Design and Development of an Autonomous Payload Return Vehicle

Introduction

- **Space Hardware Club**
  - Student-run organization, supports undergraduate research projects in the areas of rocketry, space satellites, and high altitude ballooning (HAB)
- **Problem**
  - HAB projects involve carrying a scientific payload into the upper atmosphere
  - Often descend under unguided parachute and lands in unfavorable locations
- **Solution**
  - Creation of an autonomous payload return vehicle
  - Ram-Air Parafoil Targeted Object Return (RAPTOR)
- **Inspiration**
  - Joint Precision Airdrop Delivery System (JPADS)
  - Developed by the US Army and Air Force

JPADS

Photo Source: https://airborne-sys.com/product/firefly-military-cargo-delivery-parachute/

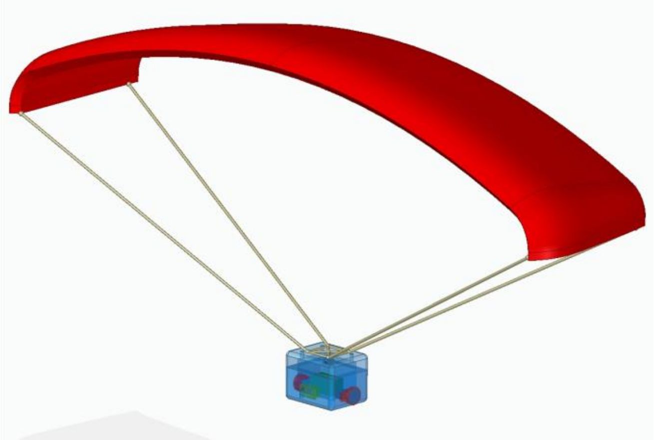
Systems Overview

- **High Altitude Weather Balloon Operation**
  - Payload ascends to generally 25,000 meters
  - Descends after it releases from the line or balloon bursts
  - Typical payloads descend under a standard parachute
  - Payload lands and is is recovered

- **RAPTOR System Operation**
  - RAPTOR ascends on a standard high altitude balloon
  - Captures atmospheric data and GPS position
  - Releases from the balloon line prior to balloon burst
  - To provide steering, servos articulate the parafoil's trailing edge
  - Guides system to desired landing location

- **RAPTOR System Requirements**
  - Maximum mass of 1.8 kilograms
  - Release mechanism for balloon line
  - Landing speed of 7 meters per second
  - Atmospheric data collection sensors and GPS

High Altitude Balloon



RAPTOR

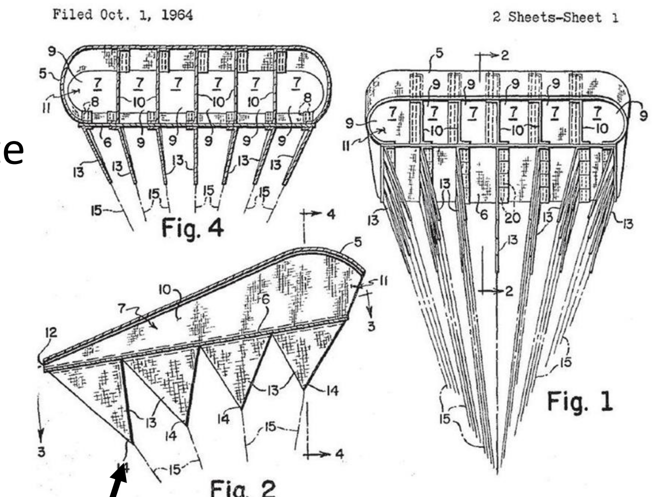
Balloon Photo Source: https://phys.org/news/2013-05-tropical-upper-atmosphere-fingerprint-global.html

Flight Operations

- **Flight Predictions**
  - Cambridge University Spaceflight Landing Predictor (CUSF) Simulations
  - Select a set of landing locations based on CUSF results
  - Software autonomously selects a location from this set

- **Guided Parafoil Flight**
  - Parafoil was chosen rather than a standard parachute
  - Parafoils are inflatable airfoils - generates lift
  - Deflection of the trailing edge causes turning
  - Servos pull on the parafoil’s brake lines

- **FAA Compliance**
  - Maximum mass of 1.8 kilograms
  - Not classified as an Unmanned Aerial Vehicle (UAV)
  - Guidance at 3,100 meters to clear airspace
  - Tower notification

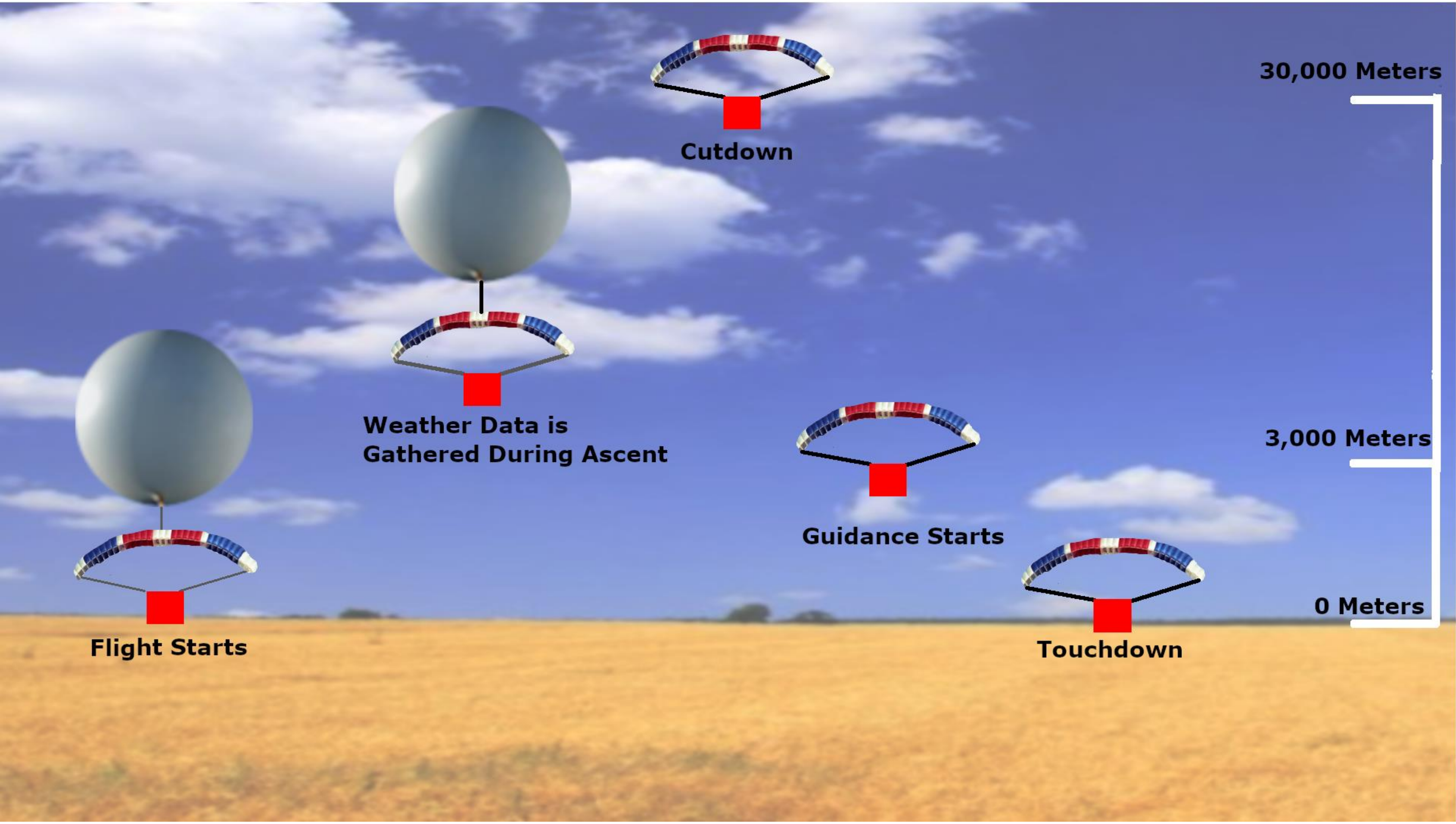


Parafoil Diagram

Brake Lines

Photo Source:https://patents.google.com/patent/US3285546

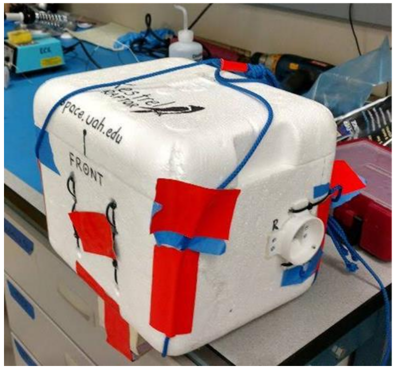
Concept of Operation



Project Development

Kestrel

- Electronics testing bed
- Mechanical components prototyping
- Basic flight software testing



Falcon

- Developing basic parafoil control
- Flight algorithms
- Additional mechanical development
- Electronic redesign

Phoenix

- Improved parafoil control with larger parafoil
- Reliable cutdown
- Printed Circuit Board (PCB) development
- Expanded guidance algorithms

Flight Timeline

Flight #	Date	Payload	Summary
1	April 21, 2018	Kestrel	• Mechanical prototypes • Electronic brown-out
2	August 31, 2018	Kestrel	• Stable electronics • Successful flight
3	October 6, 2018	Falcon	• Successful payload operations • Debris caught in parafoil
4	October 27, 2018	Falcon	• Mechanical release failure • Software updates
5	November 17, 2018	Falcon	• Mechanical release failure • Unsuccessful recovery

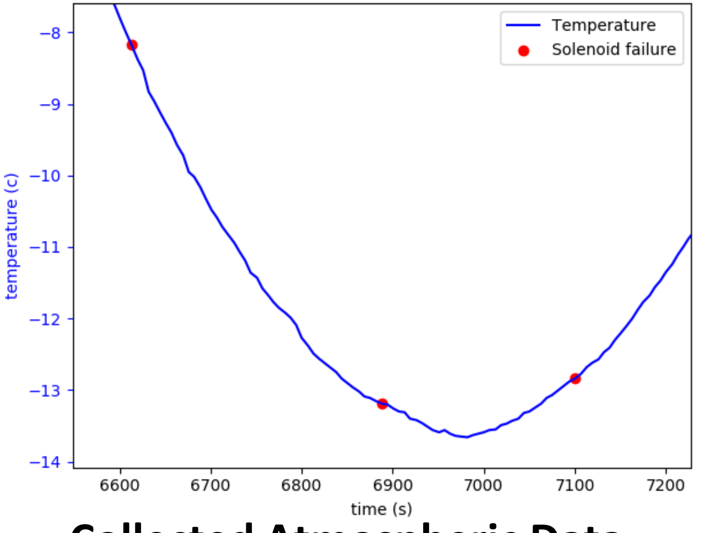
Flights 1-2: Kestrel

- **Flight Objectives**
  - Construct a flight ready payload
  - Prototype mechanical, electrical, and software systems
  - Verify systems function at high altitude

- **Flight Results**
  - Incremental mechanical design improvements
  - Inspired brown-out safeguards for electronics and software
  - Verified system was operational at low temperature
  - Atmospheric sensor and data acquisition was successful

Kestrel Payload

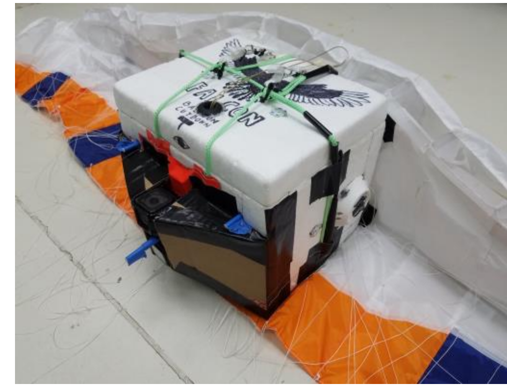
Team Photo Prior to First Flight



Collected Atmospheric Data

Flights 3-5: Falcon

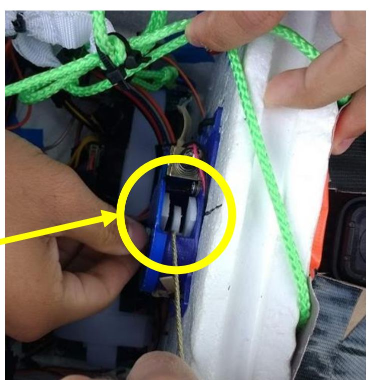
- **Flight Objectives**
  - Implement initial active descent control using parafoil
  - Very low target altitude of 300 meters
  - Collect data regarding parafoil flight characteristics



Falcon Payload

- **Flight Results**
  - Inconsistent mechanical release mechanism for balloon line
  - Successful parafoil deployment
  - Unable to achieve steady-flight
  - Increased electrical and software system capabilities
  - Increase knowledge of parafoil behavior
  - Payload was lost to a tree during 5th flight

Line Tangled



Mechanical Release Failure

Team Photo Prior to First Flight

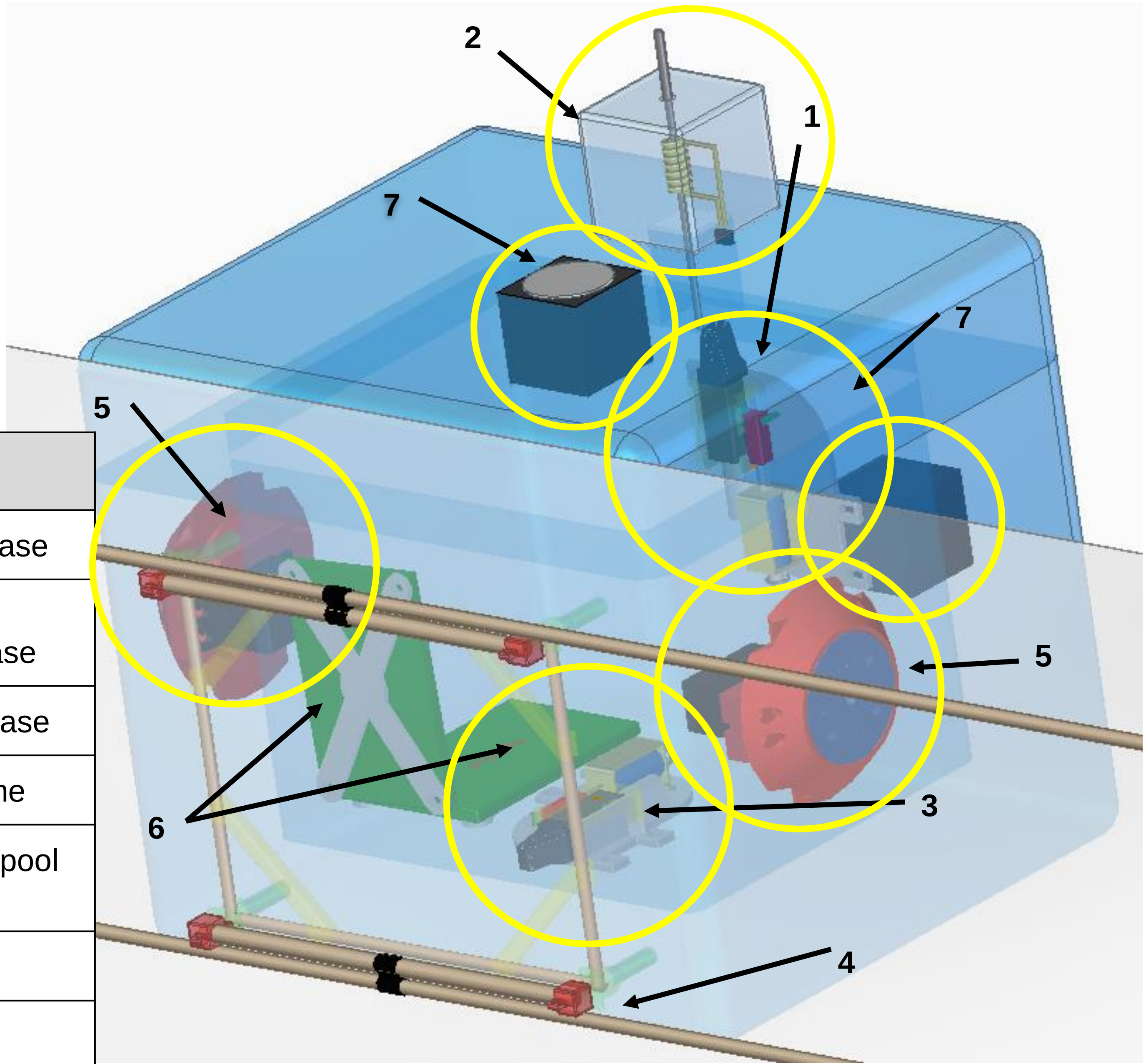
Phoenix

- **Phoenix Objectives**
  - Cumulative design incorporating knowledge from Kestrel and Falcon
  - Low and high altitude flight capability
  - Stand-alone payload flight with improved guidance
  - Develop a parafoil flight characteristic model

- **System Changes**
  - *Electrical*: single battery power source and use a custom PCB
  - *Mechanical*: new primary release mechanism and addition of secondary release
  - *Software*: improved error handling
  - *Aerospace*: increase parafoil size and lift capacity
  - *System*: more rigorous testing and flight procedures

Phoenix Parafoil Testing

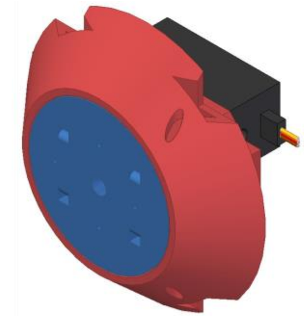
Payload Overview



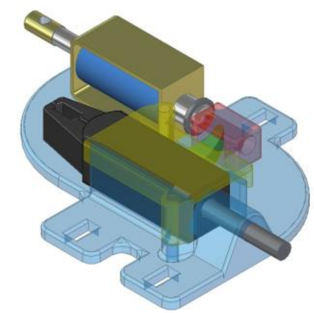
#	Component
1	Balloon Release
2	Secondary Balloon release
3	Parafoil Release
4	Parafoil Frame
5	Brake Line Spool and Motor
6	Electronics
7	GoPros

Mechanical Design

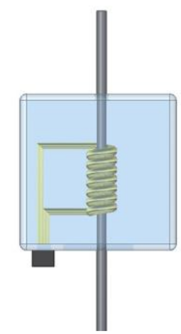
- **Brake Line Controller**
  - Adjusts brake lines on parafoil
  - Uses continuous rotation servo
  - Brake line is wrapped around the blue spool
  - Additively manufactured (3D printed)
- **Primary Release Mechanism**
  - Used to release the payload from the balloon line and deploy parafoil
  - Electronic solenoid provides brown-out resilience
  - Bow release is set manually and is opened with the solenoid
- **Secondary Release Mechanism**
  - Used during testing to prevent the loss of the payload
  - Hotwire is used to burn the balloon line and release payload



Brake Line Controller



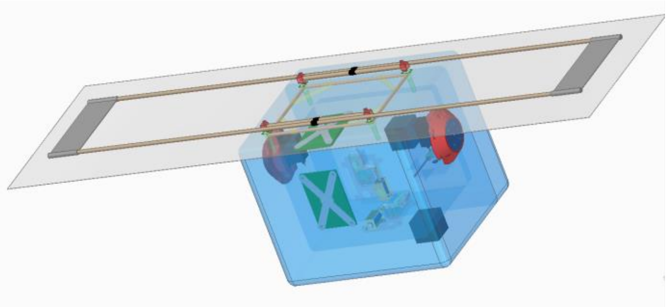
Primary Release Mechanism



Secondary Release Mechanism

Parafoil Design

- **Semi-Rigid Frame**
  - Inspired by a similar project*
  - Intended to ease parafoil inflation at high altitude
  - Decreases parafoil line tangling



CAD Rendering of Semi-Rigid Frame

- **Parafoil Attachment**
  - Secured externally to the payload
  - Deployed by a release mechanism
  - Prevented parafoil from spinning and tangling the 200+ parafoil lines
  - Decreases chance of free-fall

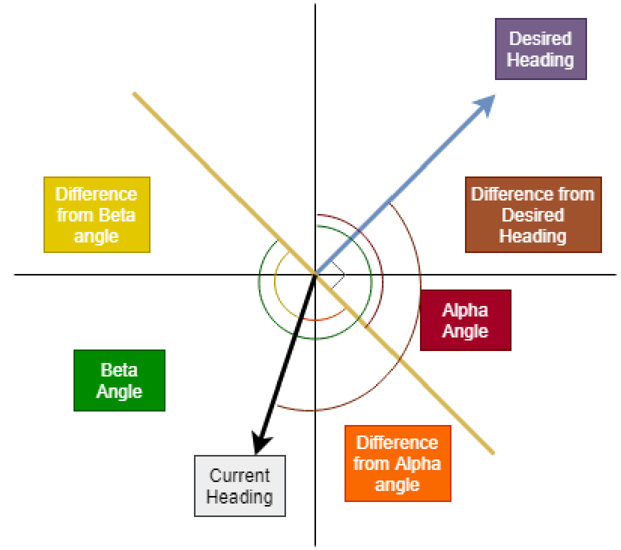
Dowel Rod Frame inside Parafoil

Semi-Rigid Parafoil Secured to Payload

* Benton, J. E., and Yakimenko, O. A., "On Development of Autonomous HAHO Parafoil System for Target Payload Return," AIAA paper.

Flight Software

- **Structure**
  - Uses Arduino framework, C++ object oriented programming
- **Guidance**
  - Basic landing location determination will be replaced by a feed-forward neural network combined with a decision tree
  - Run validation using current location every second
- **Control**
  - Inertial turning system to be upgraded by a data-driven PID controller

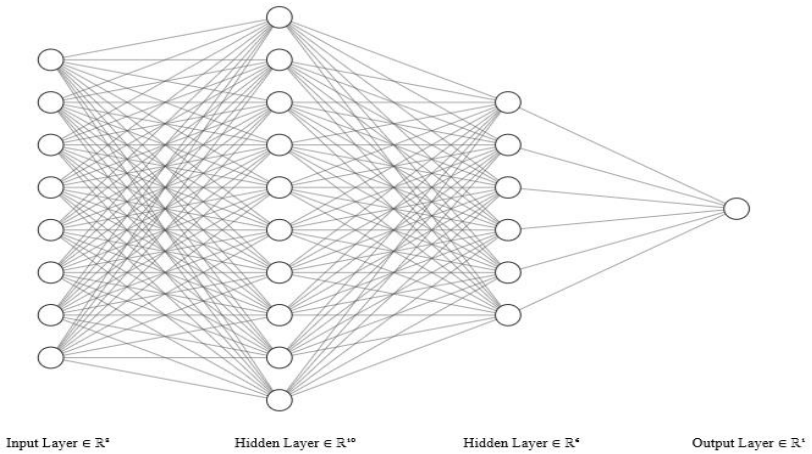


Current Inertial System

Guidance Testing

Machine Learning

- **Landing Location Selection**
  - Groundnet examines satellite imagery to determine locations prior to flight
  - Chosen locations are graded by team members in terms of desirability
- **Landing Location Determination**
  - Skynet determines viability of locations based on current location, wind speed, wind direction, heading, altitude, and velocity during flight
  - Feed forward neural network is trained prior to flights using CUSF simulation data
  - Locations above viability threshold are fed into a decision tree to determine optimal landing location based on the given data



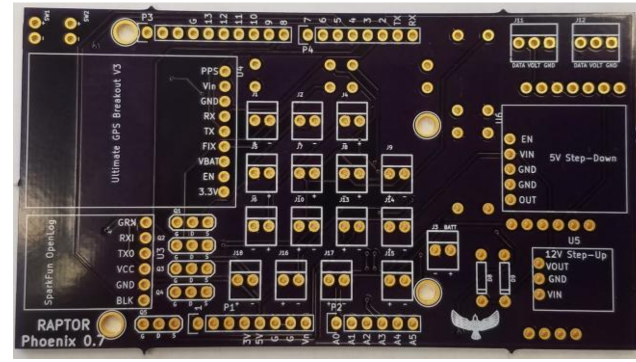
Skynet Architecture

Photo Source:http://alexlenail.me/NN-SVG/index.html

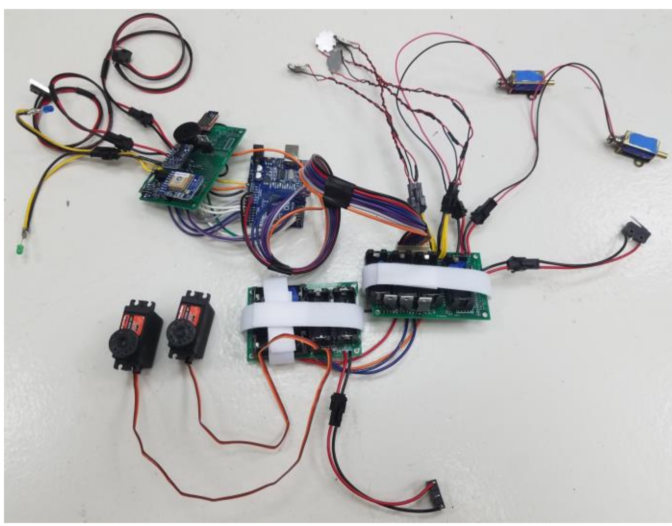
Electrical Subsystem

- **Power Source**
  - Originally used several separate power sources
  - Single rechargeable Lithium-Ion battery

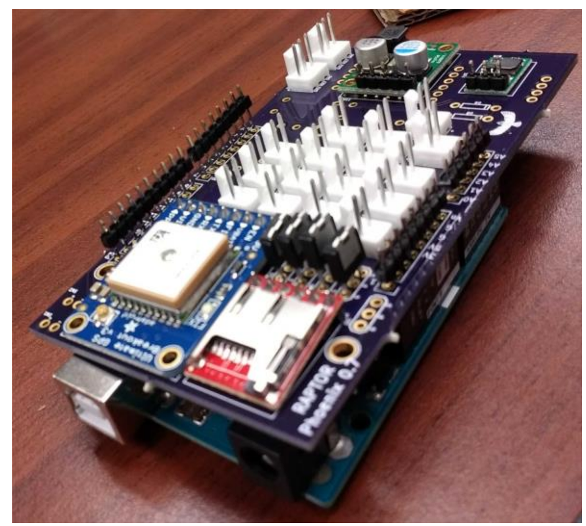
- **Unified Sensor PCB**
  - Designed as a shield for an Arduino Uno
  - PCB contains all of the sensors and components plug into the shield
  - Decreases electronic weight and wiring complexities



Phoenix PCB



Falcon Electrical System



Phoenix PCB with Components

Conclusion

- **Future Project Development**
  - *Hawk*: Ability to carry a payload train
  - *Eagle*: Culmination of RAPTOR design improvements and final product

- **Project Variant**
  - *Thunderbird:* Design for returning high-power and model rockets

- **Development Schedule**
  - Phoenix is currently under development
  - Test flights planned during the summer of 2019

Falcon being Launched

Falcon in Flight

Questions