Characterizing the Potential of Active Aircraft Diversion Technologies for Remotely Redirecting an Aircraft

A thesis

submitted by

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Abstract

Since the 1930s, airplane hijackings have been used by terrorist organizations to further their own agendas, often staking civilian lives in the process. Adversarial (but not necessarily hostile) unmanned aerial vehicle intrusions into sensitive military or political areas have also threatened otherwise peaceful U.S. defense operations. In these scenarios, non-lethal active aircraft diversion (AAD) technologies can be used as an anti-terrorism and defense solution. Laser-based AAD technologies utilize a high powered laser aimed at a target aircraft’s wings to force an aircraft to turn or oscillate. Given this technology, the goal of this thesis is to characterize the ability to divert an aircraft for three specific pilot cases: no pilot, pilot with limited visibility, and pilot with full capability. Simulations indicate that the laser-based diversion has great potential for diverting an unpiloted aircraft originally flying straight and level. Human-in-the-loop (HITL) simulations with certified pilots show that lasers can also enable a limited diversion capability for aircraft navigated by pilots with limited visibility. Furthermore, HITL simulations demonstrate potential for enhanced (not necessarily laser-based) AAD diversion on fully capable pilots when large control forces (hundreds of bounds) are available for diversion.
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Characterizing the Potential of Active Aircraft Diversion Technologies for Remotely Redirecting an Aircraft
Chapter 1: Introduction

1.1 Motivation for Active Aircraft Diversion

Since the 1930s, airplane hijackings have been used by terrorist organizations to further their own agendas, such as increasing publicity for their cause and using passengers as hostages to negotiate terms (“History”; Quandt). With the September 11th attacks on the United States, airplane hijackings took on a different tone as it was the first airplane hijacking scenario in which suicide hijackers were not interested in negotiations or keeping themselves or the hostages alive. As Robert T. Holden observes in his paper, “The Contagiousness of Aircraft Hijacking,” the number of airplane hijacking attempts increases after a successful hijacking is executed, partially due to the increased media coverage and publicity of airplane hijackings. Three years and one day later, Frank Eugene Corder crashed a stolen Cessna aircraft onto the South Lawn of the White House (Labaton). From the range of these scenarios, it is clear that technologies to counteract future aircraft hijackings and other terrorist attacks are necessary to prevent unnecessary damage and loss of life.

Unmanned aerial vehicles (UAVs) have also become a tool and a weapon for defense institutions throughout the world. Unmanned systems have been in use by the U.S. military for over half a decade, and UAVs, also known as unmanned aircraft systems, alone have “flown almost 400,000 flight hours in support of Operations Enduring Freedom and Iraqi Freedom” as reported in the Unmanned Systems Roadmap from the U.S. Office of the Secretary of Defense. While the United States military is the leader in UAV deployment, a host of other nations use UAVs as well for a variety of purposes including surveillance and reconnaissance (Wilson). UAV intrusions are events
in which an adversarial (but not necessarily hostile) UAV is steered close to a strategic military or political area to perform a surveillance mission. In this scenario as well, technologies could be developed to mitigate or prevent the situation from escalating into conflict.

Active aircraft diversion (AAD) is the act of redirecting a flying aircraft, regardless of the aircraft pilot’s intentions. AAD can be used to simply redirect an aircraft and divert it away from a target or even to steer it to a specific, alternate location. Concerns that motivate the use of AAD include airplane hijackings and UAV intrusions. The main focus of this thesis, therefore, will be to characterize the use of an AAD method for anti-terrorism and defense purposes.

1.2 Laser-based AAD and its Limitations

Laser-based AAD employs the use of a high powered laser to force an aircraft to turn or oscillate regardless of the pilot’s actions. While the laser concept will be explained in detail in the subsequent chapters, the premise of this method is simple. A laser stationed on the ground or on a friendly aircraft can be aimed at the wings of a target aircraft to create turbulence. That turbulence in turn increases drag for an otherwise laminar-flow airfoil. Strategically aiming the laser to vary drag over time on different parts of the target aircraft’s wings can alter the control characteristics of the aircraft and make it difficult for the pilot to maintain level flight. Furthermore, if drag effects are intentionally directed on one wing or another, the aircraft can be steered by the laser operator. This concept is the basis for laser-based AAD and is described in detail in the following chapter.

The great benefit of laser-based AAD is that it is a non-lethal solution for terrorist and defense situations. No additional people need to sacrifice their safety to
implement this solution, such as fighter pilots. Furthermore, laser-based AAD is not meant to harm any of the passengers on the aircraft, including the hijackers, unless the pilot puts all of his or her effort into aborting the mission and crashing the aircraft directly into the ground for example. Another benefit to laser-based AAD is that it is not necessary to install equipment on the target aircraft in advance for this solution to work. Therefore, laser-based AAD can be implemented on any laminar flow aircraft whenever necessary.

While laser-based AAD can theoretically control the aircraft, it has limitations just like any other technology. Due to how the laser creates drag, laser-based AAD is only applicable to aircraft that exhibit laminar (non-turbulent) flow over its wings. Aircraft that fall into this category generally include general aviation (GA) aircraft and UAVs. Controlling big commercial airliners such as the Boeing 747 therefore, are not applicable. For this thesis, the Navion will be used as the test aircraft because it is a well-documented GA aircraft that exhibits laminar flow over its wings. The US Air Force Flight Handbook describes the L-17 aircraft by Ryan Aeronautical as “a four-passenger, single-engine, all-metal, low-wing airplane...[with] hydraulically retractable tricycle landing gear, flaps and conventional controls.”

Laser-based AAD is also limited in the amount of drag that can be produced on an aircraft. This affects the maximum amount of control the laser can have on turning or oscillating an aircraft. The greatest challenge for this thesis was that this limited amount of drag is tiny in comparison to the equivalent of what a human pilot can generate. Therefore, human pilots with full visual feedback can easily overcome forces generated by the baseline laser AAD configuration. To address this issue, alternative technologies that increase aerodynamic forces on an aircraft will be discussed. Methods
for controlling the baseline or enhanced laser to divert an aircraft were developed and tested taking these limitations into account.

1.3 Thesis Contributions

Based on the enhanced and laser-based AAD technology, the goal of this thesis is to characterize the ability to divert an aircraft for three specific pilot cases: no pilot, pilot with limited visibility, and pilot with full capability. Diversion capability was assessed for the baseline laser AAD configuration on the no pilot case and pilot with limited visibility case. Then, diversion capability was assessed for the enhanced AAD configuration using larger control forces on pilots with full capability. The major thesis contributions to this goal are depicted visually in Figure 1 and summarized below.

![Diagram](image.png)

**Figure 1**: Characterizing the potential for laser-based and enhanced AAD for three pilot cases.

1. **Assess capability of baseline laser AAD configuration to divert an aircraft away from an intended target**.
   a. Simulations indicate that the laser-based diversion has great potential to divert an unpiloted laminar flow aircraft originally flying straight and
level. For instance, a Navion aircraft originally traveling in a straight line can be forced to turn in a circular trajectory of 4,000 feet in diameter.

b. Human-in-the-loop (HITL) simulations with certified pilots show that lasers can enable a limited diversion capability for aircraft navigated by pilots with limited visibility. Test results of pilots flying under low visibility fog conditions indicate that the laser induces 14 out of 18 flights to divert away from the target toward a specific direction.

2. **Assess potential of using larger aerodynamic forces to enhance baseline laser AAD configuration.**

HITL simulations demonstrate potential for general (not necessarily laser-based) AAD diversion on fully capable pilots when large control forces (hundreds of bounds) are available for diversion. For instance, tests demonstrate that aircraft are diverted from a target for 42% of the flights when the enhanced AAD control forces saturate at 975 pounds.

### 1.4 Thesis Overview

The research presenting the thesis contributions is organized in the following manner. Chapter 2 describes the experimental apparatus used for conducting research for the thesis. Brief descriptions of MATLAB, X-Plane, and HITL studies are introduced for the reader to get an understanding of how the simulations in the following chapters were conducted.

Chapter 3 describes the technical basis for laser-based AAD and presents how it can be used to divert aircraft from an intended target. The laser-induced turbulence model is explained to demonstrate how aircraft diversion is possible from a high-powered laser. Results that show the capability of the laser to divert an unpiloted
aircraft originally flying straight and level are presented. Results from the Limited
Visibility HITL simulation also show the laser’s limited capability to divert an aircraft
when human pilots fly under dense fog.

Chapter 4 explains the potential for using larger aerodynamic forces to divert an
aircraft. Simulations that show limitations to the baseline laser-based AAD concept
motivate the study of higher control force levels, which might be obtained by an
enhanced (not necessarily laser-based) AAD technology. To evaluate the potential for
enhanced AAD control forces, the Large Forces HITL simulation is presented to
characterize pilot performance in response to the enhanced AAD controller for fully
capable pilots with full visibility. The study measures performance at several saturation
force levels and compares them to the controller’s ability to maintain passenger safety.

Chapter 5 summarizes the thesis contributions and presents suggestions for
future work. The chapter concludes with the impact of this thesis on civilian and anti-
terrorism applications.
Chapter 2: Experimental Apparatus

This chapter introduces the software, test equipment, and human study procedures used in this thesis to characterize AAD technologies.

2.1 MATLAB for Control Law Prototyping

MATLAB (Mathworks, Natick, MA) was used as a tool to prototype various control laws, obtain quick simulation results, and choose which control laws to investigate and refine further. The most successful of these control laws were subsequently implemented in the HITL simulations.

MATLAB is a popular technical computing language and environment for performing tasks such as signal processing, algorithm development, and data visualization. Its main benefit is its ability to compute and visualize simulations of systems from mathematical models relatively quickly. Because of the ease at which systems can be simulated, MATLAB was primarily used to test and prototype various control laws. Laser control laws are algorithms that specify the wing that the laser is aimed at and the duration. The goal for MATLAB was to simulate aircraft dynamic states such as yaw angle and forward velocity to evaluate the effectiveness of laser control laws to divert an aircraft. A diagram of aircraft rotations based on their axes of motion is shown in Figure 2.
Under the assumptions that an aircraft is flying over a small region of the earth that is locally flat, the equations of forces for the rigid-body motion of the aircraft are

\[
\begin{bmatrix}
\dot{u} \\
\dot{v} \\
\dot{w}
\end{bmatrix} = \begin{bmatrix}
-g \sin \theta \\
g \sin \varphi \cos \theta \\
g \cos \varphi \cos \theta
\end{bmatrix} + \frac{1}{m} \begin{bmatrix}
F_{\text{thrust}} \\
0 \\
0
\end{bmatrix} + \begin{bmatrix}
\dot{X}^b \\
\dot{Y}^b \\
\dot{Z}^b
\end{bmatrix} - \begin{bmatrix}
wv - rv \\
ru - pw \\
pv - qw
\end{bmatrix}
\] (2.1)

and the equations of moments are

\[
\begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r}
\end{bmatrix} = \begin{bmatrix}
I_{xx} & 0 & I_{xz} \\
0 & I_{yy} & 0 \\
I_{zx} & 0 & I_{zz}
\end{bmatrix}^{-1} \begin{bmatrix}
I^b \\
M^b \\
N^b
\end{bmatrix} - \begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r}
\end{bmatrix} \times \begin{bmatrix}
I_{xx} & 0 & I_{xz} \\
0 & I_{yy} & 0 \\
I_{zx} & 0 & I_{zz}
\end{bmatrix} \begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r}
\end{bmatrix}
\] (2.2)

where \([u, v, w]\) are body-axis components of the velocity of the center of mass with respect to the reference axes,

\([p, q, r]\) are body-axis components of the angular velocity with respect to the reference axes,

\([\varphi, \theta, \psi]\) are roll, pitch, and yaw angles of aircraft body axes with respect to the reference axes,

\([L, M, N]\) are roll, pitch, and yaw moments with respect to the reference axes,

\([X, Y, Z]\) are aerodynamic forces such as lift, lateral, and drag force.
$F_{\text{thrust}}$ is the thrust force generated by the propeller

$[I_{xx}, I_{yy}, I_{zz}, I_{xy}, I_{xz}, I_{yz}]$ are the moments of inertia of the aircraft

$m$ is the mass of the aircraft (Ducard; Bryson).

The concept for how a laser creates a drag force and moment on an aircraft to divert an aircraft is presented in detail in Chapter 3. However, the mathematical model of the aircraft incorporating the laser is explained here as it was implemented in MATLAB. Assuming that the drag force produced by the laser or enhanced AAD is aimed perpendicular to the leading edge of the wing and is level with the x-axis of the aircraft, the equations above can be modified to include:

$$
\begin{bmatrix}
\dot{u} \\
\dot{v} \\
\dot{w}
\end{bmatrix} = \begin{bmatrix}
-g \sin \theta \\
g \sin \phi \cos \theta \\
g \cos \phi \cos \theta
\end{bmatrix} + \frac{1}{m} \left( \begin{bmatrix}
F_{\text{thrust}} \\
0 \\
0
\end{bmatrix} + \begin{bmatrix}
X^b \\
Y^b \\
Z^b
\end{bmatrix} + \begin{bmatrix}
F_{\text{drag}} \\
0 \\
0
\end{bmatrix} \right) - \begin{bmatrix}
w - r^v \\
r^u - p^w \\
p^v - q^u
\end{bmatrix} (2.3)
$$

and

$$
\begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r}
\end{bmatrix} = \begin{bmatrix}
I_{xx} & 0 & I_{xz} \\
0 & I_{yy} & 0 \\
I_{xz} & 0 & I_{zz}
\end{bmatrix}^{-1} \begin{bmatrix}
I^b \\
M^b \\
N^b
\end{bmatrix} + \begin{bmatrix}
L_{\text{drag}} \\
M_{\text{drag}} \\
N_{\text{drag}}
\end{bmatrix} - \begin{bmatrix}
p \\
q \\
r
\end{bmatrix} \times \begin{bmatrix}
I_{xx} & 0 & I_{xz} \\
0 & I_{yy} & 0 \\
I_{xz} & 0 & I_{zz}
\end{bmatrix} \begin{bmatrix}
p \\
q \\
r
\end{bmatrix} (2.4)
$$

where $F_{\text{drag}}$ is the laser or enhanced AAD aerodynamic force imparted on the wing

$[L_{\text{drag}}, M_{\text{drag}}, N_{\text{drag}}]$ are roll, pitch, and yaw moments induced by $F_{\text{drag}}$.

Equations 2.3 and 2.4 can be rewritten as a set of six nonlinear equations, where the bold elements indicate additions due to AAD forces and moments to the standard nonlinear aircraft dynamics equations as derived by Stengel:

$$
\dot{u} = -g \sin \theta -qw +ru + \frac{F_{\text{thrust}} + X^b}{m} + \frac{F_{\text{drag}}}{m} (2.5)
$$

$$
\dot{v} = g \sin \phi \cos \theta - sv + pw + \frac{Y^b}{m} (2.6)
$$

$$
\dot{w} = g \cos \phi \cos \theta - pv + qu + \frac{Z^b}{m} (2.7)
$$
For simplification, it was assumed that \( N_{drag} \) and \( M_{drag} \) are negligible compared to \( N_{drag} \). Given that \( I_{xz} = 0 \), the only variables that become affected by the AAD forces and moments are \( \dot{u} \) and \( \dot{r} \).

From the full set of twelve linearized equations of motion, in which six are presented above, a state-space model was developed. The model represented in state-variable form is:

\[
\dot{x} = Ax + B_p u_p + B_l u_l
\]  

(2.11)

where \( x \) is a vector containing the states of the system, \( A \) is the state matrix, \( B_p \) is the aircraft input matrix, \( u_p \) is the aircraft control inputs, \( B_l \) is the laser input matrix, and \( u_l \) is the laser control input (Franklin). All states of the system were assumed to be directly measured with no noise, such that the output vector is defined as \( y = x \).

Aircraft flight dynamics are described by twelve nonlinear equations of motion: two coupled sets of six equations each that describe the lateral and longitudinal dynamics. Thus, separate lateral dynamics and longitudinal dynamics models were created and simultaneously solved during the simulations. The states of the lateral dynamics model included side velocity (\( \nu \)), roll rate (\( \dot{\phi} \)), yaw rate (\( \dot{\psi} \)), roll angle (\( \phi \)), yaw angle (\( \psi \)), integral of roll angle (\( \int \dot{\phi} \)), integral of yaw angle (\( \int \dot{\psi} \)), and crossrange (\( r \)). The linearized lateral dynamics model represented in state-variable form is:
The states of the longitudinal dynamics model included axial velocity ($u$), vertical velocity ($w$), pitch rate ($q$), pitch angle ($\theta$), range ($x$), and altitude ($z$). The linearized longitudinal dynamics model represented in state-variable form is:

\[
\begin{bmatrix}
\dot{v} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \\ \dot{\psi} \\ \dot{\psi}
\end{bmatrix} =
\begin{bmatrix}
-0.254 & 0 & -1.76 & 0.322 & 0 & 0 \\
-0.08 & -8.4 & 2.19 & 0 & 0 & 0 \\
2.55 & -0.35 & -0.76 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
v \\ p \\ r \\ \phi \\ \psi \\ \psi
\end{bmatrix}
\]

\[
+ \begin{bmatrix}
0 & 0.1246 \\
29 & 2.55 \\
-0.222 & -4.6 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
[\dot{u}]_p \\
[\dot{w}]_p
\end{bmatrix} + \begin{bmatrix}
0 \\
0.0464 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
w \\
q \\
x \\
\theta
\end{bmatrix}
\]

The states of the longitudinal dynamics model included axial velocity ($u$), vertical velocity ($w$), pitch rate ($q$), pitch angle ($\theta$), range ($x$), and altitude ($z$). The linearized longitudinal dynamics model represented in state-variable form is:

\[
\begin{bmatrix}
\dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{x} \\ \dot{z}
\end{bmatrix} =
\begin{bmatrix}
-0.045 & 0.036 & 0 & -0.322 & 0 & 0 \\
-0.370 & -2.02 & 1.76 & 0 & 0 & 0 \\
0.191 & -3.96 & -2.98 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & -1.76
\end{bmatrix}
\begin{bmatrix}
u \\ w \\ q \\ \theta \\ x \\ z
\end{bmatrix}
\]

\[
+ \begin{bmatrix}
0 & 1 \\
-0.282 & 0 \\
-11 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
[\dot{u}]_p \\
[\dot{w}]_p
\end{bmatrix} + \begin{bmatrix}
0 \\
0.22814 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
w \\
q \\
x \\
\theta
\end{bmatrix}
\]

The state matrices, $A$, and the aircraft input matrices, $B_p$, of both lateral and longitudinal dynamics were specific to a Navion aircraft (Teper; Bryson). The actuators for controlling lateral motion include the ailerons and rudder, and for controlling
longitudinal motion include elevator and thrust. The control inputs for the aircraft, \( u_p \), are determined by the control law,

\[
u_p = -Kx \tag{2.14}\]

where the feedback gains, \( K \), are determined by an optimal linear quadratic regulator (LQR) technique in MATLAB. The aircraft control inputs imitate the control inputs that a pilot makes on the various actuators mentioned above.

The laser input matrix, \( B_l \), was determined under two assumptions: (1) the laser is aimed perpendicular to the leading edge of the wing and level with the x-axis of the aircraft, and (2) the laser-induced pitching moment is so small that it is considered negligible. Based on these assumptions, the additional elements in Equations 1.5 and 1.10 are gathered into the \( B_l \) vector. Thus, the \( B_l \) vector describes the maximum saturation force level of the laser.

The laser control input, \( u_l \), determines how the laser actuation is controlled. Specifically, it describes the location (left wing if \( u_l < 0 \); right wing if \( u_l > 0 \)) and intensity of the laser (\( 0 \leq |u_l| \leq 1 \)). For this thesis, control laws were designed to maximize the laser’s diversion capability and will be discussed in the subsequent chapters. The MATLAB code used to run the simulations are presented in Appendix A.

While there are clear advantages to quickly prototyping control laws in MATLAB, there are also disadvantages. The mathematical model in the MATLAB code is a linearized model of the Navion aircraft. While MATLAB can realistically simulate aircraft dynamics during straight and level flight, the model degrades for flight that exhibit great deviations from this condition, such as when the aircraft tries to roll over 90 degrees in one direction. The LQR model used to simulate the pilot’s response to the laser control laws is also a simplified linear model. While this model allows MATLAB to simulate how
a pilot and aircraft responds to a laser control law, the linear pilot model cannot mimic the complexity of human behavior during flight. For example, the LQR pilot model has a quicker reaction time than a human pilot for correcting small deviations in straight and level flight. Thus, a higher-fidelity simulation environment is desired.

2.2 X-Plane for Desktop Flight Simulation

X-Plane (Laminar Research, Columbia, SC) flight simulation software was used to validate control law designs and conduct HITL simulations because of its ability to produce higher-fidelity (more realistic) simulations than MATLAB. The flight simulation software allows users to control many aspects of simulated flight, including aircraft, weather conditions, starting location, instrument failure modes, and navigation. Among other higher-fidelity flight simulation software such as Microsoft FlightSim, X-Plane was chosen because it allowed users to alter the existing flight simulation through user-written code called plugins and was supported by an extensive and growing online developer community. In particular, plugins can interact with and alter the X-Plane physics model that determines how an aircraft will fly.

The ability to write plugins to modify the simulation was critical for validating control law designs and conducting HITL simulations. In Section 2.1, it was shown that two states, yaw rate and forward velocity, are affected when laser forces are applied to the aircraft’s wings. To simulate the effect of AAD forces on an aircraft, plugins were written that extracted the two states, recalculated their values based on if a laser was aimed at the wing, and reassigned the state values. X-Plane would then read the new values and simulate how the aircraft would fly in response to the new values. The specific equations used in the plugin were the following:
\[ u_{new} = u_{prev} + \frac{F_{drag}}{m} \Delta t \quad (2.15) \]

\[ r_{new} = r_{prev} + \frac{N_{drag}}{I_{zz}} \Delta t. \quad (2.16) \]

where \( \Delta t \) is the time step of each X-Plane rendering cycle, and \( F_{drag} \) and \( N_{drag} \) are the same values as in Equations 2.5 and 2.10.

In these plugins, several datarefs were used to calculate AAD forces and update the existing aircraft dynamics to exhibit the effect of the laser or enhanced AAD forces on the aircraft. Other datarefs describing the aircraft dynamics states were continuously written into a text document during each simulation for post processing. A description of every dataref used for HITL simulation, control law implementation, and post-processing is listed in Table 1. The plugins written in Visual C++ for validating control law designs and implementing the HITL simulations are presented in Appendices C and D.

**Table 1: List of datarefs used in X-Plane plugins to simulate AAD forces on an aircraft and run HITL simulations.**

<table>
<thead>
<tr>
<th>Dataref name</th>
<th>Unit</th>
<th>Description (“Datarefs”)</th>
</tr>
</thead>
<tbody>
<tr>
<td>local_x</td>
<td>meters</td>
<td>The location of the plane in OpenGL coordinates</td>
</tr>
<tr>
<td>local_y</td>
<td>meters</td>
<td>The location of the plane in OpenGL coordinates</td>
</tr>
<tr>
<td>local_z</td>
<td>meters</td>
<td>The location of the plane in OpenGL coordinates</td>
</tr>
<tr>
<td>local_vx</td>
<td>meter/second</td>
<td>The velocity of the plane in local OGL coordinates</td>
</tr>
<tr>
<td>Variable</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>local_vy</td>
<td>meter/second</td>
<td>The velocity of the plane in local OGL coordinates</td>
</tr>
<tr>
<td>local_vz</td>
<td>meter/second</td>
<td>The velocity of the plane in local OGL coordinates</td>
</tr>
<tr>
<td>phi</td>
<td>degrees</td>
<td>The roll of the plane</td>
</tr>
<tr>
<td>theta</td>
<td>degrees</td>
<td>The pitch relative to the plane normal to the Y axis</td>
</tr>
<tr>
<td>psi</td>
<td>degrees</td>
<td>The true heading of the plane from the Z axis</td>
</tr>
<tr>
<td>P</td>
<td>degrees/second</td>
<td>The roll rotation rates (relative to the flight)</td>
</tr>
<tr>
<td>Q</td>
<td>degrees/second</td>
<td>The pitch rotation rates (relative to the flight)</td>
</tr>
<tr>
<td>R</td>
<td>degrees/second</td>
<td>The yaw rotation rates (relative to the flight)</td>
</tr>
<tr>
<td>total_flight_time_sec</td>
<td>seconds</td>
<td>The total time since the flight got reset by something</td>
</tr>
<tr>
<td>frame_rate_period</td>
<td>seconds</td>
<td>The frame rate period of the flight simulator</td>
</tr>
<tr>
<td>autopilot_mode</td>
<td>N/A</td>
<td>The autopilot master mode (off=0, flight director=1, on=2)</td>
</tr>
</tbody>
</table>

### 2.3 Human-in-the-Loop Simulation for Control Law Validation

HITL studies were conducted with certified pilots to test the effectiveness of AAD control laws. This final step was critical in understanding how the control laws affected human pilot performance. This section describes the recruited pilots, experimental apparatus, and procedure for conducting the HITL simulations.
2.3.1 Pilot Recruitment

Six certified pilots with flight experience within the last three months were recruited from local flight schools and university flight clubs to participate in the HITL simulation. Their flight experience ranged from flying recreationally during the weekends to being a military fighter pilot. Table 2 shows that the amount of logged flight hours for the group ranged from 90 hours to 2,100 hours. While all pilots were required to have flight certification and have recent flight experience, only two were also instrument rated. Instrument rating indicates that a pilot has logged additional flight hours and has completed training with an instructor to fly by instruments (FAA). Pilots with instrument rating, therefore, are allowed to fly during the night and in weather conditions such as fog and rain.

Table 2: Pilot flight experience.

<table>
<thead>
<tr>
<th>Pilot</th>
<th>Flight Hours</th>
<th>Instrument Rating</th>
<th>Pilot Currency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot 1</td>
<td>90</td>
<td>N</td>
<td>recent</td>
</tr>
<tr>
<td>Pilot 2</td>
<td>2100</td>
<td>Y</td>
<td>recent</td>
</tr>
<tr>
<td>Pilot 3</td>
<td>200</td>
<td>N</td>
<td>recent</td>
</tr>
<tr>
<td>Pilot 4</td>
<td>700</td>
<td>Y</td>
<td>recent</td>
</tr>
<tr>
<td>Pilot 5</td>
<td>100</td>
<td>N</td>
<td>recent</td>
</tr>
<tr>
<td>Pilot 6</td>
<td>290</td>
<td>N</td>
<td>recent</td>
</tr>
</tbody>
</table>
2.3.2 Laboratory Equipment Setup

All HITL studies were conducted in the Automated Systems and Robotics (ASAR) Lab in Bray Laboratory, Medford, MA. The experimental apparatus, as shown in Figure 3, consists of a computer monitor (12” x 15” display) with X-Plane software, keyboard, and flight simulation control hardware, FlightSim Yoke and Pro Pedals (CH Products, Vista, CA). The ASAR Lab environment was consistent throughout the studies with bright ambient light, low radio chatter and engine noise from X-Plane, and no other distractions.

Figure 3: Equipment setup for HITL simulations.
The equipment setup was also consistent throughout the studies. The pilots were only allowed to use the FlightSim Yoke to control the aircraft’s roll and pitch motion and were told to disregard the other buttons. The pro pedals were used to control the aircraft’s yaw motion. The X-Plane interface displayed two views: the cockpit window and the instrument panel (as seen in Figure 4). The instruments that the pilots were allowed to use during the simulations included a compass, airspeed indicator, artificial horizon, altimeter, turn and slip indicator, directional gyro, and rate of climb indicator. Throughout the simulations, the pilots were allowed to toggle between cockpit and instrument views by pressing a button on the keyboard.

Figure 4: Instrument panel in X-Plane.
2.3.4 Study Procedure

Each pilot participated in an individual session in which the participant was introduced to the study, given several tasks to complete in X-Plane, and then debriefed at the end. Each session lasted approximately one hour. The study procedure is presented below:
STUDY PROCEDURE

I. Introduction to Study and X-Plane (15 min)
   a. Explain study to participant and sign consent form.
   b. Ask about flying background: flight hours, certification.
   c. Load X-Plane and introduce hardware, cockpit views, instruments, and basic capability.
   d. Have participant set up and calibrate their own flight controls.
   e. Load “practice.sit” and let pilot fly in free flight.

II. Large Forces, 1st set (15 min)
   a. The participant goal is to fly towards a mountain peak using pilotage (visual cues) only.
   b. The 1st series contains 5 sequential runs, each restarting at the same location and initial flight conditions.
      i. Laser magnitudes are as follows (multiples of baseline laser force): mag = -30x, -10x, -50x, -20x, -30x.
   c. The laser control is a simple bang-bang at 0.5 Hz based on yaw rotation rate (r) and acceleration (rdot).
      i. If r > 0 and rdot > 0, then laser = -mag
      ii. If r > 0 and rdot < 0, then laser = mag
      iii. If r < 0 and rdot > 0, then laser = mag
      iv. If r < 0 and rdot < 0, then laser = -mag

III. Large Forces, 2nd set (15 min)
   a. Same goal and laser condition as above, except
      i. Laser magnitudes are as follows: mag = -40x, -10x, -40x, -50x, -20x.

IV. Limited Visibility (10 min)
   a. The participant goal is to fly north at a constant altitude using instruments only.
   b. The series contains 3 sequential runs, with same initial conditions.
   c. The baseline laser force is used.
   d. The laser control is a set pattern: 2 seconds on left wing, then one second on right wing.

V. Conclusion (5 min)
   a. Thank them for participating in study, give them monetary compensation, and ask if they have any questions.
   b. Give them contact info for follow up questions or interest in attending thesis defense.
During the introduction, the participants were told that this study would investigate a non-lethal method for diverting hijacked planes. They were then briefed on the tasks they would perform. All participants were aware that a laser would be involved in altering their flight; however, specifics regarding how the laser worked or would affect the aircraft’s flight dynamics were not discussed. Participants then flew the Navion in X-Plane using the flight control hardware in free flight to familiarize themselves with the equipment setup. Due to time constraints, they were only allowed to practice using the flight simulator for five minutes.

During the study, all pilots were asked to fly in X-Plane and complete two tasks, briefly summarized below. Regardless of the task, the setup for each flight was the same. All pilots flew on a Navion aircraft model N122BW (Wilson Aircraft). The flights started with the Navion flying in straight and level flight at a speed of 176 feet per second (approximately 104 knots), an altitude of 6,000 feet, and with no laser or enhanced AAD forces acting on it. No additional weather conditions or turbulence were introduced during the flights. The AAD forces were activated on an aircraft at a randomized time between five and ten seconds after the flight began. All flights were terminated after 130 seconds, regardless of the performance of the pilot to a given task. This duration was chosen because it is a sufficiently long enough period to observe aircraft diversion effects from the laser and also short enough to keep the overall HITL study with the pilots within one hour.

The first task was to fly the aircraft due north at constant altitude under dense fog as seen in Figure 5. This low-visibility weather condition is called instrument meteorological conditions (IMC). Further details regarding this task are presented under section 3.3 (Effect of Laser on Pilot with Limited Visibility).
Figure 5: Dense fog view from out of cockpit window.

The second task was to fly the aircraft toward a specific mountain peak in the distance as directly as possible under full visibility conditions as seen in Figure 6. This clear weather condition is also called visual meteorological conditions (VMC). The target peak that the participants were asked to fly toward is the peak to the right, labeled with a red arrow. Further details regarding this task are presented under section 4.3 (Effect of Large Aerodynamic Forces on Pilot). After participants completed both tasks, they were given an opportunity to ask questions regarding the study.
The data recorded during the study included raw flight data, verbal comments from participants, and videos. The raw flight data, previously listed in Table 1, were critical for analyzing the participants’ performance during the tasks. Comments that participants expressed during the study were also recorded because they gave insight into what the participants’ perceptions of the AAD forces were like. Videos of several flight runs were recorded through X-Plane’s video capture feature. These videos display a recording of what the pilot saw on the monitor during the flight. Due to the large video file size of one full flight, only two flights per HITL task were recorded for Pilot 1 and 2.
Chapter 3: Laser-based Active Aircraft Diversion

The goal of laser-based AAD is to divert an aircraft from its intended target regardless of the pilot’s intentions. The challenge is to characterize the forces generated by the baseline laser AAD concept, and determine whether they are able to generate measurable diversion of aircraft trajectories.

In order to assess the effectiveness of laser based AAD, it is first necessary to describe the baseline laser-based AAD concept in detail. The maximum forces a laser can generate are characterized for applicable UAV and GA aircraft for comparison. Then the rest of the chapter is dedicated to presenting the capability of the laser to divert an unpiloted aircraft (as is possible for UAVs) as well as an aircraft navigated by a human pilot with limited visibility. The findings from these investigations show that a considerable amount of diversion can occur in an unpiloted aircraft. The findings also show that a limited diversion can also occur for aircraft navigated by pilots with limited visibility.

3.1 Laser-Induced Turbulence Model

The notion of using a laser to divert aircraft was originally proposed by Dr. Richard Wlezien. Research investigating the fluid mechanics effects of a laser on an airfoil is currently being conducted by Alfram Bright at Tufts University. His feasibility studies of the laser-induced turbulence model described below make use of the Brilliant QSwitched Nd: YAG oscillator laser model (Quantel, United Kingdom). Its pulse duration is 1064 nm and outputs 900 mJ of energy in 6 ns (Bright; “Q-Switched”). This configuration is one example of implementing laser-based AAD for testing purposes.
In theory, the laser itself is stationed on the ground and aimed at the leading edge of the target aircraft’s wings as shown in Figure 7.

![Figure 7: Illustration of high power laser aimed at leading edge of aircraft wing creating turbulent flow over and under the wing.](image)

The physical location of the laser may be application specific, however, and is not specifically considered in our simulations. The laser may also be attached to another aircraft; for example, the Airborne Laser Test Bed, developed by the Missile Defense Agency, uses lasers attached to the nose of a modified Boeing 747-400 Freighter (Missile). Attaching the laser to an aircraft may improve the laser’s ability to continuously aim at the leading edge of the target aircraft’s wings as the target aircraft turns. In the simulations for this thesis, an assumption is made that the entire leading edge is visible to the laser at all times.

Aircraft diversion is based on the concept of laser-induced turbulence. This concept only applies to low speed aircraft with laminar airfoils. Laminar flow is characterized by smooth streamlines and turbulent flow is characterized by rough and choppy streamlines as shown in Figure 8.

![Laminar Flow](image)
In this model, the laser is focused on a spot in front of the leading edge of the wing which rapidly heats up the air. This hot air pocket bursts and triggers the laminar boundary layer on the leading edge of the airfoil to become turbulent. As the airflow continues down the wing, it creates turbulence in its wake. The focal point of the laser can be shifted quickly enough to “paint” the entire leading edge of the wing to produce turbulence along the entire length of the leading edge. Based on preliminary experiments with Wlezien and Bright, several assumptions are made. We assume that it is possible to instantaneously create turbulence over the entire surface of the wing, and that both the top and bottom surface of the wing can be painted separately (Wlezien; Bright). Thus, maximum drag on a wing occurs when both the top and bottom wing surfaces are painted at the same time and the laminar boundary layer over the entire airfoil converts to turbulent.

A model is used to describe the maximum aerodynamic force generated by the laser. Fundamentally, the maximum force is the difference between the drag forces for a turbulent boundary layer laser and laminar boundary layer airfoil. Therefore, when the laser is activated the boundary layer transitions from laminar to turbulent and an increased drag force results:

\[ F_{\text{drag}} = F_{\text{turbulent}} - F_{\text{laminar}}. \] (3.1)
To estimate this difference, wing surfaces are approximated as flat plates. The equations for laminar and turbulent drag force on an airfoil over a two-sided flat plate are respectively,

\[ F_{\text{laminar}} = 2 \left[ C_{f,\text{laminar}} \left( \frac{1}{2} \rho V^2 \right) A \right] \]  \hspace{1cm} (3.2)

\[ F_{\text{turbulent}} = 2 \left[ C_{f,\text{turbulent}} \left( \frac{1}{2} \rho V^2 \right) A \right] \]  \hspace{1cm} (3.3)

where \( C_f \) is the coefficient of skin friction, \( \rho \) is the density of air, \( V \) is the aircraft velocity, \( A \) is the surface area of the wing, and the multiplier, 2, represents flow above and below the wing.

To assess the impact of the increased drag on the target aircraft, a rigid-body dynamics analysis was used. The turbulent drag force is distributed, but for purposes of analysis, the bulk force was modeled as acting on a particular point on the wing, referred to as the center of pressure. The center of pressure is not coincident with the plane’s center of mass. The increased drag force modeled as a bulk force is defined as the variable, \( F_{\text{drag}} \), and the perpendicular distance from the center of pressure to the aircraft centerline is defined as the variable, \( d \). These two variables are related by the following equation, where \( M_{\text{drag}} \) is the corresponding moment:

\[ M_{\text{drag}} = F_{\text{drag}} \cdot d. \]  \hspace{1cm} (3.4)

The increased drag force and corresponding moment effect on an aircraft are shown in a top-down view in Figure 9.
Implicit in the above equation is the assumption that the laser-generated drag is always aligned with the axis of the centerline of the aircraft and perpendicular to the leading edge of the wing. A more sophisticated aerodynamic analysis would be necessary to fully capture all of the detailed aerodynamics for laser-generated drag; however, such an analysis is beyond the scope of this chapter. A full explanation of the calculations above is referenced in Appendix B.

This physical mechanism is the basis for the baseline AAD concept: the laser can be aimed at one wing or the other to trigger an asymmetric change in drag force and moment. If the laser is aimed at the right wing (as shown in Figure 9a), then the resulting laser moment can force the aircraft to rotate around its center of mass in a clockwise direction (Figure 9b). By aiming the laser at a wing on a specific side of the aircraft and specifying the laser exposure time, the laser can force the aircraft to slightly rotate in an intended direction. The algorithm for designating the location, intensity, and duration of the laser is referred to as the laser control law, or laser controller, for the remainder of this thesis. Properly designed control laws can force the aircraft to turn, oscillate, or perform other motions for the purposes of aircraft diversion.

Figure 9: (a) Laser drag force and (b) resulting moment creates rotational movement about aircraft’s center of mass.
A major limitation to the laser generated drag force is that the force saturates as soon as the entire wing becomes turbulent. In other words, there is a maximum force level that is associated with the laser-based configuration. Forces imparted on an aircraft may be modulated below this level as well, by painting only a portion of the wing. Importantly, the maximum saturation force is very much smaller than the forces that a pilot can generate using aircraft controls. For this reason, the major challenge of laser-based AAD is that fully capable pilots can easily overcome forces generated by the laser. This made it necessary to investigate time-varying forces and restrict pilot capability in some way, such as by limiting their visibility, in order to make the baseline laser-based ADD concept useful.

The maximum drag able to be generated by the laser depends on the size of the wing and the speed of the target aircraft. To understand what drag forces and moments a laser can produce on laminar wing aircraft, calculations for three applicable aircraft were compared as shown in Figure 10: the Insitu ScanEagle UAV, the Cessna Skyhawk, and the Navion L-17 aircraft.
The ScanEagle UAV is currently in use by the U.S. military, and has been deployed for surveillance and reconnaissance missions in the Iraq War and against Somalian piracy.
(Garamone; Clark). The Cessna Skyhawk is the world’s best selling single-engine airplane and also the first aircraft that both U.S. and Iraqi Air Force pilots fly during training (Mola; Carden). The Navion is a popular classic single-engine aircraft that was manufactured for both military and civilian customers (Huber).

Maximum drag force and moment values for each aircraft were computed using Equations 3.1 and 3.4. The laser moment arm, \( d \), was assumed to be a quarter of the wing span. Parameters used to estimate maximum drag and moments are listed in Table 3 or provided in Appendix B. At the bottom of the table, the maximum laser drag forces and moments are listed. The Cessna and Navion have relatively similar force values of 19.1 lbs and 19.5 lbs, respectively. For the UAV, only 0.21 lbs of laser force can be generated. For the rest of the thesis, the Navion aircraft is used for all simulations. The maximum laser drag force for the Navion is 19.5 lbs and the maximum corresponding moment is 162.8 lb·ft. These values were substituted as \( F_{drag} \) and \( N_{drag} \) in Equations 2.5, 2.10, 2.15, and 2.16, then implemented in MATLAB and X-Plane.

<table>
<thead>
<tr>
<th></th>
<th>ScanEagle UAV</th>
<th>Cessna 172 Skyhawk</th>
<th>Navion L-17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Span, ft</td>
<td>10.2</td>
<td>35.8</td>
<td>33.4</td>
</tr>
<tr>
<td>Wing Surface Area, ft(^2)</td>
<td>5.7</td>
<td>87</td>
<td>92</td>
</tr>
<tr>
<td>Chord Length, ft</td>
<td>1.2</td>
<td>4.5</td>
<td>5.7</td>
</tr>
<tr>
<td>Cruise Speed, ft/sec</td>
<td>82.0</td>
<td>183</td>
<td>176</td>
</tr>
<tr>
<td>Average Weight, lb</td>
<td>40</td>
<td>2450</td>
<td>2750</td>
</tr>
</tbody>
</table>
Now that how the laser works and how much force and moment it can generate on an aircraft is established, several issues need to be addressed. What effect does this force and moment have on a flying aircraft? How much can the laser controller divert an aircraft with a pilot in active control of it or without a pilot in command? What do the laser forces feel like for a pilot?

### 3.2 Effect of Laser on Unpiloted Aircraft

An important first qualification for the baseline laser ADD concept is to determine whether the laser generated drag forces are sufficiently large to divert an aircraft in the absence of pilot control forces. It is not immediately obvious that the laser-generated turbulent drag forces are large enough to effectively divert an aircraft, as these drag forces are very small relative to the weight of the aircraft (the drag force to weight ratio is less than 0.01 for the Navion, and similar for the other two aircraft in Table 3). Importantly, the scenario in which the pilot has no control authority may actually be an important application for the proposed technology. In particular, this capability is relevant for situations such as diverting an encroaching UAV, assuming that the UAV is controlled by a remote pilot whose flight control can be cut off through radio-frequency jamming (Ball).

To determine the effects of a laser on an aircraft with no pilot feedback, flight simulations of the Navion were created in X-Plane. Throughout the simulation, no

<table>
<thead>
<tr>
<th>Roughness height, in</th>
<th>0.001</th>
<th>0.0025</th>
<th>0.0025</th>
</tr>
</thead>
<tbody>
<tr>
<td>LASER FORCE, lb</td>
<td>0.21</td>
<td>19.1</td>
<td>19.5</td>
</tr>
<tr>
<td>LASER MOMENT, lb·ft</td>
<td>0.53</td>
<td>171.5</td>
<td>162.8</td>
</tr>
</tbody>
</table>
external disturbances such as weather, turbulence, and aircraft failures were present. The Navion was initially started at straight and level flight. After 40 seconds, all autopilot functions were turned off and the laser was activated on the right wing of the aircraft. The laser was programmed to impart the full 19.5 lb drag force on the center of the right wing continuously. A plot of the laser controller is shown in Figure 11. The flight trajectory of the aircraft was recorded for over two minutes to capture the effects of the laser on the aircraft.

![Laser Controller](image)

**Figure 11: Laser controller for making unpiloted aircraft spiral in place.**

Targeting the laser on the right wing with the maximum saturation laser force caused the unpiloted Navion to curve along a circular trajectory of approximately 3000 feet in diameter. The blue line in Figure 12 shows the trajectory of the aircraft in response to the laser. The aircraft can be seen to start flying straight and level, then slowly deviate and spiral to the right after the laser is activated on the wing. The tightness of the turn is comparable to a turn that a pilot can make. If the laser was not activated, then the trajectory of the aircraft would remain a straight line. This spiraling trajectory is significant because the laser is able to force the aircraft to deviate from its straight flight and remain in a 3000 diameter area simply by aiming the laser continuously on one wing.
Figure 12: Trajectory of unpiloted aircraft spiraling to right due to laser.

To further investigate the capability of the laser to divert an aircraft, the simulation was conducted again with the same initial conditions, but a different laser controller. This time, the laser was manually switched during the flight between the left and right wing in order to force the aircraft to bank into a right turn, then straighten and head towards a different direction. The laser controller for this simulation is shown in Figure 13.

Figure 13: Laser controller used to redirect an unpiloted aircraft.

The trajectory in the figure below demonstrates that the aircraft can indeed be forced to turn and be redirected toward a different direction by the laser. This case
demonstrates the potential to divert an approaching aircraft and send it back in the
direction from which it arrived.

Figure 14: Trajectory of unpiloted aircraft being redirected by laser.

These results show the ability of the laser to stop an aircraft from advancing by
making it spiral in place or redirecting it toward a different direction. With the
demonstration of these two diversion behaviors, one can imagine the other diversion
behaviors that the laser can generate on an unpiloted aircraft. The results show
promise for developing laser-based AAD methods in combination with signal jamming
technologies specifically for diverting UAVs.

3.3 Effect of Laser on Pilot Given Limited Visibility

Since the human pilot can exert vastly greater moments on an aircraft than
possible with laser-based AAD, it is necessary to consider limiting pilot flying capabilities
for laser-based AAD to be useful. Literature on aircraft accident investigations and pilot
behavior in the cockpit motivate the use of limiting pilot visibility to increase the success
of baseline laser forces to divert an aircraft with an active pilot. Shappell et al.
conducted a study that investigated over 1000 commercial aviation accidents that
occurred in the United States over a 13-year period. They observed that “nearly one
half of all commuter/on-demand accidents occurred in a visually impoverished
environment. Of those, an alarming 70% resulted in fatalities.” While the goal of AAD is
not to result in an aircraft accident, this finding suggests that imposing limited visibility
conditions on a pilot can potentially make the pilot underperform to an extent that low
laser saturation levels can exert a meaningful diversion.

One method for limiting pilot visibility is to create temporary visual impairment
by shining a white-light dazzler on the cockpit windows. The dazzler delivers “a dazzling
and disabling light flash of maximum eye-safe energy” (Upton). This non-damaging
effect lasts for approximately two minutes. The distraction, disorientation, or
discomfort that often accompanies vision impairment could be used to divert the
aircraft during this time (Nakagawara). However, this method can be too disconcerting
to the hijackers and potentially force the aircraft to crash.

Another method that limits pilot visibility, yet is potentially safer than the
dazzler, is to reduce the visibility on the cockpit itself. While this may also be
disconcerting to the pilot, the pilot still has the capability of flying the aircraft using
cockpit instruments and other navigational tools. By definition, this flying condition is
called instrument meteorological conditions (IMC)(Pilot/Controller). In the study
conducted by Shappell et al., they observed that nearly 30% of all commuter and on-
demand operations occurred during IMC. Other studies also make similar conclusions
regarding pilot performance under IMC (Hunter; Drinkwater). Furthermore, another
study investigating pilot behavior during landing approaches through low-level wind
shear stated that instrument resolution “might not be sufficiently high to rapidly detect
an abnormal situation” (Martens). Therefore, there is an opportunity to extract the
greatest deviation in the aircraft using the laser on a pilot in this limited visibility condition. These observations were used to develop and test an aircraft diversion strategy on pilots flying under imposed instrument meteorological conditions in X-Plane.

In this section, a HITL simulation is presented in which the following conditions are applied: (1) reduce pilot navigation capability by limiting cockpit visibility and disabling other navigational tools, such as radio beacons and GPS and (2) impart a laser on the aircraft using a laser controller whose diversion effects are undetectable to the pilot.

### 3.3.1 Setup for Limited Visibility HITL Study

A study was conducted to investigate whether a laser controller with an alternating pattern can cause a pilot to deviate from an intended path while flying under IMC using only the cockpit instruments shown previously in Figure 4. The laser controller was designed to push a pilot off-course in small increments that are undetectable by the pilot. Furthermore, an alternating pattern switching between the left and right wings was incorporated so that the aircraft would temporarily point away from the target and then correct its heading immediately after. The hypothesis is that the pilot would not detect a measurable change in heading from the compass or gyroscope while the aircraft drifted incrementally to the side. The laser controller is shown in Figure 15.
This laser controller was tested on six pilots in a HITL simulation. The pilots’ task was to fly due north at a constant altitude of 6,000 feet, starting at straight and level flight with a speed of 176 feet per second. They were specifically instructed that their main priority was to stay on-course. They were not told any information regarding the laser except that a laser might interfere with the aircraft handling. Weather visibility was set to the lowest possible setting in X-Plane, resulting in completely foggy flying conditions as shown previously in Figure 5. Pilots had essentially zero visibility out the cockpit window and were forced to fly guided by cockpit instruments only.

Randomly between five to ten seconds into the flight, the laser was activated. The laser was programmed to aim at the left wing of the aircraft for two seconds, then the right wing for one second. No other disturbances, such as wind or aircraft failures, were present throughout the simulation. Each pilot flew three flight attempts and each flight lasted for two minutes. The plugin code used to implement this study in X-Plane is referenced in Appendix C.
3.3.2 Results for Limited Visibility HITL Study

Recorded pilot trajectory data show a range of abilities among pilots and with respect to attempt number. Each pilot flew three times each, resulting in a total of 18 trials. Trajectory data for Pilot 1 are shown in Figure 16 as an example of a typical data set analyzed in this study. The blue, green, and pink lines show the trajectories of the plane being navigated by Pilot 1 during the first, second, and third attempt at completing the task, respectively. The trajectories have been plotted along the x-axis (flying from the left side of the plot to right) so that the y-axis displays the cross-track deviation distance from the intended path at a given point along the way.

Pilot 1 deviated over 2,500 feet from the path during the first attempt. On the second and third attempts, the pilot became increasingly better at staying on course; however, this observation was not consistent among all pilots. Flight trajectory plots for all pilots are shown in Figure 17. Regarding Pilot 3’s trajectories, the flights were terminated after it was fully obvious that the aircraft was no longer in straight and level flight and the pilot was not able to restore stable flight conditions.
Figure 17: Flight trajectory plots for Limited Visibility HITL simulation.
Aircraft trajectory data for only the first attempt were assembled in one plot in Figure 18. Each line in the figure depicts the trajectory of the aircraft flown by a different pilot.

![Aircraft Trajectory Diagram](image)

**Figure 18:** First attempt trajectories of all pilots; two pilots hold instrument rating (IR) certification.

To assess the ability of the laser to divert the pilot in the absence of visual feedback, it is useful to consider a conceptual scenario in which a hijacker is attempting to crash an aircraft into a building or skyscraper. For this analysis, the average width of a skyscraper was assumed to be several hundred feet. Therefore, a diversion might be considered successful if the hijacked plane were diverted by 500 feet or more from the intended path. The dotted lines in the figure mark 500 foot boundaries. Based on this metric, 5 out of 6 pilots failed at staying within 500 feet of the target during their first attempt. Only Pilot 2 was able to successfully fly within 500 feet of the intended path.
Among the others, only Pilot 4 was able to fly within 1,000 feet. Note that the two pilots who remained the closest to the intended path were the only pilots of the group labeled to have instrument rating (IR) qualifications in the figure legend. An instrument rating indicates that the pilot has completed additional training and is certified to fly under IMC (FAA). This suggests that experienced pilots are more likely to succeed at reaching the intended target than pilots with less experience.

This observation is made much clearer when the number of task failures per pilot is aggregated by attempt number. Figure 19 shows that all four of the non-instrument rated pilots were able to stay within 500 feet of the target for all flight attempts. This is in contrast to the instrument rated pilot results. One of the instrument rated pilots succeeded in staying within 500 feet of the target for all flight attempts, and the other succeeded during the second and third attempt.

![Bar chart](chart.png)

**Figure 19:** Percentage of IR and non-IR pilot task failures for flying due north in IMC.

During the simulations, pilots verbally commented that they weren’t sure if a laser was on or not. One pilot also commented that he was consistently drifting toward the right more than the left. When the flights were analyzed based on final cross-range deviation, the results also confirmed his remark. Across all pilots and all attempts, 14
out of 18 flight runs resulted in cross-range deviation to the right of the target. Figure 20 shows the cross-range deviation for all flights, where negative values indicate deviation to the right and positive values indicate deviation to the left. Note, the plot does not contain cross-range deviation data for Pilot 3 because those flights were terminated before 130 seconds.

![Cross-range deviation for all flights](image)

*Figure 20: Cross-range deviation of aircraft for pilots flying due north in IMC.*

The figure clearly shows that pilots deviated toward the right more than the left on average. Assuming that cross-range deviation would be equally distributed with respect to the centerline if the laser was not present, this shows a trend for the laser to force an aircraft to deviate to the right.

Figure 20 shows the capability of the laser to divert aircraft in a particular direction. Interestingly, aircraft tended to fly toward the right even though the laser was aimed longer on the left wing throughout the flights. Furthermore, pilots flying toward the left deviated 2453 feet on average while pilots flying toward the right deviated an average of 920 feet. One possible explanation for this effect could be that
since the aircraft was tilted to the left for longer periods of time (two seconds each) than the right, pilots were more likely to observe a heading toward the left and accidentally overcorrect to the right.

The overall results show that the laser controller is indeed able to divert aircraft in a particular direction when pilot capability is reduced by limiting pilot visibility through artificially-induced IMC. Furthermore, the undetectable laser controller was successful in diverting aircraft from a target for non-instrument rated pilots. The findings suggest that if a greater laser force level could be applied to the aircraft or if another method for reducing pilot capability was implemented, any type of pilot can potentially be successfully diverted from its target.

### 3.4 Summary

This chapter demonstrates the feasibility of laser-based AAD for diverting unpiloted aircraft and aircraft navigated by pilots with limited visibility. Results indicate that an unpiloted aircraft can clearly be diverted from its intended path and redirected, even if the laser drag force and moment are relatively tiny compared to the equivalent force and moment that a human pilot can generate. This is a significant first step in demonstrating that the laser induced turbulence model is able to divert an aircraft, especially for UAV applications. If laser-based AAD is combined with technologies that distort or cut off control signals from reaching the UAV, then this method could allow the laser controller to have full command over the direction that the UAV flies.

The HITL simulation also demonstrates the ability of the laser to divert an aircraft navigated by a pilot with limited visibility, specifically by artificially imposing IMC. The laser controller is able to direct the aircraft to divert in small increments toward a certain direction. Furthermore, all non-instrument rated pilots were
successfully diverted from their intended target. This result highlights the possibility of successfully diverting all pilots if laser forces could be increased or if other visibility limiting techniques were used.
Chapter 4: Diversion Using Large Forces

This chapter investigates the ability to divert aircraft if control forces imparted on the aircraft are increased as much as fifty times larger than those of the baseline laser AAD level described in Chapter 3. This enhanced AAD scenario is relevant because human pilots can easily overcome the forces generated by the baseline laser given nominal sensory data, such as visual cues from out the cockpit window. Applying larger aerodynamic forces and moments approaching what a pilot can generate via control surfaces opens up more possibilities for controlling the aircraft regardless of pilot capability.

The question of what range of control forces results in effective diversion is motivated by initial simulations in MATLAB. In this section, control law design based on the understanding of airplane upsets and pilot induced oscillations are presented. MATLAB simulations testing several control laws show that it is indeed necessary to consider the use of larger forces and moments to divert an aircraft when a pilot is actively navigating to maintain straight and level flight.

Generating larger aerodynamic forces that maximize diversion requires two major assumptions. First, a means to enhance the baseline laser forces is needed. Alternative technologies can be used in combination with the laser to produce these higher forces. Possible approaches discussed later in this chapter include an aerial limpet strategy, alternative aircraft surfaces, and increased turbulence. Second, sensory information regarding the target aircraft is assumed to be available for commanding enhanced AAD control forces through feedback control. Sensor information might be provided by any number of technologies including radar, optical sensing, or an inertial measurement unit. For this thesis, implementation of alternative technologies is not
expanded upon; actuation and sensing capability is simply assumed to exist such that desired control laws can be implemented.

To investigate how human pilots actually perform when enhanced AAD forces are applied to the aircraft, a second HITL simulation was conducted. A variable structure laser controller was implemented in the study to create as much disorienting control effects as possible on the pilot. A range of varying enhanced AAD force levels were applied to the pilots’ aircraft and their flight performance against the laser were recorded. The results show that it is indeed more difficult for a pilot to reach a target as larger aerodynamic forces are applied to the aircraft. Furthermore, the data suggests that neither pilot experience nor the number of attempts at flying against larger forces is correlated to pilot performance. However, as diversion capability increases, pilot disorientation also increases. This result highlights an important consideration when designing control laws: to divert the aircraft as much as possible while minimizing the risk of danger to the passengers.

4.1 Effect of Laser on Pilot with Full Capability

This section establishes the case for baseline laser forces on pilots with full capability. The hypothesis is that meaningful diversion is not possible using baseline laser force levels. To support this result, several attempts were made at designing the most effective control law to significantly divert an aircraft navigated by a fully capable pilot under perfect flight conditions (full visibility, no external weather or turbulence, and no aircraft malfunctions). The control law design process began by getting an understanding of how diversion occurs naturally during flight, such as through airplane upsets and pilot induced oscillations (PIOs). Based on the background knowledge, two laser controllers were developed to maximize diversion by focusing on creating
deviations in yaw angle: (1) to try to excite oscillations by introducing a destabilizing control law, and (2) try to introduce yaw oscillations by using feedback control on pilot commands with a delay.

4.1.1. Aircraft Upsets and Pilot Induced Oscillations

To design control laws that maximize diversion effects on an aircraft, we investigated cases in which aircraft unexpectedly get diverted and tried to implement control laws that induce similar aircraft behavior. Airplane upsets are naturally occurring aircraft diversion incidents. According to the Airplane Upset Recovery Training Aid recommended by the Federal Aviation Administration (FAA), airplane upsets are unintentional situations in which an aircraft’s pitch attitude is greater than 25 degrees up or 10 degrees down, bank angles are greater than 45 degrees, or is within the mentioned parameters but at unsafe speeds. Airplane upsets can be caused by environmental factors, systems anomalies, and pilot actions. Environmental factors that cause airplane upsets include turbulence and airplane icing. Flight instruments, autoflight systems, and flight control system anomalies also cause airplane upsets. Pilot-induced airplane upsets can be caused due to instrument cross-check, inattention, distraction from primary cockpit duties, and vertigo or spatial disorientation. Furthermore, airplane upsets can be caused by a combination of these causes.

Because it was not possible to design a control law that exactly mimics any of the specific causes mentioned above, the next feasible step was to design a control law that produces conditions present in pilot induced upsets, also known as PIOs. The Department of Defense Interface Standard for Flying Qualities of Piloted Airplanes, MIL-STD-1797A defines PIOs as “sustained or uncontrollable oscillations resulting from efforts of the pilot to control the aircraft.” PIOs have been described as “ranging from
an annoying aircraft motion to inability to complete the task to, in the most extreme cases, jeopardizing the safety of the aircraft and crew” and are not necessarily initiated by the pilot as the name implies, but “results from the interaction of the pilot and the dynamics of the vehicle being controlled” (Klyde, McRuer, and Myers iii). When PIOs occur, pilots feel a variety of effects from delay between pilot actuator input and aircraft response to a complete lack of actuator response. These feelings often force pilots to make larger actuator inputs and intensify the situation (Klyde, Investigating; Gatley).

Based on these observations, the laser controller design goals were to produce conditions present in PIOs to potentially cause aircraft diversion. Two precepts have been identified in modern PIO theory: oscillatory characteristics such as limit cycles and out-of-phase behavior (Mitchell; Amato et al.). Given this information, the laser controller design goals were to (1) induce oscillatory aircraft behavior or (2) create out-of-phase pilot response behavior to induce aircraft deviation. These two goals map into the two laser controllers listed at the end of the previous section.

4.1.2 Unstable pole placement

In the absence of any pilot or external control, the Navion is naturally stable. As such, all its eigenvalues are negative when trimmed for straight and level flight. A control law that induces unstable oscillatory behavior in the aircraft is desired to create diversion. Therefore, pole placement was considered to create unsteady aircraft dynamics in the hopes of creating limit cycle behavior. In the following analysis, only the lateral dynamics of the aircraft will be considered.

The system is characterized by four eigenvalues that describe the lateral dynamics of the aircraft, as shown in Table 4. For all original open loop poles, the real part of the poles is negative (on the left hand side of the complex plane). If the real part
of any pole is greater than zero (on the right hand side of the complex plane), then the system becomes unstable.

Table 4: Pole locations for Navion aircraft lateral dynamics.

<table>
<thead>
<tr>
<th>Original Open Loop Poles</th>
<th>Target Location after Pole Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.4327</td>
<td>-8.4327</td>
</tr>
<tr>
<td>-0.4862 + 2.3335i</td>
<td>-0.4862 + 2.3335i</td>
</tr>
<tr>
<td>-0.4862 – 2.3335i</td>
<td>-0.4862 – 2.3335i</td>
</tr>
<tr>
<td>-0.0088</td>
<td>2.2</td>
</tr>
</tbody>
</table>

To investigate the effect of making the lateral aircraft dynamics unstable, the place command in MATLAB was used to move one pole to the right hand plane, as shown in Table 4. The $K$ matrix obtained from using the place command in MATLAB was inserted into the full-state feedback control law (refer to Equation 2.14) and simulated using the MATLAB code in Appendix A. Individual poles were selected and moved to the right hand plane while the other poles were held constant for each simulation run.

The greatest yaw angle deviation resulted from moving the fourth pole, $s = -0.0088$, to the new location, $s = 2.2$. The results from this pole placement are shown in Figure 21. The top plot in red shows the laser imparting between 0 and 19.5 lb of force (the maximum baseline force level) on the aircraft over the course of 20 seconds. Positive laser force values indicate that the laser is aimed at the right wing and
negative values indicate that the laser is aimed at the left wing. The bottom plot in blue shows the yaw angle of the aircraft over time in response to the laser.

![Graph showing laser force and yaw angle over time](image)

**Figure 21: The effect of unstable pole placement on aircraft performance.**

Figure 21 shows desired unstable limit cycle behavior; however, the amount of deviation is less than one degree. Even though the laser is saturating and imparting the maximum amount of force possible on the aircraft, the baseline laser force is not great enough to cause meaningful aircraft diversion.

### 4.1.3 Time Delay

An out-of-phase pilot response behavior can potentially be created if the pilot’s actuation efforts do not correlate to an expected aircraft response. Therefore, time delay was considered for producing unexpected aircraft behavior. To test this, the previous unstable pole placement laser control law was used and a time delay, $\Delta t$, was added such that

$$u_t = -Kx(t - \Delta t).$$

MATLAB simulations were run for different time delay durations to determine if the aircraft behavior would produce yaw angle deviation.
The greatest yaw angle deviation that was produced during this experiment was less than one degree. This was achieved with an unstable pole placement control law with a time delay of 1.5 seconds. Figure 22 shows the laser controller behavior over 20 seconds in red and the yaw angle deviation of the aircraft in blue. While the aircraft exhibits growing instability in the first ten seconds, the laser force saturates by 10 seconds and creates a low amplitude limit cycle. In this case as well, the laser force is not great enough to create meaningful aircraft diversion.

![Figure 22: The effect of unstable pole placement and time delay on aircraft performance.](image)

The time delay control law exhibits similar inability to divert an aircraft more than one degree. While both laser control laws presented here indeed produce limit cycles, the small yaw angle deviations clearly show that the baseline laser force is too limited to produce meaningful aircraft diversion on its own.

**4.1.4 Final Controller Design**

Even though the control laws were unable to produce meaningful aircraft diversion, another interesting result could be seen. Observing the control input plots, it appears that both control laws appear to be approaching a bang-bang controller. A
bang-bang controller is a controller that switches abruptly between two states (Sachs) and are a member of a class of controllers called variable structure controllers. The control equation for a bang-bang controller is

\[ u = \begin{cases} \{-u_{max}, & f(x) < 0 \\ u_{max}, & f(x) \geq 0 \end{cases} \]  

(4.2)

where \( f(x) \) is a function of the state vector \( x \).

From the results above, the laser controller appears to be switching the maximum saturation force abruptly between left and right wings. This observation was observed early in the research process and motivated following control law designs. Instead of designing increasing sophisticated control laws, the rest of the thesis (including HITL simulations) was spent developing simple bang-bang controllers.

### 4.2 Alternative Technologies for Producing Large Forces

For AAD technologies to effectively divert an aircraft navigated by a fully capable pilot, the baseline laser forces must be enhanced in some way to obtain larger control forces. It is reasonable to infer that the size of the previous limit cycles can be amplified if the laser control saturation limit was increased above that for baseline laser AAD technology. While the investigation of how larger forces can be generated is beyond the scope of this thesis, preliminary ideas are presented here: the aerial limpet strategy, use of alternative aircraft surfaces, and increased turbulence.

The aerial limpet strategy gets its name from underwater limpet mines that look like their namesake mollusk. Limpet mines are attached to the hull of ships by magnets and can cause vessel damage if they are not detected and removed before they are detonated (Bingham, Hinders, and Friedman). While the aerial limpet strategy does not call for destruction of the aircraft, the strategy is based on non-destructively locking a
UAV to the target aircraft. Flight control surfaces on the UAV could be manipulated to selectively add drag to one side of the target aircraft.

Another strategy is to aim the laser at other surfaces on the hijacked aircraft in addition to the wing. Any drag force generated by the laser can impart a moment on the aircraft as long as the moment arm between the center of mass of the aircraft and the point of action of force is greater than zero. Greater forces and moments can hypothetically be produced if the laser targets surfaces farther from the center of mass. Some promising targets are the aircraft tail structures, specifically the horizontal and vertical stabilizers. Since the vertical stabilizer lies along the aircraft’s centerline, only a pitching moment can be generated by the laser. A laser aimed at the horizontal stabilizers, however, can generate a pitching and yawing moment. Table 5 summarizes maximum forces and moments that can be achieved by aiming the laser at the front wings (nominal case) or both front wings and stabilizers (maximum case).

Table 5: Increased forces and moments that can be produced by aiming the laser at alternative surfaces.

<table>
<thead>
<tr>
<th></th>
<th>Force (lb)</th>
<th>Yaw Moment (lb-ft)</th>
<th>Pitch Moment (lb-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Left or Right Wing</strong></td>
<td>19.5</td>
<td>162.8</td>
<td>0</td>
</tr>
<tr>
<td><strong>Upper half</strong></td>
<td>9.75</td>
<td>122.1</td>
<td>5.4</td>
</tr>
<tr>
<td><strong>Lower half</strong></td>
<td>9.75</td>
<td>40.7</td>
<td>-5.4</td>
</tr>
<tr>
<td><strong>L or R Horizontal Stabilizer</strong></td>
<td>9.9</td>
<td>32.7</td>
<td>14.9</td>
</tr>
<tr>
<td><strong>Vertical Stabilizer</strong></td>
<td>3.0</td>
<td>0</td>
<td>13.2</td>
</tr>
<tr>
<td><strong>TOTAL, nominal</strong></td>
<td>19.5</td>
<td>162.8</td>
<td>0</td>
</tr>
<tr>
<td><strong>TOTAL, maximum</strong></td>
<td>32.4</td>
<td>195.5</td>
<td>28.1</td>
</tr>
</tbody>
</table>

The values are computed assuming that the surfaces are flat rectangular plates and that turbulence is instantaneously generated over the entire surface. In concept,
the laser can paint any combination of surfaces and the resulting forces and moments would be a summation:

\[ F_{\text{drag}} = \sum F_i \]  
\[ M_{\text{drag,yaw}} = \sum M_{i,yaw} \]  
\[ M_{\text{drag,pitch}} = \sum M_{i,pitch} \]

where \( i \) is the index referring to a particular surface.

An important implicit assumption of these equations is that the airflow on each surface must be laminar for the laser induced turbulence model to apply. This assumption may not be valid for the Navion as the propwash may already make the airflow over the tail turbulent. Propwash may limit which surfaces can be painted by the laser, such as the fuselage, which might also in concept be added to the table as an additional surface on which drag could be generated. To analyze this strategy further would require a detailed calculation of flow over aircraft surfaces to identify which surfaces feature laminar airflow and which are turbulent.

One final strategy to increase laser forces and moments is to simply increase the intensity of turbulence generated by the laser. This concept is motivated by an implicit assumption in the equation for the turbulent boundary layer friction coefficient for a flat plate: a spontaneous transition to turbulence due to flow instabilities. The intensity of turbulence in the boundary layer depends on the surface roughness of the flat plate. In this thesis, a surface roughness, \( e \), was selected to be 0.0025 inches, a relatively small roughness level. It might be possible to mimic a greater surface roughness by generating higher turbulence intensity with the remote laser. Modeling such an increased turbulence level would increase the effective coefficient of skin friction for
turbulent flow, $C_F$, and increase the overall drag force based on the laser induced turbulence model,

$$C_F = \left(1.89 + 1.62 \log \frac{L}{\rho} \right)^{-2.5}$$ (4.6)

where $L$ is the length of the airfoil.

While only three strategies for generating larger aerodynamic forces are presented here, a variety of other strategies may also be considered for this purpose. If laser-based AAD is to be investigated further in the future, there is a clear need to research the practicality of these and other ideas. In the remainder of this chapter, it is assumed that such a technology is available to produce increased force levels, which could be very much larger than those possible with the baseline laser AAD technology.

### 4.3 Effect of Enhanced AAD Forces on Active Pilot

With the addition of alternative technologies, an enhanced AAD system can potentially produce forces strong enough that are capable of diverting aircraft with any type of pilot. The key question with enhanced AAD forces is if it's possible to divert an aircraft using a controller without overpowering the pilot directly? What force level might be used? To resolve these questions, another HITL study is presented. In this study, pilots are asked to fly toward a target while enhanced AAD forces are acting upon the aircraft and no other distractions such as weather or turbulence are present. A spectrum of AAD saturation forces is considered in order to identify the tradeoff between diversion effectiveness and increased saturation force levels.

#### 4.3.1 Setup for Large Forces HITL Simulation

The same six pilots for the previous HITL simulation were asked to complete a second flying task in order to test the limits of pilot performance against aerodynamic
forces of varying magnitude. The task was to fly toward a mountain peak in the distance and cross over it if possible over the course of 130 seconds. An image of the mountain peak in question is shown previously in Figure 6. Note that the skies are clear and the pilots have full visibility in contrast to the previous HITL simulation.

A variable structure controller was implemented in X-Plane to simulate the application of enhanced AAD forces on the aircraft. The variable structure controller dictated which wing to target in an algorithm that was meant to tamper with the pilot’s ability to control the Navion to the maximum extent possible. The specific form of the control law is:

\[
    u_i = \begin{cases} 
    -u_{\text{max}}, & \psi > 0 \text{ and } r > 0 \\
    u_{\text{max}}, & \psi > 0 \text{ and } r < 0 \\
    -u_{\text{max}}, & \psi < 0 \text{ and } r < 0 \\
    u_{\text{max}}, & \psi < 0 \text{ and } r > 0 
    \end{cases}
\]  

(4.7)

where \(u_{\text{max}}\) is a different force value per flight run, \(\psi\) is the aircraft yaw angle, and \(r\) is the aircraft yaw rate. An implementation of the controller on one flight run is shown in Figure 23.

![Figure 23: Controller for Large Forces HITL Simulation.](image)

Two different initialization conditions were considered. For Pilots 1, 2, and 3, the laser was activated between five to ten seconds into the flight runs. For Pilots 4, 5, and 6, the laser was activated at the beginning of the flight runs.
Pilots were asked to fly toward the mountain peak a total of ten times, with a break in between. The variable structure controller was set to a different saturation force level at the beginning of each run. A specific sequence of saturation force levels was used for all pilots. The specific sequence is presented in Table 6.

Table 6: Sequence of laser forces imparted on the aircraft during the Full Visibility HITL simulation.

<table>
<thead>
<tr>
<th></th>
<th>Sequence of Aerodynamic Forces (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First set</td>
<td>585, 195, 975, 390, 585</td>
</tr>
<tr>
<td>Second set</td>
<td>780, 195, 780, 975, 390</td>
</tr>
</tbody>
</table>

Note that the values in the table are multiples of the laser force (19.5 lb) for the baseline laser AAD configuration. Specifically, these values correspond to 10, 20, 30, 40, and 50 times the baseline laser force. All five distinct saturation levels were tested twice throughout the overall simulation. The X-Plane plugin that implemented the simulation can be referenced in Appendix D.

4.3.2 Results for Large Forces HITL Simulation

The HITL simulation demonstrated a wide range of pilot responses to the variable structure controller, with notable variations for individual pilots, saturation levels, and attempt number. Aircraft trajectories of each run were recorded for all pilots. Ideally, this would have resulted in a total of 60 trajectories in all (ten trials for each of the six pilots). However, data were unable to be recorded for three trials, resulting in 57 trajectories. The specific trials that were lost include the 390 lb trial in set one for Pilot 5, and the 195 lb and second 780 lb trials in set two for Pilot 6. Figure 24 shows all of the flight trajectory data for each pilot. The trajectories shown are
separated by pilot and set number, so two plots correspond to one pilot with five trajectories in each plot. Each colored line depicts a different saturation force level and the black asterisk represents the location of the target mountain peak. The black dotted line depicts the ideal trajectory if the pilot navigated the aircraft straight toward the mountain peak.

As means of understanding the raw data, it is useful to look at one particular plot in detail. The first plot of Figure 24 shows the first set of trajectories for Pilot 1. This plot shows that Pilot 1 was unable to stay on course when a 585 lb or 975 lb force was applied to the aircraft. The pilot stayed relatively close to the straight line trajectory for the remaining three runs of saturation force levels of 195 lb, 390 lb, and 585 lb. Overall, it is apparent from the trajectories that large aerodynamic forces have an effect on the pilot’s ability to maintain its course.

![Graph of Pilot 1's trajectories](image_url)
Because the amount of raw data was very large, it was necessary to develop specific metrics to assess diversion effectiveness as a function of saturation level and other experimental variables. Two particularly important experimental variables are the pilot and the trial number. As a first means of characterizing diversion capability across multiple trials, a binary trajectory quality metric was defined based on two rules. A flight was considered a fail if it displayed either of these two characteristics:

1. The pilot flew away from the target for the majority of the flight run and the final heading was clearly directed away from the target.

2. The pilot was more than halfway towards the mountain peak in the along-track direction and the final position was at least 1,000 feet beyond the straight line trajectory in the cross-track direction.

Flight trajectories that meet the task failure criteria are shown in Figure 25 for visual reference.
The number of flights that resulted in task failure were tabulated and plotted with respect to the saturation force level that was being applied to the aircraft during the flight. This graph can be seen in Figure 26.

**Figure 25:** Flight trajectories that meet task failure criteria.

**Figure 26:** Task failure with respect to saturation force level.
The figure shows that there is a clearly increasing task failure trend as the forces get larger. However, the greatest percentage of task failure occurs for the flights in which the lowest tested force of 195 lbs was imparted on the aircraft. This finding seems counterintuitive to what was observed during the simulations, as pilots seemed to navigate toward the mountain peak with the greatest ease for this force compared to the other higher forces. One reason why this outlier could exist is that the target mountain peak is several hundred feet wide near the top. This means that even if a pilot had the target in sight and was flying toward it throughout the entire flight, the trajectory could be interpreted as a failure simply because the pilot was aiming toward the left or right side of the peak. Another reason could be the subjective nature of the task failure criteria. Regardless, future work will need to be done to investigate the significance of high task failures at 195 lbs.

The number of task failures were also tabulated and plotted with respect to the individual pilot and his or her flight experience. This result is shown in Figure 27. Each diamond in the plot represents an individual pilot.

![Figure 27: Number of task failures in relation to pilot experience for Large Forces HITL simulation.](image-url)
Even though the data points are not evenly spread across flight hours, the figure still shows that an increase in flying experience does not necessarily correlate to a decreased number of task failures. For example, both Pilot 2 (a more experienced pilot) and Pilot 5 (a lesser experienced pilot) encountered the same number of task failures. This finding suggests that the variable structure controller creates an effect that is disorienting for all pilots, regardless of flight experience. However, several pilots verbally commented during the X-Plane simulation that they would never actually steer the aircraft so forcefully in real life because of fear that the aircraft would break with such forceful actuator treatment. This highlights one major limitation to the HITL simulations: the unrealistic nature of the simulation regarding the lack of motion feedback and unbreakable aircraft.

In several of the trials, pilots were forced to fly into potentially unsafe situations. Since the intent of this thesis is to develop a nonlethal diversion technique, it is important that such unsafe situations be avoided if possible. As a means of assessing the safety of each trial, the definition of a flight upset condition given in Section 4.1.1 was used. Flight data for all pilots were analyzed for the frequency of airplane upset incidents—when pitch attitude is greater than 25 degrees up or 10 degrees down or when bank angles are greater than 45 degrees. For each flight run, each instance an airplane upset condition was met was flagged. Figure 28 shows an example airplane upset time history plot that shows the frequency and duration of airplane upsets during one flight run.
Figure 28: Example airplane upset time history plot from Pilot 1.

After airplane upset incidents were identified, the total time that a flight experienced airplane upset conditions was gathered. Figure 29 shows the average total airplane upset time across all pilots. The data are grouped by aerodynamic force level to show that the amount of time that a pilot experiences an airplane upset condition increases as the applied aerodynamic force magnitude also increases. Furthermore, the data were separated by the first or second attempt that a pilot encountered a specific aerodynamic force level. The similarity between red and blue bars suggests that pilots do not necessarily become adapted to the variable structure controller nor become better at staying on course in the presence of large aerodynamic forces.

Figure 29: Total aircraft upset time for all pilots.
While task failures indicate that the aerodynamic forces are affecting the ability of the pilot to fly on course, it does not necessarily mean that the aircraft is being efficiently diverted. The figure above shows that as aerodynamic forces increase, the safety of the passengers correspondingly decreases. The goal of AAD is to divert the aircraft from its intended target while keeping its passengers safe. Therefore, the tradeoff between diversion and safety must always be considered and optimized for future control law design.

4.4 Summary

This chapter discusses the motivation, technology, and feasibility of using enhanced AAD forces to divert an aircraft in a broader capacity than presented previously. MATLAB simulations suggest that the baseline laser AAD configuration alone is unable to divert an aircraft significantly because the saturation forces are too small. Therefore, alternative technologies to enhance the baseline laser forces were presented.

Under the assumption that at least one of these alternative strategies is technically feasible, a HITL study was conducted to study the impact of large AAD force levels on pilots’ ability to fly toward a target. The HITL simulation highlighted promising aspects of enhanced AAD. Though the number of trials conducted was limited, the experimental observations suggest the potential of using the variable structure controller to disorient pilots. All of the pilots encountered failure at flying toward the mountain peak regardless of their flying experience. Furthermore, pilots did not become adapted to the variable structure controller or learn to overcome the controller over several attempts. This is important because the controller could be compromised if pilots were able to respond to and correct aircraft deviation. Other than the lowest
saturation level, failures generally increased as saturation force levels also increased.
The lowest saturation level of 195 lbs generated the largest task failure rate of 45%.
This anomaly should be investigated further for future work. The largest saturation
level of 975 lbs generated the second largest task failure rate of 42%. However, since
the pilots verbally commented that they would not fly the aircraft to such great
actuation levels in real life, it can be prudent to expect that actual pilots would abort the
task under the same aerodynamic forces more readily in real life than the simulations
suggest.

The results also showed that as saturation force levels increased, disorientation
also increased. This observation brings up an important issue in control law design for
laser-based AAD: the trade-off between creating high levels of aircraft diversion and
maintaining the safety of its passengers. This concept highlights the need to design
control laws that optimize both aircraft diversion and safety to fully achieve the goals of
AAD.
5.1 Thesis Contributions

This thesis investigates, develops, and tests methods for controlling laser-based AAD for creating non-lethal solutions in defense scenarios. The goal is to divert an aircraft while maintaining the safety of the passengers. The major thesis contributions are reiterated here along with commentary on their impact on the main thesis goal.

**Quantify ability of laser to divert an aircraft away from an intended target.**

X-Plane simulations and HITL studies have shown that a laser can effectively divert aircraft as long as certain conditions are met. While laser drag forces and moments were calculated and found to be relatively small, the laser was able to turn and redirect an unpiloted Navion. This most promising result can be applied to using laser-based AAD on UAVs in particular. The HITL simulation also demonstrated the ability of the laser to divert an aircraft with a pilot given limited visibility under IMC. The laser was able to divert most aircraft to one side of the target; however, large diversion effects were only noticed in the non-instrument rated pilot group. This demonstrates the limited ability of laser-based AAD on pilots with limited visibility, and motivates the use of enhanced AAD or other pilot capability reducing methods.

**Quantify feasibility of using larger aerodynamic forces to safely divert an aircraft away from an intended target.**

It was apparent from initial control law design in MATLAB that the existing laser forces and moments were not sufficient enough to force a pilot to fly away from its intended target. Therefore, some alternative technologies to complement the laser were identified to show the range of solutions that could be implemented to create
larger aerodynamic forces on an aircraft. The HITL simulation expanded on this idea and collected information on how pilots react to the disorienting effects of a variable structure controller implemented with enhanced AAD forces. The results that pilot experience and adaptation to the laser do not compromise the laser’s diversion ability show that a variable structure controller is robust enough to disconcert any pilot who encounters it. Furthermore, diversion capability generally increased as enhanced forces increased. While it is encouraging that the enhanced forces and controller increase aircraft diversion, one must remember that the main goal is to safely divert an aircraft. To this end, the next step in designing control laws for use with larger forces requires the simultaneous optimization of both diversion and passenger safety.

5.2 Future Work and Thesis Impact

This thesis characterizes the ability of AAD to divert aircraft under various conditions. Based on the findings, several suggestions for future work are proposed. The first suggestion is in regards to the Limited Visibility HITL simulation. The results suggest that the laser can divert an aircraft to one side of the target. However, experiments that demonstrate how the pilots perform the same task without a laser present is beneficial to more rigorously separate the specific contributions of the laser and the limited visibility IMC to diversion.

Regarding the Large Forces HITL simulation results, another suggestion is to investigate why the lowest of the enhanced AAD force levels caused the greatest diversion, while the other force levels showed a different trend. The criteria for task failure should be scrutinized as part of the investigation.
In the longer term, it can be practical to model a UAV and perform flight simulations on the aircraft similar to the work that was presented here on the Navion aircraft model.

To implement enhanced AAD, simultaneous development on alternative technologies should occur. Depending on what type of aircraft diversion a sponsor is interested in, alternative technologies should be developed to impede pilot command signals to UAVs, induce IMC on an aircraft cockpit window, or increase aerodynamic forces on an aircraft. Other methods for reducing pilot visibility could also be investigated.

Like many other technologies developed for the military, there are many benefits for converting this technology to be used in civilian applications. The concept of adding forces on an aircraft to force it to move in a particular direction can be used to assist aircraft in a variety of situations, such as assisted takeoffs and landings. While this topic is beyond the scope of this thesis, there are several possibilities of using laser-based AAD for non-defense applications as well. Overall, AAD technologies have the greatest impact on defense and anti-terrorism applications. These technologies can be used to prevent destruction, reduce conflict, and save unnecessary loss of life.
Appendix A: MATLAB Code for Control Law Design

function planesim()

% Basic equations of lateral motion of Navion plane
%A = [-.254 -1.76 0 0.322;2.55 -0.76 -0.35 0;-9.08 2.19 -8.4 0;0 0
% 1 0];
%Anew = [-.254 0 -1.76 0.322;-9.08 -8.4 2.19 2.55 -0.35 -0.76
% 0;0 1 0 0];
%Bnew = [0; 0; 0.0464; 0];
%C = eye(4);
%D = 0;
sys = ss(Anew,Bnew,C,D);

% Modify state vector to
% [y-vel roll-rate yaw-rate roll-angle integ-yaw]
%Amod = [Anew zeros(4,4);0 0 1 0 0 0 0 0;0 0 0 1 0 0 0 0;0 0 0 0 1
% 0 0 0;...,
% 1 0 0 1.76 0 0 0];
%Bmod = [Bnew; 0; 0; 0];
%Cmod = eye(8);
%Dmod = 0;
sysLat = ss(Amod, Bmod, Cmod, Dmod);

Ts = 1/20; % Sampling frequency of 20 Hz
sysdLat = c2d(sysLat,Ts);
[AdLat,BdLat,CdLat,DdLat] = ssdata(sysdLat);

% Bp matrix for pilot includes inputs for changes in aileron and
% rudder
%Bp = [0 0.1246;29 2.55;-0.222 -4.6;0 0 0;0 0 0 0];
syspLat = ss(Amod, Bp, Cmod, Dmod);
sysdpLat = c2d(syspLat, Ts);
[ApLat,BpLat,CpLat,DpLat] = ssdata(sysdpLat);

% LQR "Pilot" for lateral controls
QLat = diag([1e-5 1e-5 1e-5 1/(10*pi/180)^2 1/(10*pi/180)^2 1e-5
% 1e-5 1/1^2]);
RLat = [1/(20*pi/180)^2 0;0 1/(20*pi/180)^2];
kpLat = lqr(sysdpLat,QLat,RLat);

% Initial conditions for simulation
%xLat(:,1) = [0 0 0 0 0 0 0 0]';
t(1) = 0;

klLat = [-60.4766 8.4285 -116.7928 23.6794 0 0 0 0]; % Gains for
% unstable pole placement
max = 1800; % controls length of simulation time
for n = 1:max
    upLat(:,n) = -kpLat*xLat(:,n);
    ulLat(n) = 1;
    xLat(:,n+1) = AdLat*xLat(:,n) + BdLat*ulLat(n) +
        BpLat*upLat(:,n);
    t(n+1) = t(n) + Ts;
end
ulLat(max+1) = 1;

% Basic equations of longitudinal motion of Navion plane
% State vector is [x-velocity z-velocity pitch-rate pitch-angle x]
F = [-0.045 0.036 0 -0.322 0 0; -0.370 -2.02 1.76 0 0 0;...
    0.191 -3.96 -2.98 0 0 0; 0 0 1 0 0 0; 1 0 0 0 0 0;...
    0 1 0 0 0 -1.76];
G = [0.22814; 0; 0; 0; 0; 0];
H = eye(6);
J = 0;
sysLon = ss(F, G, H, J);
sysdLon = c2d(sysLon, Ts);
[AdLon, BdLon, CdLon, DdLon] = ssdata(sysdLon);

% Gp matrix for pilot includes inputs for changes in elevator and throttle
Gp = [0 1; -0.282 0; -11 0; 0 0 0 0];
syspLon = ss(F, Gp, H, J);
sysdpLon = c2d(syspLon, Ts);
[ApLon, BpLon, CpLon, DpLon] = ssdata(sysdpLon);

% LQR "Pilot" for longitudinal controls
QLon = diag([1e-5 1e-5 1e-5 1/(15*pi/180)^2 1/50^2 1e-5]);
RLon = [1/(25*pi/180)^2 0; 0 1/(50)^2];
kpLon = lqr(sysdpLon, QLon, RLon);

% Initial conditions for simulation
xLon(:,1) = [0 0 0 0 0 0]';
kLon = zeros(1,6);

for n = 1:max
    upLon(:,n) = -kpLon*xLon(:,n);
    xLon(:,n+1) = AdLon*xLon(:,n) + BdLon*ulLat(n) +
        BpLon*upLon(:,n);
end

figure(1)
subplot(2,1,1)
stairs(t,ulLat, 'r')
title('Effect of unstable pole placement on Navion aircraft dynamics')
ylabel('Laser Input')
subplot(2,1,2)
stairs(t, xLat(5,:)*180/pi)
ylabel('yaw angle (deg)')
xlabel('time (sec)')
Appendix B: Calculation of Laser Drag Force and Moment on Aircraft Wing

When calculating the laser drag force and moment on an aircraft, several assumptions are made: the wing is modeled as flat plate, the turbulent boundary layer starts at edge of flat plate, and the plane is flying at $h = 6,000$ ft with atmospheric temperature of $T = 37.6^\circ F$ (Shames 640-64).

The Reynolds number is determined using the equation:

$$
Re = \frac{\rho_{air}VL}{\mu} = 5.18 \times 10^6
$$

where $\rho_{air} =$ air density $= 0.001988$ slug/ft$^3$  
$V =$ aircraft velocity $= 176$ ft/sec  
$L =$ chord length $= 5.7$ ft  
$\mu =$ dynamic viscosity of air $= 3.85 \times 10^{-7}$.

The admissible roughness coefficient is

$$
e_{adm} \leq L \left[ \frac{100}{Re} \right] = 1.1 \times 10^{-4} ft = 0.0013\ in
$$

where $e =$ roughness height.

The actual roughness coefficient of the wing varies based on wing surface features (such as rivets), natural wear over time, and other factors such as ice accretion and insect residue. To consider a rough plate assumption, $e > 0.0013$ inches must be satisfied.

The following empirical formula is used to calculate the coefficient of skin friction for turbulent flow,

$$
C_f = \left( 1.89 + 1.62 \log \frac{L}{e} \right)^{-2.5}
$$
where $e$ can be substituted for a variety of values, such as:

- $0.0016 \text{ in.} < e < 0.009 \text{ in.}$ for insect residue (Siochi),
- $e = 0.0025 \text{ in.}$ for rivets (Braslow), and
- $e = 0.14 \text{ in.}$ for ice accretion (Lynch).

If ice accretion is ignored and $e = 0.0025 \text{ in.}$, then $C_{f, turbulent} = 0.00403$. Therefore, the drag force over a turbulent boundary layer for the top and bottom of a flat plate is

$$F_{turbulent} = 2 \left[ C_f \left( \frac{1}{2} \rho V^2 \right) A \right] = 22.8 \text{ lbs}$$

where $A =$ area of flat plate $= 92 \text{ ft}^2$.

To determine the drag force over a laminar boundary layer, the coefficient of skin friction must be calculated and substituted into the drag force equation:

$$C_{f, laminar} = \frac{1.328}{\sqrt{Re}} = 5.86 \times 10^{-4}$$

$$F_{laminar} = 2 \left[ C_{f, laminar} \left( \frac{1}{2} \rho V^2 \right) A \right] = 3.3 \text{ lbs}.$$  

The overall drag force that is imparted by the laser is

$$F_{drag} = F_{turbulent} - F_{laminar} = 19.5 \text{ lbs}.$$  

The corresponding drag moment that is imparted by the laser is

$$M_{drag} = F_{drag} d = 162.8 \text{ lb-ft}$$

where $d =$ distance from center of moment to halfway down one wing $= 8.35 \text{ ft.}$
Appendix C: X-Plane Plugin for Limited Visibility HITL Simulation

// Custom Commands created by BlueSideUpBob
// "simulationMagN" UTR Test (left 2 sec, right 1 sec)

#include "XPLMProcessing.h"
#include "XPLMDataAccess.h"
#include "XPLMDisplay.h"
#include "XPLMMenus.h"
#include "XPLMUtilities.h"
#include <string.h>
#include <stdio.h>
#include <stdlib.h>
#include <windows.h>
#include <math.h>
#include <fstream>
#define pi 3.14159265
using namespace std;

// These will hold the XPLMDataRefs
XPLMDataRef xDataRef;
XPLMDataRef yDataRef;
XPLMDataRef zDataRef;
XPLMDataRef vxDataRef;
XPLMDataRef vyDataRef;
XPLMDataRef vzDataRef;
XPLMDataRef phiDataRef;
XPLMDataRef thetaDataRef;
XPLMDataRef psiDataRef;
XPLMDataRef pDataRef;
XPLMDataRef qDataRef;
XPLMDataRef rDataRef;
XPLMDataRef latestTimeDataRef;
XPLMDataRef frpDataRef;
XPLMDataRef apmodeDataRef;

// These will hold written data
ofstream simulationMagN_data_file;

// These will hold temporary values for the datarefs during calculations
float time;
float deltat;
float m;
float r;
float phi;
float theta;
float psi;
float Fx;
float Fy;
float Fz;
float Flaser;
double secretEnd;
int secret;
int counter;

// These will hold new values for the datarefs
float rNew;
float vxNew;
float vyNew;
float vzNew;

// This will hold the laser control magnitude
float uL;

// These are for hot key designations
XPLMHotKeyID HotKey1 = NULL;
XPLMHotKeyID HotKey2 = NULL;
XPLMHotKeyID HotKey3 = NULL;

// These will set the laser and data writes
void MenuHandler(void *, void *);
void MyHotKeyCallback(void * inRefcon);
float MainLoopCB(float elapsedMeMain, float elapsedSimMain, int counterMain, void * refconMain);
float MenuLoopCB(float elapsedMeMenu, float elapsedSimMenu, int counterMenu, void * refconMenu);
float SwitchLoopCB(float elapsedMeSwitch, float elapsedSimSwitch, int counterSwitch, void * refconSwitch);

PLUGIN_API int XPluginStart(char * outName, char * outSig, char * outDesc)
{
    XPLMMenuID myMenu;
    int mySubMenuId;

    strcpy(outName, "CustomCommands");
    strcpy(outSig, "komatsu.CustomCommands");
    strcpy(outDesc, "Plugin for JK Thesis");

    // Get our dataref handles here
    xDataRef = XPLMFindDataRef("sim/flightmodel/position/local_x");
    yDataRef = XPLMFindDataRef("sim/flightmodel/position/local_y");
    zDataRef = XPLMFindDataRef("sim/flightmodel/position/local_z");
    vxDataRef = XPLMFindDataRef("sim/flightmodel/position/local_vx");
    vyDataRef = XPLMFindDataRef("sim/flightmodel/position/local_vy");
    vzDataRef = XPLMFindDataRef("sim/flightmodel/position/local_vz");
    phiDataRef = XPLMFindDataRef("sim/flightmodel/position/phi");
    thetaDataRef = XPLMFindDataRef("sim/flightmodel/position/theta");
psiDataRef = XPLMFindDataRef("sim/flightmodel/position/psi");
pDataRef = XPLMFindDataRef("sim/flightmodel/position/P");
qDataRef = XPLMFindDataRef("sim/flightmodel/position/Q");
rDataRef = XPLMFindDataRef("sim/flightmodel/position/R");
latestTimeDataRef = XPLMFindDataRef("sim/time/total_flight_time_sec");
frpDataRef = XPLMFindDataRef("sim/operation/misc/frame_rate_period");
apmodeDataRef = XPLMFindDataRef("sim/cockpit/autopilot/autopilot_mode");

// Create laser menu
mySubMenuItem = XPLMAppendMenuItem(XPLMFindPluginsMenu(), "Laser", 0, 1);
myMenu = XPLMCreateMenu("Laser", XPLMFindPluginsMenu(), mySubMenuItem, MenuHandler, 0);
XPLMAppendMenuItem(myMenu, "Stop laser", (void *)"Stop", 1);

// Open text files
simulationMagN_data_file.open("simMagNResults.txt");
if (simulationMagN_data_file.fail())
    return false;

// Register callbacks
XPLMRegisterFlightLoopCallback(MainLoopCB, -1.0, NULL); // Implement main loop
XPLMRegisterFlightLoopCallback(MenuLoopCB, 0, NULL); // Implement laser force on wing
XPLMRegisterFlightLoopCallback(SwitchLoopCB, 0, NULL); // Implement switching pattern of laser

// Register hot keys
HotKey1 = XPLMRegisterHotKey(XPLM_VK_F1, xplm_DownFlag, "Starts run 1", MyHotKeyCallback, (void *)"1");
HotKey2 = XPLMRegisterHotKey(XPLM_VK_F2, xplm_DownFlag, "Starts run 2", MyHotKeyCallback, (void *)"2");
HotKey3 = XPLMRegisterHotKey(XPLM_VK_F3, xplm_DownFlag, "Starts run 3", MyHotKeyCallback, (void *)"3");

return 1;
}

PLUGIN_API void XPluginStop(void)
{

    // Unregister the callbacks
    XPLMUnregisterFlightLoopCallback(MainLoopCB, NULL);
    XPLMUnregisterFlightLoopCallback(MenuLoopCB, NULL);
    XPLMUnregisterFlightLoopCallback(SwitchLoopCB, NULL);

    // Unregister hot keys
    XPLMUnregisterHotKey(HotKey1);
    XPLMUnregisterHotKey(HotKey2);
    XPLMUnregisterHotKey(HotKey3);

    // Close data file

simulationMagN_data_file.close();

PLUGIN_API void XPluginDisable(void)
{
}

PLUGIN_API int XPluginEnable(void)
{
    return 1;
}

PLUGIN_API void XPluginReceiveMessage(
    XPLMPluginID    inFromWho,
    long            inMessage,
    void *          inParam)
{
}

float MainLoopCB(float elapsedMeMain, float elapsedSimMain, int counterMain, void * refconMain)
{
    // Start time, counter
time = XPLMGetDataf(latestTimeDataRef);

    // Only at beginning of flight run
    if (time < 0.04)
    {
        // Turn off autopilot
        XPLMSetDatai(apmodeDataRef, 0);

        // Determine random time between 5 and 10 seconds
        secret = rand() % 5 + 5;
        secretEnd = secret + 0.03;
    }

    // Start laser at specified random time
    if (time >= secret)
    {
        if (time < secretEnd)
        {
            // Turn on laser
            uL = -1;
            counter = 1;
            XPLMSetFlightLoopCallbackInterval(MenuLoopCB, - 1.0, 1, NULL);
            XPLMSetFlightLoopCallbackInterval(SwitchLoopCB, 1, 1, NULL);
        }
    }

    // Write data to main file once program starts running
    simulationMagN_data_file << time << "\t";
    simulationMagN_data_file << uL << "\t";
    simulationMagN_data_file << XPLMGetDatad(xDataRef) << "\t";
    simulationMagN_data_file << XPLMGetDatad(yDataRef) << "\t";
    simulationMagN_data_file << XPLMGetDatad(zDataRef) << "\t";
}
```c
simulationMagN_data_file << XPLMGetDataf(vxDataRef) << "\t";
simulationMagN_data_file << XPLMGetDataf(vyDataRef) << "\t";
simulationMagN_data_file << XPLMGetDataf(vzDataRef) << "\t";
simulationMagN_data_file << XPLMGetDataf(phiDataRef) << "\t";
simulationMagN_data_file << XPLMGetDataf(thetaDataRef) << "\t";
simulationMagN_data_file << XPLMGetDataf(psiDataRef) << "\t";
simulationMagN_data_file << XPLMGetDataf(qDataRef) << "\t";
simulationMagN_data_file << XPLMGetDataf(rDataRef) << "\t";
simulationMagN_data_file << XPLMGetDataf(frpDataRef) << "\n";
return (float) -1.0;
}

float MenuLoopCB(float elapsedMeMenu, float elapsedSimMenu, int counterMenu, void * refconMenu)
{
    // Get dataref values
    deltat = XPLMGetDataf(frpDataRef);
    phi = XPLMGetDataf(phiDataRef);
    theta = XPLMGetDataf(thetaDataRef);
    psi = XPLMGetDataf(psiDataRef);

    // Modify yaw rate, r
    rNew = XPLMGetDataf(rDataRef) + 0.0464*180/pi*uL*deltat; // [deg/sec]

    // Modify forward velocity, u
    Flaser = 19.5*4.48822162; // lbf to N
    m = 2750*0.45359237; // lbm to kg
    Fx = Flaser*sin(theta*pi/180)*sin(psi*pi/180);
    Fy = -Flaser*sin(theta*pi/180)*cos(psi*pi/180);
    Fz = -Flaser*cos(theta*pi/180);
    vxNew = XPLMGetDataf(vxDataRef) + Fx/m*uL*deltat; // [m/sec]
    vyNew = XPLMGetDataf(vyDataRef) + Fy/m*uL*deltat;
    vzNew = XPLMGetDataf(vzDataRef) + Fz/m*uL*deltat;

    // Set datarefs with new values
    XPLMSetDataf(rDataRef, rNew);
    XPLMSetDataf(vxDataRef, vxNew);
    XPLMSetDataf(vyDataRef, vyNew);
    XPLMSetDataf(vzDataRef, vzNew);

    return (float) -1.0;
}
```
float SwitchLoopCB(float elapsedMeSwitch, float elapsedSimSwitch, int counterSwitch, void * refconSwitch)
{
    // Force laser to alternate btwn L/R wings for 2 or 1 sec, respectively
    if (uL == 1)
    {
        uL = -1;
        counter = 1;
    }
    else if (counter < 2)
    {
        counter = counter + 1;
    }
    else
    {
        uL = 1;
    }

    return (float) 1;
}

void MenuHandler(void *mRef, void *iRef)
{
    // Only do below if "Stop laser" is selected in menu
    if (!strcmp((char *) iRef, "Stop"))
    {
        // Temporarily stop laser
        uL = 0;
        XPLMSetFlightLoopCallbackInterval(MenuLoopCB, 0, 1, NULL);
        XPLMSetFlightLoopCallbackInterval(SwitchLoopCB, 0, 1, NULL);
    }
}

void MyHotKeyCallback(void * inRefcon)
{
    // Load run 1 "simulationMagN.sit" situation
    if (!strcmp((char *) inRefcon, "1"))
    {
        // Temporarily stop laser
        uL = 0;
        XPLMSetFlightLoopCallbackInterval(MenuLoopCB, 0, 1, NULL);
        XPLMSetFlightLoopCallbackInterval(SwitchLoopCB, 0, 1, NULL);

        // Restart situation
        XPLMLoadDataFile(xplm_DataFile_Situation, "Output/situations/simulationMagN.sit");
        XPLMSetsDataf(latestTimeDataRef, 0);
        XPLMSpeakString("Run 1 u t r");
    }

    // Load run 2 "simulationMagN.sit" situation
    if (!strcmp((char *) inRefcon, "2"))
{  // Temporarily stop laser
    uL = 0;
    XPLMSetFlightLoopCallbackInterval(MenuLoopCB, 0, 1, NULL);
    XPLMSetFlightLoopCallbackInterval(SwitchLoopCB, 0, 1, NULL);

    // Restart situation
    XPLMLoadDataFile(xplm_DataFile_Situation, "Output/situations/simulationMagN.sit");
    XPLMSetDataf(latestTimeDataRef, 0);
    XPLMSpeakString("Run 2 u t r");
}

// Load run 3 "simulationMagN.sit" situation
if (!strcmp((char *) inRefcon, "3")) {
    // Temporarily stop laser
    uL = 0;
    XPLMSetFlightLoopCallbackInterval(MenuLoopCB, 0, 1, NULL);
    XPLMSetFlightLoopCallbackInterval(SwitchLoopCB, 0, 1, NULL);

    // Restart situation
    XPLMLoadDataFile(xplm_DataFile_Situation, "Output/situations/simulationMagN.sit");
    XPLMSetDataf(latestTimeDataRef, 0);
    XPLMSpeakString("Run 3 u t r");
}
Appendix D: X-Plane Plugin for Large Forces HITL Simulation

// Custom Commands created by BlueSideUpBob
// Edited by Janet Komatsu – 2/26/2011, in VisualC++
// "mountainSim" Psychophysics Test, Set #1 – simple yaw feedback

#include "XPLMProcessing.h"
#include "XPLMDataAccess.h"
#include "XPLMDisplay.h"
#include "XPLMMenus.h"
#include "XPLMUtilities.h"
#include <string.h>
#include <stdio.h>
#include <stdlib.h>
#include <windows.h>
#include <math.h>
#include <fstream>
#define pi 3.14159265
using namespace std;

// These will hold the XPLMDataRefs
XPLMDataRef xDataRef;
XPLMDataRef yDataRef;
XPLMDataRef zDataRef;
XPLMDataRef vxDataRef;
XPLMDataRef vyDataRef;
XPLMDataRef vzDataRef;
XPLMDataRef phiDataRef;
XPLMDataRef thetaDataRef;
XPLMDataRef psiDataRef;
XPLMDataRef pDataRef;
XPLMDataRef qDataRef;
XPLMDataRef rDataRef;
XPLMDataRef rdotDataRef;
XPLMDataRef latestTimeDataRef;
XPLMDataRef frpDataRef;
XPLMDataRef apmodeDataRef;

// These will hold written data
ofstream mtnSim_data_file;

// These will hold temporary values for the datarefs during calculations
float time;
float deltat;
float m;
float r;
float rdot;
float phi;
float theta;
float psi;
float Fx;
float Fy;
float Fz;
float Flaser;
double secretEnd;
int secret;
int mag;

// These will hold new values for the datarefs
float rNew;
float vxNew;
float vyNew;
float vzNew;

// This will hold the laser control magnitude
float uL;

// These are for hot key designations
XPLMHotKeyID HotKey1 = NULL;
XPLMHotKeyID HotKey2 = NULL;
XPLMHotKeyID HotKey3 = NULL;
XPLMHotKeyID HotKey4 = NULL;
XPLMHotKeyID HotKey5 = NULL;

// These will set the laser and data writes
void MenuHandler(void *, void *);
void MyHotKeyCallback(void * inRefcon);
float MainLoopCB(float elapsedMeMain, float elapsedSimMain, int counterMain, void * refconMain);
float MenuLoopCB(float elapsedMeMenu, float elapsedSimMenu, int counterMenu, void * refconMenu);
float SwitchLoopCB(float elapsedMeSwitch, float elapsedSimSwitch, int counterSwitch, void * refconSwitch);

PLUGIN_API int XPluginStart(char * outName, char * outSig, char * outDesc)
{
    XPLMMenuID myMenu;
    int mySubMenuId;

    strcpy(outName, "CustomCommands");
    strcpy(outSig, "komatsu.CustomCommands");
    strcpy(outDesc, "Plugin for JK Thesis");

    // Get our dataref handles here
    xDataRef = XPLMFindDataRef("sim/flightmodel/position/local_x");
    yDataRef = XPLMFindDataRef("sim/flightmodel/position/local_y");
    zDataRef = XPLMFindDataRef("sim/flightmodel/position/local_z");
    vxDataRef = XPLMFindDataRef("sim/flightmodel/position/local_vx");
    vyDataRef = XPLMFindDataRef("sim/flightmodel/position/local_vy");
    vzDataRef = XPLMFindDataRef("sim/flightmodel/position/local_vz");
    phiDataRef = XPLMFindDataRef("sim/flightmodel/position/phi");
thetaDataRef = XPLMFindDataRef("sim/flightmodel/position/theta");
psiDataRef = XPLMFindDataRef("sim/flightmodel/position/psi");
pDataRef = XPLMFindDataRef("sim/flightmodel/position/P");
qDataRef = XPLMFindDataRef("sim/flightmodel/position/Q");
rDataRef = XPLMFindDataRef("sim/flightmodel/position/R");
rdotDataRef = XPLMFindDataRef("sim/flightmodel/position/R_dot");
getTimeDataRef = XPLMFindDataRef("sim/time/total_flight_time_sec");
frpDataRef = XPLMFindDataRef("sim/operation/misc/frame_rate_period");
apmodeDataRef = XPLMFindDataRef("sim/cockpit/autopilot/autopilot_mode");

// Create laser menu
mySubMenuItem = XPLMAppendMenuItem(XPLMFindPluginsMenu(), "Laser", 0, 1);
myMenu = XPLMCreateMenu("Laser", XPLMFindPluginsMenu(), mySubMenuItem, MenuHandler, 0);
XPLMAppendMenuButtonItem(myMenu, "Stop laser", (void *)"Stop", 1);

// Open text files
mtnSimData_file.open("mtnSimResults.txt");
if (mtnSimData_file.fail())
  return false;

// Register callbacks
XPLMRegisterFlightLoopCallback(MainLoopCB, -1.0, NULL); // Implement main loop
XPLMRegisterFlightLoopCallback(MenuLoopCB, 0, NULL); // Activate laser
XPLMRegisterFlightLoopCallback(SwitchLoopCB, 0, NULL); // Implement control of laser

// Register hot keys
HotKey1 = XPLMRegisterHotKey(XPLM_VK_NUMPAD1,
xplm_DownFlag, "Starts run 1", MyHotKeyCallback, (void *)"1");
HotKey2 = XPLMRegisterHotKey(XPLM_VK_NUMPAD2,
xplm_DownFlag, "Starts run 2", MyHotKeyCallback, (void *)"2");
HotKey3 = XPLMRegisterHotKey(XPLM_VK_NUMPAD3,
xplm_DownFlag, "Starts run 3", MyHotKeyCallback, (void *)"3");
HotKey4 = XPLMRegisterHotKey(XPLM_VK_NUMPAD4,
xplm_DownFlag, "Starts run 4", MyHotKeyCallback, (void *)"4");
HotKey5 = XPLMRegisterHotKey(XPLM_VK_NUMPAD5,
xplm_DownFlag, "Starts run 5", MyHotKeyCallback, (void *)"5");
return 1;
}

PLUGIN_API void XPluginStop(void)
{
  // Unregister the callbacks
  XPLMUnregisterFlightLoopCallback(MainLoopCB, NULL);
  XPLMUnregisterFlightLoopCallback(MenuLoopCB, NULL);
XPLMUnregisterFlightLoopCallback(SwitchLoopCB, NULL);

// Unregister hot keys
XPLMUnregisterHotKey(HotKey1);
XPLMUnregisterHotKey(HotKey2);
XPLMUnregisterHotKey(HotKey3);
XPLMUnregisterHotKey(HotKey4);
XPLMUnregisterHotKey(HotKey5);

// Close data file
mtnSim_data_file.close();

PLUGIN_API void XPluginDisable(void)
{
}

PLUGIN_API int XPluginEnable(void)
{
    return 1;
}

PLUGIN_API void XPluginReceiveMessage(
    XPLMPluginID inFromWho,
    long inMessage,
    void * inParam)
{
}

float MainLoopCB(float elapsedMeMain, float elapsedSimMain, int counterMain, void * refconMain)
{
    // Start time, counter
time = XPLMGetDataf(latestTimeDataRef);

    // Only at beginning of flight run
    if (time < 0.04)
    {
        // Turn off autopilot
        XPLMSetDatai(apmodeDataRef, 0);

        // Determine random time between 5 and 10 seconds
        secret = rand() % 5 + 5;
        secretEnd = secret + 0.03;
    }

    // Start laser at specified random time
    if (time >= secret)
    {
        if (time < secretEnd)
        {
            // Turn on laser - roll/yaw feedback strategy
            XPLMSetFlightLoopCallbackInterval(MenuLoopCB, -1.0, 1, NULL);
            XPLMSetFlightLoopCallbackInterval(SwitchLoopCB, 2, 1, NULL);
        }
    }
}
// Write data to main file once program starts running
mtnSim_data_file << time << "\t";
mtnSim_data_file << uL << "\t";
mtnSim_data_file << XPLMGetDatad(xDataRef) << "\t";
mtnSim_data_file << XPLMGetDatad(yDataRef) << "\t";
mtnSim_data_file << XPLMGetDatad(zDataRef) << "\t";
mtnSim_data_file << XPLMGetDatad(vpDataRef) << "\t";
mtnSim_data_file << XPLMGetDatad(vyDataRef) << "\t";
mtnSim_data_file << XPLMGetDatad(vzDataRef) << "\t";
mtnSim_data_file << XPLMGetDatad(phiDataRef) << "\t";
mtnSim_data_file << XPLMGetDatad(thetaDataRef) << "\t";
mtnSim_data_file << XPLMGetDatad(psiDataRef) << "\t";
mtnSim_data_file << XPLMGetDatad(qDataRef) << "\t";
mtnSim_data_file << XPLMGetDatad(rDataRef) << "\t";
mtnSim_data_file << XPLMGetDatad(frpDataRef) << "\n";

return (float) -1.0;
}

float MenuLoopCB(float elapsedMeMenu, float elapsedSimMenu, int counterMenu, void * refconMenu)
{
    // Get dataref values
    deltat = XPLMGetDataf(frpDataRef);
    phi = XPLMGetDataf(phiDataRef);
    theta = XPLMGetDataf(thetaDataRef);
    psi = XPLMGetDataf(psiDataRef);
    r = XPLMGetDataf(rDataRef);
    rdot = XPLMGetDataf(rdotDataRef);

    // Modify yaw rate, r
    rNew = XPLMGetDatad(rDataRef) + 0.0464*180/pi*uL*deltat; // [deg/sec]

    // Modify forward velocity, u
    Flaser = 19.5*4.44822162; // lbf to N
    m = 2750*0.45359237; // lbm to kg
    Fx = Flaser*sin(theta*pi/180)*sin(psi*pi/180);
    Fy = -Flaser*sin(theta*pi/180)*cos(psi*pi/180);
    Fz = -Flaser*cos(theta*pi/180);
    vxNew = XPLMGetDatad(vxDataRef) + Fx/m*uL*deltat; // [m/sec]

    // Set datarefs with new values
    XPLMSetDatad(rDataRef, rNew);
    XPLMSetDatad(vxDataRef, vxNew);
    XPLMSetDatad(vyDataRef, vyNew);
    XPLMSetDatad(vzDataRef, vzNew);

    return (float) -1.0;
float SwitchLoopCB(float elapsedMeSwitch, float elapsedSimSwitch, int counterSwitch, void * refconSwitch)
{
    // yaw feedback strategy to make unstable
    if (r > 0 && rdot > 0)
    {
        uL = -mag;
    }
    else if (r > 0)
    {
        uL = mag;
    }
    else if (rdot > 0)
    {
        uL = mag;
    }
    else
    {
        uL = -mag;
    }

    return (float) 2;
}

void MenuHandler(void *mRef, void *iRef)
{
    // Only do below if "Stop laser" is selected
    if (!strcmp((char *) iRef, "Stop"))
    {
        // Temporarily stop laser
        uL = 0;
        XPLMSetFlightLoopCallbackInterval(MenuLoopCB, 0, 1, NULL);
        XPLMSetFlightLoopCallbackInterval(SwitchLoopCB, 0, 1, NULL);
    }
}

void MyHotKeyCallback(void * inRefcon)
{
    // Load run 1 "mountainSim.sit" situation
    if (!strcmp((char *) inRefcon, "1"))
    {
        // Temporarily stop and reset laser
        uL = 0;
        XPLMSetFlightLoopCallbackInterval(MenuLoopCB, 0, 1, NULL);
        XPLMSetFlightLoopCallbackInterval(SwitchLoopCB, 0, 1, NULL);
        mag = -30;

        // Restart situation
        XPLMLoadDataFile(xplm_DataFile_Situation, "Output/situations/mountainSim.sit");
        XPLMSDataf(latestTimeDataRef, 0);
        XPLMSpeakString("Run 1");
    }

    // Load run 2 "mountainSim.sit" situation
    if (!strcmp((char *) inRefcon, "2"))
    {
        // Temporarily stop laser
        uL = 0;
        XPLMSetFlightLoopCallbackInterval(MenuLoopCB, 0, 1, NULL);
        XPLMSetFlightLoopCallbackInterval(SwitchLoopCB, 0, 1, NULL);
        mag = -30;

        // Restart situation
        XPLMLoadDataFile(xplm_DataFile_Situation, "Output/situations/mountainSim.sit");
        XPLMSDataf(latestTimeDataRef, 0);
        XPLMSpeakString("Run 2");
    }
}
{  // Temporarily stop and reset laser
    uL = 0;
    XPLMSetFlightLoopCallbackInterval(MenuLoopCB, 0, 1, NULL);
    XPLMSetFlightLoopCallbackInterval(SwitchLoopCB, 0, 1, NULL);
    mag = -10;

    // Restart situation
    XPLMLoadDataFile(xplm_DataFile_Situation, "Output/situations/mountainSim.sit");
    XPLMSetDataf(latestTimeDataRef, 0);
    XPLMSpeakString("Run 2");
}

// Load run 3 "mountainSim.sit" situation
if (!strcmp((char *) inRefcon, "3"))
{
    // Temporarily stop and reset laser
    uL = 0;
    XPLMSetFlightLoopCallbackInterval(MenuLoopCB, 0, 1, NULL);
    XPLMSetFlightLoopCallbackInterval(SwitchLoopCB, 0, 1, NULL);
    mag = -50;

    // Restart situation
    XPLMLoadDataFile(xplm_DataFile_Situation, "Output/situations/mountainSim.sit");
    XPLMSetDataf(latestTimeDataRef, 0);
    XPLMSpeakString("Run 3");
}

// Load run 4 "mountainSim.sit" situation
if (!strcmp((char *) inRefcon, "4"))
{
    // Temporarily stop and reset laser
    uL = 0;
    XPLMSetFlightLoopCallbackInterval(MenuLoopCB, 0, 1, NULL);
    XPLMSetFlightLoopCallbackInterval(SwitchLoopCB, 0, 1, NULL);
    mag = -20;

    // Restart situation
    XPLMLoadDataFile(xplm_DataFile_Situation, "Output/situations/mountainSim.sit");
    XPLMSetDataf(latestTimeDataRef, 0);
    XPLMSpeakString("Run 4");
}

// Load run 5 "mountainSim.sit" situation
if (!strcmp((char *) inRefcon, "5"))
{
    // Temporarily stop and reset laser
    uL = 0;
XPLMSetFlightLoopCallbackInterval(MenuLoopCB, 0, 1, NULL);
XPLMSetFlightLoopCallbackInterval(SwitchLoopCB, 0, 1, NULL);

mag = -30;

// Restart situation
XPLMLoadDataFile(xplm_DataFile_Situation, "Output/situations/mountainSim.sit");
XPLMSetDataf(latestTimeDataRef, 0);
XPLMSpeakString("Run 5");

"}
Bibliography


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