Retrofitting a Private Aircraft for Autonomous Operation

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Retrofitting a Private Aircraft for Autonomous Operation

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**Dan Syzotek:** Private Pilot, Design Consultant, Engineer at Smiths Interconnect

**Dr. Fred J. Looft:** Advisor, Consultant, Electrical and Computer Engineering Professor at WPI
Abstract

The purpose of this project was to address the feasibility of retrofitting a four passenger private aircraft into an autonomous cargo transportation vehicle. A custom mechanical control mechanism prototype was developed that would replace a human pilot. The prototype developed addressed the three main controls on aircraft; roll, pitch and lift. Using knowledge of the selected aircraft configuration, the mechanical design each component was designed, analyzed to meet FAA guidelines and industry standards, and then constructed to demonstrate operation.
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1.0 Introduction

According to data gathered in 2002 from the Bureau of Transportation Statistics of the U.S. Department of Transportation, the United States has the largest transportation system in the world serving more than 288 million residents and 7 million domestic establishments. (4) Since 2002 the current population total in the U.S. has increased to approximately 324 million, (5) and with this increase in the U.S. population, there has also been an increase for freight being moved around the country to meet the growing demand. “On a typical day in 2002, about 43 million tons of goods valued at about $29 billion moved nearly 12 billion ton-miles on the nation's interconnected transportation network.” (4) The transportation of goods and services account for 10.4 percent of the U.S. Gross Domestic Product total and employ 15.6 percent of the total labor force in the U.S...

Within the context of the transportation infrastructure, the UPS delivered 4.7 billion packages and documents in 2015, which can be seen in figure 1 below, with the United States Postal Service (USPS) not far behind with 4 billion packages in 2014. (6)

![Figure 1- UPS 2015 Data](image)

Every year billions of dollars of goods are purchased both in store and over the internet and then sent via delivery companies such as USPS or UPS to personal homes. These purchases range from fresh fruit, flowers, clothing, and electronics to pretty much anything that can be put into a box,
all with the expectation on receiving that purchase with next-day express shipping. The current delivery system utilizes an intricate freight transportation system, which encompasses millions of trucks, aircraft, and smaller vehicles travelling on millions of miles of highway, roads and hundreds of hub airports while being supported by a highly sophisticated information technology system and trained labor force. UPS alone uses 104,926 package cars, vans, tractors and motorcycles, 237 jets and 306 leased charter aircraft (Figure 1 above).

The demand for goods and services is increasing annually from the growing population of not only the United States, but also the world and therefore the need for a more developed transportation system for services and goods is needed. An example of at least one enhanced delivery service being considered is the Amazon Prime Air concept in which the internet-shopping site Amazon will delivery your package to the specified location in thirty minutes or less using unmanned aerial technology. Figures 2 and 3 all show Amazon Prime Air’s unmanned aerial fleet.

![Figure 2 – Amazon Prime Air Drone Version 1](image)

![Figure 3 – Amazon Prime Air Drone Version 2](image)

This innovative system brings in a new era of freight delivery, which could potentially increase safety, and efficiency of the transportation system. (7) This system does have limitations though, such as the weight of the package and the distance this unmanned aerial vehicle can fly. Therefore, these unmanned aerial vehicles seem to best be deployed in densely populated areas such as cities.
This poses the question how can one provide cargo to more rural locations without an expensive and custom transportation system. An unmanned, autonomous cargo plane may just be the answer.

1.1 Problem Statement

The goal of the Senior Capstone Project\textsuperscript{1} is to design and test a prototype mechanical interface for small aircraft in an effort to demonstrate the feasibility of retrofitting a single engine aircraft (Piper Cherokee 140)\textsuperscript{2} into an autonomous cargo delivery vehicle. The development of such a mechanical system will need to meet FAA standards and use Supplemental Type Certificates (STC) components to ensure safety and reduce the risks of a mechanical system. The objectives of this project are to: perform background research on small aircraft and autopilots, explore existing autonomous cargo systems, design a mechanical interfacing system for a Piper Cherokee 140, build this mechanical system, test the prototype and write a detailed report.

\textsuperscript{1} The Senior Capstone Project at Worcester Polytechnic Institute is called a Major Qualifying Project or MQP.

\textsuperscript{2} This Project is using a Piper Cherokee 140 as a build model since another multidisciplinary project was using a Piper Cherokee 140 and allowed the author to gather information on the aircraft.
2.0 Background

2.1 Introduction

The freight forwarding system utilized currently has not been significantly altered for nearly 200 years. The use of UAV fleet would decrease cargo delivery time, reduce package and cargo delivery costs, and provide potential benefits in other industries where, for example, the perishability of a payload is a factor. To better understand the potential benefits of implanting autonomous delivery vehicles we need to first understand which airports can be used, which aircraft are optimal for the job and finally what safety concerns need to be addressed.

2.2 Airport Specifications

There are just under 22,000 airports in the United States (8), approximately a third of these airports, 7,251 to be specific, have a runway that is between 2,000 and 3,000 feet long. Yet only approximately one hundred airports are currently used for mass cargo delivery. The commercialization of an unmanned fleet of aircraft that were capable of making cargo/package deliveries to airports with shorter runways than the major hubs and located in potentially rural areas would expand upon the current system. That basic concept is that there are easily a few thousand airports located with a ten-mile radius of most populated areas around the United States that could be used for cargo delivery, but would require aircraft with short runway capabilities due to the shorter runway lengths of most untowered airports compared to towered airports.

An airport’s runway length depends on a few things; first, what is the purpose of the airport (cargo transportation, travel arrangements, etc…), second what types of aircraft are taking off and landing at this airport and finally the elevation of the airport. The higher the altitude the less dense the air is which means aircraft have less lift and therefore airplanes need to take-off and land at faster speeds.

For the purpose of the project, the target airport would be either non-towered or towered airports that have a runway length no shorter than 2,000 feet. Typically, non-towered airports have runway lengths between 2,000 to 4,000 feet long, while towered airports typically range from 5,000 to 10,000 feet long. Some examples of non-towered airports would be 3B3 – Sterling Massachusetts and KAFN – Jaffrey New Hampshire. 3B3 is only 2 miles away from the city of Sterling Massachusetts and has a runway length of 3,086 feet long, this airport has a runway that is slightly longer than the target range, but would meet the needs of this project. More importantly, this airport is only 2 miles away from a city with a population of 7,896 people (10), KAFN has a runway length of 2,982 feet long and is located only 1 mile southeast of Jaffrey, a city of 2,478 people (11). Both airports are within a very short drive of thousands of people, with the addition of a transportation service stationed at these airports the cargo could be picked up and delivered to a customer within the day.

2.3 Aircraft Possibilities

There are thousands of airplanes on the market, that date back to the 1950s and earlier, but not all of these planes are ideal for retrofitting into automated aircraft for cargo/package transportation. In this case, small single engine aircraft are preferred since the controls are basic and it is easier to
add a mechanical interface since fewer of the plane’s components are run by electronic controls. The designer/developer also needs to consider cargo capacity, range and in case the takeoff and landing distances among other factors. Since this project, looks to provide cargo delivery to smaller airports the takeoff and landing distances are extremely important. Below is a list of possible aircraft that can land on runways shorter than 2,000 feet. As can be seen in this table of representative single engine aircraft readily available on the market.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Airplane Type</th>
<th>Distance to Reach Elevation of 50 Feet</th>
<th>Distance to Land from Elevation of 51 Feet</th>
<th>Payload Capacity</th>
<th>Airplane Range</th>
<th>Range Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cessna</td>
<td>152</td>
<td>1340 ft</td>
<td>1200 ft</td>
<td>120 lbs</td>
<td>580 NM</td>
<td>75% power at 8,000 ft</td>
</tr>
<tr>
<td>Cessna</td>
<td>172S</td>
<td>1630 ft</td>
<td>1335 ft</td>
<td>120 lbs</td>
<td>638 NM</td>
<td>75% power at 8,500 ft</td>
</tr>
<tr>
<td>Piper</td>
<td>PA-28-140 Cherokee Cruiser</td>
<td>1700 ft</td>
<td>1080</td>
<td>125 lbs</td>
<td>625 NM</td>
<td>75% power at 7,000 ft</td>
</tr>
<tr>
<td>Piper</td>
<td>PA-28-161 Warrior II</td>
<td>1650 ft</td>
<td>1160 ft</td>
<td>200 lbs</td>
<td>525 NM</td>
<td>75% power at 8,000 ft</td>
</tr>
<tr>
<td>Cirrus</td>
<td>SR22</td>
<td>1432 ft</td>
<td>2262 ft</td>
<td>130 lbs</td>
<td>811 NM</td>
<td>75% Power at 8,000 ft</td>
</tr>
</tbody>
</table>

*Note: The data is assuming perfect conditions (zero wind, clear day), at pressure altitude of 2000 feet and temperature of 30 degrees Celsius*

Table 1 – List of some of the airplanes on the market capable of landing on runways shorter than 2,000 feet

The limiting factor when trying to find an airplane that can land on a runway that is only, for example, 2,000 feet long is the size of the baggage compartment available for cargo. A typical UPS or USPS package can range from ounces to pounds, for example, a hardcover book of approximately 700 pages averages one pound and 15 ounces. This means depending on the aircraft and baggage capacity the pilot could transport approximately sixty books. Larger packages with electronics can easily be ten or twenty pounds. The feasibility of using one of the aircraft listed in Figure 3 is reduced if only comparing the maximum capacity for the cargo hold. By comparison, cargo aircraft can carry thousands or tens of thousands of pounds of packages and cargo, which changes the target aircraft that one would use. The target aircraft for this application would be a single or double engine plane with capabilities of carry one to two thousand pounds. Some examples can be seen in Table 2 below.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Airplane Type</th>
<th>Distance to Reach Elevation of 50 Feet</th>
<th>Distance to Land from Elevation of 51 Feet</th>
<th>Payload Capacity</th>
<th>Airplane Range</th>
<th>Range Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilatus</td>
<td>PC-12 NG</td>
<td>2,602 ft</td>
<td>2,170 ft</td>
<td>6,194 lbs</td>
<td>1,845 NM</td>
<td>High Speed Cruise</td>
</tr>
<tr>
<td>Quest</td>
<td>Kodiak 100</td>
<td>1353 ft</td>
<td>1381 ft</td>
<td>3,535 lbs</td>
<td>904 NM</td>
<td>Max Cruise Power at 8,000 ft</td>
</tr>
</tbody>
</table>

Table 2 – List of Airplanes capable of carrying larger cargo loads

Note that these are not the only aircraft on the market and depending on the users’ needs there may be other aircraft available and better matched to specific cargo carrying and range requirements.
2.4 Industry Background

Freight forwarding is the portion of the cargo delivery chain from origin to carrier and then to the cargo’s final destination. Freight bundlers, FedEx, United Parcel Service (UPS), and DHL Express, all attempt to utilize airplane transportation of goods, but the majority of shipping is still relying on rail and truck shipping since delivery means are limited. The United States Postal Service handles nearly all of the last mile transportation of goods and does so using trucks now. This current system is not very efficient or cost effective, it takes 2-8 days to transport “ shipments up to 70 lbs. and up to 130 inches in combined length and girth,”(12). This current system will sort each package prior to shipping and again upon arrival at a distribution center before being loaded into a truck for delivery. This system seems to be inefficient, a package will easily be sorted three or more times, then loaded onto a truck that will emit CO2 and in addition create congestion on the road. A fleet of UAV and airplanes has been hypothesized to increase the efficiency of a delivery 4-5 times and as noted above, companies such as Amazon have already started to look into the possibilities of unmanned delivery services.

2.5 Current Autonomous Aircraft

Currently there is a variety of autonomous/unmanned vehicles on the market such as cars, tractors, robots in manufacturing plants and some airplanes. Unmanned aerial vehicles already exist as demonstrated by the military drones and the majority of all large aircraft, which have the capability of flying autonomously using their autopilot.

There are a few options on the market to date when it comes to small-unmanned aircraft. The most noticeable name is the Centaur from Aurora Flight Sciences, an optionally piloted aircraft (OPA). The Centaur combines the best of manned and unmanned aircraft capabilities boasting three modes of operation (manned, unmanned and augmented) you may want to define these (Centaur). This is a custom aircraft designed to meet the need of an optionally piloted aircraft, it took multiple years to develop and perfect the system. The system that is used inside of the plane is comparable to a robot arm that mounts to the yoke, which allows a human pilot to still be able to fly the aircraft if desired.

Amazon Prime Air as discussed briefly in the introduction has been developing drones for short range and long-range deliveries; the figure below is one of their long-range test drones.
2.6 Safety Concerns

The opinion of the pilot community varies from pilot to pilot, some would like to see autonomous aircraft, but a great others express concern with using fully autonomous aircraft. Current autopilot systems allow for the aircraft to cruise, land and takeoff without the need of a pilot, but pilots are still required because they provide an extra level of safety an in the case of problem a pilot can utilize their knowledge to override the autopilot.

According to certain pilots’ autopilots are all right, but do not provide the experience, capabilities, and judgement that a human can. Computers cannot feel the turbulence and engines pull the plane like a human pilot can, also the weather and air drafts can change at a moment’s notice at 40,000 ft. causing the need to react instantaneously. Most computers can process information in split seconds, but do not have the capability of understanding what the plane is encountering. (13) For the moment, airplanes need to utilize both human and machine control to ensure the safety of their passengers and cargo.

There have been recorded issues with autonomous systems in the past, one such event occurred in July of 2013 that took the lives of three and seriously injured 49 others. It was determined that the pilot choose the wrong autopilot setting which stopped the aircraft from tracking its own speed causing the aircraft to be moving too slow while descending too rapidly. In this case, an overreliance on the autopilot system resulted in fatality, but the Federal Aviation Administration (FAA) does not approve of heavy usage of autonomous systems (relying on and fully using autonomous systems when flying). The FAA estimated 90 percent of all operations done on an aircraft are done using some sort of autonomous system since airlines discourage pilots from flying manually under normal conditions. (14)
3.0 Problem Statement

3.1 Introduction

Currently, if a person wants to send a package, the package will be transported through a variety of methods including; airplane, truck, and or train. The package will most likely pass through two distribution centers before the package is loaded onto a truck for deliver to the recipient’s home. These delivery trucks can be seen everywhere that people drive on the roads, and have been noted to cause traffic jams. However, the package will spend a period of its life waiting to be processed and then again another part of its life sitting in a truck before delivery. To solve this, the addition of autonomous delivery system can reduce the time packages spend waiting to be delivered and ship out the package on an autonomous cargo delivery aircraft.

3.2 Problem Statement

The problem that this project aims to solve is how one retrofits a currently available small aircraft into an autonomous vehicle designed for cargo delivery. The specific project focus was to develop a, mechanical mechanism that could operate a small aircraft’s yoke and pedals, much like a human operator. The proposed device will be easily attached onto the airplanes seat sliders, yoke and foot pedals without the need to modify any part of an airplanes cockpit.

This project also aims to discuss the feasibility of retrofitting current aircraft and how it would be accomplished, by anyone with little to no experience of aircraft design. Therefore, the purpose of this project is to create a prototype that simulates the systems capabilities and ability to manipulate the controls of any current standard aircraft on the market.

3.3 Objectives and Project Deliverables

Objectives
The specific goals of this project were to research, design, simulate, and build selected components for an autonomous aircraft retrofit. To accomplish these goals, the following objectives will be accomplished:

1. Perform background research on all relevant autopilot systems and current aircraft specifications that will connect and control the autonomous aircraft retrofit system.
2. Explore system designs best suited to achieve the project goals based on existing aircraft and autopilot designs
3. Design the mechanical interfacing system.
4. Develop analysis of all designs.
5. Produce a prototype that proves the designs can operate.
6. Write a detailed report.
**Project Deliverables**

*Perform Background Research:*

The author researched the types of aircraft on the market as well as how current aircraft systems are controlled. In order to design an autonomous aircraft retrofit, the author needed to understand how an aircraft operates and how the existing controls function. The background research was critical to understanding the limitations of an aircraft and the FAA restrictions on autonomous aircraft so the author could develop solutions for each limitation or restriction.

*Explore System Designs:*

To better design a system that retrofits an aircraft into an autonomous aircraft, the author needed to have a detailed understanding of aircraft, specifically small-scale aircraft and autopilot systems. To accomplish this we need to know how manipulating aircraft controls changes how an aircraft flies, how each control is connected, and the forces needed to manipulate each control. The understanding of how aircraft are designed gave the author ideas on how to develop their system.

*Design the System*

The design is the absolute objective of this project. The design of the retrofit system for aircraft was utilizing a variety of methods, such as: computer aided design, finite element analysis and computer aided manufacturing. The design was influenced by all findings from objectives 1 and 2. From, these findings the retrofit system design was refined to meet safety requirements and needs to operate an aircraft.

*Develop the System*

The author used simulations to ensure the design was capable of meeting the needs and safety requirements. The purpose of these simulations was to understand the weaknesses of each design and how each design will respond in real world conditions.

*Produce a Prototype*

The author built a prototype to demonstrate the design is capable of moving each aircraft control and how the system would be attached on an aircraft. The prototype on displays how the system works and not the exact loads it can handle.

*Write a Detailed Report*

Finally, the author wrote all findings and results into a full report in the order of accomplishment to the detail of how the autonomous aircraft retrofit was designed and validated. The report contains the results of the background research, systems engineering items, design work, simulation results, and testing.
4.0 System Concepts

4.1 Introduction

The design of a fully autonomous aircraft is one that involves expertise in Electrical, Mechanical and the Computer Science fields, but for this project, the focus was on a retrofit design (the mechanical aspect). The first steps taken were to define the problem, the stakeholders, all relevant analysis and specific restrictions the author needed to follow ensuring a completely documented design.

4.2 Stakeholder Analysis

To successfully design a product, the customer or stakeholders requirements were critical to identify prior to designing and critical to keep in mind while designing. The next few sections will cover; who the possible stakeholders are, what their needs are, and their possible requirements. In addition, what regulations must be followed for this system to be an acceptable certified aircraft system.

Stakeholders

This idea will change how corporations transport cargo on a national and international scale. Any company that deals with large-scale movement of goods such as FedEx, UPS, and DHL Express, would be interested in such a product since it will reduce their expenses by 4 to 5 times in cargo transportation.

In addition to these corporations, any pilot that would like to turn their aircraft into an autonomous vehicle would have an interest. The application of this system is not limited to cargo transportation and private pilots; this system is part of the autonomous revolution in which we have been attempting to perfect automation in technology we use/see every day. The stakeholders could be expanded to the general population as well.

Stakeholder Needs

The stakeholder needs varies from stakeholder to stakeholder, the commercial cargo transportation needs a system that is durable and capable of handling many loads overtime with little maintenance. While the everyday pilot will be looking for ease of attaching and removing since this system probably will not always be in their aircraft. As a result, the design will have to be a compromise to meet the needs of these stakeholders.

4.3 CONOPS

CONOPS refers to the concept of operations, which describes what the system will do and how it will operate. The functional requirements are what the system must do to operate. All functional requirements should be derived from the stakeholders needs.

Expected Operational Environment

This system is expected to be mounted inside a small-scale aircraft’s cockpit; it will be partially insulated from the elements. It should be mounted in such a way that it will ensure proper user, and will not affect a pilot from using the second set of controls in an aircraft. Some general rules regarding the mechanism are; the system is required to be mounted completely down to the seat sliders and other specified mounts for the designed system to properly operate.
System Requirements

Below is a list of all the requirements that the system had to meet for it to be acceptable design for an aircraft. Note these requirements directly affected how the system was designed.

- Simpler is easier
- Must not interfere with any of the current actuators in the plane
- Don’t damage the aircraft; either structurally or visibly
- Removable systems
- Pilot has to stay in left seat
  - Means the autonomous actuators that mount to the right seat need to be compact for either easy removal and so the pilot does not get ensnared while trying to evacuate
- The system must be capable of handling all normal loadings for normal operation
- The system must be capable of handling all FAA specified loadings
  - This refers to when the aircraft encounters turbulence, the forces on the system will be greater

Operational Requirements

The operational requirements define how the system functions, defines any special operations or information regarding how it works.

- Need both front seats for crew of two, pilot and flight engineer
- Fully operational mechanical system that interacts with the yoke and pedals
- Mechanical fail safes (pins) to release autonomous system to engage human control
- Anyone can use it, you don’t need any special degree to understand how it operates

<table>
<thead>
<tr>
<th>Airplane Control</th>
<th>Purpose</th>
<th>Maximum Operator Force (lbs) Short term</th>
<th>Maximum Actuator Force (lbs)</th>
<th>Maximum Actuator Throw (in)</th>
<th>Maximum Full Actuation Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yoke</td>
<td>Aileron</td>
<td>25</td>
<td>125</td>
<td>9</td>
<td>1.5</td>
</tr>
<tr>
<td>Yoke</td>
<td>Stabilator</td>
<td>50</td>
<td>50</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Foot Pedals</td>
<td>Rudder</td>
<td>150</td>
<td>160</td>
<td>12</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3 - The desired operational forces and actuation time

Design Requirements

The design requirements constrain how each part is designed and to what standard these parts need to be manufactured to.

- Wanting to resell the plane restricts what modifications we can make to the aircraft
  - Do not cut the foot pedals
  - Do not drill into the T-bar or frame
  - Avoid chemical bonding; welding, glue, etc.
- Mounts to the seat sliders since they are already rated to handle the loads/forces of a pilot
- Cannot weigh more than a pilot (upper limit is 240 lbs.)
- Title 14, Code of Federal Regulations (14 CFR), part 21, section 21.191(g) defines what amateur built aircraft are.
- Title 14, Code of Federal Regulations (14 CFR), part 21, section 21.319 defines how design changes need to be logged.
Title 14, Code of Federal Regulations (14 CFR), part 23, section 23.23 defines load distribution limits

Title 14, Code of Federal Regulations (14 CFR), part 23, section 23.25 defines weight limits

Title 14, Code of Federal Regulations (14 CFR), part 23, section 23.29 defines empty weight and the corresponding center of gravity
4.4 Final System Architecture

Upon completing analyzing the stakeholder needs, the author went through a design iteration process, which is explained in the table below. There were some common design considerations, such as:
- Removable system
- Don’t damage the aircraft; either structurally or visibly
- Capable of handling all normal loadings and FAA specified loadings
- Simple design which is easy to use

The list consists of all requirements, which can be found in section 4.3 CONOPS.

For more detail, sketches and design concepts please reference Appendix A (page 53).

Table 4 - Design Evolution Table

<table>
<thead>
<tr>
<th>Design Part</th>
<th>Design Considerations</th>
<th>Design Changes</th>
<th>Reason for Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support Tower</td>
<td>- Removable system</td>
<td>- The support tower design did not change much, since it was designed using a truss like concept</td>
<td>- The triangle, truss-like design provides the best structural support</td>
</tr>
<tr>
<td></td>
<td>- Capable of handling all normal loadings and all FAA specified loadings</td>
<td>- Only fillets were added to corner edges</td>
<td>- The corner edge fillets distributed the loading more evenly throughout the entire tower</td>
</tr>
<tr>
<td></td>
<td>- Anyone can use this part</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Mounts to the seat sliders</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support Tower Cap</td>
<td>- Removable system</td>
<td>- Fillets were added to all edges</td>
<td>- This better distributed the loading throughout the part design, makes the part stronger</td>
</tr>
<tr>
<td></td>
<td>- Capable of handling all normal loadings and all FAA specified loadings</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Anyone can use this part</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support Tower Strut</td>
<td>- Removable system</td>
<td>- The distance from the center of the axle alignment hole to the part side was made larger</td>
<td>- By moving the hole, there was more material around the sides of the through hole which made the part stronger</td>
</tr>
<tr>
<td></td>
<td>- Capable of handling all normal loadings and all FAA specified loadings</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Anyone can use this part</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Part</td>
<td>Removable system</td>
<td>Capable of handling all normal loadings and all FAA specified loadings</td>
<td>Anyone can use this part</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>------------------</td>
<td>---------------------------------------------------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Yoke Connector Back Plate</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Yoke Connector Front Plate</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Shaft to (Yoke) Connector Plate</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Linear Actuator Collar</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Component</td>
<td>Removable system</td>
<td>Capable of handling all normal loadings and all FAA specified loadings</td>
<td>Anyone can use this part</td>
</tr>
<tr>
<td>----------------------------</td>
<td>------------------</td>
<td>------------------------------------------------------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>Linear Actuator Mount</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Linear Actuator</td>
<td>- Picked one that could handle the loads over the needed time</td>
<td>- Need to pick a better actuator</td>
<td>-</td>
</tr>
<tr>
<td>Rotational Motor Mount</td>
<td>- Removable system</td>
<td>- This is a custom mount that needed to be designed specifically for the motor being used</td>
<td>-</td>
</tr>
<tr>
<td>Pillow Block Ball Bearings</td>
<td>- Removable system</td>
<td>- These were purchased components that really only needed to meet specified forces</td>
<td>-</td>
</tr>
<tr>
<td>Rotational Bag Motor</td>
<td>- Picked one that could handle the loads over the needed time</td>
<td>- Choose a BAG motor, supplied by VEX Robotics</td>
<td>-</td>
</tr>
<tr>
<td>U-mount Rotational Motor Mount</td>
<td>- Removable system</td>
<td>- Added a fillet to the inner u-shape</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>- Increased distance the hole is from the edge</td>
<td>-</td>
</tr>
<tr>
<td>Part Description</td>
<td>Features</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td></td>
</tr>
</tbody>
</table>
| 18-8 Stainless Steel Clevis Pin  | - Removable system  
- Capable of handling all normal loadings and all FAA specified loadings  
- Anyone can use this part | - Purchased part that was selected for its material type and strength  
- Specified part that is purchased |
| Floor Strut Cap                  | - Removable system  
- Capable of handling all normal loadings and all FAA specified loadings  
- Anyone can use this part  
- Cannot damage the aircraft  
- Design to fit around specific floor strut in Piper Cherokee 140 | - Added filleted edges  
- Reduced stress concentrations and increased the parts strength |
| Seat Slider Frame                | - Removable system  
- Capable of handling all normal loadings and all FAA specified loadings  
- Anyone can use this part  
- Cannot damage the aircraft  
- Design to fit around specific seat sliders in Piper Cherokee 140 | - Parts did not require changes  
- The part was capable of handling significantly larger loadings than it would ever experience |
The final system design was based off a series of theoretical requirements, because there are multiple potential stakeholders the design needed to be robust, but simple to use. To make a system simple the designs for each part needed to be simple, which was achieved by having the fewest moving components to reduce the chance of anything failing. In addition, each design was created with the thought of safety to ensure that if a pilot was in the aircraft the mechanisms could be released from the controls allowing the pilot to regain full control over the system. To do so, on each axle a clevis pin would be added, which a strap could be attached to make it easier for grabbing for the pilot. This clevis pin would also act as the axle, which means the clevis pin needs to be made out of materials strong enough to handle such loadings. Hence why a stainless steel clevis pin was chosen. The use of a clevis pin on the linear actuator to the yoke connector is critical since that will drive the yoke’s rotation and movement in/out, once disconnected it will no longer affect the pilot’s control of the aircraft.

Potential designs were created for operating the foot pedals, but due to size constraints and also how the foot pedals operate, these designs were not capable of meeting the need. The first design concept looked at was a gear and chain drive system that would connect onto a gear by the base of the pilot’s seat a gear connected onto the foot pedal and a gear positioned by the firewall. The design concept is displayed in the figure below.

![Figure 5 – Foot Pedals Chain Drive](image)

There are three problems with this design:
- First, there was no place to mount the gear by the firewall
  - FAA regulations prevent the pilot from mounting to the firewall and mounting to the aluminum body of the plane
- Second, if the chain were to snap or disconnect midflight this would pose a serious safety concern
  - Which a pilot might not be able to fix midflight
- Third, this design would require modifications to the foot pedals

Remember simple is better and this mechanism has a considerably more moving parts than necessary. The next possible mechanism that was designed consisted on using linear actuators to move the pedals. The author found it almost twice as hard to pull a foot pedal compared to pushing a foot pedal, therefore two linear actuators would be required to push one-foot pedal at a time. There was no place to mount these linear actuators in the foot space of the cockpit without modifying the frame or body of the aircraft.
The third and final foot pedal actuator design was a combination of a linear actuator and, shaft and triangle frame. The linear actuator was mounted on one of the triangle’s corner and when it opened up the triangle would rotate on a shaft pushing one of the corners forward and the other pulling backwards. The design concept can be seen in the figure below.

There were two problems with this design; again the mounting of the system by the cockpit foot space and secondly for this system to perform properly an equilateral triangle was needed with a side length of eight inches. This triangle rotates around a shaft in the center of one of the sides and its path covered a distance of 17.8854 inches, the cockpit foot space at its widest point was only 17.25 inches. Thus, this mechanism would not be able to fully rotate and therefore would not completely move the pedals the full stroke distance. The figure below shows the calculations made to find the path of rotation of the triangle frame.
It was decided to move forward and design components that would fit and could operate within the restrictions and needs of the stakeholders. The system seen in the figure below is the final system design that operates the yoke. A motor which is positioned on the back of the yellow block, the linear actuator and the linear actuator mount, would turn the linear actuator and thus the yoke connector and by extension the yoke. The rotation of the yoke adjusts the ailerons, which will control the aircraft’s roll. The linear actuator pulls and pushes the yoke in and out, which adjusts the stabilators to control the aircraft’s pitch.

To ensure the system would allow for the full movement of the yoke, the yoke’s position was plotted for the complete stroke. The yoke of the Piper Cherokee 140 does not follow a linear path, but a curved path, which resulted in the implementation of two pivot points. The figure below is the plotted path of the yoke.
One pivot point is underneath the rotational motor, there are two pillow block ball bearing mounts, which allow the mechanism to angle up or down. The second pivot point is the linear actuator shaft to yoke connector plate. It is made with a u shaped slot, which allows the linear actuator, also move upwards and downwards. These pivot points guarantee this system moves the yoke through its complete path.

The linear actuator mount encloses around the linear actuator's body in two halves that are a perfect opposite match of the body. Each half is bolted together with eight stainless steel bolts; there are eight tapped holes that are $\frac{1}{4}$-20 threads. This mount holds the linear actuator in place while it operates the movement of the yoke in the airplane. This linear actuator will pull the linear actuator back to angle the nose of the aircraft upwards and push the yoke forwards to angle the nose of the aircraft downwards. The yoke controls the pitch of the aircraft, which controls which way the plane flies vertically. These mounts will need to be machined using 5-axis capabilities since it has very intricate designs that match the details on the linear actuator body. The same goes for the rotational motor mount.

The linear actuator collar was designed to mount over the end of the linear actuator shaft, which has a lip (two different diameters on the shaft), the first part has an outer diameter of 0.75” and the second side of the shaft has an outer diameter of 1.00”. The change in shaft diameter had to be addressed because the linear actuator shaft affects the design of the shaft to yoke connector design. If the mount were to be 0.75” between the inner sides, the linear actuator shaft would not be able to move. Therefore, this collar expands the 0.75” diameter part of the shaft to and outer diameter of 1.00” with axle holes, which allow an axle to pass through the collar and linear actuator shaft. The shaft to yoke connector mount now needs a 1.00” between inner sides and will no longer get jammed when moving the linear actuator shaft up or down in the vertical direction, because of the two different diameters of the shaft.
This design of the part is simple to manufacture and requires a drill and vice. One would use aluminum 1.00” diameter stock that is 0.25” thick. This part will need to be restrained in the vice and then using a ¾” drill the first hole (the bigger of the two) would be made, the second hole is a 0.125” diameter hole made in the side of the part. The result is a part that slides right over the shaft and will not be under any great stress or deformation.

The support tower was designed using triangle, truss-like concept and has a support tower cap which slides over the top section of the support tower. This then has a strut that extends forward and down to the floor strut cap. This strut supports the tower and helps prevent it from shifting when the motor and linear actuator are manipulating the yoke control.

The floor strut cap, support tower cap, shaft to yoke connector and other parts had filleted edges to relieve the stress concentrations. A filleted edge distributes the forces along a wider surface area, which reduces the total deformation, and equivalent stresses. The addition of a fillet is a good design technique since it serves to structurally enhance a design.

The support tower is connected to a custom seat slider frame, which has a series of custom sliders just like the bottom of a pilot seat in the Piper Cherokee 140. These seat slider mounts guarantee the frame will connect with the existing seat sliders in the aircraft and are rated to handle the loadings/forces of a pilot. The seat sliders were the optimal position to mount this system, especially since its purpose is to replace the pilot. Please note that the seat sliders are not universally the same in all aircraft so they would have to be redesign to interchange between aircraft.

The final system design focusses on simplicity and ease of use. Anyone could use this design and retrofit their airplane to be an autonomous aircraft. The overall system weight is 44.63661 lbs., the weight of all the parts can be found in the table below.
This system weight is less than a quarter of the maximum allowed load that could be positioned onto the seat sliders such that the weight and balance of the aircraft will not be compromised and the weight and balance will be within the design limits for flight center of gravity limits.

4.5 Summary

All designs were based off a Piper Cherokee 140, and thus are subject to change if this theoretical system would want to be implemented in another type of aircraft. As mentioned above the seat sliders are different per aircraft, the path of the yoke can also be different, size/shape of the yoke and the distance of each stroke will vary between aircraft. These and many other parts are subject to change. Overall, the system works and it is a simple design that the author believes the average pilot would be capable of attaching and using in flight. Note that this system has not been tested in flight and needs to be tested in flight before anyone should consider using.
5.0 Results and Analysis

5.1 Introduction

Each component was analyzed using Workbench 2017 (ANSYS) to perform finite element analysis (FEA). The purpose was to determine whether this theoretical system would be possible and where the weak points are on each component of the system. The figures below display the findings of the FEA for each component. A theoretical force of 100 Newton per meter (73.7562 ft. lb. force) was applied per the defined direction/location and a fixed support was applied in the specified direction/location.

5.2 Test Results

Original Floor Strut Cap Design

The original floor strut cap would deform a total of 7.7958e-8 m when a 100 Nm (73.7562149277 ft. lbs. force) force is applied directly to its left vertical side, which is the equivalent of 3.0692125984252e-6 inches (Figure 11). When the support tower strut is connected to the floor strut cap, support tower cap and by extension the support tower, the total deformation on this part will be significantly less. The assembly will always be stronger than the single part. Note the part deforms at the top of the long pieces with the holes in it.

![Figure 10 – The total deformation of the floor strut cap with a 100 Nm force being applied perpendicularly to the left vertical face and there was a fixed support on the right vertical face.](image)

The original floor strut cap would deform a total of 1.5862e-8 m when a 100 Nm (73.7562149277 ft. lbs. force) force is applied directly to its top horizontal face, which is the equivalent of 6.2448819e-7 inches (Figure 12). Again, when the entire system is connected together the system will be even stronger. The part deforms only above the hole, since that is the weakest point of the part where the force is being applied. If the author were to add more distance between the edge and hole, this would increase the strength and reduce the total deformation.
Figure 11 – The total deformation of the floor strut cap with a 100 Nm force being applied straight downward to the top horizontal faces and there was a fixed support on the bottom horizontal faces.

The original floor strut cap will experience an equivalent stress of approximately 80,000 Pa when a 100 Nm (73.7562149277 ft. lbs. force) force is applied directly to its left vertical side, which is the equivalent of 11.603019 lbs. per square inch (PSI) (Figure 13). Note that the stress concentrates around the ninety-degree corner of the top two long pieces with holes in it. The addition of a filleted edge will reduce the equivalent stress, the revised part and analysis can be found in the next section, Revised Floor Strut.

Figure 12 - The equivalent stress of the floor strut cap with a 100 Nm force being applied perpendicularly to the left vertical face and there was a fixed support on the right vertical face.
The original floor strut cap will experience an equivalent stress of approximately 28,000 Pa when a 100 Nm (73.7562149277 ft. lbs. force) force is applied directly to its top horizontal face, which is the equivalent of 4.0610567 PSI (Figure 14). The stress concentration is still primarily around the ninety degreed corners on the long pieces with holes, but because of how it is designed; the loading is actually spread out over the other two pieces that extend downwards, which reduced the total equivalent stress.

Figure 13 - The equivalent stress of the floor strut cap with a 100 Nm force being applied straight downward to the top horizontal faces and there was a fixed support on the bottom horizontal faces.
Revised Floor Strut

The revised floor strut cap would deform a total of $8.2927 \times 10^{-8}$ m when a 100 Nm (73.7562149277 ft. lbs. force) force is applied directly to its left vertical side, which is the equivalent of $3.26484251969 \times 10^{-6}$ inches (Figure 15). This is actually deforming approximately $0.2 \times 10^{-6}$ inches more than the original design.

![Figure 15](image)

Figure 14 – The total deformation of the revised floor strut cap with a 100 Nm force being applied perpendicularly to the left vertical face and there was a fixed support on the right vertical face.

The revised floor strut cap would deform a total of $1.4552 \times 10^{-8}$ m when a 100 Nm (73.7562149277 ft. lbs. force) force is applied directly to the top horizontal faces, which is the equivalent of $5.7291385827 \times 10^{-7}$ inches (Figure 16). Under this analysis, the part will deform approximately $0.5 \times 10^{-7}$ inches less than the original design.

![Figure 16](image)

Figure 15 – The total deformation of the revised floor strut cap with a 100 Nm force being applied straight downward to the top horizontal faces and there was a fixed support on the bottom horizontal faces.
The revised floor strut cap will experience an equivalent stress of approximately 77,000 Pa when a 100 Nm (73.7562149277 ft. lbs. force) force is applied directly to its left vertical side, which is the equivalent of 11.167906 PSI (Figure17). The revised part is experiencing less total stress by approximately 0.5 PSI.

![Image of stress distribution](Image16)

**Figure 16** - The equivalent stress of the revised floor strut cap with a 100 Nm force being applied perpendicularly to the left vertical face and there was a fixed support on the right vertical face.

The revised floor strut cap will experience an equivalent stress of approximately 27,000 Pa when a 100 Nm (73.7562149277 ft. lbs. force) force is applied directly to the top horizontal faces, which is the equivalent of 3.9160189 PSI (Figure18). The revised part is experiencing less total stress by approximately 0.2 PSI.

![Image of stress distribution](Image17)

**Figure 17** - The equivalent stress of the revised floor strut cap with a 100 Nm force being applied straight downward to the top horizontal faces and there was a fixed support on the bottom horizontal faces.
Linear Actuator Shaft Collar

The linear actuator shaft collar will deform a total of $9.8398 \times 10^{-6}$ m ($3.873937007874 \times 10^{-5}$ inches) when a 100 Nm force is being exerted on the right vertical face (Figure 19). The position of the greatest deformation is by the edge nearest the hole, because this is a known stress concentration, but this part slides over the shaft of the linear actuator and thus will be stronger when together.

![Figure 18 - The total deformation of the linear actuator shaft collar with a 100 Nm force being applied perpendicularly to the right vertical face, and there was a fixed support on the left vertical face.](image)

The linear actuator shaft collar will experience an equivalent stress of $4.7779 \times 10^5$ Pa ($69.2975807118$ PSI) when a 100 Nm force is being exerted on the right vertical face (Figure 20). The position of the highest stress concentration is by the edge nearest the hole. 69 PSI seems quite high, but is actually quite reasonable when thought about since how small the part is and how large of a force is being applied over a small volume. This part has an outer diameter (OD) of one inch, an inner diameter (ID) of three quarters of an inch and a thickness of one quarter of an inch.

![Figure 19 - The equivalent stress of the linear actuator shaft collar with a 100 Nm force being applied perpendicularly to the right vertical face, and there was a fixed support on the left vertical face.](image)
Linear Actuator Mount

The linear actuator mount will deform a total of 1.3504e-6 m (5.316534e-5 inches) when a 100 Nm force is being exerted on the left vertical face. The linear actuator within the mount will deform a total of 2.4306e-6 m (9.5692913e-5 inches) (Figure 21). Neither is large enough to cause a problem, and these parts will not have 73.7562149277 ft. lbs. force applied to them. The analysis makes sense, because the greatest deformation will occur on the part furthest away from the fixed support (the right vertical face).

![Figure 20 - The total deformation of the linear actuator mount with a 100 N force being applied perpendicularly to the left vertical face, and there was a fixed support on the right vertical face.](image)

The linear actuator mount will experience an equivalent stress of 3.7156e5 Pa (53.8902218 PSI) when a 100 Nm force is being exerted on the left vertical face. This stress is negligible and barely affects the part and linear actuator due to its design that encloses half of the linear actuator. Note that in the Figure 22, the part displays a blue color over the majority of the part; this represents an equivalent stress of 0.0025845 Pa or 3.7485003317e-7 PSI.

![Figure 21 – The equivalent stress of the linear actuator mount with a 100 Nm force being applied perpendicularly to the left vertical face, and there was a fixed support on the right vertical face.](image)
Rotational Motor Mount

The rotational motor mount will experience a total deformation of $7.4184 \times 10^{-8}$ m (2.9206299e-6 inches) when a 100 Nm force is exerted to the right vertical face (Figure 23). The majority of the deformation is occurring on the top horizontal face because the bottom horizontal face is where the part is fixed; it is connected to the pillow block ball bearings, which connect down to another series of mounts.

The rotational motor mount will experience an equivalent stress of 90,000 Pa (13.053396 PSI) when a 100 Nm force is exerted to the right vertical face (Figure 24). This part just like the linear actuator mount experiences negligible stress due to the way it is designed. The thickness of all sides and the intricate design fits perfectly around the motor.
Original Rotational Motor u-mount

The original rotational motor u-mount will experience a total deformation of $1.7028 \times 10^{-6}$ m ($6.703937 \times 10^{-5}$ inches) when a 100 Nm force is exerted to the right vertical face (Figure 25). The majority of the deformation is occurring on the top of the rounded sections because the bottom horizontal face is where the part is fixed; it is connected to the support tower. The most deformation will occur at the farthest point from the fixed support.

![Figure 24](image-url) - The total deformation of the original rotational motor u-mount with a 100 Nm force being applied perpendicularly to the right vertical face and there was a fixed support on the bottom horizontal face.

The original rotational motor u-mount will experience an equivalent stress of $7.7718 \times 10^5$ Pa (112.720429 PSI) by the inside corners and base of the part when a 100 Nm force is exerted to the right vertical face (Figure 26).

![Figure 25](image-url) - The equivalent stress of the the original rotational motor u-mount with a 100 Nm force being applied perpendicularly to the right vertical face and there was a fixed support on the bottom horizontal face.
Revised Rotational Motor u-mount

The revised rotational motor u-mount will experience a total deformation of $2.2189 \times 10^{-6}$ m ($8.7358268 \times 10^{-5}$ inches) when a 100 Nm force is exerted to the left vertical face (Figure 27). The total deformation nearly doubled, but the total deformation represents the worst-case scenario, but because the fillet was added, it increased the strength of the part, which reduces the likelihood that the part will hit the worst-case scenario and deform.

![Figure 26 – The total deformation of the revised rotational motor u-mount with a 100 Nm force being applied perpendicularly to the left vertical face and there was a fixed support on the bottom horizontal face.](image)

The revised rotational motor u-mount will experience an equivalent stress of $4.5263 \times 10^5$ Pa ($65.6484312$ PSI) by the base of the part when a 100 Nm force is exerted to the left vertical face (Figure 28). The equivalent stress reduced by nearly fifty percent and shifted the stress concentrations to all the way by the base of the part, which is where the part is mounted to the support tower.

![Figure 27 - The equivalent stress of the revised rotational motor u-mount with a 100 Nm force being applied perpendicularly to the left vertical face and there was a fixed support on the bottom horizontal face.](image)
Seat Slider Frame

The seat slider frame will experience a total deformation of $4.2768 \times 10^{-6}$ m ($0.000168377953$ inches) when a 100 Nm force is exerted to the top horizontal face in the center (Figure 29). This deformation is almost completely negligible, in addition, the forces will be distributed throughout the seat sliders upon which this part sits and then distribute the loads throughout the body of the plane. The support tower that sits on top of the seat slider frame is a triangle, truss-like shape that would spread out the load across the entire seat slider frame and not just a single point in the center of the platform.

![Figure 28 – The total deformation of the seat slider frame with a 100 Nm force being applied straight downward to the top horizontal face and there was a fixed support on the bottom horizontal faces.](image)

The seat slider frame will experience an equivalent stress of $7.9682 \times 10^5$ Pa ($115.56897$ PSI) by the corners where the top plate contacts the bottom mount when a 100 Nm force is exerted to the top horizontal face (Figure 30). The frame will again not have a single point where the force is exerted, it will be spread out over the entire top part and the seat sliders as well which will reduce the loading on this part.

![Figure 29 – The equivalent stress of the seat slider frame with a 100 Nm force being applied straight downward to the top horizontal face and there was a fixed support on the bottom horizontal faces.](image)
Original Shaft to Yoke Connector

The original shaft to yoke connector will experience a total deformation of 2.2252e-8 m (8.7606299e-7 inches) by the top of the two parallel pieces when a 100 Nm force is exerted to the left vertical face (Figure 31). Again, the location of the deformation is to be expected and the amount is extremely small.

Figure 30 – The total deformation of the original shaft to yoke connector with a 100 Nm force being applied perpendicularly to the left vertical faces and there was a fixed support on the right vertical face.

The original shaft to yoke connector will experience an equivalent stress of 2.8213e5 Pa (40.9194969 PSI) by the center holes on the two parallel pieces when a 100 Nm force is exerted to the left vertical faces (Figure 32).

Figure 31 - The equivalent stress of the original shaft to yoke connector with a 100 Nm force being applied perpendicularly to the left vertical faces and there was a fixed support on the right vertical face.
Revised Shaft to Yoke Connector

A filleted edge was added around the base of the two parallel pieces. The revised shaft to yoke connector will experience a total deformation of 3.1011e-8 m (1.2209055e-6 inches) by the top of the two parallel pieces when a 100 Nm force is exerted to the left vertical face (Figure 33).

![Figure 32 - The total deformation of the revised shaft to yoke connector with a 100 Nm force being applied perpendicularly to the left vertical faces and there was a fixed support on the right vertical face.](image1)

The revised shaft to yoke connector will experience an equivalent stress of approximately 69,000 Pa (10.007604 PSI) by the edge of the base of the two parallel pieces when a 100 Nm force is exerted to the left vertical faces (Figure 34). The equivalent stress is reduced approximately seventy-five percent.

![Figure 33 – The equivalent stress of the revised shaft to yoke connector with a 100 Nm force being applied perpendicularly to the left vertical faces and there was a fixed support on the right vertical face.](image2)
**Support Tower Cap**

The support tower cap will experience a total deformation of $6.0081 \times 10^{-9}$ m ($2.3653937 \times 10^{-7}$ inches) by the top of the two parallel pieces when a 100 Nm force is exerted to the top of the horizontal faces (Figure 35).

![Figure 34 - The total deformation of the support tower cap with a 100 Nm force being applied perpendicularly to the top horizontal face and there was a fixed support on the internal faces of the support tower cap.](image)

The support tower cap will experience an equivalent stress of approximately 18,000 Pa (2.6106793 PSI) by the edge of the base of the two parallel pieces when a 100 Nm force is exerted to the top of the horizontal faces (Figure 36). The addition of filleted edges by the base of the parallel pieces would reduce the stress concentrations even more, but increase the total deformation.

![Figure 35 – The equivalent stress of the support tower cap with a 100 Nm force being applied perpendicularly to the top horizontal face and there was a fixed support on the internal faces of the support tower cap.](image)
The support tower cap will experience a total deformation of $5.4549 \times 10^{-8}$ m ($2.1475984 \times 10^{-6}$ inches) by the top of the two parallel pieces when a 100 Nm force is exerted to the right vertical faces (Figure 37).

![Figure 36 - The total deformation of the support tower cap with a 100 Nm force being applied perpendicularly to the right vertical faces and there was a fixed support on the internal faces of the support tower cap.](image)

The support tower cap will experience an equivalent stress of approximately $2.6814 \times 10^5$ Pa ($38.890419$ PSI) by the top of the two parallel pieces when a 100 Nm force is exerted to the right vertical faces (Figure 38). The addition of filleted edges by the base of the parallel pieces would reduce the stress concentrations even more, but increase the total deformation.

![Figure 37 - The equivalent stress of the support tower cap with a 100 Nm force being applied perpendicularly to the right vertical faces and there was a fixed support on the internal faces of the support tower cap.](image)
Support Tower Frame

The support tower frame will experience a total deformation of 7.6029e-1 m (29.9326772 inches) at the center of the top platform when a 100 Nm force is exerted to the top horizontal face (Figure 39).

![Figure 38](image1.png)

Figure 38 – The total deformation of the support tower frame with a 100 Nm force being applied straight downward to the top of the horizontal face and there was a fixed support on the bottom horizontal faces.

The support tower frame will experience an equivalent stress of approximately 4.4288e5 Pa (64.23431329 PSI) at the center of the top platform when a 100 Nm force is exerted to the top horizontal face (Figure 40).

![Figure 39](image2.png)

Figure 39 – The equivalent stress of the support tower frame with a 100 Nm force being applied straight downward to the top of the horizontal face and there was a fixed support on the bottom horizontal faces.

The design tower should not move left or right due to the way it is designed, there is a support strut that extends off the support tower cap and to the floor strut cap. This strut supports the tower and holds it in a rigid position. In addition, the support tower cap encases the top of the support tower, and this adds another level of structural support to the support tower. The support
tower cap will reduce the equivalent stress and total deformation of the support tower frame’s top section, which experiences the most stress, and deformation. One improvement that could be added to this design is filleted edges on the vertices of the triangles to distribute the loads even further. Note that the triangle, truss-like design is another good design technique, because the triangle shape has been proven the strongest in nature, due to being inherently more rigid than other shapes. (15)

**Tower Support Strut**

The support tower strut will experience a total deformation of 0.0011063 m (0.0435551181102 inches) at the right end when a 100 Nm force is exerted to the top edge of the strut (Figure 41).

![Figure 40 - The total deformation of the tower support strut with a 100 Nm force being applied parallel to the ground at the top section of the strut and there was a fixed support at the bottom section of the strut.](image)

The support tower strut will experience an equivalent stress of approximately 5.828e6 Pa (845.2799355 PSI) at bottom of the strut by the hole with the fixed support when a 100 Nm force is exerted to the top edge of the strut (Figure 42).

![Figure 41 - The equivalent stress of the tower support strut with a 100 Nm force being applied parallel to the ground at the top section of the strut and there was a fixed support at the bottom section of the strut.](image)
Front Half of Yoke Connector

The front half of the yoke connector will experience a total deformation of $4.3146 \times 10^{-8}$ m ($1.698614e-6$ inches) at the right vertical face when a 100 Nm force is exerted to the left vertical face (Figure 43).

![Figure 42 - The total deformation of the front half of the yoke connector with a 100 Nm force being applied perpendicularly to the right vertical face and there was a fixed support on the left vertical faces.](image)

The front half of the yoke connector will experience an equivalent stress of approximately 58,600 Pa (8.4992114 PSI) at bottom of the alignment struts when a 100 Nm force is exerted to the left vertical face (Figure 44).

![Figure 43 - The equivalent stress of the front half of the yoke connector with a 100 Nm force being applied perpendicularly to the right vertical face and there was a fixed support on the left vertical faces.](image)
The front half of the yoke connector will experience a total deformation of approximately 2.469e-8 m (9.720472e-7 inches) at the right vertical face when a 100 Nm force is exerted to the bottom horizontal face (Figure 45).

The front half of the yoke connector will experience an equivalent stress of approximately 1.9493e5 Pa (28.2722062 PSI) at bottom of the alignment struts when a 100 Nm force is exerted to the bottom horizontal face (Figure 46).
Back Half of Yoke Connector

The back half of the yoke connector will experience a total deformation of approximately 7.7621e-6 m (0.000305594488 inches) end of the alignment strut when a 100 Nm force is exerted to the bottom horizontal face (Figure 47).

![Figure 46](image)

*Figure 46 - The total deformation of the back half of the yoke connector with a 100 Nm force being applied straight upward to the bottom horizontal face and there was a fixed support on the back vertical face.*

The back half of the yoke connector will experience an equivalent stress of approximately 2.58389e6 Pa (374.7615602 PSI) at the back of the part by the curved semicircle when a 100 Nm force is exerted to the bottom horizontal face (Figure 48).

![Figure 47](image)

*Figure 47 - The equivalent stress of the back half of the yoke connector with a 100 Nm force being applied straight upward to the bottom horizontal face and there was a fixed support on the back vertical face.*

The back half of the yoke connector will experience a total deformation of approximately 7.7621e-6 m (0.000305594488 inches) end of the alignment strut when a 100 Nm force is exerted to the bottom horizontal face (Figure 47).
The back half of the yoke connector will experience a total deformation of approximately 7.7621e-6 m (0.000305594488 inches) end of the alignment strut when a 100 Nm force is exerted straight down from the bottom horizontal face (Figure 49).

![Figure 48 - The total deformation of the back half of the yoke connector with a 100 Nm force being applied straight downward to the bottom horizontal face and there was a fixed support on the back vertical face.](image)

The back half of the yoke connector will experience an equivalent stress of approximately 2.58389e6 Pa (374.7615602 PSI) at the back of the part by the curved semicircle when a 100 Nm force is exerted straight down from the bottom horizontal face (Figure 50).

![Figure 49 - The equivalent stress of the back half of the yoke connector with a 100 Nm force being applied straight downward to the bottom horizontal face and there was a fixed support on the back vertical face.](image)
5.3 Final Parts

The images below are the final assembled parts for the prototype of the designed system. The material used to make each part is polylactic acid (PLA), epoxy and birch plywood. Each part made of PLA was made using rapid prototyping (3D printing).

![Figure 50 – Side view of the final prototype of linear actuator mount, linear actuator, shaft to yoke connector, front and back halves of the yoke connector and the yoke]

![Figure 51 – Close-up of the shaft to yoke connector, and yoke connector]
Figure 52 – Front view of the final prototype of the rotational motor mount, rotational motor u-mount, support tower top section and the support tower cap

Figure 53 – Side View of the final prototype of the rotational motor mount, rotational motor u-mount, support tower top section and the support tower cap
Figure 54 – The final prototype of floor strut cap, seat slider frame, support tower top section to support tower cap and rotational motor mounts

Figure 55 – Full Final Prototype Assembly
5.4 Conclusion

Each design for each part is capable of handling significantly higher loads than what the system would normally be expected to encounter. Structurally the system’s design is sound and it will function, but there are parts that are limiting the performance of this system. For example, the linear actuators that are available for purchase are not capable of moving large loads at the speed needed. The yoke needs to travel a little over 8.25” in approximately one second (worst-case scenario) to complete its stroke, and the user/system should be able to handle approximately 100 lbf. The linear actuator purchased for the prototype is capable of handling the 100 lbf (the rated load is 1,500 N), but not in one second, rather in 5.7mm/sec which converts to 0.224409 inches/sec. Therefore to complete move the yoke from the start of the stroke to the finish, the linear actuator would take:

\[
\frac{\text{distance of stroke in inches}}{\text{max travel speed of linear actuator in inches/sec}} = \frac{8.25 \text{ inches}}{0.224409 \text{ inches/sec}} = 36.763 \text{ sec}
\]

Most linear actuators on the market can either handle large loads, but move slower or small loads and move quicker. To meet the specified requirements a significantly larger and more powerful linear actuator would be necessary, which increases the designs total weight and thus affects the center of gravity of the plane. Also larger, more powerful linear actuators will require more power to operate which means a larger power supply is necessary and with the limited space in an aircraft this might not be possible.

The location of the deformation and stress was not shocking. The deformation typically occurred where the force was exerted the farthest from a fixed support point. The stress occurred in holes, near ninety degree angles and sections that were weakly supported sections. When ever a part was revised, and fillets were added the amount of total deformation typically increased while the equivalent stress levels decreased. This proves that the fillets and redesigns are stronger designs, but when these parts fail they will deform a significant greater amount.

This design was created to determine the feasibility of creating a mechanical autonomous retrofit for aircraft. Overall the goal was partially achieved, not an entire design was achieved due to constraints. The limiting factors in this design and concept were:
- Space constraints
- Lack of locations to mount to
- Limited technology available on the market

It is also worth mentioning again that this system was designed with the intention to implement in a Piper Cherokee 140, therefore some of the information, data, research and designs may not be capable of being implemented into another aircraft type. In addition, please note that this system by no means was tested and should not be used in an aircraft until extensively tested. Please reference the future work/considerations section for more information.

5.5 Future Work

The system needs to be manufactured to the specified FAA standards, requirements in 4.3 CONOPS and others. The system needs to then be rigorously tested before putting anyone human pilot’s life at risk. The system may also need to be adjusted to fit other aircraft and perform the proper flying techniques.
Bibliography


Appendices

Appendix A: Design Notebook, Further details on the Evolution of the Design

9/14/2016

Hall, the yoke rotates 180° to move airfoils

Current system (front view)

Spoke

New idea (front view)

2nd Spoke: Chain connected to Yoke

Motor

Yoke extends out from this connection on Spoke

Potential issues

- Motor mount rotates from forces
- Chain interfering with B (to be avoided)
- Addition of 2nd Spoke: Mount where chain drive is
- Chain drive will be epicyclic

Bolts & nuts holding motor mount in place

Side view

B 1st Travel 2" inches (required from center)

Use linear Actuators - note they have no backdriveability. 2 actuators needed & 2 3rd

Machine out custom mount to pedal

Linear actuator

Need 2 linear actuators positioned

Pedal mount on a linear actuator

Could drill hole through the pedal but then pedals need to be replaced
Yaw --- the yoke moves in/out to angle the airplane's nose to climb or drop

rudder pedals cause the pedals to travel 30° needs to be 50° to travel for pedals @ 1 second

screwed motor

cockpit side view

chain drive

metal support connected to seat sliders and to the bolts in the front of the cockpit
**Concerns**

- Create a content disclaimer on designs to protect me from potential catastrophes.
- I have concerns that failsafes aren't being implemented and the system is not being designed to handle loads w/ a factor of safety.

- For the 1st time on 9/25/16 Nick discussed failsafes:
  1. Using electromagnetic clutches?
  2. One per CS, ME & ECE?
  3. Still not sure exactly he wants?
  4. Mechanical failsafe = a pin to disconnect motor from actuator?
  5. ECE = clutches?

- Ratings, loadings, forces & specs on the plane don't exist.
  - No idea what the structural members, surfaces and parts can support.
- Side mount that attaches to side of metal by pulleys & cam/hydraulic can this support the forces our actuators will exert.
- What are the preflight checklist?
  - Need to know to ensure it operational.
In order to get the plane re-certified after this project, we need to do a few things:

1. Experimental license (specifically research & development)
2. Satisfy VFR (or IFR)
   - No handheld GPS and radio as backups

Details (as per [last meeting]):
- See if you can go look @ one
- What kind of clutches do they use?
- How are they mounted (removable?)

When modifying the airplane, remove pieces and record:
- Change in COG (Center of Gravity)
  - Everything is measured in inches from a reference plane or the plane
  - The center of moment of every object
  - The weight of object

Manufacturing notes:
- Can use already existing bolt holes to mount to
- Ream out all holes (need to be as close to perfect circle)
- Use only Army Navy (AN) fasteners
- Never use fully threaded bolts
- Use washers on the end of the nut
- Use nylon nuts or steel locking nuts
- No brazing on anything
- Materials:
  - Mild Aluminum → Prevents corrosion
  - Internal → Zinc chromate
  (Use same metals for mount structures)
Brake Handle

Addition of grenade style lock to keep handle unlocked/arched.

Slides over the button.

Cable mount

Pin holding in place

Possible safety issue:
- Cable from wheel shears and wraps around hitting pilot
- Pilot can’t easily exit plane in case of evacuation

Throttle

Ideas? Linear actuator?
Yoke connectors

Current Yoke (Front view)

Side View

Pin or strap holding shafts in place

Side View

Motor mount

Electric motor

Rack and pinion gear to move the yoke

8" in front of seat mount onto seat sliders
Mount to seat sliders

Instrument panel

Structural supports
& mounting plate

Mounting plate ⇒ put linear actuator or stepper motor on 4 mounts of the pedals

Connects to the yoke

Coupler to electric motor mounted to pinion rack & gear

The rack system will be able to move with the curve of yoke since it isn't a linear pattern
Actuators for Pedals (P16):

1st Linear Actuator (side view)

2nd Linear Actuator/pivot design

3rd Stepper Motor/Chain Drive

Pros:
- works
- cheap to build

Cons:
- catastrophic failure/dangerous
- takes up space
- need to modify the pedals
system Design # 2

- potential concern w/ previous sketches
  - the positioning of actuators for the pedals
    is no problem
  - the motor for both rotation of yoke and
    the rack and pinion perched at the top of the seat slider structure
    will amplify any movements of stresses
    a solution drop the rack and pinion
    to base or switch out w/ a pivoting arm, see sketch below

Side View

[Diagram with labeled components]

Side View

[Diagram with labeled components]

slider track

[Diagram with labeled components]

ball-screw actuator (1)

External position to raise a pin would be close to the yoke attachment
because this would allow the pilot to easily
and the yoke w/ a shaft swing off

ballscrew actuator (1)

seat sliders

Floor of Plane

Aluminum live rod end

Ball Joint

travel=10.24 inches

Reed mechanical fail-safe (2)

[Diagram with labeled components]

[Handwritten notes]
Slider Track for feet design

1/26/2016

Side View

- Motor mount
- Axle for rotational purposes
- Seat slider mount

Front (Section) View

- Custom metal strips
- Motor mount
- Axle
- Slide housing
- Self-lubricating motor caps
- Mount walls that hold arm in place and the arm rolls along the slider track
- Side Frame for slider will in can coat the top with some type of teflon spray to ensure smooth rolling

Side View of Slider Frame

- Yoke & Full extension
- Stop
- Seat
- 20"
Yoke shaft connector

potential issue
- pulling on pin, shaft will be turning and difficult to attach to yoke because it will be slipping around
- small bolt on question 
  he sent me about

Yoke connector

need = 2.1" opening to slide over yoke would be better if was adjustable

Slotted framework

fixed position on back plate

back plate (1 qty)

Front plate (1 qty)

4 threaded slots to secure rate

Threaded holes

Thread plate
(Need to look into telescoping shaft connections)

Pivot shaft base attachment to sliders

- Weld shafts to base plate, or bolt
- Use a base plate so I can make threaded holes
- Put nuts underneath
- Threaded holes in plate
- Make sure this is positioned dead center (perpendicular) to yoke

Pivot shaft mount

- Linear actuator mount
- Recessed holes
- 4 bolts
- Bolt holes

Fixed axle: 3/16 in

Always measure from this point:

- Yoke
- Offset 0.625
- 20.25 in
- 28.95 in
- Seat sliders
- 8.18 in

Rises 1.25 in
Mount top of shaft

Front view

- Mount to base
- Axle hole

Top view

- Mount to base
- Axle hole

Bottom view

- Axle slides through & locks in place
- Could use a bolt

Assuming foot pedal has these dimensions

- 5" x 2.5"
- 1/2" thickness of pedal
- Thickness of pedal
- (metal, bit)

Axle in the back is center mounted and has a diameter of 0.88", it spans across the width back of the pedal.
Conversation with Don Sproule

- Don is a mechanical engineer/director
- worked/design ed planes at Pratt & Whitney
- pilot and plane enthusiast

The most important factor when designing this system is how will it affect a plane’s weight and balance which ultimately will change the center of gravity (COG).

COG = reference point to datum typically is the firewall forward firewall = negative value behind firewall (inside cockpit) = positive value

- putting the system on left or right side of cockpit affects the balance
- look up front seat weight limit
- discuss how my system affects aircraft performance
- sliders are hooked to a wire so they are good mounting points but everywhere else is not very secure

Source of Pictures: https://www.open-airplane.com/aircraft/N15726
FAA records: http://registry.faa.gov/aircraft?mimp N15726
Other Records: https://flightaware.com/vehicles/registration/N15726
Yoke Initial Position (rotated) based on the schematic. It is highlighted in yellow, and off the bottom of the center bar of seat, it is highlighted in pink.

- **Height**: 22.6266 inches
- **Offset from Center of Seat**: 1.8302 inches
- **Distance from Seat**: 0.62122 inches

**Final Position**

- **Height**: 23.52494 inches
- **Offset from Center of Seat**: 1.8302 inches
- **Distance from Seat**: 2.00548 inches

Yoke Throw = Distance = 8.06548 - .62122
= 7.4446 inches

Yoke A Height = 22.52494 - 22.42966
= 1.09528 inches
Simplified Top Rotational Motor Concept

Side View

- Pillow Block Ball Bearing Mount
- Allows system to rotate since gear doesn’t have to be in line with
- a linear path
- Cockpit Floor

- Yoke Connector
- Linear Actuator
- Frame work connecting motor & linear actuator (custom components made to fit both so actuator)
- Frame to support new concept
- Seat slider frame

- This design eliminates moving parts which makes this design more reliable

- Concerns
- Attaching a frame backwards in such a manner as seen in the drawing
- The frame may bend

- Instead of a pillow block ball bearing mount consider a ball joint
  - Increased range of movement in both x and y direction
- he is looking into potential mechanical autopilots
  - I can take a look at @ Pittsburg & Barber
- note: the nose wheel is connected to the foot pedals and the foot pedals connect to the rudder (all controlled by foot pedals)
- Cessna's use a pneumatic autopilot w/ a slipping drive (fail-safe)
- Autopilot: Note
  1. original purpose was to ensure a plane was staying on the correct heading
  2. the first system consisted of a wing elevator that directly interfaced w/ ailerons
  3. came the rudder and trim adjustments which was used to correct airplane from heading/torque
- Current systems:
  - all electronic now
  - modern autopilots have GPs which calculates altitude, speed, air pressure & temperature
  - only restriction is the controls needed to be overridden by a pilot
  - throttle is always controlled by pilot

**CAD Model**
- mounts on seat slides is best plan
- could mount to dashboard but this obscures view of controls and prevents pilot access

**Actuators**
- since I need more powerful & faster actuators
  - look into multi-start screw drive threaded

  - For now will need 2 linear Actuators or potentially the triangle/cable concept (discussed in more detail on next page)
Triangle cable pedal Actuator

Problem - need to use two linear actuators since they can't pull a pedal (can only push)

Equilateral triangle = 1:1 ratio

Axis y where triangle triangle meets

Cables where will these cables be able to push, if - what if all rods were put in place
Path of Yoke (Plotted) Part 2

Side View

Plot line (approximately where yoke would travel)

Front View

For a better curve
- took multiple position measurements
and plotted in Excel y vs.
yoke curve

see next page
### Plotted Yoke Position

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*These data points were extracted from the CAD model of the cockpit.*

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A graph displaying the curve of the yoke is on the next page.
Plotted Position of Yoke

Distance from Center (inches)

22.4
22.0
21.6
21.2
20.8
20.4
20.0
19.6
19.2
18.8
18.4
18.0
Linear Actuators

The issues with linear actuators:
1) to achieve the cycle speed, the linear actuator will sacrifice speed or force,
2) can be able to move large force but @ a slow rate/speed,
3) very fast, but only move small loads
4) very pricey for quality product

Solution: need to develop better linear actuators, currently there is very limited technologies
5) linear actuators only push, can’t pull well

For the sake of this project a linear Actuator will be used to drive the yoke.
- pull yoke in and out which drives W/T of plane

- Potentially use multi strip screw driven linear actuators?
The motor is a ＃VEX 816 Motor part # 217-235.
Design Notes

The new rotational motor to linear actuator concept eliminates the need for an alignment slider frame, but does require a frame to support the motor mount.

Plan:
- This frame extends back off the seat slider mounting position just under 2 feet.
  * This means the seat will either have to be removed or the frame will need to be designed in a way that the frame wraps around the seat.
  * Additionally, the new system design sticks back almost completely to the seat back.
  * With these designs, the design specification of "doesn’t interfere with current systems / seats already in place" will not be met.
  * This provides a safety concern because a pilot will not easily be able to exit an aircraft with this system equipped in it.
The CAD model is able to show the movement of the yoke moving forward and backward as marked in black above.

The position in figure due to way it was designed restricts movement as it encompasses the entire shaft. This will allow for more movement.
Pedal Actuation Concerns

The triangle concept described on p. 39 will not work on this aircraft.

The pedals throw is 8 inches. The triangle that one would need to use is an Equilateral triangle with a 8 inches per each side.

\[ x = \sqrt{8^2 + 8^2} \]
\[ x = 8.9442719'' \]

The width of the cockpit by the pedals is 11.6279'' at the widest point. It gets even smaller.

See next page for more instruction
AT the widest point: 17.25"
Footpace is tapered to ≈ 14-15.5"
At the moment the Bag Motor being used (seen on page 49 and below) only has a 3/8" long shaft that is 1/8" in diameter. Not much to grab on (connect with a custom mount that press fit? alternatively, epoxy together?)

Linear Actuator 1/2" mount
This is the linear actuator purchased for the ⅓ scale model/prototype.

For full design, a linear actuator with a 0.6" stroke is required, minimum of a
Geometric Axes

2/5/2017

For the yoke to be capable of 360° rotation, the design requires a singular axis of rotation.

The motor attachment mount that connects the rotational motor to the linear actuator mount and thus linear actuator and yoke must be coincident or along the axis of rotation. Seen in red above.

Without the support tower, the rotation will be off-center, resulting in the support tower or yoke needing to move in the X-direction.

Y-axis

X-axis
Support Tower

As mentioned on the previous page, the support tower is a crucial part of the system that keeps the rotational motor and mount which connects to the linear actuator and mount.

![Diagram of support tower]

Note the truss design on the support tower. This design supports system and is extremely sturdy.

Front view

Fruss design on all 4 sides

Side wings that support this structure and prevent it from tilting when done is rotating.

The support tower sits under the rotational motor mount. This structure had to be attached onto the seat slider frame. Because the linear actuator and rotational motor take up space, the seat slider frame is positioned about 1 ft back off the struts in the front of the seat sliders.
Front strut off support tower

Isometric View

Top cap that goes on the support tower top.

Side View

Front strut for support. This prohibits the support tower from buckling under rotational torques.

Isometric view of the front strut connector.
Without the collar the shaft doesn't move properly in the y-direction because of lack of clearance between linear actuator shaft and the yoke connection.

**Shaft collar**

\[
\text{Thickness} = \frac{1}{8}''
\]

Considered putting in a ball joint or socket joint.
FEA on Rotational motor mount

Assumptions:
1. An applied force of 200 Nm
2. The torque is applied at the front of the mount as indicated with the black arrow.
- removal of rotational motor and put in an axle
- to just demonstrate the rotational aspects
- on the aircraft yoke for roll
- Calculate total system weight
- Rotational forces/torques
- Spring/ clearance between holes and material
  Fillet all edges
- Add fillers to lower stress concentrations along edges/corners
Hatchbox 3D PLA - 1kg 1.75mm PLA 3D printer filament. Dimensional Accuracy +/- 0.05 mm, 1kg spool.
- Cost = $22.99
- Purchase location: Amazon.com
- Quantity: 2 spools

Acrylic & Wood for cockpit model.