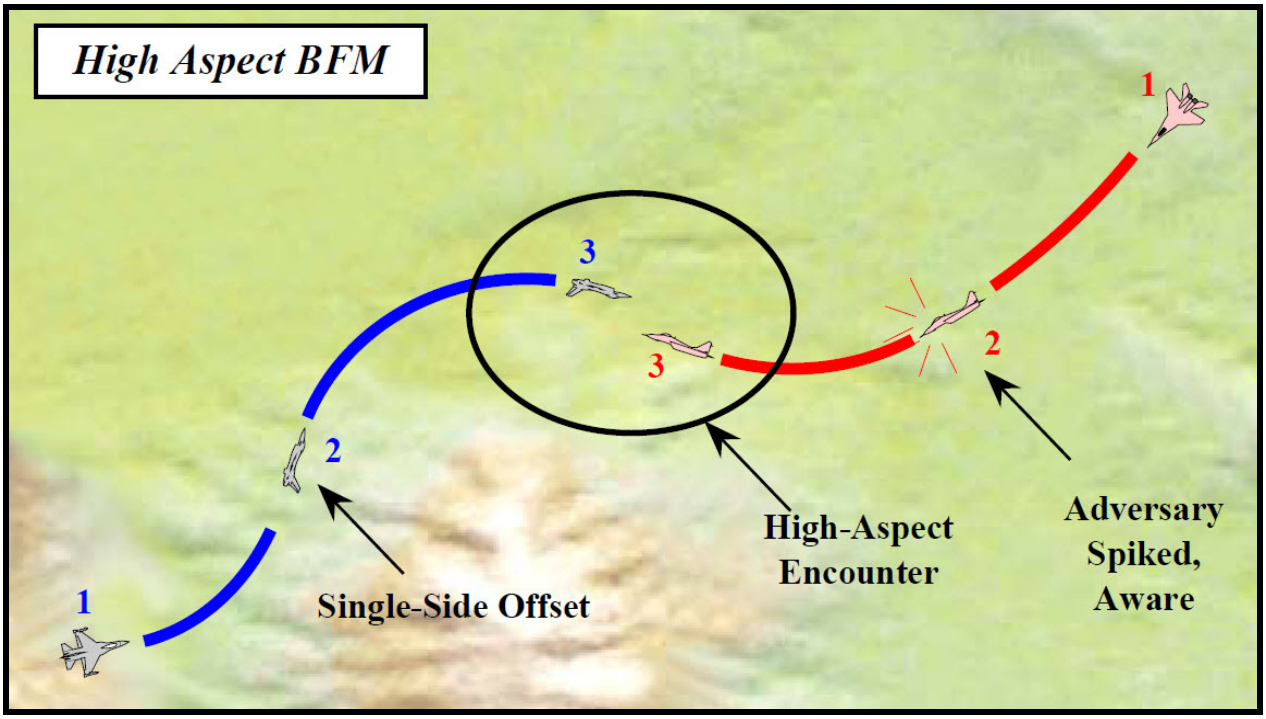


Figure 4. Typical fighter geometry in the approach to a high-aspect BFM engagement. Adapted from "Tactics, techniques and procedures 3-3" USAF, 2005, p. 4-86.

A high-aspect BFM engagement can occur due to several situations including lack of positive identification (not able to shoot missiles BVR and must visually identify the adversary), late visual pickup of the opposing aircraft, and failed weapons attempts, among others (USAF, 2005; USN, 2016). As the aircraft continue to the merge, a situation as depicted in Figure 4 occurs. The desired airspeed, altitude, vertical offset, and horizontal offset depend on many factors such as the fighter's mission, fuel and weapons on board, type of weapons remaining, turn rate and radius of the fighter, and capabilities of the adversary. However, USAF (2005) defines general merge parameters as 15,000 to 20,000 feet above sea level (MSL) and 420 to 450 knots indicated airspeed (KIAS). The upper limit of this range represents a true airspeed (TAS) of 617 KTAS (1,043 feet per second, or 318 meters per second) assuming a standard atmospheric day. This creates a nominal closure rate between the two aircraft of 2,086 feet per second (636 meters per second). As the merge approaches, there are two distinctly different engagement geometries that can occur; these geometries are known as a *two-circle* or *one-circle* engagement (USN, 2016). A two-circle engagement occurs when both aircraft turn toward the other as the merge occurs with both aircraft turning the same direction (e.g., both aircraft turning left). The name *two-circle* implies that the aircraft flight paths inscribe two circles on the ground, as illustrated in Figure 5.

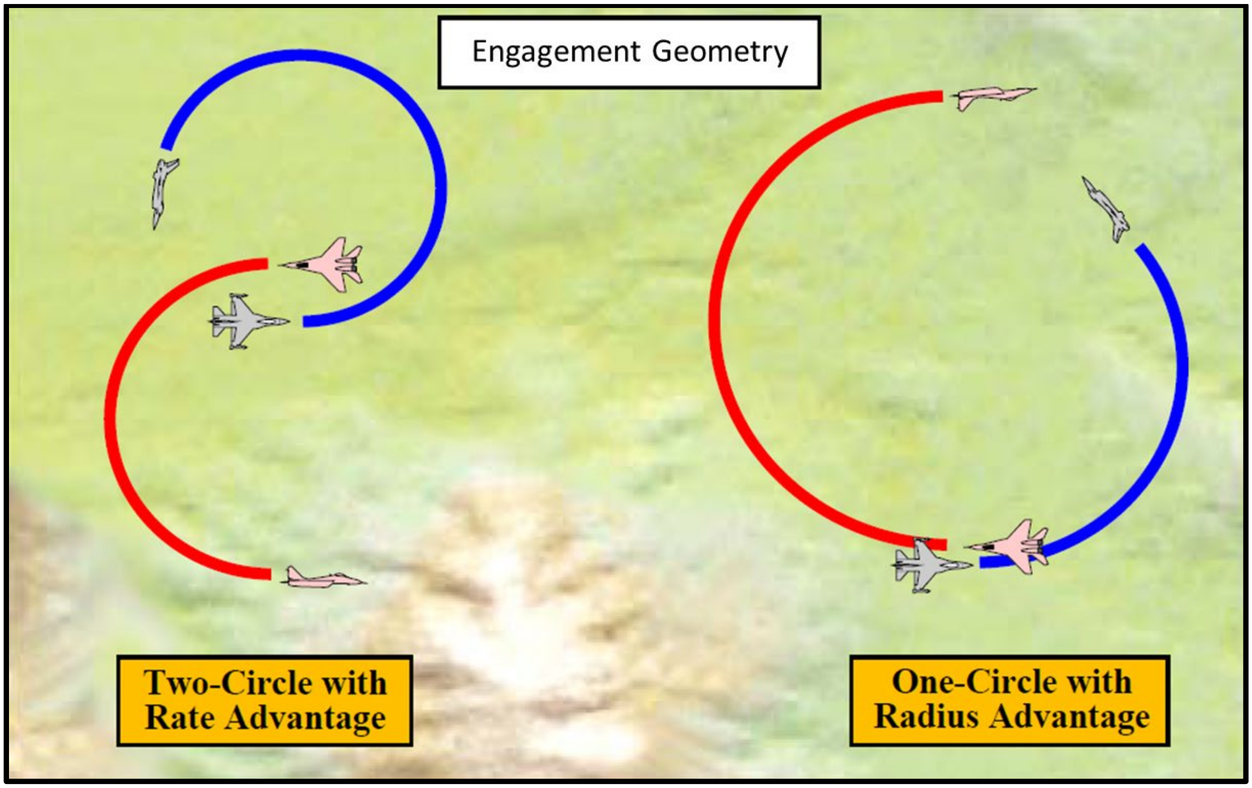


Figure 5. Engagement geometry after the merge. Adapted from “Tactics, techniques and procedures 3-3” USAF, 2005, p. 4-91.

A two-circle fight is desired when there is a distinct advantage in sustained turn rate. Since turn rate is the ratio of radial acceleration and velocity, an aircraft that can sustain a high acceleration load will have an advantage over those that cannot. However, high acceleration loads cause extreme energy loss due to induced drag which must be overcome by a high thrust-to-weight ratio (Hunt, 1965). Therefore, the two-circle fight is usually desired when an aircraft enters the fight at a high subsonic velocity (0.80-0.95 Mach).

The *one-circle engagement* occurs when the aircraft turn in opposite directions, resulting in a single circle drawn on the ground. The one-circle fight is also known as a *radius fight* since the initial objective is to turn tighter with a smaller turn radius than the opponent (USN, 2016). Since turn radius is a function of the velocity squared divided by the acceleration load, a single-circle engagement is often desirable if a fighter arrives at the merge with less than optimal kinetic energy (Hunt, 1965) or at a velocity disadvantage.

Whether the fight develops into a two-circle or one-circle fight depends on the direction in which the last aircraft turns. However, the fight can be influenced by the horizontal offset at the merge. If the offset is too great, turning away from the adversary to force a one-circle fight will give up too much turning room, resulting in a major disadvantage (USAF, 2015). The decision as to the type of fight will occur again when the aircraft come back together for the next merge. This assessment and decision process (observe, orient, decide, act) continues until one of the aircraft achieves a sustained geometrical advantage, at which time the fight becomes mature where one aircraft is distinctly offensive and the other defensive, as seen in Figure 6 (USN, 2016).

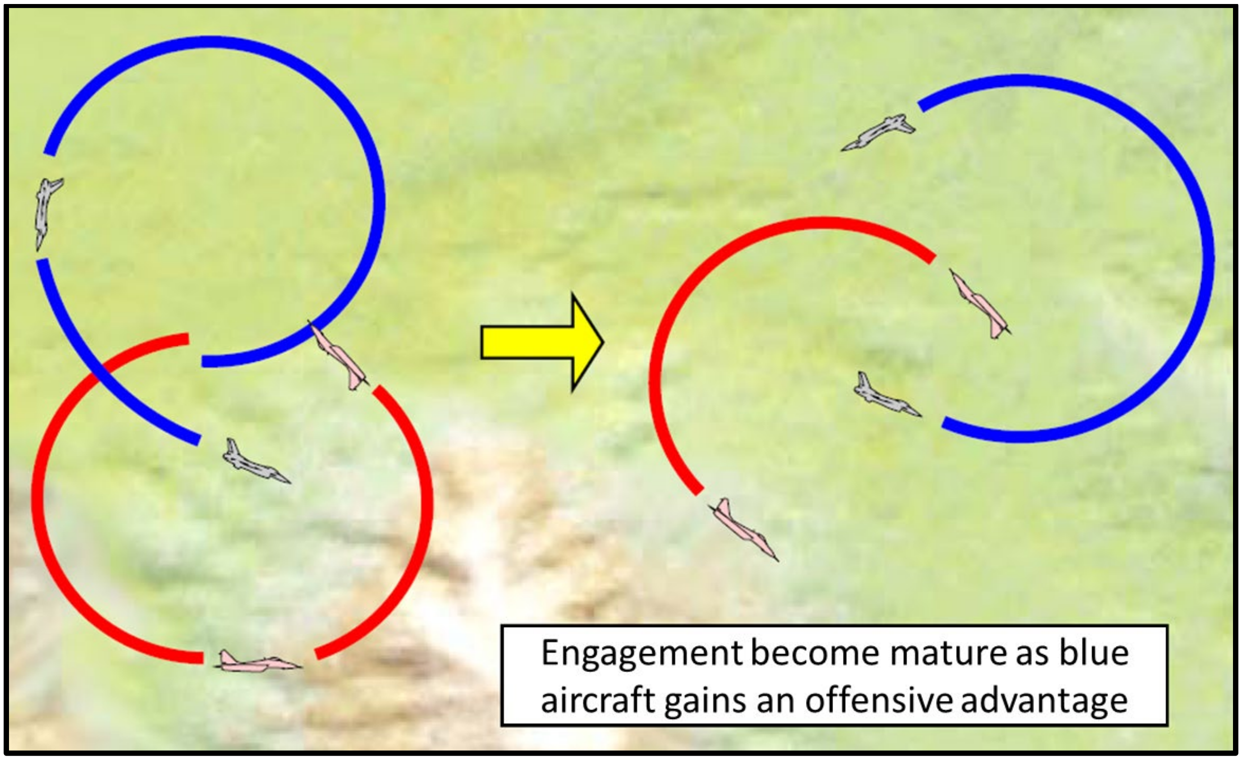


Figure 6. High aspect geometry transition to offensive and defensive roles. Adapted from "Tactics, techniques and procedures 3-3" USAF, 2005, p. 4-93.

As the engagement roles shift, the objective of the offensive fighter is to maneuver to the CZ in order to control the adversary and employ weapons (USN, 2016). The offensive aircraft accomplishes this by continuously assessing closure rate, adversary aspect ratio, angle-off the nose, and energy. If performed correctly, the offensive aircraft will arrive in a position approximately 3,000 feet behind the adversary and less than 45 degrees off the nose. From this position, the offensive fighter can initiate both a short-range missile and gun attack and is the objective for the subjects in this experiment.

Simulation

Aircraft simulators range from Basic Aviation Training Devices (BATD) to Level D Full Flight Simulator (FSS), as designated by the FAA (FAA, 2020). Regardless of the type or level of simulator, each training device is designed with a specific training task in mind. Whether the simulated task equates to a correct learned behavior in flight is known as *transfer of training*. *Simulation fidelity* is an important quality in order to transfer the required training from simulation to flight operations. Simulation fidelity is broken down into several areas. Allen, Park, and Cook (2010) discussed fidelity in two broad areas: physical and perceived. While the definition of fidelity varies amongst authors, these two general areas of fidelity remain constant. Liu, Macchiarella, and Vincenzi (2009) determined that “Definitions of fidelity mainly fall within two categories: those that describe the physical experience and those that describe the physiological or cognitive experience” (p. 64).

Physical fidelity refers to how close the simulated environment reflects the actual cockpit and environment (e.g., cockpit instruments and switches; Liu, Macchiarella, & Vincenzi, 2009). It can be further broken down into the areas of audio and visual, equipment, motion, hardware, and software, among others. For each specific simulation requirement, the physical fidelity should be of enough quality to enable the transfer of training from the simulation to the aircraft

(Liu et al., 2009). If, for example, a switch in the simulation that is required for the training task is not similar in shape and function to the aircraft, the pilot may incur a negative transfer of training or learn the task incorrectly. It is of particular importance that the physical fidelity of the simulation be considered in simulation design in order to allow a positive transfer of training.

Hochmitz and Yuviler-Gavish (2011) defined *cognitive fidelity* as referring to "the extent that the simulator engages the trainee in the types of cognitive activities involved in the real-world task" (p. 490). One of the issues surrounding the validity of a study is whether the simulation induced a level of cognitive fidelity similar to flight. Mohanavelu et al. (2020) studied cognitive task loading of fighter pilots during low and high task events. Each subject was instrumented with an advanced smart vest, which monitored the pilots stress level during prebuilt simulation vignettes through biometric measurements (e.g., electrocardiogram, temperature, heart rate, etc.). The results indicated that a relatively low fidelity simulation (i.e., no government certification) yielded significant changes in stress between vignettes (Mohanavelu et al., 2020). This suggests that the simulation induced enough cognitive fidelity to stimulate stress response similar to actual flight.

The term *perceived fidelity* is an aggregate term describing the aircrew's overall experience (Perfect, White, & Padfield, 2010). This fidelity is difficult to measure since it is generally subjective and based on many attributes of the subject such as experience and ability. Alessi (1988) contends that a higher physical fidelity does not always translate to a higher transfer of training and that the simulation must be designed around the objectives of the training. This reinforces the concept that the simulation must have enough physical and cognitive fidelity to produce sufficient perceived fidelity to learn (or transfer) a specific task. Virtual reality simulation tends to blend the categories of fidelity into an immersive environment high in perceived fidelity (Ganier, Hoareau, & Tisseau, 2014).

Oberhauser, Dreyer, Braunsting, and Koglbauer (2018) described VR as presenting "a fully synthetic environment to a user while completely omitting the real world" (p. 22). Their research employed a within-subjects experiment to determine if there is a difference between a conventional aircraft simulator and a VR aircraft simulator in the areas of pilot movement time, flight performance, and simulator sickness. The results indicated that there was a statistical difference between the simulation type in all categories (Oberhauser et al., 2018). However, there was no comparison to the real flight environment to determine which simulation type was more realistic, only that there was a difference. Symptoms of simulation sickness were more pronounced with the VR simulation that could, in part, be due to higher perceived fidelity.

Simulator sickness or discomfort is a common side effect of flight simulators. Several researchers have investigated the various causes of simulator sickness with the central theme being sensory mismatch; a difference between the sensory stimulation experienced in the simulation compared to real-world expectations (Reason, 1970). Visually induced motion sickness (VIMS) describes the mismatch between motion cues displayed in the simulation and the lack of physical movement (Chen, Bao, Zhao, & So, 2016). Reason (1978) described two requirements for VIMS: visually perceived motion does not match the vestibular system (e.g., rolling the aircraft in a motionless simulator), and the vestibular system must be involved (the head moving opposite the direction of bank). The use of a head mounted display (HMD) tends to increase the regularity of simulation sickness (Oberhauser et al., 2018).

Researchers have hypothesized several factors for the increased occurrence of simulator sickness with HMDs. Possible technological factors include system latency (specifically, head pointing latency), low-resolution displays, narrow field of view, and low fidelity of HMDs (Kinsella, 2016). However, advances in computing power, graphics capabilities, and headset resolution have led to the latest versions of high definition (HD) VR headsets. For example, the

VR headset used by Oberhauser et al. (2018) was bound by a 60-degree FOV and a resolution of 1,280 X 1,024 pixels per eye. The same year, the HTC Vive Pro consumer VR headset was introduced with 1,440 X 1,600 pixels per eye and a 110-degree FOV (www.vive.com). This increase in capabilities, along with computing power enabling frame rates in excess of 90 frames per second, and non-perceivable latency (less than 60 ms) in head pointing, have allowed VR flight simulators to provide even higher levels of perceived fidelity (Geyer & Biggs, 2018). The increased resolution and fidelity of current HMDs was expected to decrease the occurrence of simulation sickness. However, recent studies indicate the opposite: the higher fidelity (resolution and FOV) of the HMD, the higher the occurrence of simulation sickness (Geyer & Biggs, 2018).

Decreasing the rate and intensity of simulator sickness in high resolution, low latency, and wide FOV HMD is a new field of study. Manufacturer guidelines advocate limiting exposure to 30 minutes at a time, suggesting that several shorter duration exposures are recommended over longer durations (Geyer & Biggs, 2018). Regular, short exposure sessions could be a method to build up resistance to sickness. Decreased head movement has also been linked with lower occurrence of sickness as well as being actively involved in the simulation (Geyer & Biggs, 2018).

Gaps in the Literature

There is a distinct literature gap regarding latency effects in highly dynamic environments where precise control and reactions to other rapidly moving vehicles are required. No research exists that quantifies the effects of latency on WVR air-to-air combat nor assesses whether a high-speed or low-speed engagement yields different results. Further, the interaction effect between latency and engagement speed has not been studied.

Theoretical Framework

Several theoretical foundations were considered to set the framework for this study. Since the research is based on a cognitive process with imperfect information, decision-making theories were considered. The decision-making theory of *bounded rationality* was found most applicable since it considers that an individual cannot know everything, and there is a limited amount of time to make decisions. The concept of missing, delayed, or inaccurate input to the decision-making process could be operationalized through this theory. However, this theory's only focus is on one side of a decision process and does not consider an adversary continuously changing the environment.

Decision-making theory is often related to *game theory*. Myerson (1991) defines game theory as "the study of mathematical models of conflict and cooperation between intelligent rational decision-makers" (p. 1). A central requirement of game theory is that two (or more) entities make decisions that influence the other (Myerson, 1991). In the case of air-to-air combat, game theory can be further broken down into a non-cooperative, zero-sum gain conflict where both pilots are fighting to destroy the other (non-cooperative), and the success of one infers the destruction of the other (zero-sum gain). The air-to-air combat engagement exhibits both simultaneous and sequential traits where the pilots are acting simultaneously while also observing the previous maneuvers made by the other pilot (Myerson, 1991). While gaming theory appears to fit the classic condition of air-to-air combat, fitting a mathematical relationship to a highly dynamic environment with infinite possibilities, latent data, and human decision making is difficult. In what is now considered an operational adaptation of game theory, Colonel John Boyd developed the *OODA Loop theory*.

Boyd (1977) developed what is known as the OODA Loop theoretical framework through several iterations of tactical and strategic observation, experimentation, and analysis.

The OODA Loop evolved over many years beginning with Boyd's (1964) study on aerial attack. The ideas were refined in Boyd (1976) where he applied the idea of *rapid transients* (quicker decision and action) in a briefing on new air-to-air concepts. The first appearance of the entire OODA Loop came in Boyd (1977) where he described the OODA Loop as a concept for winning in a competitive world. Further refinement occurred with Boyd (1987) where the OODA Loop was discussed in terms of command and control. The OODA Loop has been the focus of many books, military strategies, aircraft designs, and air-to-air tactics.

Gray (1999) stated "The OODA loop may appear too humble to merit categorization as grand theory, but that is what it is" (p. 90). Oringa (2005) described how the OODA Loop theory became mainstream not only in an air-to-air context but in military and business strategies. Oringa (2005) contended that, unlike other theories, the OODA Loop is valid at the "…grand strategic, strategic, operational and the tactical level…" (p. 180) and focused on the success and winning in a complex, chaotic environment. Endsley and Jones (1997) applied the OODA Loop Theory to their studies of situational awareness and decision making in the domain of information warfare. They summarize the objective of information dominance as "…to reduce the time required to complete the OODA loops (at all levels) on the friendly side, while increasing it for the enemy" (Endsley & Jones, 1997, p. 10). Angerman (2004) explored the evolution of the OODA Loop into other applications and determined that the OODA Loop is hosted by a system, fueled by information, and acted upon by a process. He identified that most applications dealt with information, whether processing information, information warfare, or information fusion.

Pearson (2017), in *The Ultimate Guide to the OODA Loop* describes the basic concept of Boyd's Theory as "the ability to rapidly change beliefs based on a rapid changing and uncertain environment" (p. 16). These OODA Loop concepts are foundational to this study because they operationalize the concept of latency on overall performance and give context to the independent and dependent variables.

Summary

The effects of latency on the speed and accuracy of performing a task has been studied for many years and continues to be a subject of great interest. The majority of research pertains to ground teleoperations; performing a task where the operator is not in physical contact with the environment, and command signals are delayed through signal transmission. Current RPAs operating in a BLOS situation encounter a C2 feedback loop which can exceed 2.0 seconds. Future air-to-air combat will be carried out by autonomous or remotely piloted vehicles with either inaccurate sensor data or delayed transmissions. The typical WVR fight occurs from a neutral position in what is known as a high-aspect engagement where both aircraft closely pass each other in opposite directions. Colonel Boyd developed the OODA Loop in an effort to dissect the decision-making process during WVR combat and is the foundational theory for this research. The effect of latency on WVR air-to-air combat is unknown yet critical to winning future air battles.

CHAPTER III

METHODOLOGY

Research Method Selection

This quantitative research employed a repeated measures experimental design during air-to-air combat simulation. Field (2013) describes repeated measures as “a term used when the same entities participate in all the conditions of an experiment or provide data at multiple time points” (p. 544). Verma (2016) provides a similar description “in repeated measures design each subject is tested under all treatments” (p. 2). Crowder and Hand (2017) identify two requirements for a repeated measures experiment: there is only one group and the same characteristic (i.e., dependent variable) is measured under different conditions or at different times. The design allows multiple, randomized, single-blind treatments of each subject, including a no-treatment control measurement (Creswell, 2014; Verma, 2016). Each subject experienced all of the treatments (6) for each type of engagement (high-speed and low-speed) assigned in the order specified through a balanced Latin square during a 1.0 hour simulation session.

Vogt et al. (2012) recommend using a within-subjects design to reduce the impact of differences between participants. Exposing each participant to all treatments removes the variability between participants since the effect on the DV is compared to other treatment results from the same participant. Field (2013) points out that in a within-subjects design, the participant’s performance for each treatment condition should be highly related. This relationship corresponds to a lower unsystematic variation, or noise, when using a repeated-measures design than a between-subjects design (Field, 2013). With lower noise, the effect of the experimental treatment (systematic variation) is more apparent and will yield a larger effect size (Field, 2013). Since the focus of this study is on the difference or change in performance due to latency and not on an absolute score of performance, a within-subjects repeated measures design will “have more power to detect effects than independent designs" (Field, 2013, p. 18). Therefore, the most appropriate experimental design to answer the research question is a within-subjects repeated measure design.

Population/Sample

Population and sampling frame. All fighter pilots are trained in air-to-air combat, but the level of training and proficiency can vary depending on the aircraft and mission. In order to ensure tactical currency and maintain a homogenous population, participants were current fighter pilots or former fighter pilots who have maintained flight currency in the past five years. All participants have completed basic and advanced air-to-air training and have achieved a qualification equivalent to 4-Ship Flight Lead (USAF) or Division Lead (USN and USMC). Only manned fighter pilots with air-to-air mission qualification in aircraft such as the F-15C, F-15E, F-16C, F-18, F-22, and F-35 were considered. Pilots who have graduated from USN Top Gun or USAF WIC were preferred due to their advanced knowledge, skill, training, and proficiency. While the total number in this population is not openly available to the public, Mattock, Asch, Hosek, and Boito (2019) estimated the current USAF active duty fighter pilot population to be 3,050 with a 6.5% separation/retirement rate per year. The USN and USMC together approximately double this population. Therefore, the population of this study was active duty and veteran fighter pilots qualified in a fighter aircraft with an air-to-air mission and pilot currency in the past five years.

The largest concentrations of pilots fitting the population are stationed near primary USN, USMC, and USAF fighter bases such as Naval Air Station Fallon, Nellis Air Force Base, and Marine Corps Air Station Yuma. The largest concentration is at Nellis Air Force Base with estimates indicating that approximately 215 active duty fighter pilots and 125 veteran fighter pilots are available. This presents a unique opportunity to collect data at one location while ensuring access to pilots with various aircraft experience. Therefore, the sampling frame for this study included active duty and veteran fighter pilots stationed at or visiting Nellis AFB. Permission to include active duty pilots was obtained through coordination with the AFRL. The simulation system was transported to the location where data collection took place.

Sample size. The a priori sample size was calculated in G*Power 3.0.10 for each factor in the repeated measures, within factors ANOVA (Faul, 2016). Since G*Power only allows for one within-subjects and/or one between-subjects factor, a single output will not capture the required sample size for this experiment containing two within-subjects variables. Two G*Power calculations were generated to find the worst-case sample size for an ANOVA comparing the DV means of IV_1 and another for IV_2.

The parameter labels in G*Power do not reflect the standard statistical or experimental nomenclature for a repeated measures ANOVA. The parameter "groups" refers to the number of levels of the factor, and "repetition" refers to the number of levels in which each subject participated. To calculate the sample size required for IV_1, the parameters included a small effect size (0.20), alpha (0.05), power (0.8), number of groups (6), repetitions (6), correlation among measures (0.5), and nonsphericity correlation (.75; Cunningham, 2007). Also, consideration must be given to the possibility of violating the assumption of sphericity. Verma (2016) discussed a moderate violation of sphericity where the nonsphericity correction (ε) is approximately .75 which was adopted for this calculation. Given these inputs, G*Power calculated the IV_1 required sample size as 36 which should be considered conservative given the likely effect size (Faul, 2016). A similar calculation was performed for IV_2 with the only change being the number of groups (2) and repetitions (2) which yielded a required sample of 52. See Figures 7 and 8.

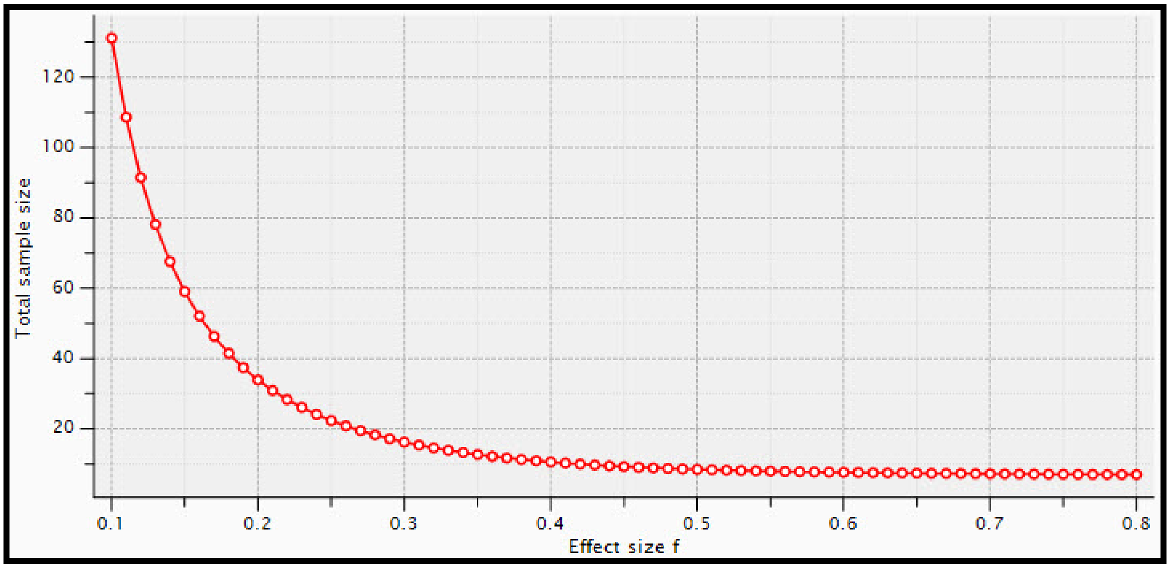


Figure 7. Sample size of IV$_1$ as a function of effect size. Adapted from "G*Power (Version 3.0.10) [Computer software]" by F. Faul, 2016.

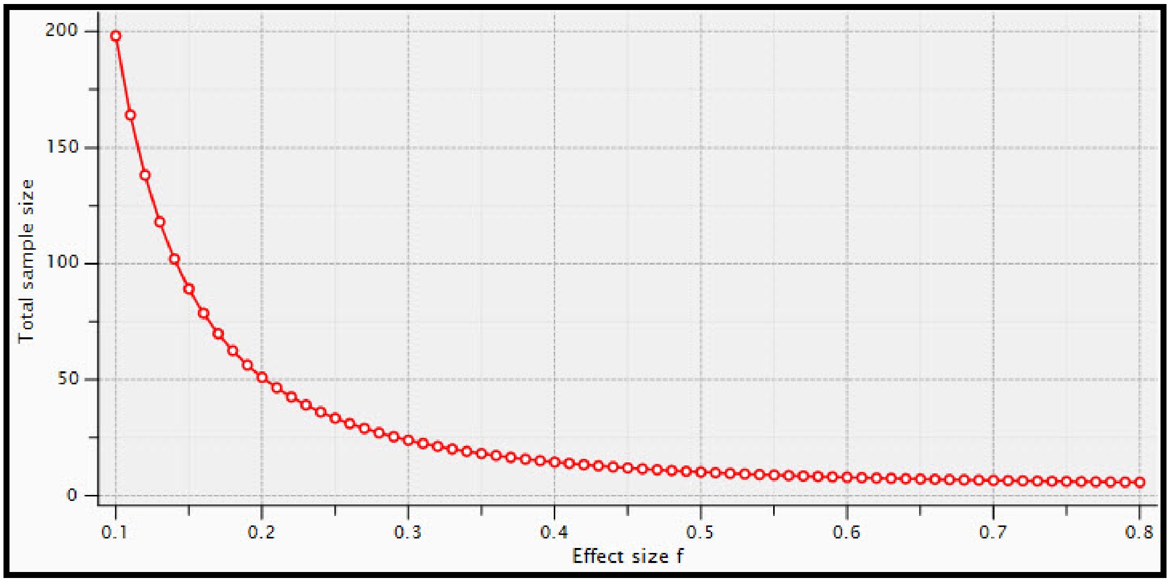


Figure 8. Sample size for IV$_2$ as a function of effect size. Adapted from "G*Power (Version 3.0.10) [Computer software]" by F. Faul, 2016.

While these inputs are relatively standard for a two-way repeated measures ANOVA, previous research in teleoperation indicates a medium effect size should be expected, although a small effect size is used in this calculation (Gorsich et al., 2018). Sample size calculations for a small to medium effect size (.35) decreases the sample size to 18 and 20, respectively, while increasing the correlation among measures to 0.75 had the same effect. G*Power generated plots of sample size versus effect size for IV_1 and IV_2 can be seen in Figures 7 and 8, respectively. Given this information, the desired sample size was 52 and was a conservative target for this study.

Since the effect size calculation for a repeated measures ANOVA is not calculated the same as for an independent ANOVA, some clarity is required. In a repeated measures ANOVA, the effect size of the main ANOVA is not as useful as the effect in the pairwise comparison (Field, 2013). For this research, the effect size for each IV was calculated along with the p-value for each treatment category compared to the previous treatment category to determine if there was a statistically significant difference (e.g., treatment D was compared to treatment C).

Sampling strategy. The sampling strategy purposefully selected participants from the sampling frame. Participant recruitment took place through on-site advertisement and email invitation from the commander. The principal investigator-initiated selection ensured purposeful sampling was maintained (i.e., ensuring a mix of pilots from different fighter aircraft). The recruitment information included a description of the research, eligibility requirements, risks to the participant, expected duration, benefits to the field, and incentive for participants. Participant prescreening, management, and scheduling was accomplished through face-to-face discussions to ensure each subject met the participant qualifying criteria. This information was destroyed after the completion of the simulation to ensure confidentiality of the participants.

Data Collection Process

Design and procedures. Data collection took place at Nellis AFB using the simulation system. Participants received appropriate demographic prescreening prior to participation to ensure population compliance. Each subject was scheduled for an individual 60-minute simulation period which is less than the 90-minute time period allotted to a typical simulation training flight (P. Zuppas, personal communication, May 25, 2019). The subjects were offered an incentive to participate in the research consisting of a coffee shop $10 gift card funded by the PI.

The simulation period began with a 5-minute introduction including the purpose of the research, description of the simulation, the subject's objective during simulation, safety, and acknowledgment of pertinent IRB and consent information. Following the scripted introduction, each subject experienced a 10-minute simulation familiarization and practice period followed by 12, 2-minute recorded experimental data runs (i.e., 6 runs for high-speed and 6 runs for low-speed). The objective of the familiarization and practice period was for the subject to become accustomed to the performance of the simulated aircraft, become familiar with the simulation environment, and comfortable with the VR headset. While many repeated measure experiments attempt to avoid learning or the carry-over effect, this experiment intended for the subjects to learn as much as possible before data collection (Gorsich et al., 2018). The practice period also aligns with the fact that all military pilots receive extensive training on their weapon systems to understand its strengths and weaknesses before entering combat. The familiarization and practice period also reduced the effects of confounding variables such as non-familiarity with the simulation hardware/software, control manipulation, and display systems. Simulation familiarity and practice are common for experiments of this type (Gorsich et al., 2018). Following the familiarization and practice period, the experimental data runs ensued.

The experimental sequence consisted of 12 engagements with an approximate duration of 120 seconds each. Based on results from the field test, the high-speed engagement concluded after 105 seconds, while the low-speed engagement concluded in 90 seconds. After each engagement, there was a 45-60 second rest period prior to the next run. For each engagement, one of the six preset latency categories was assigned through a balanced Latin square design until all latency levels were experienced by each subject, on each engagement type. The treatment order was assigned through a Latin square balanced to control for first-order carry-over effects. The subjects were blind to which category and order of latency they are receiving. However, the pilot became aware of the amount of latency after the first few seconds of the experimental run. The experiment was a within-subjects, repeated measures design utilizing a Latin square for counterbalancing.

The parameters of each engagement were closely controlled. The data runs for each category of fight (i.e., high-speed and low-speed) began from the same starting point, altitude, and range saved in the primary test profile. However, each engagement varied the adversary starting velocity vector, introducing slight differences in the engagement geometry; this input was made to decrease predictability. Both the target and the attacking aircraft remained the same (airframe performance, visual depiction, and avionics). The high-speed simulation runs began with the attacker (subject) placed 3.5 NM from the target aircraft, while the low-speed engagements were from a line-abreast formation. For the high-speed engagement, both aircraft began the engagement at 450 KTAS (232 m/s), 20,000 feet (6,098 m) mean sea level (MSL), and approximately pointed at the other aircraft, as defined by USAF (2005) and USN (2016). Each low-speed simulation run began with both aircraft at 250 KTAS (129 m/s). These parameters are similar to those stated in USAF (2005) and USN (2016) as typical high aspect WVR starting parameters. The adversary (target) flight AI profile was set to “expert,” commanding the target aircraft to attempt to shoot the attacker throughout the engagement.

The adversary AI in the simulation software allows specific profiles to be selected. The adversary profiles are similar to those installed in current fighter simulators to approximate the fighting capabilities of adversary pilots. The virtual “expert” adversary is representative of a highly-competent pilot and will take quick advantage of mistakes made by the live pilot while allowing a consistent presentation for the subjects to fight. Employing a virtual adversary versus a human adversary reduced the confounding variables introduced by inserting another human in the loop. The adversary profile was evaluated for consistency during the field test and displayed a high level of accuracy and consistency, as described by the SMEs.

Each engagement concluded at a time specified by the field test. Since an engagement CS changes throughout the fight, angles (and CS) were assessed at multiple times during the engagement. The assessment occurred near the end of the engagement and consisted of three measurements which were at start + 1:15, 1:30, and 1:45 for the high-speed engagements and start + 1:00, 1:15, and 1:30 for the low-speed engagements. The assessment times were determined during the field test. All engagements were recorded through the simulation system at a parametric update rate of greater than 10Hz for posttest analysis and data collection.

Apparatus and materials. The experiment took place in a purpose-built simulator funded through a grant from Embry-Riddle Aeronautical University (ERAU). The simulator consists of a Volair Simulation Cockpit, Thrustmaster HOTAS Warthog Stick and Throttle quadrants, 48 in curved Samsung display, 24-core Dell Alienware Area-51 gaming computer specifically designed for high-resolution virtual reality, and a Vive Pro virtual reality headset. The simulator software was the Digital Combat Simulator (DCS) by Eagle Dynamics. This software, developed by the fighter SMEs at The Fighter Collection, is designed with highly accurate aircraft performance and adversary tactics models (https:www.digitalcombatsimulator.com). The DCS includes specific tailoring of authentic adversary tactics allowing precise control and a suite of data retrieval tools. Additionally, the AFRL Modern Air Combat Environment (MACE) and SMEs were used to ensure the aircraft and adversary simulation models were appropriate for the study. MACE is an AFRL and DoD approved air combat simulation.

A unique requirement for this experiment was inducing a system delay. To achieve this, original computer code was developed in the form of a unique Windows driver for which the PI retains copyright. The driver is delay-selectable allowing an input range from 0.000 to 2.000 seconds in 0.001 second increments. The delay is certified by the developer to an accuracy of ±0.0015 seconds (1.5 milliseconds). The delay was placed between the pilot controls and the simulation software allowing the PI to manipulate IV_1, as depicted in Figure 9. The signal processing path was tested prior to each simulation session to ensure the system was operating correctly.

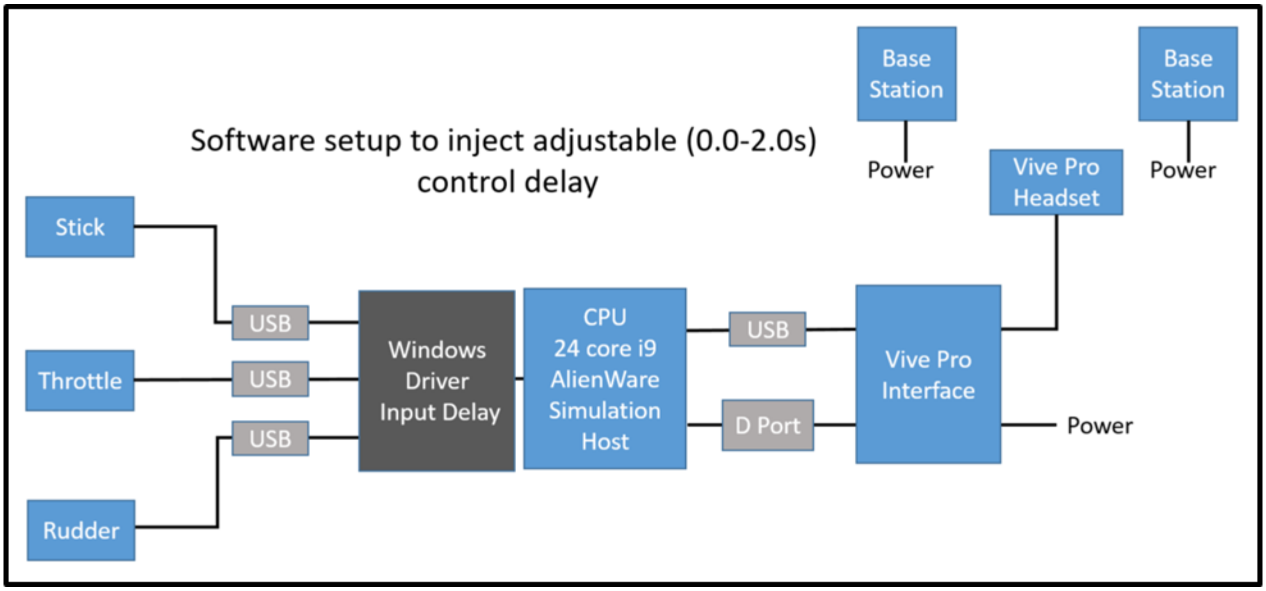
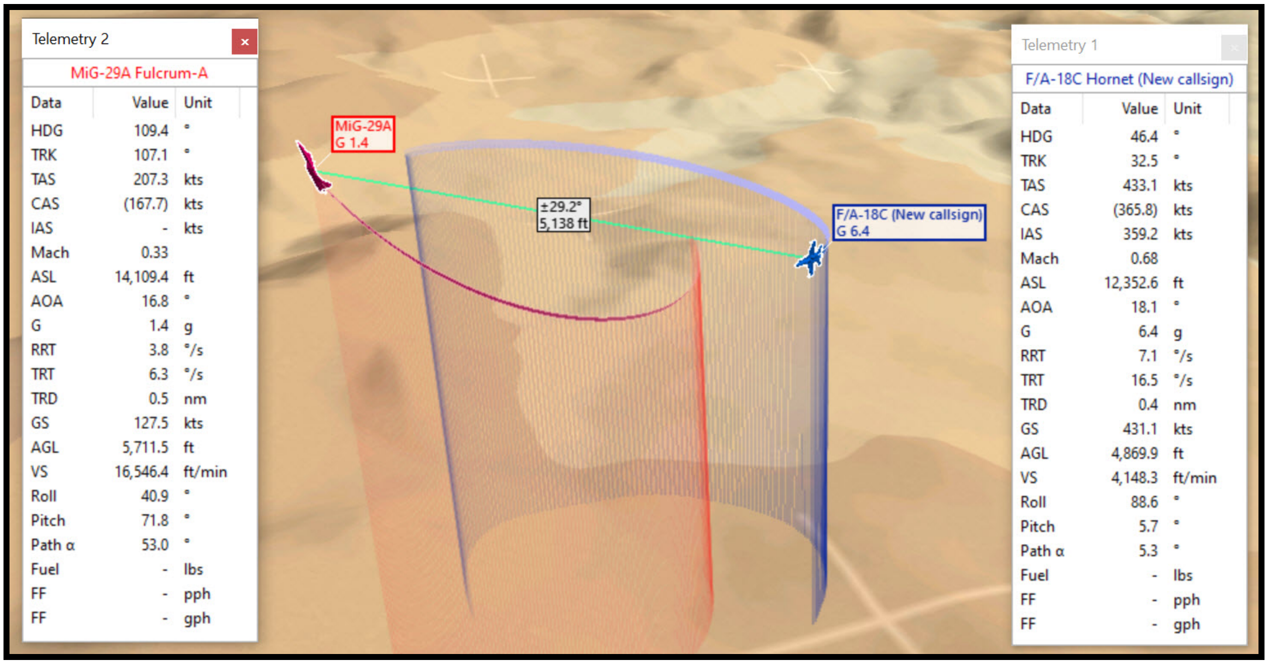


Figure 9. Block diagram of the simulation hardware and latency input control device.

Sources of the data. Since empirical data was harvested directly from the simulation, the only permissions required were realized through the IRB process. The data source was through the tactical debrief software TacView, as seen in Figure 10 (https://www.tacview.net). TacView provides performance and pairing data required for the DV calculation. Data from each experimental run was saved on the simulation computer and backed up on an external drive for future analysis. The values for the target deviation angle and attacker deviation angle were harvested from the pairing data for input into Equation 1 to yield the DV. None of the data was proprietary or classified nor were other permissions required.



Telemetry 2

MiG-29A Fulcrum-A

Data	Value	Unit
HDG	109.4	°
TRK	107.1	°
TAS	207.3	kts
CAS	(167.7)	kts
IAS	-	kts
Mach	0.33	
ASL	14,109.4	ft
AOA	16.8	°
G	1.4	g
RRT	3.8	°/s
TRT	6.3	°/s
TRD	0.5	nm
GS	127.5	kts
AGL	5,711.5	ft
VS	16,546.4	ft/min
Roll	40.9	°
Pitch	71.8	°
Path α	53.0	°
Fuel	-	lbs
FF	-	pph
FF	-	gph

Telemetry 1

F/A-18C Hornet (New callsign)

Data	Value	Unit
HDG	46.4	°
TRK	32.5	°
TAS	433.1	kts
CAS	(365.8)	kts
IAS	359.2	kts
Mach	0.68	
ASL	12,352.6	ft
AOA	18.1	°
G	6.4	g
RRT	7.1	°/s
TRT	16.5	°/s
TRD	0.4	nm
GS	431.1	kts
AGL	4,869.9	ft
VS	4,148.3	ft/min
Roll	88.6	°
Pitch	5.7	°
Path α	5.3	°
Fuel	-	lbs
FF	-	pph
FF	-	gph

Figure 10. Tacview debriefing software and associated performance and pairing data. Adapted from TacView (Version 1.8.0).

Ethical Consideration

An IRB was required for this study since it utilized human subjects from which data was collected. Protection of the human participant's rights, welfare, and privacy was paramount. The researcher completed Collaborative Institutional Training Initiative (CITI) training and all other ERAU IRB requirements. The ERAU IRB concluded that the study is "exempt." Follow-on coordination with the AFRL and the USAF Warfare Center allowed the subjects to include active duty pilots. Informed consent forms complied with the specific requirements from the ERAU IRB process and were discussed prior to subject participation.

The experiment was confidential; only the PI had access to identifying knowledge, allowing data to be matched to the participant. There were three main concerns for inadvertently disclosing the identity of the subjects: through the PI's knowledge of the participants, demographic data, and simulation recordings. To safeguard the participant's identity, only the PI was aware of and able to match the data with the participant's identity. Neither personally identifiable information nor demographic data was gathered during the simulation. The simulation test data was stored on a password protected computer only accessible by the PI. In no case was the participant's identification gathered or recorded. Since the simulation recordings did not include video, audio, or any information linking the data to the pilot, the data was archived at the completion of data analysis.

The impact of COVID-19 on the study required additional safety measures during the experiment. Military operational flight units have implemented procedures to protect individuals from COVID exposure, and similar procedures were adopted for this study. Procedures were put in place to limit physical proximity and sterilize equipment. This included temperature evaluations, the use of masks, room occupancy limitations, and robust cleaning practices. Subjects were screened for temperature and symptoms prior to entering the facility, VR face covering were used, and the simulation hardware was sterilized between subjects with an Ultraviolet-C light and wipes.

Measurement Instrument

Variables and scales. The Independent Variables (IV), often referred to as the *within-subjects factors*, are the total latency (IV_1) induced into the simulation system through the delay driver and the engagement type (IV_2). The IV_1 is operationalized by assigning the given latency to the delay driver. There are several considerations when bounding IV_1. The lower limit approaching $t = 0$ corresponds to low/no latency, such as the case with a manned aircraft where the pilot can see the other aircraft and control inputs are immediately transferred to the aircraft. The upper limit of possible latency varies depending on the source considered. However, discussions with Lt. Colonel B. Opp, a current MQ-9 pilot, estimates the maximum round trip transmission latency (t) to be no longer than 2.0 seconds (personal communication, May 15, 2020). His operational observation is based on thousands of hours of RPA flying and corresponds to de Vreis (2005) prediction of a maximum delay of 1.672 seconds, not considering trans-Atlantic transmission times. Therefore, this dissertation planned to test the IV_1 at values (or treatments) $0.0 \leq t \leq 2.0$, where t is the assigned latency. However, during the field test, control of the aircraft became marginal with delays of 1.5 seconds and beyond due to pilot-induced oscillations. Therefore, the maximum latency tested in the trials was limited to 1.25 seconds. The interval between delay settings must take into consideration enough granularity to identify changes in the DV while maintaining an acceptable number of trials for each simulation session/subject. Based on previous literature and maximum simulation time of 1.5 hours, the treatment interval of 0.25 seconds (0.00, 0.25 0.50, 0.75, 1.00, 1.25) was selected. While the IV_1 corresponds to a specific time, the experiment treated each time as a separate treatment identified as A through F. The IV_1 is classified as an ordinal, categorical variable.

The second independent variable (IV_2) is the engagement entry speed: high-speed or low-speed. The specific engagement types are described in Chapter 2 and operationalized by the engagement starting parameters. The subjects experienced each engagement type six times with the corresponding treatment of IV_1 varying on each test run. Therefore, each subject completed 12 test runs during the simulation. The IV_2 is classified as a nominal, categorical variable.

The Dependent Variable (DV) is the calculated combat score of the engagement. The score was derived from specific angles at the conclusion of the engagement, as defined by Shin, Lee, Kim, and Shim (2018) and described in USAF (2005). The CS is defined by Equation (1):

$$\text{CS} = \frac{(\pi - |\lambda A|)^2 - (\pi - |\lambda T|)^2}{\pi^2} \tag{1}$$

where λA is the deviation angle (in radians) of the attacker, and λT is the deviation of the target as defined in Figure 11.

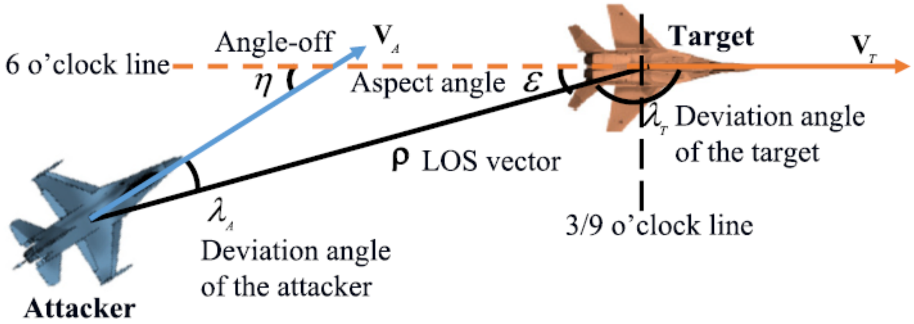


Figure 11. Angular definitions for computation of CS. Adapted from "An autonomous aerial combat framework for two-on-two engagements based on basic fighter maneuvers" by H. Shin, J. Lee, H. Kim, and D. Shim, 2018, *Aerospace Science and Technology, 72,* p. 306. Copyright 2017 by Elsevier Masson SAS.

While the computation of CS does not directly measure combat success, it codifies the likely outcome of the engagement, as described by USAF (2005) and Shin et al. (2018). The CS is, in effect, the normalization of a geometric relationship between the attacker and the target, where 1.0 equates to the optimal offensive position (i.e., attacker directly behind and pointing at the target where λA = 0 and λT = π), and -1.0 indicates the worst possible defensive position (i.e., attacker directly in front of the target where λA = π and λT = 0). Several examples of the computed CS for various geometries between the attacker (A) and target (T) are displayed in Figure 12. The DV (CS) is continuous and measured at the ratio level.

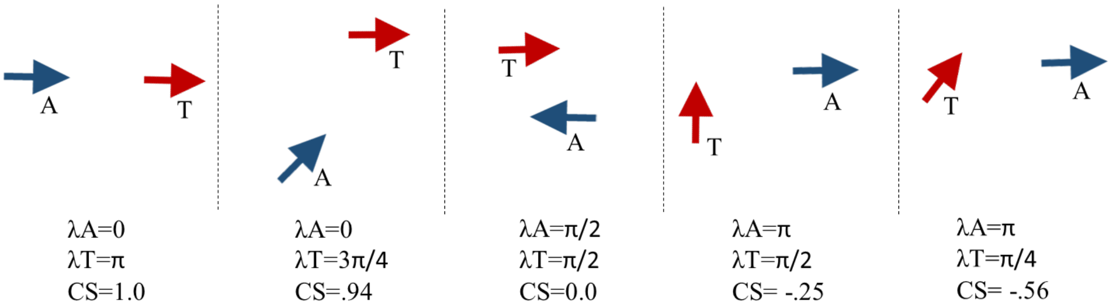


Figure 12. Examples of computed CS for various engagement geometries.

Data Analysis Approach

Reliability assessment method. Validity and reliability are important in all research. Although several forms of validity may be considered, for a within-subjects experiment, internal, construct, and external validity are of particular importance and further discussed in this section. Reliability, or "…the consistency of coding or measurement" (Vogt et al., 2012, p. 321) is typically discussed in terms of interrater, test-retest, and internal consistency reliability. Interrater, or measurement reliability for this experiment, and test-retest reliability are expanded to support the argument for design reliability.

Vogt et al. (2012) describe experimental reliability as "…the consistency or stability of an observation, measurement, or test from one instance to the next" (p. 349). For this dissertation, there are two areas of application: measurement consistency and test-retest consistency. Measurement consistency in this experiment was supported by digital parameter retrieval from the simulation program resulting in a highly accurate and consistent 3D angle measurement for input to the CS equation (Equation 1). The principal researcher was present for every simulation period ensuring homogeneity of instruction, scenario, and collection. The inherent strengths of a within-subjects experiment help to increase test-retest reliability. This is because the subjects serve as their own control during the experiment. Many of the threats to test-retest reliability are also considerations for internal validity specifically, fatigue and order effects. The field test specifically addressed test-retest reliability by subjecting SMEs to the same treatment level that produced consistent results.

Validity assessment method. Interval validity refers to the systematic error or bias in an experiment and ensures that the effect on the DV can be attributed to the IVs (Shadish, 2002). In a repeated measures experiment, each subject serves as their own control, thereby variability between subjects is reduced over a similar between-subjects experiment (Creswell, 2014; Verma, 2016). However, potential threats to internal validity in a repeated measure experiment include practice, fatigue, sensitization, attrition, and order effects (Vogt, Gardner, & Haeffele, 2012). Negative practice effects were reduced by the practice simulation session as discussed in the Design and Procedures section. Fatigue was minimized by limiting the simulation session to 1.0 hour, which is a shorter duration than the standard simulation period to which pilots in the population are accustomed (1.5 hours). Sensitization was not a threat for this experiment since the DV is a measure of performance. Attrition during the simulation was a consideration. However, there were no cases of attrition during the simulation, most likely due to the standard simulation duration and intensity of training of which the fighter pilots normally experience. While 12 data runs appear to be a substantial task, this intensity is less than that experienced in normal training for the targeted population.

The threat of carryover effect (order effect) was reduced by semi-randomly assigning the treatment order for each subject through a balanced Latin Square crossover matrix for each engagement velocity (i.e., two, 6x6 matrices, one for each velocity). Since a completely counterbalanced design would require *n*! participants (where *n* = number of treatments at each speed, or 6), it was not reasonable to recruit 720 subjects (Williams, 1949). The Williams' Design is a common method used to decrease carryover effect within small samples. For a set of six-treatments, the treatment order was determined by the sequence (*1, 2, n, 3, n-1, 4*) which yielded the matrix in Figure 13 (Williams, 1949). This matrix was applied for each engagement velocity, reducing the carryover effect resulting from the order of which latency levels were applied. Additionally, the field test indicated that subjects that were aware of the treatment order were no more successful than those who did not.

Subject	Treatment Order					
1	A	B	F	C	E	D
2	B	C	A	D	F	E
3	C	D	B	E	A	F
4	D	E	C	F	B	A
5	E	F	D	A	C	B
6	F	A	E	B	D	C

Figure 13. Balance Latin square for six treatments.

Control of possible covariates must be considered as well. Vogt, Gardner, and Haeffele (2012) describe the need to control covariates to reduce or eliminate other possible influences on the causal relationship between the IV and DV. Several methods are discussed including the use of a within-subjects design and Latin squares, both of which are adopted for this dissertation. Since a within-subjects design uses each participant as their own control and focuses on changes to the DV versus values of the DV, many of the possible covariates are eliminated or held constant for the individual subject. The balanced Latin square is employed to reduce the possibility of order and learning effect. This along with the researcher's ability to administer the IV and assign treatments helps to ensure internal validity (Vogt et al., 2012).

There are two main considerations for construct validity, or the correspondence between the experimental procedures and the theoretical construct (Shadish, 2002). The first is the validity of the latency variable IV_1. Since the variable is considered quantification of Boyd's decision process, it represents an accurate delay in the completion of the OODA Loop and, according to Boyd (1977), will influence the success of the operation. Although Boyd's (1977) Orient and Decide phases may fluctuate at a participant level, they were considered constant for the sampled participants. Since, in repeated measures design, each participant acts as their own control, the differences between pilots in the Orient and Decide phases will not affect the construct validity. Additionally, IV_1 represents the total delay in the system feedback loop or the total round-trip latency. Combining the outgoing and incoming latencies is a common practice in teleoperation latency experiments (Conklin, 1957; Corde et al., 2002; Gorsich et al., 2018). The results of studies using this technique, including this dissertation, should be interpreted as the best case scenario for a given latency level.

The second consideration for construct validity is the degree to which the CS relates to success in combat. Since the CS is derived from the relative position of each aircraft at the conclusion of the engagement, the question becomes whether the desired position (CS = 1) significantly increases success in combat. Given that this position allows the attacker to best employ all weapons on the target aircraft (radar missile, IR missile, gun) while the opposite position (CS = -1) does not allow any weapons employment, construct validity at the extreme values is ensured (USAF, 2005; USN, 2016). Intermediate values of CS also align with the definitions of an offensive and defensive position by both the USAF (2005) and USN (2016). At low levels where CS approaches 0.0 and rapid changes in the sign of CS may occur (e.g., -0.10 to +0.10), it is difficult to evaluate an advantage. However, the CS equation is less sensitive to situations where both deviation angles are large since the numerator approaches zero exponentially. For this reason, small changes in an angle near a neutral situation will not overly influence the CS. Additionally, three CS measurements for each engagement were averaged as informed by the field test, resulting in a more valid score.

Vogt et al. (2014) describe external validity (or generalizability) as whether the conclusions of the experiment can be applied beyond the participants to the population and is dependent on the appropriateness of the sample. The population for this dissertation is highly trained military pilots; the same level of pilots typically chosen to pioneer the use of new fighter aircraft. All of the pilots in the population have completed multiple, similarly structured, and rigorous military training regimens. Therefore, the knowledge, skills, and abilities among the population are considered homogeneous, and the results from the sample can be aptly generalized throughout the population.

The ability to transfer research conclusions to other populations and environments is defined as research transferability. While this dissertation is focused on control latency, it applies to autonomous systems as well. An autonomous system requires accurate sensor input to determine internal and external geometry. In a highly dynamic environment, the sensor data could be corrupted, delayed, spoofed, or inaccurate. These breaks in accurate sensor data are similar to a teleoperation transmission delay. In both cases (human operator or automated), the decision-making information (OODA Loop taxonomy) is delayed or inaccurate causing the operator to act on imperfect data. The information obtained from this dissertation can inform future engineers of the latency effects in applications such as sense and avoid, ground avoidance, and takeoff and landing operations.

A key to ensuring reliability and validity is the field test. The field test took place prior to the data collection phase through the use of SMEs. A field test is appropriate since the objective was for SMEs to provide feedback on the simulation setup, engagement parameters, and data collection points to increase credibility, reliability, and validity. The SMEs did not provide recorded data during the field test. The goal was for a few SMEs to fine-tune the experimental process to enable high-quality data during the experimental phase. The SMEs participating in the field test were barred from participating in the experiment. The specific objectives of the field test were:

- Test the simulation system in a field environment.
- Confirm the upper limit of latency to bound the experiment.
- Confirm an effective latency interval for each treatment.
- Confirm engagement time at which to measure the CS.

- Confirm reliability in a test-retest process.
- Confirm the interval at which to measure the CS.

Data analysis process/hypothesis testing. A two-way repeated measures ANOVA tested whether the mean of the dependent variable varied by latency treatments levels and each tactical scenario (i.e., high-speed and low-speed). The results determined if there was a significant difference between the treatments on the population and if there was an interaction effect between the IVs. If there is a significant statistical difference ($p < .05$), then further analysis will be performed with custom contrasts (Field, 2013; Verma, 2016). However, the ANOVA only determines if there was a statistical difference in treatments on the DV, not which treatment is significant or how many of the treatments are significantly different. In order to determine which specific treatment is significant, more tests were required. For this, pairwise comparisons are more appropriate than a post hoc test because the DV is expected to decrease with an increased latency, and only two treatment levels were compared at once (e.g., latency A compared to latency B).

Assumptions. The assumptions associated with the two-way repeated measures ANOVA include:

1. The IV is categorical with three or more values.
2. The DV is continuous.
3. There are no significant outliers.
4. The DV is approximately normally distributed.
5. No significant sphericity exists in the data (Field, 2013; Verma, 2016).

The first two assumptions are fulfilled through the research design, and the last three are determined during data analysis. If any of the data-driven assumptions are not met, methods are employed to correct for the unfulfilled assumption. Outliers were identified through data exploration, specifically the box plot and studentized residuals. If outliers are present, further investigation will determine whether to retain, remove, or alter the data point(s). The Shapiro-Wilk test for normality will be used to test normality for each within-subjects factor. Significance levels greater than .05 ($p > .05$) indicate an acceptable level of normality. Should any of the data be non-normal, data transformation will be attempted. However, since the ANOVA is considered robust against deviations from normality, continuing the analysis with non-normal data will be considered (Field, 2013; Verma, 2016).

The sphericity assumption is commonly violated in repeated measures experiments and can lead to Type I errors. This assumption will be tested by Mauchly's Test of Sphericity where non-significant results ($p > .05$) indicate that the assumption is met. Should the assumption of sphericity be violated, the degrees of freedom (*df*) are modified to correct the validity of the F-value. The selected correction method is based on the severity of the violation (ε), but in most cases, the Greenhouse-Geisser correction is used if $\varepsilon < 0.75$ (Verma, 2016).

Custom contrasts is a method used to compare the means of treatments to identify statistical differences in a repeated-measures ANOVA. A subset of custom contrast is simple contrast that compares two treatment means. For example, the two-way repeated measures ANOVA only describes whether there is a significant difference somewhere in the treatments, simple contrasts will determine specific differences (e.g., compare treatment A to treatment B). The analysis of each treatment compared to the next through simple contrasts (i.e., pairwise comparison) will give insight to where and how the combat score decreases with treatment level. Once the simple contrasts are completed for both tactical scenarios, they will be compared to determine whether there is a difference between how latency affects the scenarios (e.g., is the degradation caused by latency more pronounced in one tactic over the other).

Summary

This research utilized an experimental design with highly trained air-to-air military pilots as the population. The ERAU IRB determined the experiment to be in the exempt category and the AFRL IRB agreed, allowing collection from active duty pilots. The experimental design was within-subjects and employed a repeated measures factorial strategy in order to minimize the effect of differences between participants (Field, 2013). Since each participant acts as their own control, the effect size is expected to be larger than a similar between-subjects architecture. The data was collected through a purpose built simulator and harvested by tactical debrief software. The hypotheses were tested by way of a two-way repeated measures ANOVA and pairwise comparison.

CHAPTER IV

RESULTS

The purpose of this research was to determine the effects of latency on combat success during a WVR air-to-air combat engagement. The research was approved through the ERAU IRB process for human subjects and pursued in coordination with the Air Force Research Laboratory and the United States Air Force Warfare Center. A purposeful sampling method allowed selection of 29 active duty fighter pilots across a broad range of combat aircraft. A purpose built VR simulator running proprietary latency-injection software was used to collect data, as illustrated in Figure 14. Each pilot experienced all six latencies in both high-speed and low-speed engagements which were scored to evaluate the combat success of each engagement. A two-way repeated measures ANOVA was used to determine the relationship between the IVs and DVs. The results indicate that there was a statistically significant interaction effect between engagement entry speed and latency. This interaction illustrates that the effect of latency on combat score varies in a different way depending on the engagement starting speed. The effects of latency and engagement speed on combat score were also statistically significant.

Field Test

A field test was conducted prior to finalizing the simulation scenarios and collection points. Three fighter pilot SMEs were used for the study. A field test was appropriate since the objective was for SMEs to provide feedback on the simulation setup, engagement parameters, and data collection points to increase credibility, reliability, and validity. The specific objectives of the field test were:

- Test the simulation system in a field environment.
- Confirm the upper limit of delay to bound the experiment.
- Confirm an effective delay step for each treatment.

- Confirm engagement time at which to measure the CS.
- Confirm reliability in a test-retest process.
- Confirm the intervals at which to measure the CS.

At the conclusion of the field test, it was determined that a control latency of 1500 ms and above commonly produced severe pilot induced oscillations (PIO) which made aircraft control difficult. Several ground impacts occurred at 1500 to 2000 ms. Due to this result, the maximum latency for the experiment was limited to 1250 ms, and the interval between latency treatments was decreased to 250 ms, yielding treatments of 0000, 0250, 0500, 0750, 1000, and 1250 ms.

Engagement assessment times were established during the field test for both the high and low-speed starting parameters, in order to increase test-retest reliability. A single assessment time (e.g., at 1.00 min into the engagement) did not result in an accurate or consistent combat score, as determined by the SMEs. Therefore, three assessment times of 1:00, 1:15, and 1:30 after the merge occurred were averaged in order to determine a more accurate depiction of the engagement. The SMEs concluded that the averaging over three data points delivered a more reliable and valid CS. Considering the attackers average turn rate of approximately 24 deg/s resulting in a 360 deg turn in 15 s, the interval for engagement assessment was determined to be 15 s. An additional 15 seconds was added to the assessment points for the high-speed engagement to allow for the time between simulation start and the merge. Therefore, the assessment times for the high-speed engagement occurred at 75, 90, and 105 post merge, while the low-speed assessments were schedule for 60, 75, and 90 s.

Demographics Results

A sample of 29 participants, which included 348 separate and distinct engagements over the 12 IV combinations, was collected at a military base between October 26, 2020, and

November 2, 2020, as seen in Figure 14. One participant was removed for outliers and will be discussed. All of the pilots were screened prior to simulation entry to ensure compliance with the sample requirements and confirmed by local personnel. The sample was purposely recruited by word of mouth and included pilots from the F-15C, F-15E, F-16C, F-22, and F35. Simulation periods were both scheduled and ad hoc and took place in a private office supplied by the base. Due to the active-duty status of subjects involved, the confidential nature of the IRB, and subsequent AFRL approval, no demographics or personally identifiable information was collected. All of the participants were highly experienced male fighter pilots.

The sample size requirements in Chapter 3 were calculated for both a small and small-to-medium effects size. Previous research on the effect of latency in teleoperations indicated a medium effect size or larger, which was also expected in this dissertation experiment. As seen in Figure 7 and Figure 8, the expected sample size given a small to medium effect size was 20. The results of this dissertation research showed a large effect size of both latency and engagement speed on combat score. Given a large effect size, the minimum sample size was 10 participants.

COVID-19 protocols for both ERAU and the base were followed for participant safety. This included temperature evaluation, the use of VR masks, limiting room occupancy, sanitizing the simulation between subjects with alcohol wipes and UVC light, and frequent hand washing and sanitization.

Descriptive Statistics

Each engagement (348 total) was scored at three assessment times, in order to record a reliable measurement of each engagement. The average of the three assessments was used as the combat score for the engagement. The descriptive statistics for all of the qualified engagements (28) are listed in Table 1.

Figure 14. Experiment subject flying test profile in VR simulator.

Table 1

Descriptive Statistics of Combat Scores

IV_2	IV_1	N	Mean	SD	Min.	Max.
High-speed	0.000	28	.539	.155	.096	.869
	0.250	28	.491	.152	.098	.821
	0.500	28	.387	.216	-.224	.717
	0.750	28	.314	.192	-.179	.605
	1.000	28	.342	.163	-.061	.790
	1.250	28	.133	.221	-.311	.556
Low-speed	0.000	28	.659	.102	.510	.917
	0.250	28	.616	.121	.314	.932
	0.500	28	.568	.132	.332	.907
	0.750	28	.453	.136	.150	.739
	1.000	28	.308	.200	-.144	.627
	1.250	28	.189	.229	-.469	.668

The mean combat scores for each latency level are plotted in Figure 15 for the high-speed engagements and Figure 16 for the low-speed engagements. The combination of these two charts illustrates the overall mean combat score at each latency level. Figure 17 depicts how CS varied with latency when combining the high and low-speed engagement results. However, this chart should be interpreted with care since there was a statistically significant interaction effect indicating that the latency effect on CS during the high-speed engagements was not the same as during the low-speed engagements.

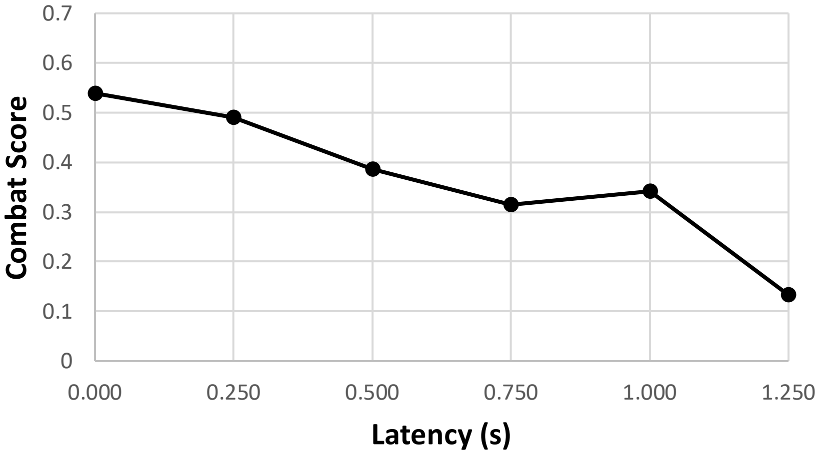


Figure 15. Mean combat scores for high-speed engagements by Latency.

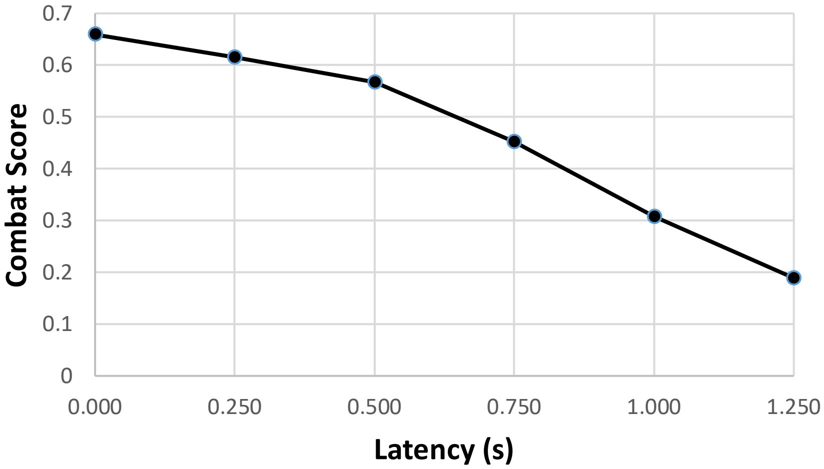


Figure 16. Mean combat scores for low-speed engagements by Latency.

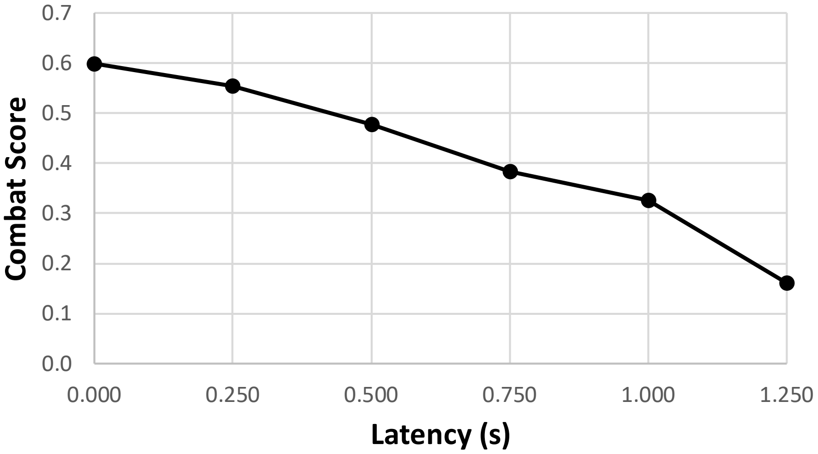


Figure 17. Mean combat scores for all engagements by Latency.

Assumption Testing Results

Two of the five assumptions for the two-way repeated measures ANOVA were incorporated into the experimental design. The other three assumptions were statistically tested: outliers, normality, and sphericity.

Outliers. The assumption of no significant outliers was tested through SPSS. Testing highlighted one participant that was responsible for two outliers (studentized residuals of values greater than ± 3). Further investigation of the participant's scores across all treatments revealed several major discrepancies and warranted further analysis. Through the use of TacView replay for each engagement, it was evident that the subject had lost sight of the adversary in several engagements and struck the ground on occasion. Due to the introduction of these uncontrolled confounding variables, the subject was removed from the sample. After the participant was removed, there were no other significant outliers. This reduced the sample size to N=28.

Sphericity. Since there are more than two levels of one of the within-subjects factors, the assumption of sphericity must be considered. The assumption was tested with Mauchly's test of sphericity for the two-way repeated measures ANOVA. Mauchly's test indicated that the assumption of sphericity was met for the two-way interaction, $x^2(14) = 23.32$, $p = .056$.

Normality. The Shapiro-Wilk test for normality, histograms, and Q-Q plots were used to determine if the DV (combat score) was normally distributed. The combat scores of all qualified engagements are show in Figure 18 and are approximately normally distributed, as seen in the histogram and confirmed in the Q-Q plot.

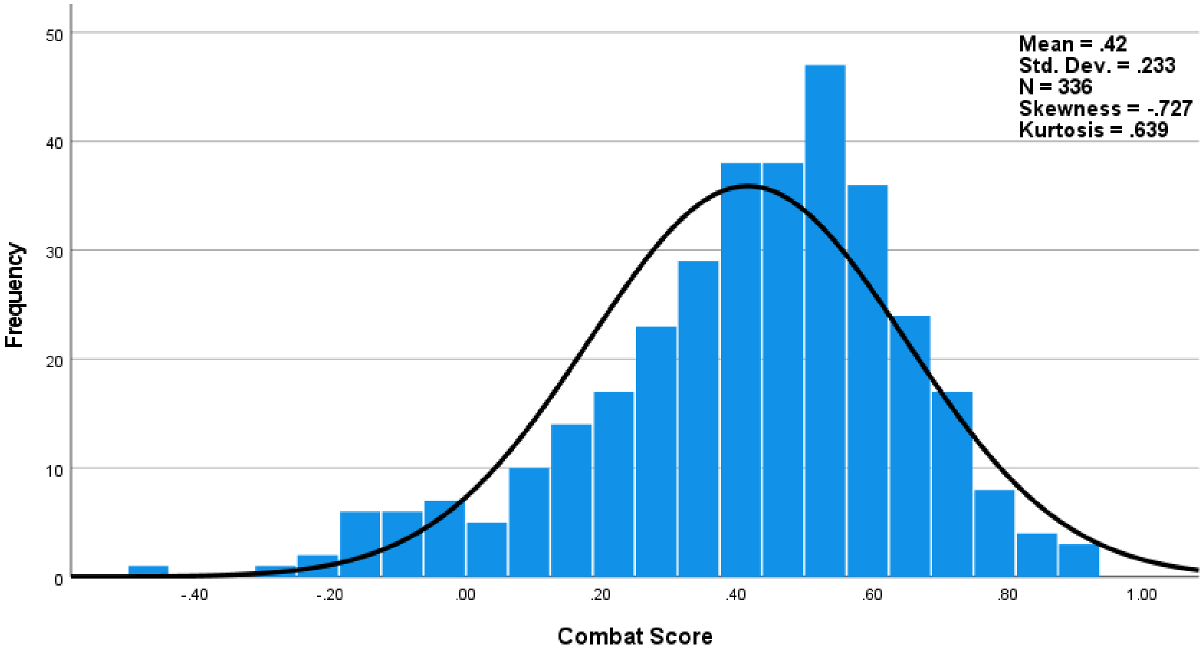


Figure 18. Histogram of all qualified engagements.

The Shapiro-Wilk test was appropriate for the *individual* treatments considering the small sample size. The individual treatment combat scores were normally distributed ($p > .05$) across the 12 treatments with three exceptions. The treatment High-speed 500 ms ($p = .005$), High-speed 750 ms ($p = .018$), and Low-speed 250 ms ($p = .034$) were found to violate the assumption of normality. Data transformation was attempted to normalize the distribution but was not successful due to the distribution of data not being similar shape throughout all combinations of the within-subjects factors. Since the ANOVA is considered robust against violations of normality and violations only existed in 3 of the 12 combinations, the choice to continue with the ANOVA was appropriate (Field, 2016; Glass, Peckham, & Sanders, 1972).

Reliability and Validity Testing Results

The reliability and validity of this study was ensured through several experimental techniques developed to increase these attributes. The field test results improved reliability by codifying the digital scoring technique and improving test-retest reliability. This was accomplished by establishing a more realistic combat score through outcome averaging over three time points versus assessing the DV at only one point in the engagement. The field test also determined the optimum time and interval for assessing the DV, further improving reliability.

The validity of the experiment was ensured by several methods including the use of a within-subjects design to minimize the impact of individual differences in performance between the subjects. Treatments were applied through the use of a balanced Latin square to control first order carry-over effects. Prior to test runs beginning, each subject received a 10 minute practice period which improved internal validity by acquainting the subject with the simulation and performance of the aircraft, eliminating confounding variable associated with nonfamiliarity.

Interaction Effect

The two-way repeated measures ANOVA indicated that there was a significant two-way interaction between engagement speed and latency, $F(5, 135) = 3.71$, $p = .004$, partial $\eta^2 = .121$. This significant interaction indicates that the effect of latency on combat score is dependent on both the amount of latency and the speed of the engagement. In other words, there is a statistically significant difference between how the high-speed and low-speed engagements react to latency. These results are consistent with the graphical depiction in Figure 19 of the estimated marginal means, which illustrates that the DV reacts differently around the 1.00 second latency treatment depending on the other within-subject factor, Engagement Speed. Therefore, the CS cannot be predicted without considering the engagement speed.

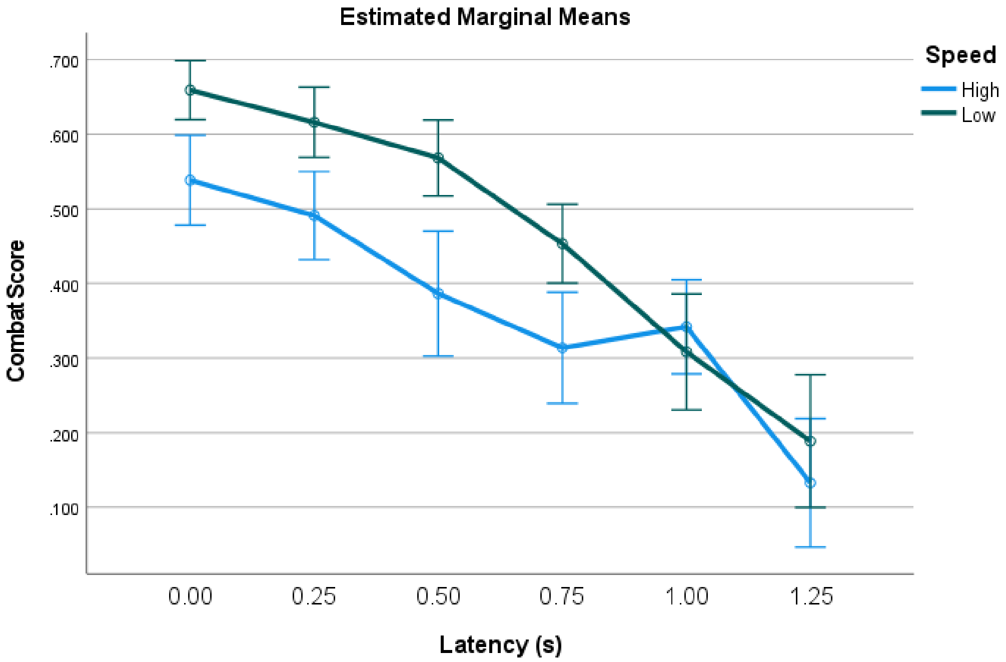


Figure 19. Plot of marginal means and 95% CI for high and low-speed engagements.

Main Effects

The main effects for a two-way repeated measures ANOVA that has a significant interaction effect must be considered cautiously. Due to the significant interaction, the main effects could be misleading or incomplete. However, exploring the main effects can yield more insight to the relationships. The main effect of engagement speed showed a significant difference between high and low-speeds with a mean difference = .098, $F(1, 27) = 15.62$, $p = .001$, partial $\eta^2 = .367$. While the interaction effect met the assumption of sphericity, the main effect of latency did not, $x^2(14) = 31.54$, $p = .005$. After applying the Greenhouse-Geisser correction, the main effect of latency was also significant, $F(3.56, 96.24) = 72.57$, $p < .001$, partial $\eta^2 = .729$. The pairwise comparisons for latency are illustrated in Table 2.

Table 2

Pairwise Comparisons for Effect of Latency (Main Effects)

	All Engagements		
Latency (s)	Latency(s)	Mean Diff	Sig.
0.000	0.250	.045	.091
	0.500	.121*	.004
	0.750	.215*	.000
	1.000	.274*	.000
	1.250	.438*	.000
0.250	0.000	-.045	.091
	0.500	.076*	.035
	0.750	.170*	.000
	1.000	.228*	.000
	1.250	.393*	.000
0.500	0.000	-.121*	.004
	0.250	-.076*	.035
	0.750	.094*	.007
	1.000	.152*	.000
	1.250	.317*	.000
0.750	0.000	-.215*	.000
	0.250	-.170*	.000
	0.500	-.094*	.007
	1.000	.058	.601
	1.250	.223*	.000
1.000	0.000	-.274*	.000
	0.250	-.228*	.000
	0.500	-.152*	.000
	0.750	-.058	.601
	1.250	.164*	.000
1.250	0.000	-.438*	.000
	0.250	-.393*	.000
	0.500	-.317*	.000
	0.750	-.223*	.000
	1.000	-.164*	.000

* indicates a statistically significant difference in mean combat score.

Simple Main Effects

Since there was a significant interaction effect for the two-way repeated measures ANOVA, analyzing the main effects could yield inaccurate conclusions as to the significance of the findings. Instead, the simple main effects were examined to further understand the relationships between the variables. This was accomplished through use of the one-way repeated measure ANOVA. The test for sphericity was required during analysis of the simple main effects for latency since there are six treatments, but not for engagement speed since there are only two treatments.

The latency during the low-speed engagement met the assumption of sphericity, $x^2(14) = 21.07$, $p = .101$. The difference in CS for latency treatments during the slow-speed engagements was statistically significant, $F(5, 135) = 62.87$, $p < .001$. The results of the pairwise comparison for latency during the low-speed engagements are illustrated in Table 3. The latency during the high-speed engagement did not meet the sphericity assumption, $x^2(14) = 48.63$, $p < .001$. The degrees of freedom were corrected using the Greenhouse-Geisser adjustment to correct the validity of the F value. The CS for the latency treatments during the high-speed engagements was statistically significant, $F(3.34, 90.27) = 21.69$, $p < .001$. The results of the pairwise comparison for latency during the high-speed engagements are illustrated in Table 3.

Table 3.

Pairwise Comparison between Latencies by Engagement Speed (Simple Main Effects)

	High-speed Engagement				Low-speed Engagement		
Latency (s)	Latency(s)	Mean Diff	Sig.	Latency(s)	Latency(s)	Mean Diff	Sig.
0.000	0.250	.047	1.000	0.000	0.250	.043	1.000
	0.500	.152	.161		0.500	.091*	.038
	0.750	.225*	.002		0.750	.206*	.000
	1.000	.197*	.000		1.000	.351*	.000
	1.250	.406*	.000		1.250	.470*	.000
0.250	0.000	-.047	1.000	0.250	0.000	-.043	1.000
	0.500	.105	.230		0.500	.048	.955
	0.750	.177*	.023		0.750	.163*	.000
	1.000	.149*	.002		1.000	.308*	.000
	1.250	.358*	.000		1.250	.427*	.000
0.500	0.000	-.152	.161	0.500	0.000	-.091*	.038
	0.250	-.105	.230		0.250	-.048	.955
	0.750	.073	1.000		0.750	.115*	.002
	1.000	.045	1.000		1.000	.260*	.000
	1.250	.254*	.000		1.250	.380*	.000
0.750	0.000	-.225*	.002	0.750	0.000	-.206*	.000
	0.250	-.177*	.023		0.250	-.163*	.000
	0.500	-.073	1.000		0.500	-.115*	.002
	1.000	-.028	1.000		1.000	.145*	.002
	1.250	.181*	.001		1.250	.265*	.000
1.000	0.000	-.197*	.000	1.000	0.000	-.351*	.000
	0.250	-.149*	.002		0.250	-.308*	.000
	0.500	-.045	1.000		0.500	-.260*	.000
	0.750	.028	1.000		0.750	-.145*	.002
	1.250	.209*	.001		1.250	.120	.195
1.250	0.000	-.406*	.000	1.250	0.000	-.470*	.000
	0.250	-.358*	.000		0.250	-.427*	.000
	0.500	-.254*	.000		0.500	-.380*	.000
	0.750	-.181*	.001		0.750	-.265*	.000
	1.000	-.209*	.001		1.000	-.120	.195

* indicates a statistically significant difference in mean combat score.

Note. Values of 1.000 are an artifact of SPSS when using the Benferroni adjustment and indicate a non-significant relationship, not an actual value of 1.000. This is to avoid an alpha error accumulation through multiple pairwise comparisons.

The pairwise comparison between engagement speeds for each latency level is displayed in Table 4. Included in Table 4 are the means, difference between means, significance, and *F* value for each pair. There was a significant ($p < .008$) difference in means between the high-speed and low-speed engagement means except at 1.00 and 1.25 second latencies.

Table 4

Pairwise Comparison Between Engagement Speeds by Latency (Simple Main Effects)

Latency(s)	Mean High-speed	Mean Low-speed	Mean Diff	Sig.	*F*(1, 27)
0.000	.539	.659	0.121*	<.001	20.50
0.250	.491	.616	0.125*	.001	15.19
0.500	.387	.568	0.182*	.002	11.71
0.750	.314	.453	0.140*	.006	8.72
1.000	.342	.308	-0.034	.465	0.55
1.250	.133	.189	0.056	.292	1.16

* indicates a statistically significant difference in mean combat score.
Note. Since six separate pairwise comparisons were calculated, the significance level to avoid type-1 errors should be adjusted to .05/6 = .008.

Hypothesis Testing Results

There were three alternative hypotheses and their associated null hypotheses proposed in this study. The results for each hypothesis are described below.

The first alternate hypothesis stated that there is a significant decrease in combat success between fighter pilots experiencing no latency and those experiencing latency during one-versus-one, WVR combat. Since there was a significant interaction between within-subjects factors, this hypothesis was tested by analyzing the simple main effects of latency. The results indicate that there was a statistically significant decrease in combat score during both high-speed, $F(3.34, 90.27) = 21.69, p < .001$, and low-speed engagements, $F(5, 135) = 62.87, p < .001$. Therefore, the null hypothesis was rejected.

The second alternate hypothesis stated that there is a significant difference in combat success based on initial engagement speed during one-versus-one, WVR, air-to-air combat. Since there was a significant interaction between within-subjects factors, this hypothesis was tested by analyzing the simple main effects of engagement speed on combat score at each latency level. The results indicate that there was a statistically significant difference in combat score between high-speed and low-speed engagements with latency levels of 0.00, 0.25, 0.50, and 0.75 seconds (see Table 4 for tabulated test specifics). Therefore, the null hypothesis was rejected for these latency levels. However, for latency levels of 1.00 and 1.25 seconds, there was no statistically significant difference between engagements fought at high-speed versus low-speed. Therefore, the findings fail to reject the null hypothesis for those latencies.

The third alternative hypothesis stated that there is a significant interaction between command and control latency and engagement speed during one-versus-one WVR, air-to-air combat. This hypothesis was tested with the two-way repeated measures ANOVA which indicated there was a significant interaction effect between factors on the dependent variable, $F(5, 135) = 3.71$, $p = .004$, partial $\eta^2 = .121$. Therefore, the null hypothesis was rejected.

Summary

The results of this research indicate that there is a significant difference in the combat capability when command and control latency is present. There is also a difference in the mean combat scores between engagements at high-speed and those at low-speed during engagements at low to moderate (0.25 - 0.75 s) latency levels. However, there was no statistical difference in means between the two engagement speeds at higher latencies (1.00 - 1.25 s). It is clear that there is a significant interaction effect between the two within-subjects factors (engagement speed and latency) indicating that latency alone is not a good predictor variable for combat score and that engagement speed must be taken into consideration. While the low-speed engagements exhibited a decrease in mean combat score at each increase in latency (although not all significant), the high-speed engagements did not. During the high-speed engagements, there was no statistical difference between mean combat scores at latency levels of 0.500, 0.750, and 1.000 seconds, although the score at 1.000 seconds was higher than at 0.750 seconds.

CHAPTER V

DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

The results of this experiment clearly illustrate the effect of latency and engagement speed on combat success during a WVR fight. However, there are several areas worthy of further examination including the performance of the simulated aircraft, analysis of the research questions, the theoretical and practical implications of the research, and recommendations for designers and further research. However, before discussing the conclusions of this study, it is important to consider the performance of the simulated aircraft and adversary aircraft.

While the results of this study indicate that pilots can still gain and maintain an offensive position even at the highest tested latency, consideration must be given to the superior performance of the simulated aircraft. During the experimental runs, subjects often max-performed the aircraft resulting in acceleration loads as high as 11.0 Gz, while the maximum observed adversary load was 7.3 Gz. This was especially true at higher latency levels when the pilots found themselves in poor tactical position and used superior aircraft performance to outmaneuver the adversary. There was a similar observation for the aircraft angle of attack. While the maximum observed AoA for the adversary was 25.2 degrees, the subjects routinely maneuvered the simulated aircraft to AoA greater than 35 degrees (indicated by a warning tone) and, in some instances, as high as 56 degrees.

It was clear that the superior performance of the simulated aircraft influenced the combat outcome of the engagements. However, this was an intentional aspect of the test plan designed to give pilots a maneuvering advantage similar to what would be available in an F-UCAV (Trsek, 2007). While the specific combat score was undoubtedly influenced by aircraft performance, it was clear that the decrease in performance is present regardless of the superior performance of the F-UCAV. Therefore, the conclusions of this study should be taken as degradation of combat effectiveness (i.e., the difference between engagements without latency and those with latency) and not a specific value of combat success.

If, for example, the combat was between two evenly matched aircraft and pilots of similar skill, experience, and currency, the degradation due to latency would result in a negative combat score. The matched engagement would yield a combat score near zero, when latency is not present. When a latency of 1.250 seconds is added to one of the aircraft, a decrease in combat score of 0.406 should be expected during the high-speed engagement. This degradation should not be taken lightly since this corresponds to a highly defensive position (see Figure 12) and would likely result in a combat loss.

Discussion

There were three research questions proposed for this research. Since there was a significant interaction effect, the research questions will be addressed in the opposite order as presented in Chapter 1.

Research question number three asked: what is the possible interaction between command and control latency and engagement speed during one-versus-one, WVR, air-to-air combat? The significant interaction effect indicates that the effect of latency on combat score depends on both latency and engagement speed. Further, it signifies that latency does not affect the high-speed and low-speed engagements in the same way. Examination of Figure 17 illustrates that during the low-speed engagements, the combat score decreased consistently with increased latency, while the high-speed engagements plateaued with latencies of 0.50, 0.75, and 1.00 seconds; there was no significant difference between combat scores at these latencies. The plateau is unique to this research and differs from ground vehicle teleoperations research (Gorsich et al., 2018; Luck et al., 2006).

This result could be due to the geometry of the high-speed engagement that allows the pilot to maintain a turn with a constant plane of motion (USN, 2016). During a turn with the lift vector orientation remaining constant, the latency is only perceptible while increasing or decreasing the turn rate of the aircraft (i.e., changing the acceleration load in Gz). This constant turn also occurred at a higher airspeed than during the low-speed fight, which allowed a higher sustained acceleration load. The higher loading (Gz) resulted in a higher sustained turn rate which subsequently allowed the pilot to remain in an offensive position while only adjusting the acceleration load. This conclusion was supported by observation during the engagements and during engagement playback.

The second research question asked: to what extent does initial engagement speed affect combat success during one-versus-one, WVR, air-to-air combat? Overall, the reduction in combat score was similar between the two engagement speeds. However, the high-speed engagement experienced a total degradation of -.406 between zero latency and 1.250 seconds of latency, while the low-speed engagement decreased -.470, as seen in Table 1. This result indicates that latency had a larger effect on the low-speed engagement than on the high-speed engagement. This is supported by the increased slope of the linear regression for the low-speed engagements as compared to the slope of the high-speed engagements. Additionally, while there was a significant difference between the engagement speeds at the lower latencies, there was no significant difference at latencies of 1.000 and 1.250 seconds.

Further examination reveals that the advantages in CS of the low-speed engagement observed at low latencies did not carry over to high latencies. Observations during the simulation indicated that the early advantage in the low-speed engagements was centered around the superior AoA limit of the simulated aircraft which allowed a higher energy bleed rate at the start of the fight. This high bleed rate slowed the simulated aircraft much faster than the adversary aircraft and resulted in a rapid offensive advantage (USAF, 2005). This was evident during the engagement review where pilots were consistently in an offensive position earlier during the low-speed engagements as compared to the high-speed engagements. As the engagement continued, the early advantage of the low-speed engagement dissipated and was no longer statistically significant at the higher latencies.

Another point of discussion is the comparative decrease in score between zero latency and 1.000 seconds. While the low-speed engagement score decreased by 0.351 in this region, the high-speed engagement only decreased by 0.197. The decrease in CS during the high-speed engagement was 44% less than the low-speed engagement. This result further indicates there is a significant advantage of engaging in a high-speed two-circle fight when latency is present.

The first research question asked: to what extent do different levels of command and control latency affect combat success during one-versus-one, WVR, air-to-air combat? The research results clearly indicate that there is a significant decrease in CS with increasing latency regardless of engagement speed. This result was expected and similar to UGV research (Gorsich et al., 2018; Luck et al., 2008). However, there are several areas which should be noted. First, there was not a significant difference between 0.000 and 0.250 seconds of latency for either engagement speed, indicating that delays up to 0.250 seconds did not affect combat success. This was true through analysis of both the main effects and simple main effects. Observation also supported that the 0.250 second delay was acceptable and, often, not noticed by the subjects. This result is similar to Gorsich et al. (2018) which found no significant difference between zero latency and 0.2 seconds of latency for trained subjects.

Secondly, for the high-speed engagements, there was not a significant difference between 0.000, 0.250, and 0.500 seconds of latency, although there was a decrease in the mean combat score. The standard deviations included in Table 1 indicate that there is a larger variance associated with the high-speed engagements than the low-speed engagements which influenced the *p* value. The higher CS deviations could be due to the subject's initial merge gameplan and geometry during the high-speed engagements which allowed more tactical options (variations) than the low-speed fight (USN, 2016). Interestingly, the higher variation during the high-speed engagements occurred at lower latencies and became similar to the low-speed engagements at high latency. This is evident in both Table 1 and Figure 17.

Finally, the data, observation, and engagement playback lead to the conclusion that there were several effects of latency of which the pilot must contend including lift vector control, airspeed control, and general aircraft control. At lower latencies, the main obstacle was lift vector orientation and control. While the pilots may know where the optimal location of their lift vector should be, the latency caused them to either undershoot or overshoot the desired position (i.e., rolled past the desired position). As latency increased, this issue was compounded, often leading to an orientation in the opposite direction than desired. Latencies of 0.750 seconds and above contributed to large variations in airspeed since the throttle and speedbrakes were also delayed as part of the command and control link. These large energy excursions led to a larger than desired turn radius or a lack of energy required to complete a maneuver. The airspeed control issues coupled with poor lift vector control often resulted in difficulty controlling the aircraft. These results are illustrated in Figure 20.

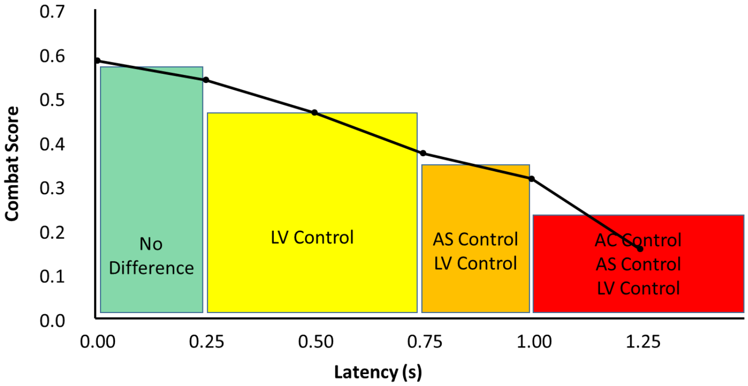


Figure 20. Observed piloting issues associated with latency. Note: Mean Combat Score values displayed are based on the main effects of both engagement speeds.

Conclusions

Theoretical contributions. The theoretical foundation of this study was the OODA Loop (Boyd, 1977). While the original construct of the OODA Loop theory was based around making tactical decisions faster than the adversary, this study indicates that technology-based latency influences the engagement outcome similar to a slow decision-making cycle. This is foundation to the understanding of the OODA Loop since, in its original form, it described the human decision-making process where the individual observes an action, orients based on knowledge and previous experience, decides on an action, and executes the action. This study adds depth to the theory illustrating that technology-induced latency has a similar effect as slow human decision making, resulting in lower performance. Therefore, latency, when combined with the human decision-making process, compounds the effect resulting in significantly lower performance.

The current understanding of the OODA Loop process was that command and control latency would only affect the Observe and Act phases of the OODA Loop. However, this study indicates that latency affects the entire OODA Loop and that the Orient-Decide-Act process was particularly influenced by latency. The ability of the pilots to maintain congruency between orientation and action proved more difficult as latency increased. This caused the pilots to spend most of their time in the O-D-A phases while occasionally returning to the Observe phase. An accurate analogy would be that the pilots were stuck in a Do-Until Loop between orientation, decision, and action, as illustrated in Figure 21.

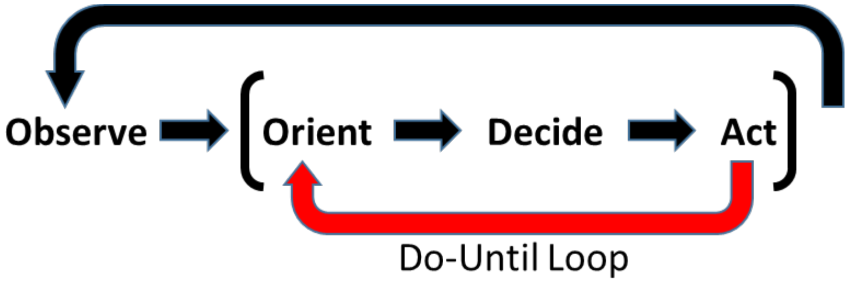


Figure 21. Illustration of Do-Until loop acting internal to OODA Loop process.

The Do-Until loop was continued until the action determined in the decide phase was satisfactorily completed. Other studies of latency identified the move-and-wait strategy to compensate for delays in command and control, the effect seen in this study could be interpreted as a dynamic move-and-wait (Marano et al., 2015; Sheridan & Ferrell, 1963; Storms et al., 2017; Vozar et al., 2017).

Practical contributions. There are several practical outcomes of the study that are of particular interest. Although there was a significant decrease in combat score with increased latency, pilots were able to maintain an offensive advantage even at the highest tested latency. As mentioned above, this could be partially attributed to the superior performance of the simulated aircraft but also supports the conclusion that given enough performance advantage, an offensive position is possible even with a 1.250 second latency. This result is surprising given the conclusions of previous studies (Dougherty et al., 2002; Gorsich et al., 2018). This leads to the question: how much superior performance is required to completely offset the effects of latency?

The results of the Field Test effectively bounded the upper limit of latency based on manual aircraft control. When latencies of 1.500 seconds and above were tested, severe aircraft control issues emerged, often resulting in ground impact during engagements. At the other end, the experimental results revealed that a latency of 0.250 seconds was not significantly different than the combat scores without latency. These results support the conclusion that C2 latencies of 0.250 seconds and below are acceptable and that latencies above 1.250 seconds are unacceptable for a manually controlled aircraft. The results also support the conclusion that latencies greater than 0.250 seconds but less than 1.250 seconds may be at least partially offset by superior aircraft performance during both high-speed, two circle engagements and low-speed, one-circle engagements (USAF 2005; USN 2016).

The experimental results indicate that there was not a significant difference in CS between zero latency and 0.500 seconds of latency during the high-speed, two circle fight. Additionally, there was not a significant difference between 0.500 and 1.000 seconds of latency for the high-speed fight. A possible conclusion stemming from these results is that the two-circle fight is less susceptible to degradation due to latency. This conclusion is supported by observation during the experiment that orientation and maneuvering was easier during the two-circle fight versus the one-circle fight where the lift vector orientation changes rapidly (USN 2016). The practical application of these results is that when latency above 0.250 seconds is present, the two-circle fight is desired over the low speed one-circle fight.

In a few cases, subjects achieved very high combat scores even at the highest tested latency. One subject was able to achieve an average engagement score of .668 with a latency of 1.250 seconds. Results like this indicate that pilot technique may play a larger role than expected in countering the effects of latency and should be explored in future studies.

While demographic data were not collected, the researcher was aware of the fighter aircraft in which each participant was qualified. Anecdotal evidence pointed toward pilots scoring higher who were accustomed to flying aircraft with small stick movement and digital flight controls. These pilots appeared to use much less control input and were able to better deal with the latency of the simulation. Pilots accustomed to large control stick inputs often over-controlled the aircraft, resulting in disorientation, loss of sight with the adversary, and low combat scores.

This study illustrates the desire to limit latency to 1.000 seconds or less where acceptable combat scores can be expected. Although the physical distance from the GCS to the F-UCAV will always induce latency, improvements in encryption, translation, and switching could reduce the expected latency to less than 1.000 second and should be pursued. In the case of a high-speed, two circle engagement, the expected decrease in combat capability for latencies less than 1.000 seconds could be offset by increased aircraft performance.

Human factors were not a major area of investigation for this study. However, it is of interest to note that many previous studies sited simulator sickness, intensified by the VR system, as a major barrier for studies such as this. While a few subjects in this study indicated they had minor symptoms, in no case did simulator sickness cause the subjects to discontinue the trial. There may be several factors contributing to why this population did not experience these issues during a high demand, aggressive maneuvering simulation; most likely, training, experience, and currency. This study illustrated that it is possible to conduct WVR engagements through use of VR without critical issues with motion/simulator sickness.

A final and ancillary practical contribution of this study was demonstrating that a properly configured VR simulator can produce an effective air-to-air training environment. While not the purpose of this experiment, the simulation provided an effective and efficient environment in which to practice manual flight skills. This was supported by pilot comments during the experiment, SMEs, and other simulation and aviation experts. Considering that the cost of the VR simulation was approximately 1/1000th the cost of a modern fighter simulator, VR simulation should be an integral venue for future training.

Limitations of the Findings

Several limitations to this study were discussed in Chapter 3. It should be emphasized that this study intentionally excluded several variables such as sensors, weapons, weapon cueing, and weapon performance with the objective of isolating the ability of the pilot to maneuver to and remain in the control zone. Understanding how latency affects the basic fighter maneuvers employed by the subjects is the first step in developing tactics to overcome latency. Along with the limitations previously discussed, there were several limitations to the findings.

The simulation employed basic AI and limited aircraft performance for the adversary in order to control the infinite variations allowed by a human adversary. In some cases, the AI acted in predictable response which could have been exploited by the participant. The results were limited by the AI and may yield different results given a human (or better AI) adversary. The decrease in CS seen in this study may be significantly higher given a more capable adversary and should be considered for follow-on research.

The practice period was used to familiarize the subject with the simulation and allow them to experience latency in order to decrease variability caused by inexperience in the environment. While this achieved the desired results, it was clear that some pilots adapted quickly while others struggled with the delay, as evidenced by the 95% confidence intervals in Figure 18. Allowing pilots a longer practice period and time to develop tactics over several sessions may reduce the variability and yield more concise results.

A final limitation of the findings was the resolution of the simulation. While the VR simulator provided an excellent immersive environment, the overall resolution of the simulation was less than desired. In order to achieve a frame rate in excess of 90 frames per second, the resolution of the simulation was decreased until no scene ripping or double images occurred. The final resolution was approximately 1200 vertical lines verses the Vive Pro's full capability of

1600 lines. The result of the lower resolution was difficulty determining the adversary's aspect angle at ranges greater than roughly 1000 meters. The lower resolution could have caused a delay in the subjects' reaction to the adversary's maneuvers yielding a less than optimum lift vector placement. In this case, the overall results of the engagement would be lower than if the resolution was higher. However, the lower resolution was seen as operationally accurate during the field test since excessive acceleration loads on the pilot's ocular system causes a similar effect during actual flight.

Recommendations

This study forms the foundation for further research into countering the effects of latency. Understanding how latency affects the ability to maneuver the aircraft into a position of advantage leads the way for more specific research and practical solutions. There are several areas to explore including the use of air-to-air weapons, increasing the performance of the F-UCAV, creating delay in the observation phase of the OODA Loop, incorporating predictive algorithms to help pilots anticipate their control inputs, and automating phases of the engagement.

Recommendations for systems designers. While full automation will ultimately solve the issue of latency, sensor capability must advance to make that possible. In the interim, the use of automation at certain phases of the engagement may be possible. For example, once an offensive advantage is obtained where the F-UCAV radar can provide an accurate set of parameters to employ weapons, automation could take over to complete the engagement. This would still require the human operator to place the aircraft into a position, or envelope, where the onboard sensors could supply the AI with accurate enough parameters to complete the fight. If the sensor is jammed or spoofed, the human pilot would need to regain control and continue to fly the aircraft.

A major issue for the subjects of this study was correctly setting the lift vector due to overshooting the desired position on the roll axis. Creating an algorithm to predict the roll command input and displaying that to the pilot could offer a remedy to this issue. The display could be simply overlaid on the heads-up display to indicate where the aircraft lift vector would be oriented, should the pilot stop the roll. This would be difficult in situations where variable latency is present, but possible if latency is constant and known. The algorithm would take the pilot's control input and current aircraft flight parameters into account to predict the outcome of a control input.

The design of the GCS is critical for future F-UCAVs, whether remotely piloted or automated. This study demonstrated that a VR system is a practical alternative to the standard flat screen displays commonly seen in various GCSs. Virtual reality systems could be an alternative, or an augmentation to, future GCS designs where operational requirements necessitate a 360-degree, high resolution depiction of the environment. Designers should consider the use of VR in future F-UCAV systems.

Recommendations for future research methodology. A critical component in order to parallel a true communications loop is the incorporation of latency during the observe phase. This could be added to the simulation, although it would require significant coding and development. Based on the current study, it would be expected that this delay would further decrease combat capability for a given latency level and cause issues with radar and weapon cueing.

There was enough variation in the test results to indicate that pilot technique contributes to the combat outcome. Research should be conducted on a small subset of the sample to determine how pilot experience with latency and tactics could improve combat results. Subjects could train in the latency environment for several hours in order to refine methods to counter latency degradation then the experiment repeated to determine results.

Recommendations for future research. While this study found that a two-circle fight was superior to a single-circle fight when latency is present, this may not be transferrable to situations when high off-boresight weapons are available. In this case, both aircraft will pass through multiple weapons engagement zones during a two-circle fight where defensive systems become critical to combat success. A single-circle fight with minimum distance between the two aircraft may be a more effective tactic. This leads to the recommendation for additional research which includes exploring weapons employment during various engagement geometries.

The simulation recordings from this research could be used to explore weapons use. By applying a missile engagement zone and determining when and for how long the adversary remains in that zone could determine if and when weapons could be fired. Additionally, further simulation sessions could determine how current auto-acquisition radar and missile function in an environment with latency. However, this would require a delay in the aircraft to GCS timeline to yield accurate results.

This study has quantified the effects of latency on combat capability during an air-to-air WVR engagement and explored the effect of tactics on the outcome. It has further added depth and breadth to the OODA Loop theory by including the concept of the dynamic move-and-wait Do-Until loop. It has provided several practical contributions to the problem of command and control latency during air-to-air and outlined several areas for further study.

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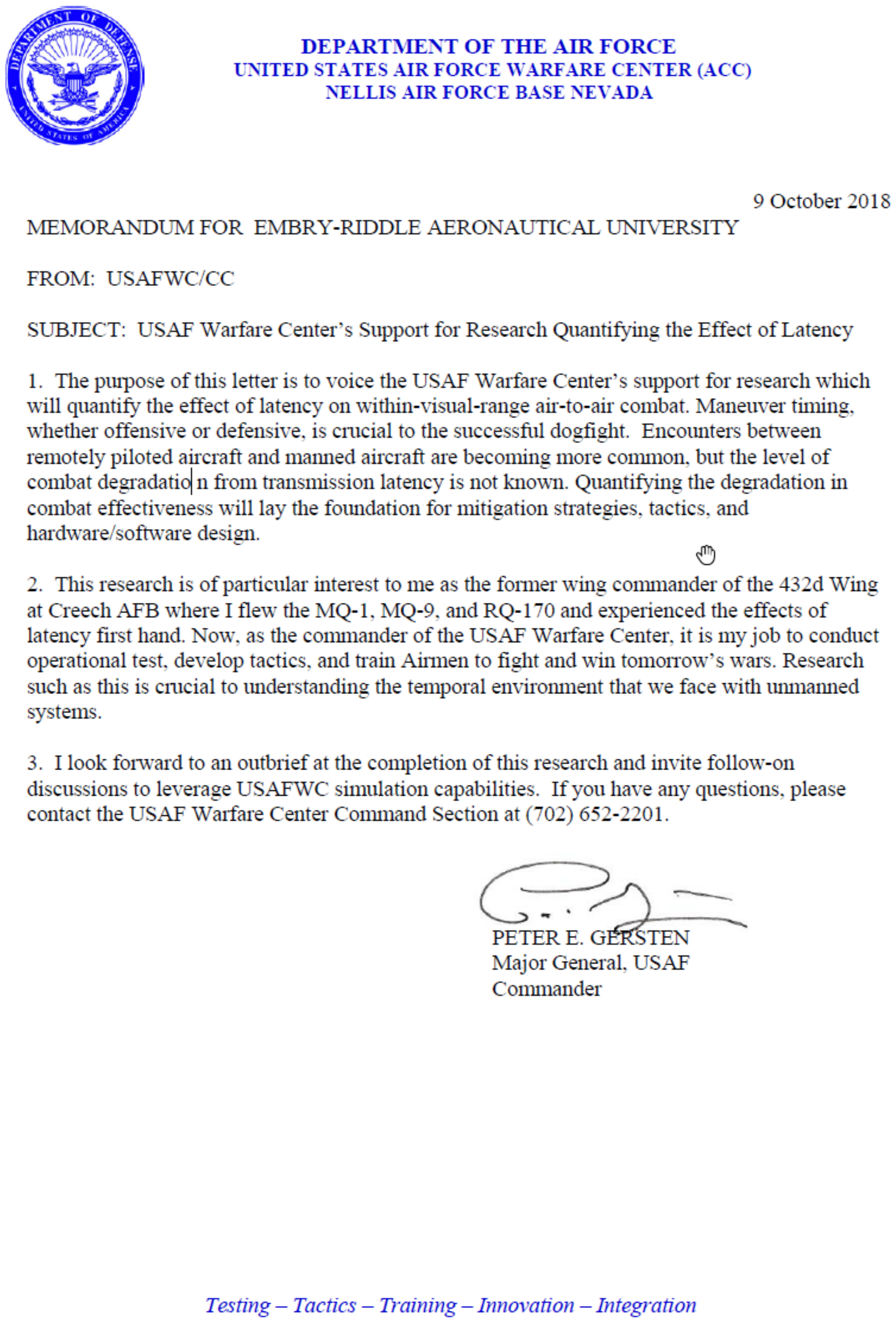
APPENDIX A

USAF Warfare Center Support



DEPARTMENT OF THE AIR FORCE
UNITED STATES AIR FORCE WARFARE CENTER (ACC)
NELLIS AIR FORCE BASE NEVADA

9 October 2018

MEMORANDUM FOR EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

FROM: USAFWC/CC

SUBJECT: USAF Warfare Center's Support for Research Quantifying the Effect of Latency

1. The purpose of this letter is to voice the USAF Warfare Center's support for research which will quantify the effect of latency on within-visual-range air-to-air combat. Maneuver timing, whether offensive or defensive, is crucial to the successful dogfight. Encounters between remotely piloted aircraft and manned aircraft are becoming more common, but the level of combat degradation from transmission latency is not known. Quantifying the degradation in combat effectiveness will lay the foundation for mitigation strategies, tactics, and hardware/software design.

2. This research is of particular interest to me as the former wing commander of the 432d Wing at Creech AFB where I flew the MQ-1, MQ-9, and RQ-170 and experienced the effects of latency first hand. Now, as the commander of the USAF Warfare Center, it is my job to conduct operational test, develop tactics, and train Airmen to fight and win tomorrow's wars. Research such as this is crucial to understanding the temporal environment that we face with unmanned systems.

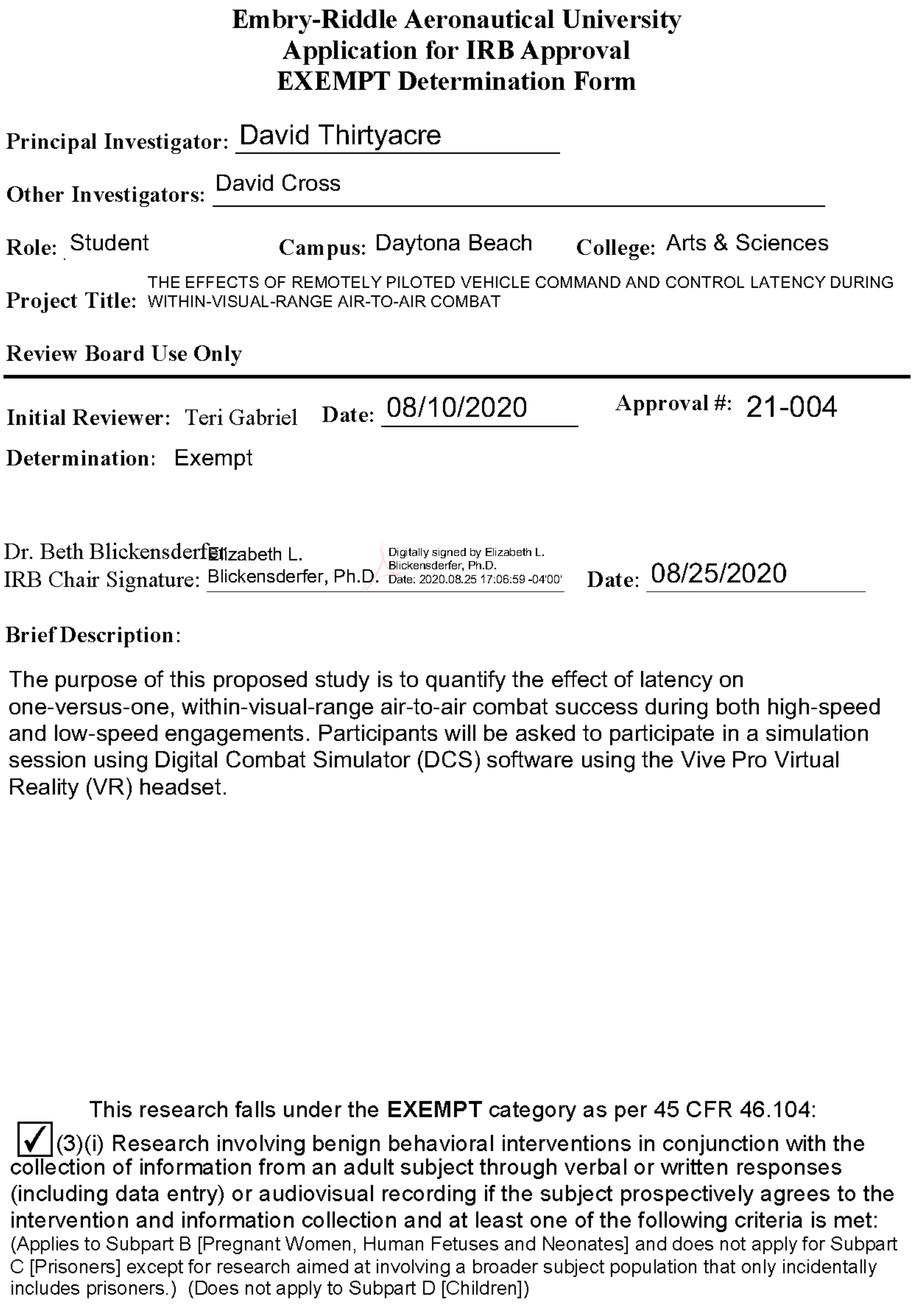
3. I look forward to an outbrief at the completion of this research and invite follow-on discussions to leverage USAFWC simulation capabilities. If you have any questions, please contact the USAF Warfare Center Command Section at (702) 652-2201.

PETER E. GERSTEN
Major General, USAF
Commander

Testing – Tactics – Training – Innovation – Integration

APPENDIX B

Permission to Conduct Research



Embry-Riddle Aeronautical University
Application for IRB Approval
EXEMPT Determination Form

Principal Investigator: David Thirtyacre

Other Investigators: David Cross

Role: Student **Campus:** Daytona Beach **College:** Arts & Sciences

Project Title: THE EFFECTS OF REMOTELY PILOTED VEHICLE COMMAND AND CONTROL LATENCY DURING WITHIN-VISUAL-RANGE AIR-TO-AIR COMBAT

Review Board Use Only

Initial Reviewer: Teri Gabriel **Date:** 08/10/2020 **Approval #:** 21-004

Determination: Exempt

Dr. Beth Blickensderfer
IRB Chair Signature: Elizabeth L. Blickensderfer, Ph.D. Digitally signed by Elizabeth L. Blickensderfer, Ph.D. Date: 2020.08.25 17:06:59 -04'00' **Date:** 08/25/2020

Brief Description:

The purpose of this proposed study is to quantify the effect of latency on one-versus-one, within-visual-range air-to-air combat success during both high-speed and low-speed engagements. Participants will be asked to participate in a simulation session using Digital Combat Simulator (DCS) software using the Vive Pro Virtual Reality (VR) headset.

This research falls under the **EXEMPT** category as per 45 CFR 46.104:

☑ (3)(i) Research involving benign behavioral interventions in conjunction with the collection of information from an adult subject through verbal or written responses (including data entry) or audiovisual recording if the subject prospectively agrees to the intervention and information collection and at least one of the following criteria is met: (Applies to Subpart B [Pregnant Women, Human Fetuses and Neonates] and does not apply for Subpart C [Prisoners] except for research aimed at involving a broader subject population that only incidentally includes prisoners.) (Does not apply to Subpart D [Children])

☑ (A) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects cannot readily be ascertained, directly or through identifiers linked to the subjects;

☑(B) Any disclosure of the human subjects' responses outside the research would not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, educational advancement, or reputation; or

☐ (C) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects can readily be ascertained, directly or through identifiers linked to the subjects, and an IRB conducts a **Limited IRB review** (use the Limited or Expedited Review form) to make the determination.

EMBRY-RIDDLE
Aeronautical University
FLORIDA | ARIZONA | WORLDWIDE

17 September 2020

Modification of Previously Approved IRB

Campus:	**Daytona Beach**	College:	**COA**
Applicant:	**David Thirtyacre**	Degree Level:	**Doctorate**
ERAU ID:	**0312022**	ERAU Affiliation:	**Student**
IRB Approval Number:	**21-004**		
Project Title:	**THE EFFECTS OF REMOTELY PILOTED VEHICLE COMMAND AND CONTROL LATENCY DURING WITHIN-VISUAL-RANGE AIR-TO-AIR COMBAT**		
Principal Investigator:	**David Thirtyacre**		
Other Investigators:	**David Cross**		

Submission Date: **09/16/2020**

Beginning Date: **08/01/2020**

Type of Funding Support (if any):

X

Beth Blickensderfer, PhD September 18, 2020

Questions:

1. Change of Protocol due to change in:

    Participant population

1b. Please summarize:

The previous population description only included "former fighter pilots" and not active duty (AD) pilots. The PI received permission from the USAF Warfare Center Commander to collect data using the AD pilots under his command at Nellis AFB, NV. The Air Force Research Laboratory (AFRL) has reviewed the ERAU IRB and requested that it include a statement that the subjects may include AD pilots. The AFRL IRB office will issue approval to collect data using AD pilots after receiving the modified ERAU IRB.

The email from AFRL and the USAFWC/CC are attached for reference.

The only modification to Section 5 is "active duty and" (in caps below)

Section 5:
The desired sample size is 50 subjects. The participants must be 18 or older and include ACTIVE DUTY AND former fighter pilots trained and qualified for air-to-air combat in the F-15, F-16, F-18, F-22, and F-35. All participants must have logged pilot in command (PIC) time within the past 5 years to be eligible. The pilots will be recruited through personal contact with the PI and by word-of-mouth only and be purely voluntary. Potential participants can sign up for time slots by emailing the PI. The information in Sections 1, 2, 3, and 4 will be provided to each potential participant verbatim prior to or during the signup process.