RiBBIT

River Bathymetry Based Integrated Technology

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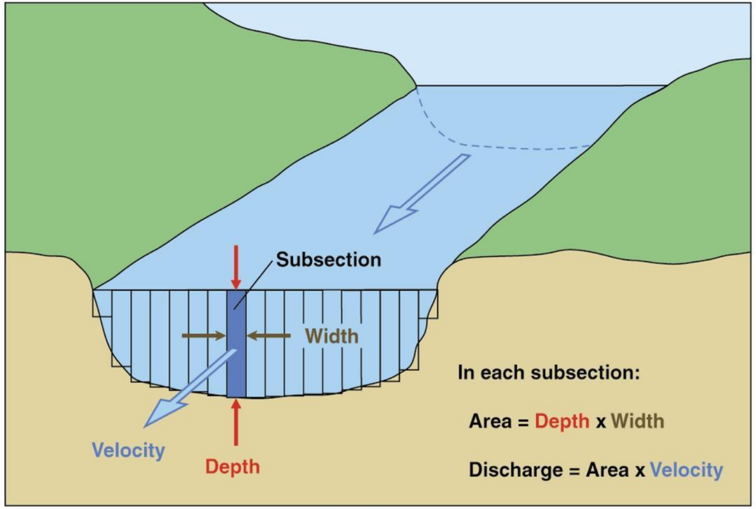
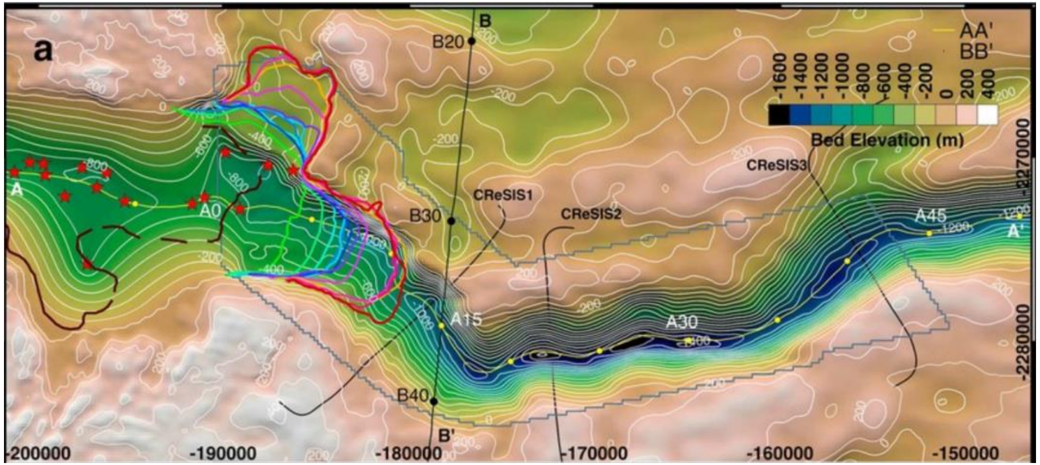
Project Background

River Discharge - The amount of water volume output of a river, calculated by multiplying river cross sectional area by the flow velocity.

Bathymetry - The measurement of depth of water.





Mission Motivation

Problem

- Rivers are a critical resource to monitor due to contributions to agriculture, urban development, hazard monitoring, and environmental monitoring.

-There is a lack of updated and accurate global data for river discharge, especially in hard to access rivers.

- A hard to access river is one which presents a physical risk for humans to access on foot.

Existing Solutions

- Earth Orbiting Satellites

- Boat tagline system with acoustic instrument and velocity tracker

- Helicopters towing radar systems

- ASTRALite EDGE

Market Gaps

- Data Resolution

- Safety

- Low-Cost

- Ease of use

- Quick set-up and data collection

Mission Statement

"The long term goal of this project is to design, manufacture, and test a drone-mounted sensor system to gather river depth profile and velocity data in hard-to-access areas for the purpose of monitoring river discharge."

CONOPS

CONOPS


2. The pilot and visual observer (users) scan the site
to make sure the environment is suitable for flight.

CONOPS

3. The users set up the GNSS base station 1 hour prior to flight. The drone and on-board sensor systems are prepared for flight.

CONOPS

4. A visual observer checks the river and surrounding environmental conditions. At any point, before or during flight, the visual observer may waive off flight if dangerous conditions (to drone or pilot) are noticed.

CONOPS

4. The drone flies to a predetermined height above the center of the river (based on river width). The Zed 2 Stereo Camera is turned on and begins recording video and depth data. The sensor suite is attached to the drone, such that it is not hanging beneath.

CONOPS

5. The camera discontinues data collection and flies to river bank. The system deploys the sonar float so that the bottom surface is in contact with the river.

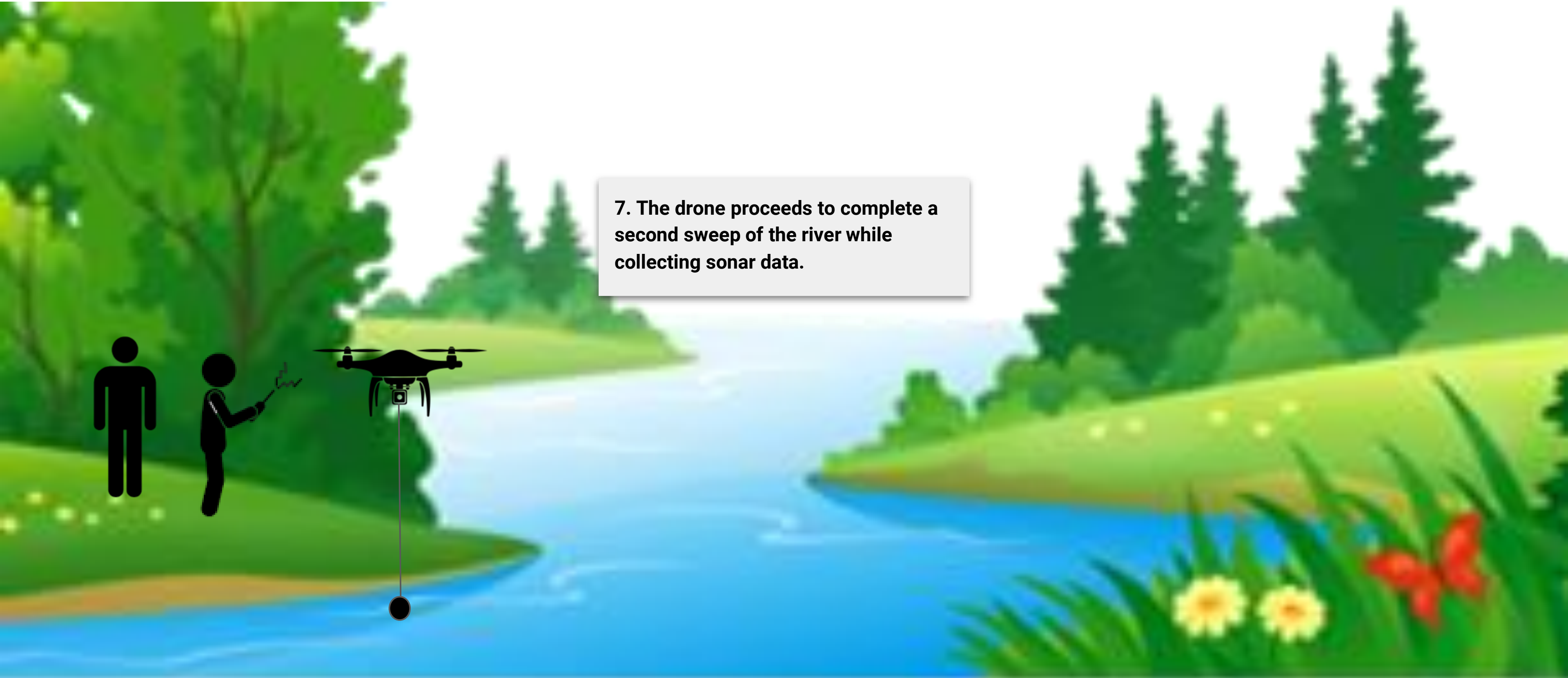
CONOPS

6. The drone pulls the sensor suite across the river while the Ping Sonar sensor collects river depth data.

CONOPS


7. The drone proceeds to complete a second sweep of the river while collecting sonar data.

CONOPS


7. The drone proceeds to complete a second sweep of the river while collecting sonar data.

CONOPS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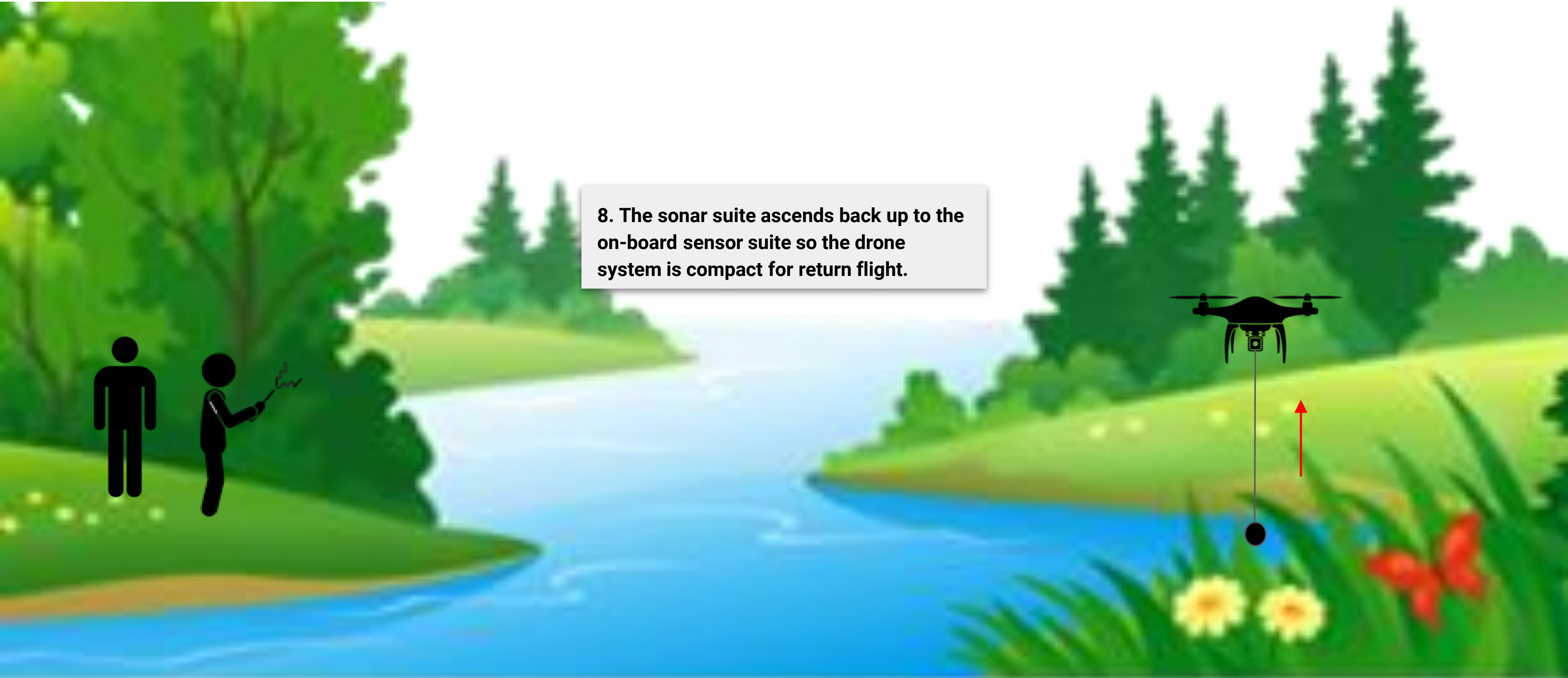
CONOPS


8. The sonar suite ascends back up to the on-board sensor suite so the drone system is compact for return flight.

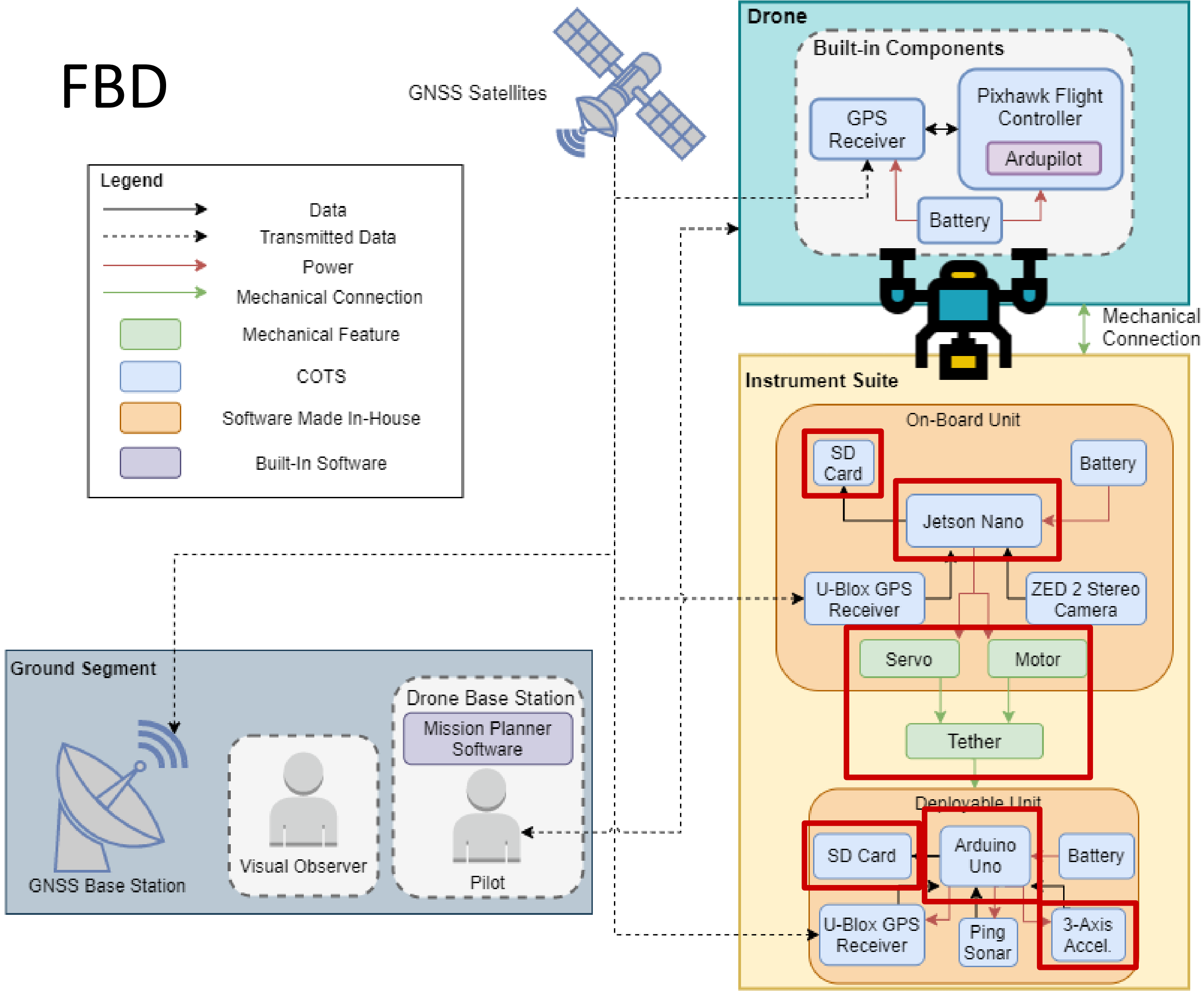
CONOPS


9. The drone flies across the river, returning to the pilot for landing.

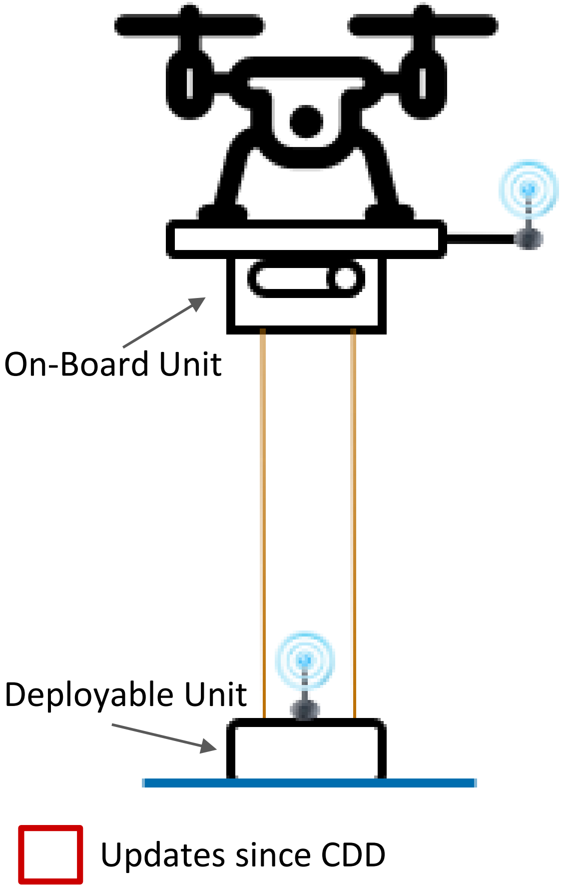
CONOPS

10. The data is off-loaded to a computer for post-processing and analysis.

FBD



GNSS Satellites
Legend
Data
Transmitted Data
Power
Mechanical Connection
Mechanical Feature
COTS
Software Made In-House
Built-In Software
Drone
Built-in Components
GPS Receiver
Pixhawk Flight Controller
Ardupilot
Battery
Mechanical Connection
Instrument Suite
On-Board Unit
SD Card
Battery
Jetson Nano
U-Blox GPS Receiver
ZED 2 Stereo Camera
Servo
Motor
Tether
Deployable Unit
SD Card
Arduino Uno
Battery
U-Blox GPS Receiver
Ping Sonar
3-Axis Accel.
Ground Segment
GNSS Base Station
Visual Observer
Drone Base Station
Mission Planner Software
Pilot



On-Board Unit
Deployable Unit
Updates since CDD

Functional Requirements

FR1	RiBBIT shall be a transportable unmanned aerial vehicle (UAV) system.
FR2	RiBBIT shall be able to operate in difficult to access river locations.
FR3	RiBBIT shall include an instrument suite payload that is compatible with the Tarot 680 drone.
FR4	The instrument suite shall be capable of measuring the bathymetric profile and stream flow of a river cross section from the bank to the other, perpendicular to the current.
FR5	The instrument suite shall be capable of measuring its position.
FR6	RiBBIT shall include and electronics suite responsible for storing the data collected by all on-board sensors and instruments.
FR7	The collected data shall be post-processed after data acquisition.
FR8	The UAV shall comply with all FAA requirements.

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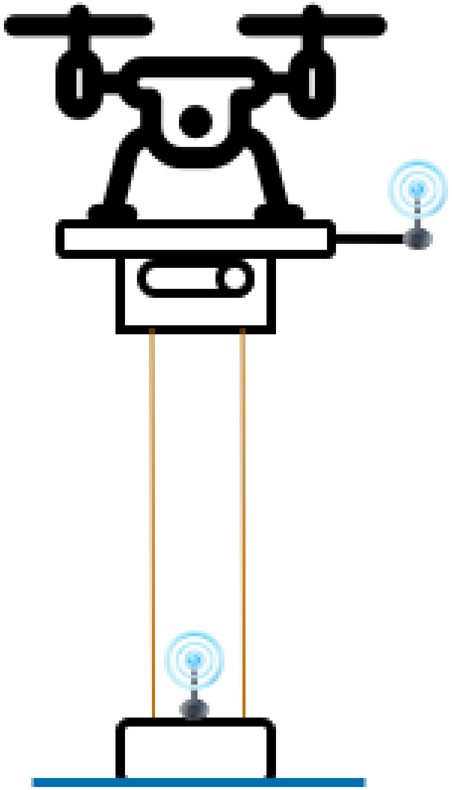
1. Critical Project Elements
2. Baseline Design
    1. UAV
    2. Depth Sensing Instrument
    3. Velocity Measuring Instrument
    4. Command and Data Handling
    5. Data Post Processing

Critical Project Elements

- UAV
- Science Instruments
  - Depth Sensing Instrument
  - Velocity Instrument
- Payload Housing and Drone Mount
- Sonar Deployment Mechanism
- Deployed Sonar Float Angular Displacement Technique
- Command and Data Handling
- Data Post-Processing



Baseline Design - UAV

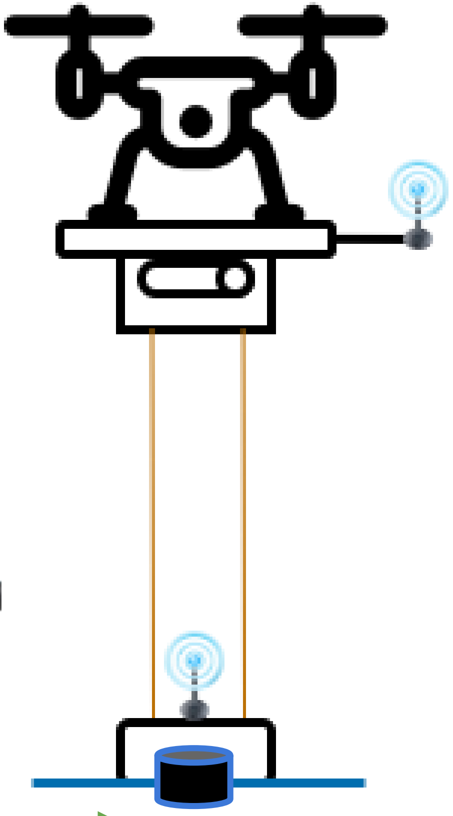
A drone is necessary to sustain stable flight over a river while dragging a payload across the water.

Selection: **Tarot 680 Pro**

Key characteristics:

- **Affordable**
- **Long flight time (33 min with max. payload)**
- **Payload Capacity (2 kg)**
- **Easy payload mounting**
- **Pilot safety and easy monitoring**
- **Live HD First Person View (FPV)**
- **PixHawk 4 Flight Controller**

Baseline Design - Depth Sensing Instrument



The river cross section is a required measurement for discharge calculations.

Measurement type: **Sonar**

Selection: **BlueRobotics Ping Echosounder**

Key Characteristics:

- **Deep water performance (30m)**
- **Highly accurate (0.5%)**
- **Compact and light**
- **Unaffected by water clarity**
- **Extremely affordable**
- **Easily integrated**
- **Integrated into Deployed Float**

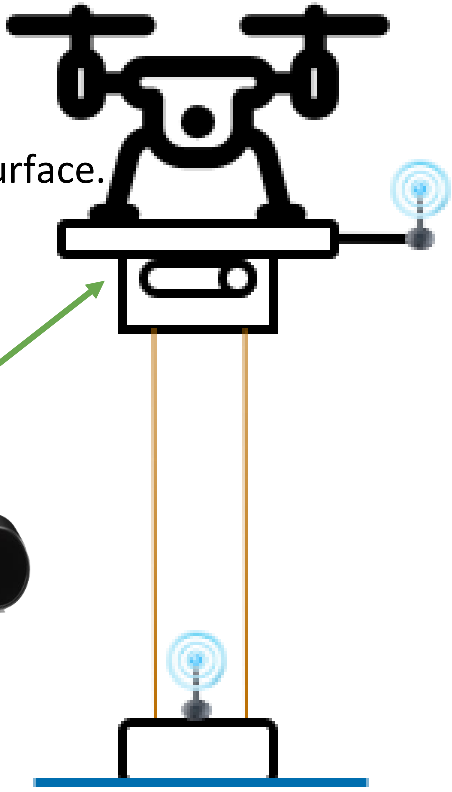
Baseline Design - Velocimetry Instrument

Velocity is a required measurement for discharge calculations.
Non-contact velocity measurements require particle velocimetry of the river surface.

Particle velocimetry needs [1,6]:

- **View of the flow field**
- **Identifiable particles within the field**
- **Control points for distance correlation of velocity.**

Selection: **StereoLab ZED 2**



Key Characteristics:

- **110° width FOV**
- **2.2k, 4416x1242 pixel resolution @ 15fps**
- **Depth and distance measurements with drone up to 15m in air**

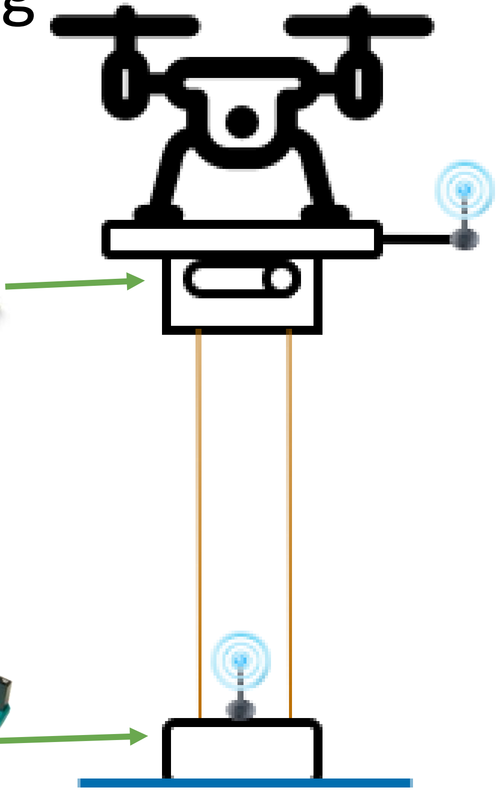
Baseline Design - Command & Data Handling

The on-board computers must meet the data storage and power needs to effectively collect all depth and velocity data.

On-Board Computer Selection: **Jetson Nano**

Key Characteristics:

- Mounted micro SD slot
- 128-core NVIDIA Maxwell architecture-based GPU
- Linux OS support

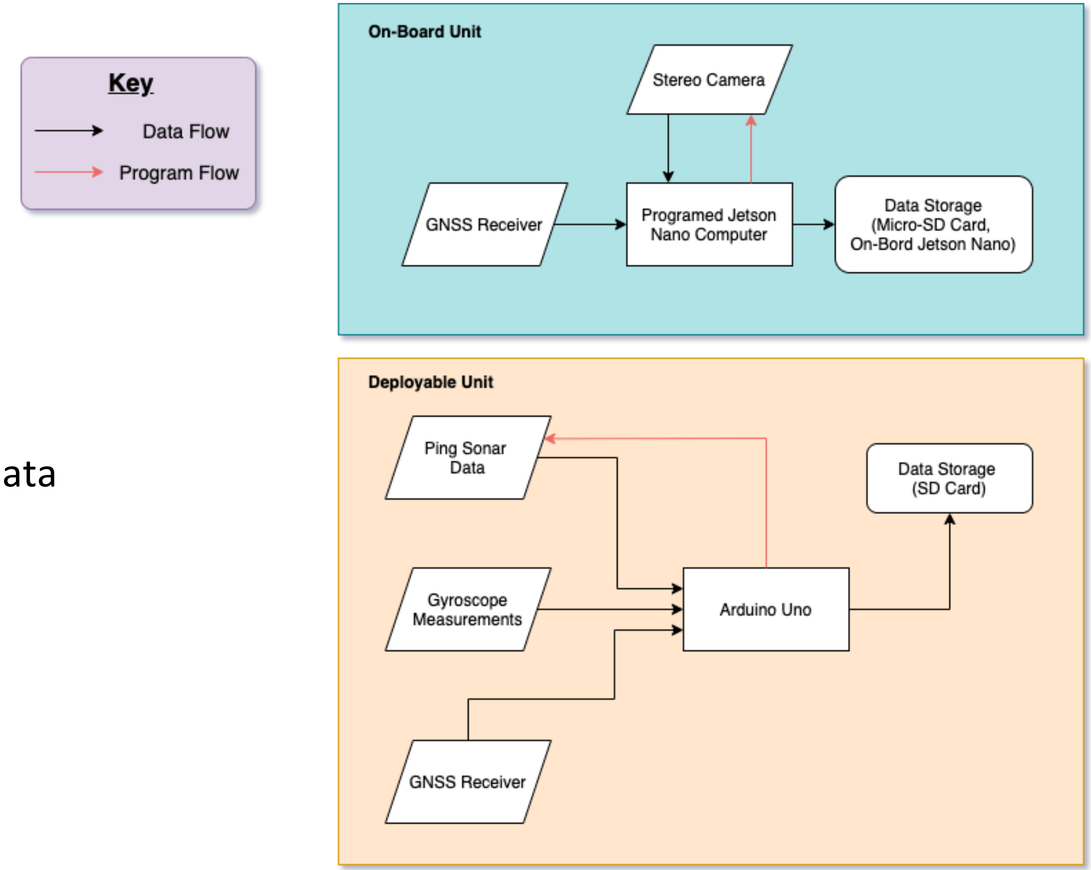


Deployable Unit Computer Selection: **Arduino Uno**

Key Characteristics:

- Connects to SD module
- Power pins: Vin, 3.3V, 5V, GND
- Serial pins: 0(Rx), 1(Tx)

Baseline Design - Software Structure



UML Diagram

Unified Modeling Language

- High-level visualization of how data will flow through the system

Baseline Design - Data Post Processing

The collected sonar, stereo camera, and GPS data shall be post-processed to ensure river discharge can be accurately computed.

River Depth Profile Steps:

1. Off-load sonar data onto computer
2. Load Positional Data, Gyro and SONAR data into Matlab
3. Plot position data vs. corrected SONAR depth data to create river profile.
4. Use numerical integration to find cross sectional area of river for discharge calculations

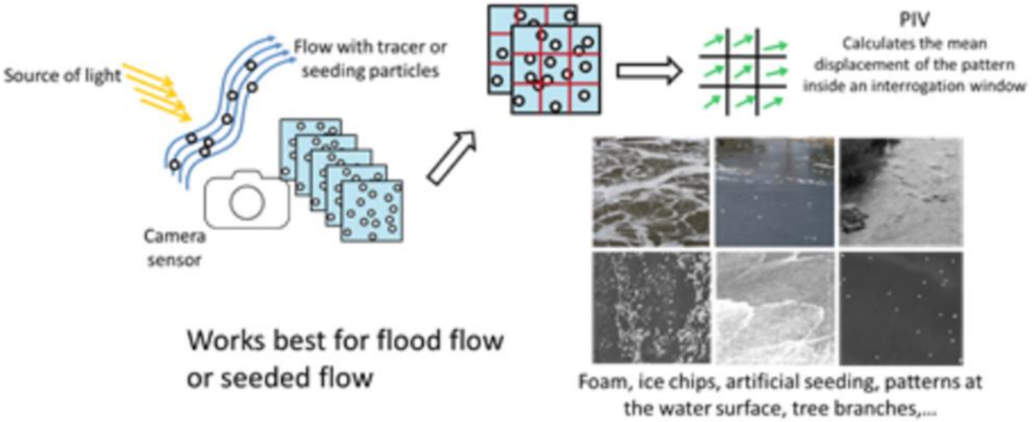
Velocimetry Steps:

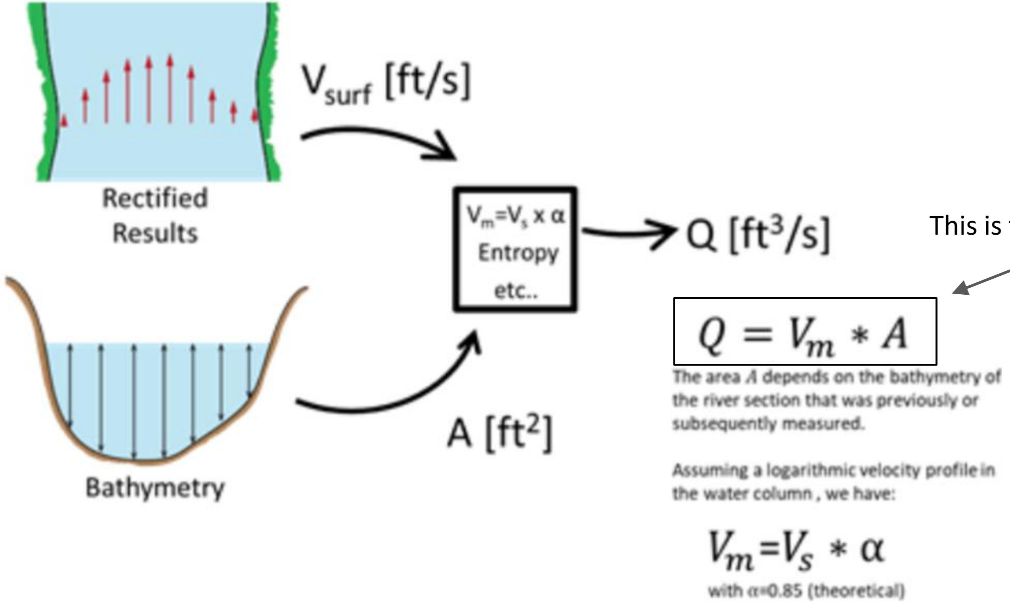
1. Off-load stereo camera data onto computer.
2. Load file via included ZED Matlab integration.
3. Calculate surface velocity via RIVeR or RIVeR-STIV Matlab functions.
   a. Includes support for 3D cloud point data for control point distance measurements.
   b. RIVeR uses Matlab function PIVLab.

<u>Discharge Calculation</u>

Take river depth profile and surface velocity and perform depth averaged velocity calculation via RIVeR Matlab function to yield discharge [6].

Data Post Processing





This is the discharge calculation

Sonar creates this profile

From [6]

USGS
science for a changing world
Surface Velocity Workgroup
CHS

1. Feasibility Elements
2. Feasibility Analysis
    1. Translated Forces and Moments Feasibility
    2. Power and Data Handling Feasibility
    3. Science Data Post Processing Feasibility
    4. Weight Feasibility
    5. Budget Feasibility

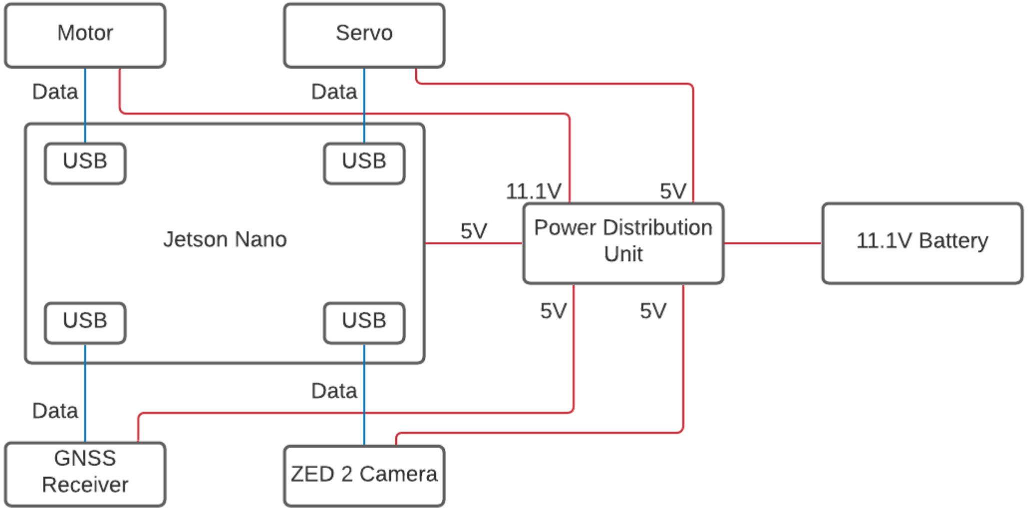
Feasibility Elements

- UAV Feasibility
  - Flight time
  - FAA Requirements
  - Translated Forces and Moments
- Science Instrument Feasibility
  - Sonar Instrument
  - Stereo Camera
- Structural Feasibility
  - Payload Housing and Drone Mount Feasibility
  - Sonar Deployment Mechanism Feasibility
  - Sonar Float Feasibility
- Power and Data Handling Feasibility
- Science Data Post Processing Feasibility
- Weight Feasibility
- Budget Feasibility

Power and Data Handling Feasibility

FR6				**RiBBIT shall be able to power and command all instruments and sensors.**
	DR6.1			There shall be a main computer on the on-board which commands and directs power to all on-board instruments.
		DR6.1.1		The main computer shall be responsible for storing the data collected by the on-board instruments.
	DR6.2			There shall be a microcontroller on the deployed sensor unit which commands and directs power to all deployed instruments.
		DR6.2.1		The micro-controller shall be responsible for storing the data collect by the deployed instruments
	DR6.3			Both the on-board and deployed sensor units shall include batteries to provide enough power for 5 minutes of continuous data acquisition.

Power and Data Handling Feasibility Analysis



On-Board Unit	
Component:	Current flow over time:
Jetson Nano	(2A)(0.5h) = 1000mAh
ZED 2	(380mA)(0.5h) = 190mAh
GNSS Receiver	(67mA)(0.5h) = 33.5mAh
Servo	(250mA)(0.5h) = 125mAh
Motor	(500mA)(0.5h) = 250mAh
Total:	1598.5mAh

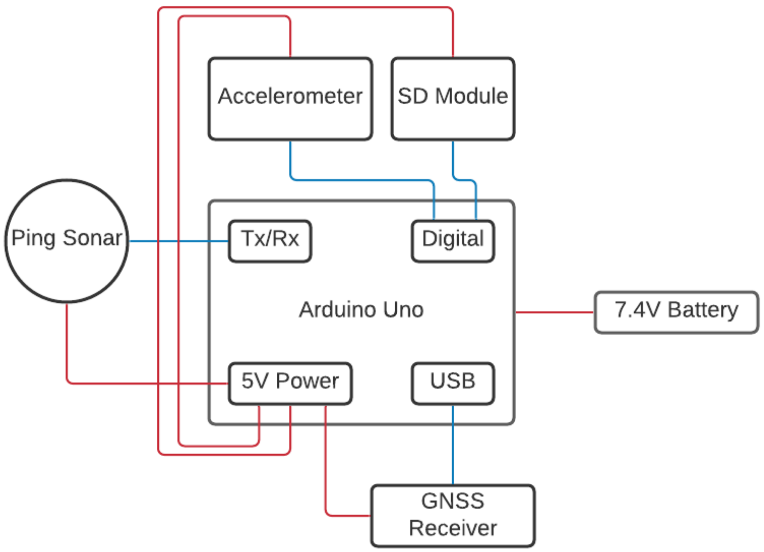
On-Board Unit Requirements:

- Near 12V provided by battery (motor requirements)
- At least 1348 mAh on battery

Solution:

- 2200mAh 11.1V lithium polymer battery

Power and Data Handling Feasibility Analysis



Deployable Unit	
Component:	Current flow over time:
Arduino Uno	(80mA)(0.5h) = 40mAh
Ping Sonar	(100mA)(0.5h) = 50mAh
GNSS Receiver	(67mA)(0.5h) = 33.5mAh
Total:	123.5mAh

Deployable Unit Requirements:

- 7-12V provided by battery
- At least 123.5 mAh on battery

Solution:

- 500mAh 7.4V lithium polymer battery

Science Data Post Processing Feasibility

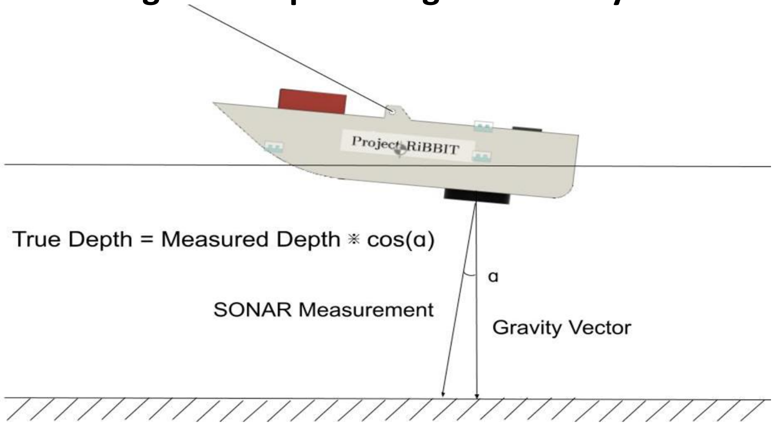
FR7				**The collected data shall be post-processed after data acquisition.**
	DR7.1			The stereo camera data shall be post-processed to calculate river velocity to an accuracy of <10% of the true surface velocity.
	DR7.2			The SONAR data shall be post-processed to model the river cross section.
	DR7.3			The river discharge shall be calculated by the product of the surface velocity multiplied by the area of the river cross section.

SONAR Technical Feasibility Analysis

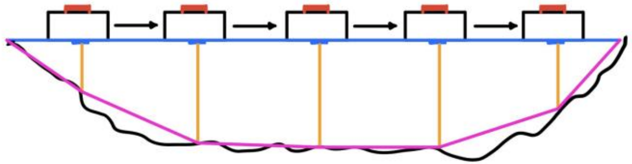
- Data collection range between 0.5 m and 30 m
- Accurate to 0.5% of the measured depth
- SONAR submersion of 3.35cm (total mass of 727g)
- 3 axis gravity vector displacement correctability
- Functionality not impacted by water clarity
- Operates on 5V at 100mA

River Depth	Estimated error	Need for gravity vector correction
1m	5 cm	yes
3m	15 cm	yes
10m	50 cm	yes
30m	150 cm	yes

Finding True Depth Along The Gravity Vector

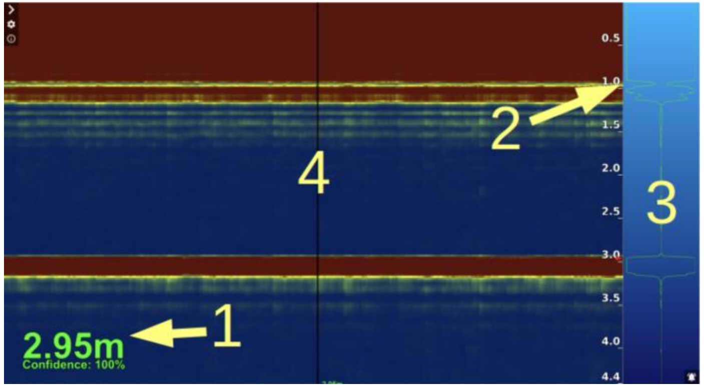


Creating The Cross Sectional River Profile



* please note that depth data (orange) would be taken at shorter intervals to create the river profile (purple) than what is illustrated above.

Sonar Data Post Processing Feasibility Analysis



Ping Sonar Post-Processing Options

Ping-Viewer Graphical User Interface

- Open source software
- Available for Windows, Mac, and Linux Systems
- Provides four important measurements:
    1. Distance Readout
    2. Distance Axis
    3. Return Plot
    4. Waterfall - plots consecutive profile samples with distance running vertically, time running horizontally, and color indicating sensor strength

Ping-Protocol

- Ping communicates with a binary message format called “Ping-Protocol”
- Ping was designed to interface with Arduino. Blue Robotics provides an Arduino library called “Blue Robotics ping-arduino” library
- Blue Robotics keeps a github repository specifically for Ping Sonar and provides starter code for requesting and receiving data from the sensor
- The ping-arduino, SD, and SPI libraries will be used to collect the sonar data and save it to an SD card.

Stereo Camera Technical Feasibility Analysis

ZED 2 FOV visualization (Sonar NOT shown)

Summary of ZED 2 data collection capabilities given height above river.

Height above river [m]	River cross section in view [m]	ZED Depth error [cm] from [2]	Pixels per cm on surface	Min observable speed [m/s]	Max observable speed [m/s]
3	8.5	3.5	5.15	0.029	63.01
5	14.2	5.4	3.09	0.048	105.03
10	28.5	16.53	1.5	0.097	210.06
15	42.8	50	1.03	0.145	315.09

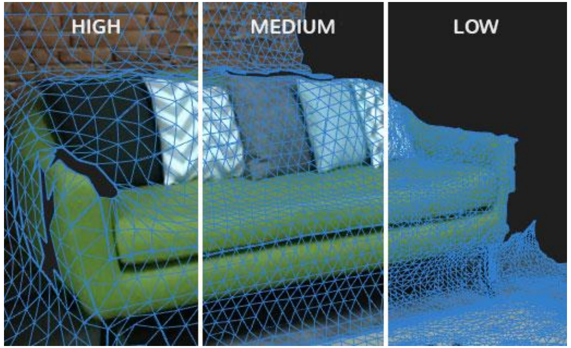
Calculations in green meet requirements, yellow are borderline or may require additional post-processing to make acceptable.

Given the system requirements the ZED 2 should be feasible for this mission.

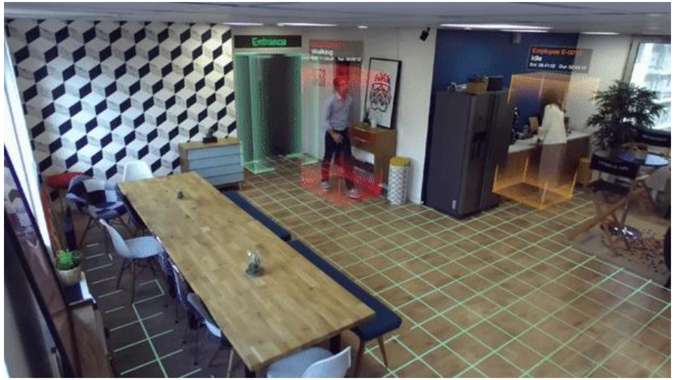
Stereo Camera Data Post Processing Feasibility Analysis

Post-Processing Options:

- Particle Image Velocimetry (PIV)
  - Works well with high resolution data
  - Stereo-Imaging Large Scale Particle Image Velocimetry (SI-LSPIV)
    - Can potentially make use of stereo capabilities of camera to model water surface and 'track' 3D features to yield velocity [3].
  - PIVLab in Matlab
- Particle Tracking Velocimetry (PTV)
  - Needs objects be present in flow field [5].
  - Can potentially make use of ZEDs AI and spacial awareness capabilities
  - PTVLab in Matlab
- Space Time Image Velocimetry (STIV)
  - Specifically for use on bodies of water using reflected light patterns [4].
  - Can use ZED 2's customizable camera settings for optimal light collection.
  - RIVeR-STIV in Matlab



Example of 3D mesh resolutions from ZED camera.



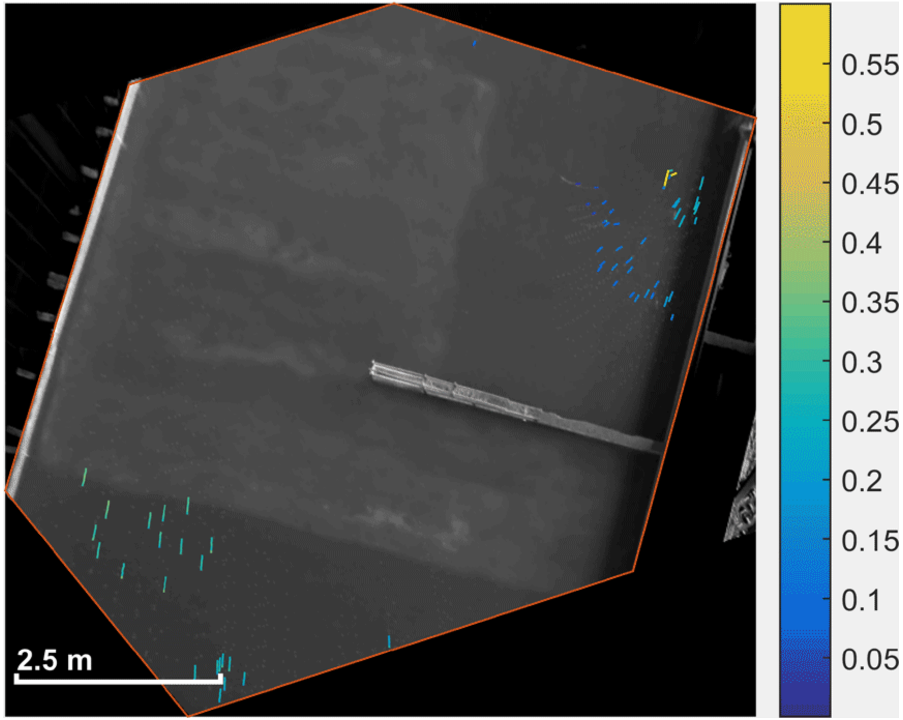
Example of ZEDs object identification and tracking capabilities.

Particle Velocimetry Examples

Particle Image Velocimetry (PIV)

Video stabilization offered by the RIVeR MATLAB program with Velocity Vectors Imposed from PIVLab from [5]

Particle Tracking Velocimetry (PTV)



PTV RIVeR MATLAB program with Velocity tracks Imposed from PTVLab from [5]

River Discharge Post Processing Feasibility Analysis

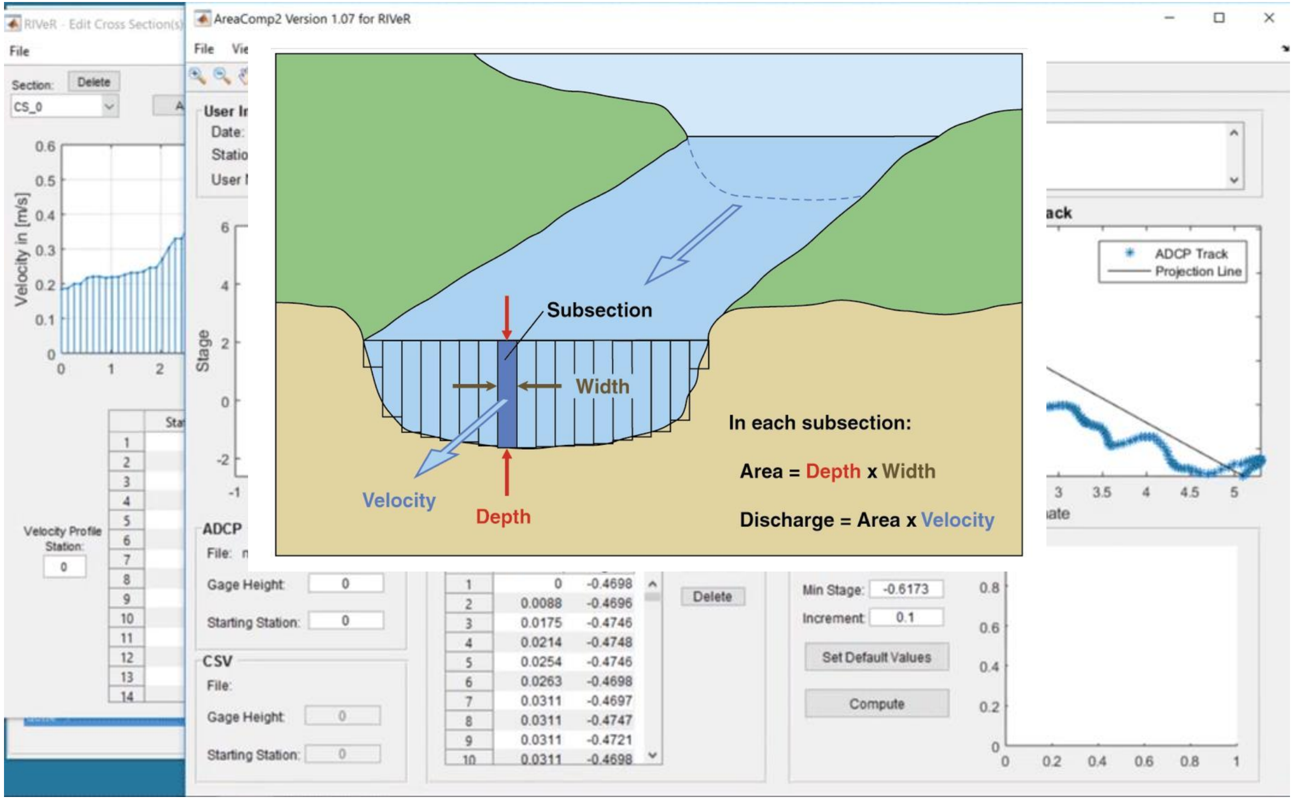
From [6]:

USGS Surface-water Method for estimating the mean-vertical velocity

- Need surface velocity and depth
- Simple
- “Assumes the vertical-velocity profile can be characterized by a logarithmic or 1/6th or 1/7th power law”

Probability Concept Method for estimating the mean-channel velocity

- Needs average and max surface point velocities and corresponding depths.
- Potentially utilize 3D stereo map with PIV or PTV measurements
- More accurate

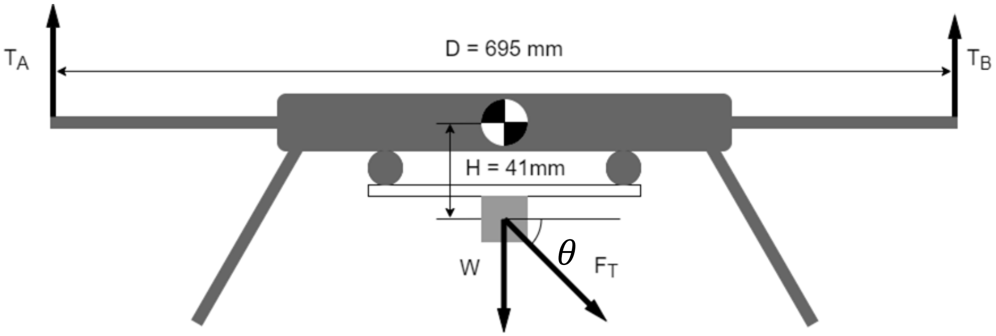


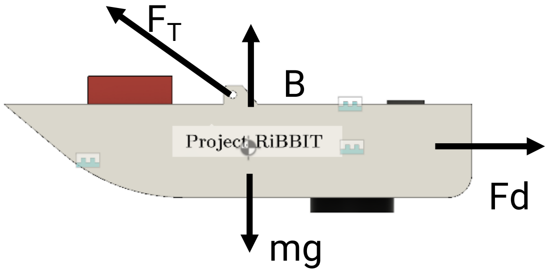
Correlating surface velocities and depth profile for discharge calculations in RIVeR from [5]

Translated Forces and Moments Feasibility

	DR3.3			The payload shall be designed such that the translated forces and moments do not exceed the drone's performance capabilities.

Translated Forces and Moments Feasibility Analysis





$$\sum Fy = 0 = T_A + T_B - T \cdot sin(\theta) - W$$

$$\sum M_{cg} = 0 = -T_A \cdot \frac{D}{2} + T_B \cdot \frac{D}{2} - F_T \cdot cos(\theta) \cdot H$$

- $T_{max} = T_A = 11.5N$
- $W = 9.07N$
- $\theta_{max} = 45°$
- $T_B = 10.4\ N$
- $F_{Tmax} = 18.2\ N$

- *Float Mass = ~400g (PLA)*
- *Total Mass = ~727g*
- F_T*=10.1N @ B = 0*

Weight Feasibility

FR3				**RiBBIT shall include an instrument suite payload that is compatible with the Tarot 680.**
	DR3.1			The payload shall be have a maximum weight of 2 kg.

Subsystem	Component	Number of Units	Weight\Unit (g)	Total Weight (g)
Avionics	Arduino Uno	1	25	25
	Jetson Nano	1	140	140
	500mAh Lipo Battery	1	36	36
	2200mAh Lipo Battery	1	203	203
	SD Shield	1	3.43	3.43
	Estimated Wiring	1	15	15
Science	ZED 2	1	124	124
	Ping SONAR	1	135	135
	Sonar Mounting Bracket	1	16.2	16.2
	Adafruit-MMA8541	1	1.3	1.3
Mechanisms	Servo by Tarot	1	55	55
	Fishing line	1	7.98	7.98
	Motor	1	215	215
	Pulley	1	1	1
Structures	Mounting Plate	1	80	80
	Sonar Float	1	400	400
GNC	U-blox C94-M8P	2	35	70
Total Weight System Weight (kg)				1.52791
Total Allowed Weight (kg)				2
Margin (kg)				0.47209

Budget Feasibility

Material	Model	Price
Drone	Tarot 680	$1833.50
Stereo Camera	ZED 2	$469.00
Sonar Sensor	Blue Robotics Ping Sonar	$311.00
Deployable Computer	Arduino Uno	$23.99
On-Board Computer	Jetson Nano	$60.00
Accelerometer	Adafruit-MMA8541	$7.95
SD Shield	SD Module	$10.00
Battery	-Turnigy 8000mAh 6S 15C LiPo -2000mAh 7.3V Lithium Polymer -500mAh 7.4V Lithium Polymer	$114.11 $16.41 $6.95
Deployment System	Tarot Servo Motor Pulley	$49.18 $13.99 $5.00
Deployment Line	Fishing Line	$1.47
Mounting Parts	Mounting plate and zip ties	$40.00
Deployable Float	PLA Filament	$17.99
GPS Receivers	U-blox C94-M8P	$399
Ground Station	Emlid REACH RS2	$0.00
Total Estimated Cost		**$3,379.14**
Contingency Budget		**$1,620.86**

Project Overview | Baseline Design | Feasibility Analysis | **Status Summary**

1. Current Standing
2. Future Work
3. References

Current Standing

Critical Project Elements	Requirement(s)	Feasibility
UAV	- RiBBIT shall be a transportable unmanned aerial vehicle (UAV) system.	✔
Depth Sensing Instrument	- The instrument suite shall use SONAR to capture depth measurements. - The SONAR instrument shall float on top of the water surface with the bottom 2.5 cm of the instrument submerged. - The angle between the SONAR instrument pointing ray and the gravity vector shall be measured.	✔
Velocity Instrument	- The instrument suite shall use a stereo camera in order to measure river surface velocities. - The camera shall be fixed to the instrument suite that is mounted to the drone. - The camera shall be able to sufficiently capture river velocity data between 0-4m/s.	✔
Structural Dynamics	- The payload shall be designed such that the translated forces and moments do not exceed the drone's performance capabilities.	✔
Command and Data Handling	- RiBBIT shall be able to power and command all instruments and sensors.	✔
Data Post-Processing	- The collected data shall be post-processed after data acquisition.	✔

Future Work

Critical Project Elements	Future Work
UAV	- Determine testing site location & regulation plan - Get certified drone pilot and familiarize with drone system
Depth Sensing Instrument	- Determine integration of depth data and angular offset data
Velocity Instrument	- Determine velocity data post-processing technique - Merging SI-LSPIV and PIV/PTV observations - Determine optimal data collection flight plan
Structural Dynamics/ Mechanisms	- Connections to drone flight controller - Further deployment system analysis and feasibility
Command and Data Handling	- Identify sensor connection work necessary - On-board computer programming for data collection
Data Post-Processing	- Sonar/stereo data integration with GNSS data - Decide on vertical velocity averaging technique

References

- [1] Thielicke, William, and Eize J. Stamhuis. “PIVlab – Towards User-Friendly, Affordable and Accurate Digital Particle Image Velocimetry in MATLAB.” Journal of Open Research Software, vol. 2, Ubiquity Press, Ltd., Oct. 2014, doi:10.5334/jors.bl.
- [2] Ortiz, L. E., Cabrera, V. E., and Goncalves, L. M. G. “Depth Data Error Modeling of the ZED 3D Vision Sensor from Stereolabs.” *ELCVIA Electronic Letters on Computer Vision and Image Analysis*, Vol. 17, No. 1, 2018, pp. 1–15. https://doi.org/10.5565/rev/elcvia.1084.
- [3] Li, W., Liao, Q., and Ran, Q. “Stereo-Imaging LSPIV (SI-LSPIV) for 3D Water Surface Reconstruction and Discharge Measurement in Mountain River Flows.” *Journal of Hydrology*, Vol. 578, 2019, p. 124099. https://doi.org/10.1016/j.jhydrol.2019.124099.
- [4] Tsubaki, R. “On the Texture Angle Detection Used in Space-Time Image Velocimetry (STIV).” *Water Resources Research*, Vol. 53, No. 12, 2017, pp. 10908–10914. https://doi.org/10.1002/2017WR021913.
- [5] Patalano, A., García, C. M., and Rodríguez, A. “Rectification of Image Velocity Results (RIVeR): A Simple and User-Friendly Toolbox for Large Scale Water Surface Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV).” *Computers & Geosciences*, Vol. 109, 2017, pp. 323–330. https://doi.org/10.1016/j.cageo.2017.07.009.
- [6] Engel, F. “Surface Velocity Workgroup: How to Articles.” *Office of Surface Water, USGS*, 2020.

Backup Slides

Appendix: Table of Contents

Baseline Design

- Payload Housing and Drone Mount
- Stereo Camera (Additional Information)
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- Deployed Sonar Float Angular Displacement Technique
- Positional Determination and Geo-Referencing

Feasibility Analysis

- Flight Vehicle/Force & Moment Work
- Payload Housing
- Drone Mounting Technique
- Sonar Deployment Mechanism
- Sonar Float
- Stereo Camera Discharge Calculations
- River Profile, Gyro, and GNSS Data Integration
- Positional Determination
- Testing Plan

CONOPS

Fall Schedule

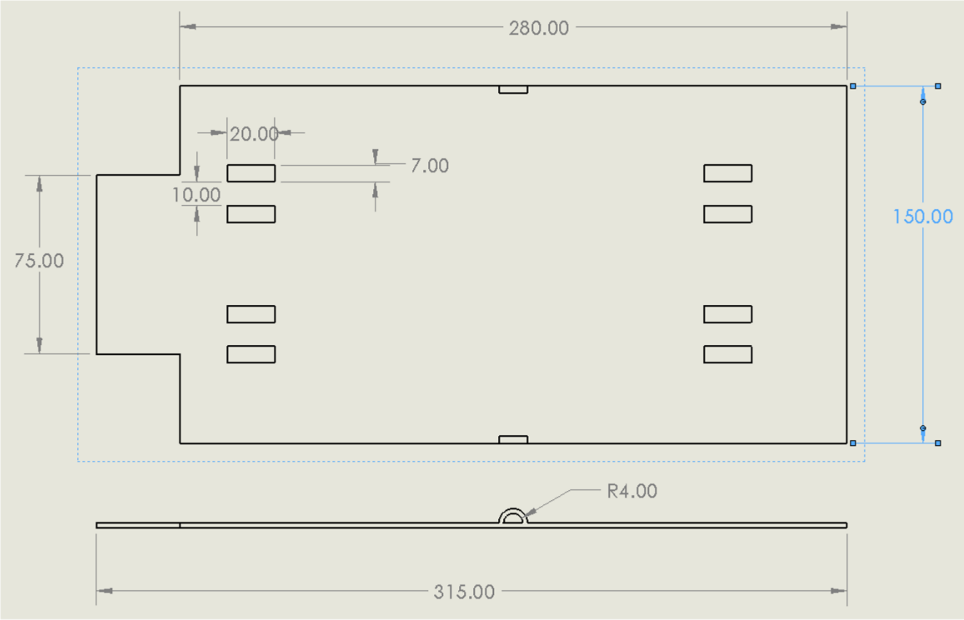
Requirements

Organizational Chart

Baseline Design Backup Slides

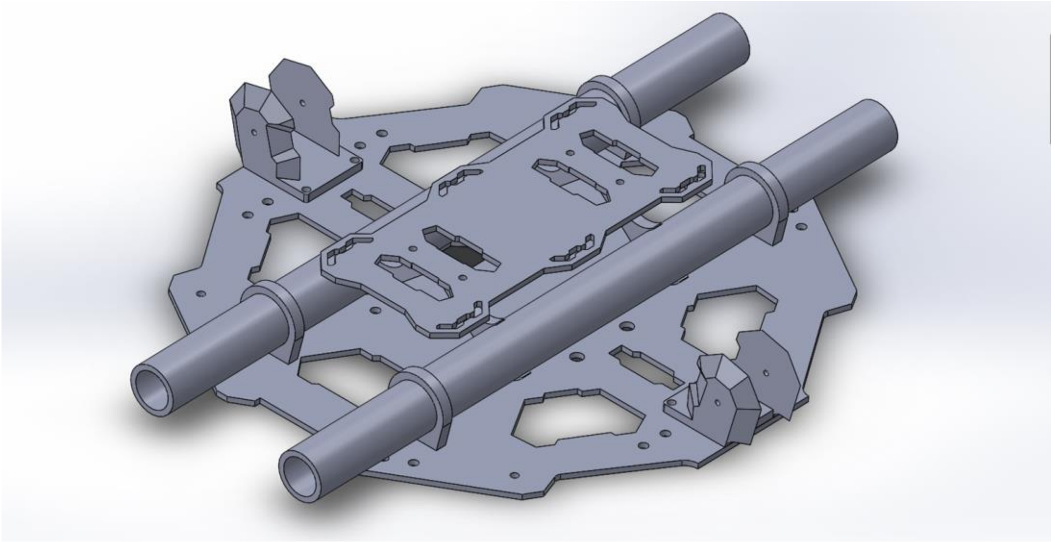
Baseline Design - Payload Housing & Drone Mount

- The mount will be 3D printed using PLA and will mount using ⅝" velcro straps or zip ties
- Units in millimeters



Baseline Design - UAV Base Plate

- Base plate to design payload housing and mounting upon
- 60 mm between Tubes



Stereo Camera Baseline Design - Further Info

Hand-held LSPIV Guidelines – On Site Checklist

Video and Site Requirements

Video

- ☐ Video resolution is at least 640 x 480 pixels (most smart phone cameras)
- ☐ Minimum of 15 frames per second
- ☐ No wide angle lens or other distortion
- ☐ Video duration at least 60 to 90 seconds
- ☐ Camera platform is as stable as possible by mounting on a tripod or bracing against a fixed object

Site

- ☐ Surface flow disturbance patters are uniform with time
- ☐ No effects of pier wake or other flow disturbances. If near a structure, shoot video looking upstream.
- ☐ Ideally, river has a stable bottom not subject to erosion

Video from bank: Field of view includes all visible items, very well defined control points

Field of View Requirements

Visible items

- ☐ Entire width of channel at measurement cross-section
- ☐ Fixed locations on both sides of the channel (e.g. banks, trees, structures)
- ☐ Minimum of 4 control points

Camera angle

- ☐ High angle is best (closest to 90°), therefore try to look down on the water as opposed to looking across it
- ☐ If standing on the bank, ensure angle is higher than 15°
- ☐ If standing on a bridge, ensure all visible items are in the field of view

Lighting

- ☐ Avoid shadows and reflections
- ☐ Avoid sparkling patterns on water surface

Video from bridge: Field of view includes both banks, control points not well defined

Control Points and Measurements

Control Points

- ☐ Minimum of 4 fixed control points, positioned as to maximize size of velocity field in camera field of view
- ☐ At least 2 on each bank, but can add more to enlarge visible velocity field
- ☐ Located at or as close as possible to the water surface
- ☐ Distance between points is known or can be measured

Note: do not need to form a perfect square

Examples: rocks, trees, stakes, pylons

Additional Measurements

- ☐ Distances between control points, including diagonals
- ☐ One cross-section bathymetry
- ☐ Fill in LSPIV Data Submission Form

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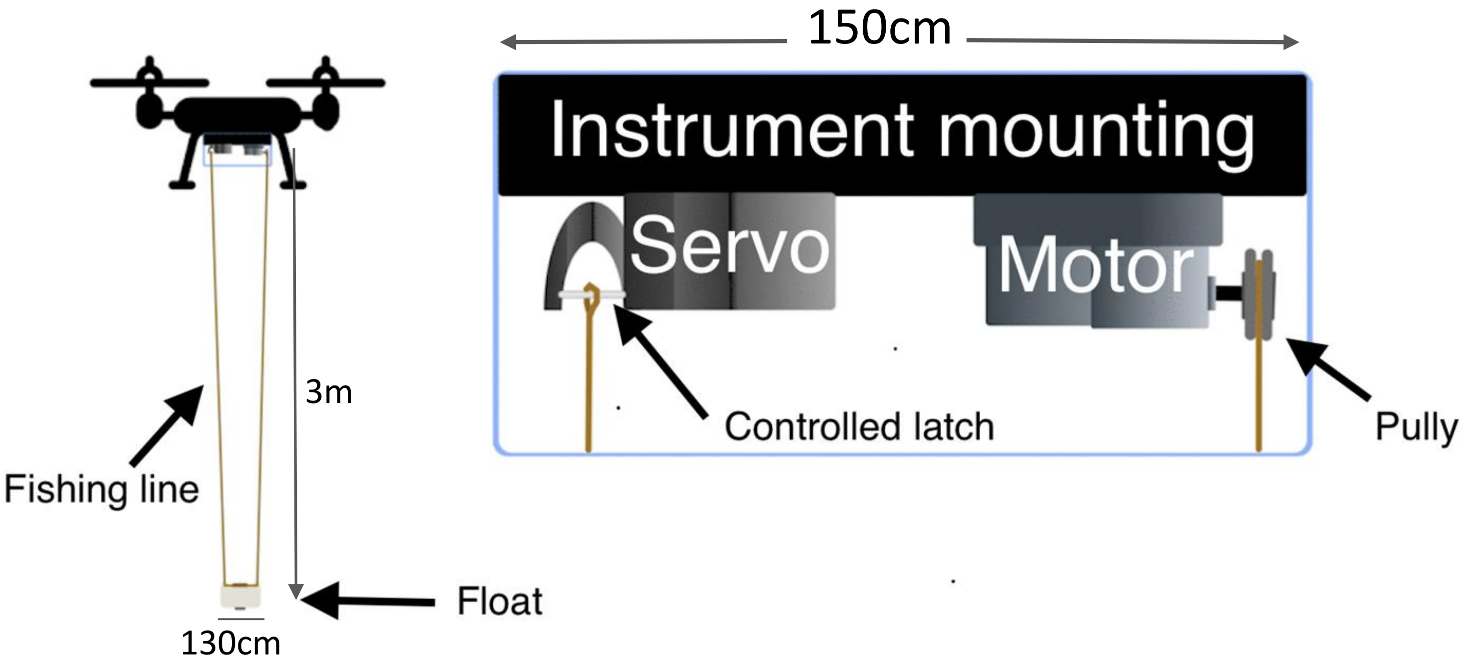
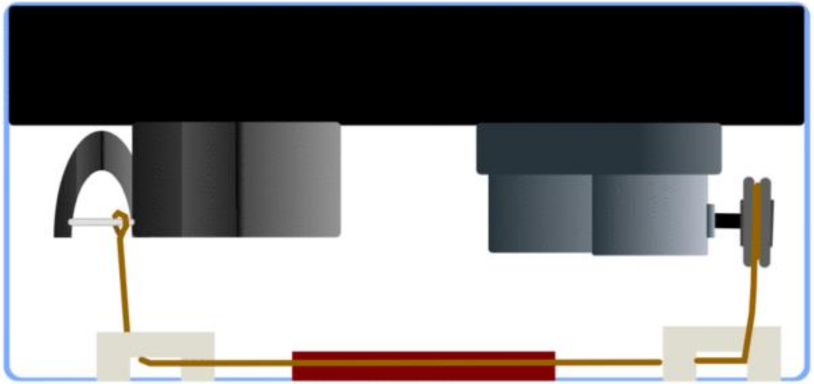
Baseline Design - Sonar Deployment Mechanism

- Components:
  - Servo
  - Fishing line
  - Motor
  - Pulley
- Max weight capacity of servo is 10kg
- Max weight capacity of fishing line is 6.8kg
- Total weight of components is 278.98g

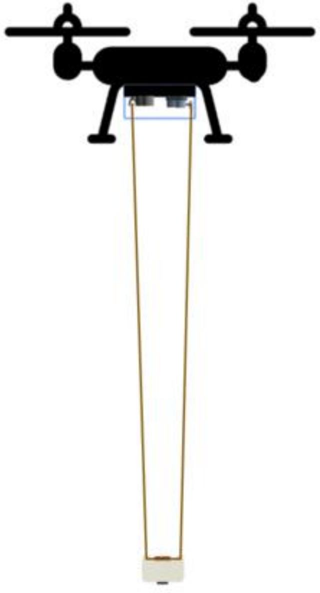
Baseline Design - Sonar Deployment Mechanism

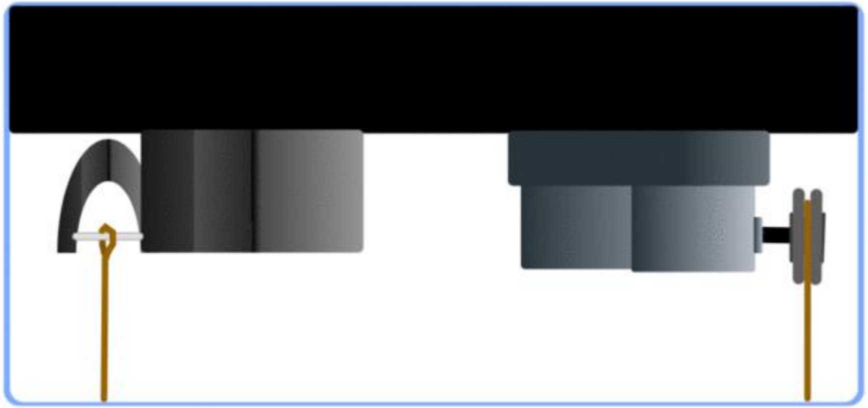


Baseline Design - Sonar Deployment Mechanism (Payload deployment)



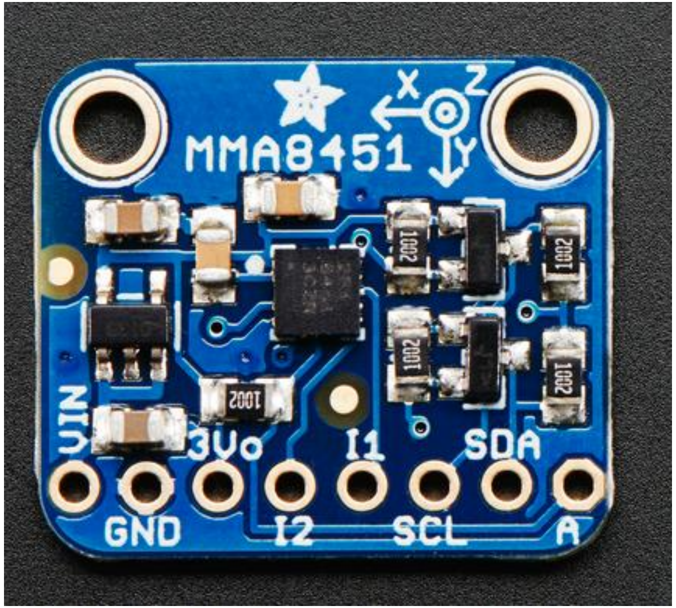
Baseline Design - Sonar Deployment Mechanism (Emergency Release)





Baseline Design - Deployed Sonar Float Angular Displacement Technique

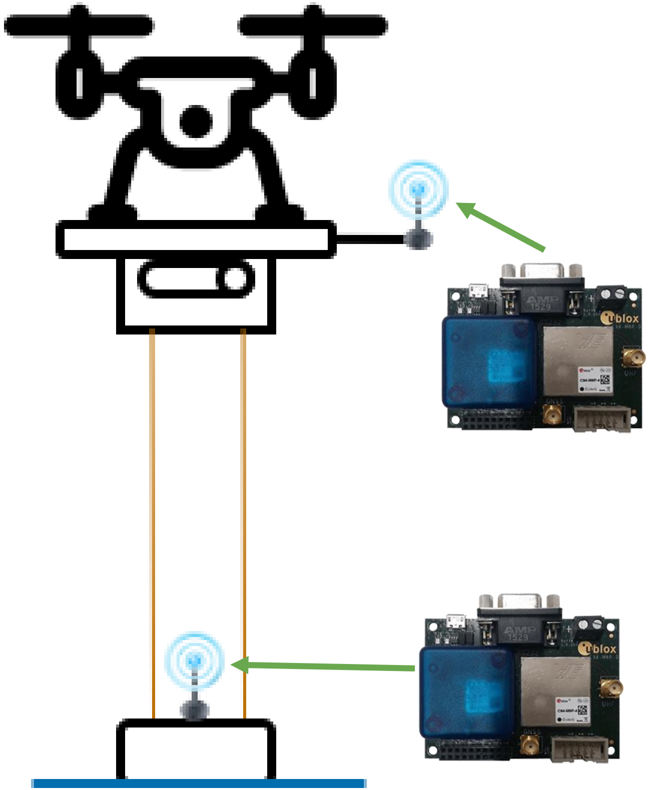
Used to track sonar angle relative to gravity vector for post processing depth corrections.



- Adafriut-MMA8541
  - 3 axis of measurements
  - Connected directly to the onboard arduino
  - 14 bit resolution
  - Weighs 1.3 grams
  - Size: 21mm x 18mm x 2mm

Baseline Design - Positional Determination & Geo-Referencing

- Base Station:
  - Emlid REACH RS2
- Rover receivers:
  - U-blox C94-M8P
    - Present on drone and sensor suite
- Precise Point Positioning (PPP) Software:
  - RTK Lib
  - JPL GipsyX



Feasibility Analysis Backup Slides

Flight Vehicle Feasibility Analysis

Requirement Overview:

FR1. RiBBIT shall be a transportable unmanned aerial vehicle (UAV) system.

DR1.1 The combined flight vehicle and payload system shall have a minimum operational flight time of 12 minutes.

DR1.2 The flight vehicle shall have a minimum carrying capacity of 1.5 kg.

FR8. The UAV shall comply with all FAA requirements.

Flight Vehicle Feasibility Analysis

Battery:

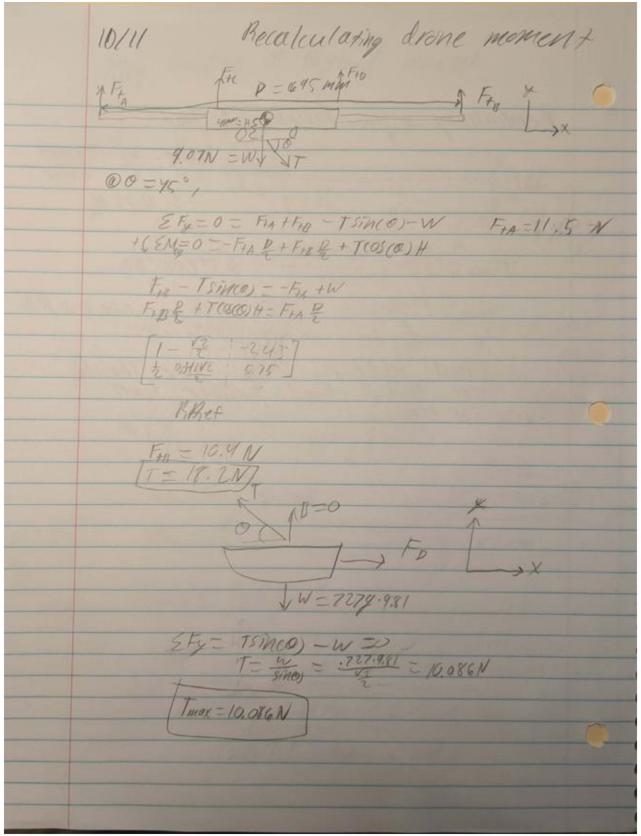
Motor Current Draw - 14.4A, Battery capacity - 8Ah, Flight time - 33m

Payload Capacity: 2kg

Carrying capacity of drone meets requirements

- Register drone
- Write down the flight procedure
- Fly below 400ft and within the visual line of site
- Do not fly at night or within restricted airspace such as airports (Boulder Municpal Airport, North Boulder)

Flight Vehicle Feasibility Analysis



10/11 Recalculating drone moment

$D = 645\ mm$

$9.07N = W$

@ $\theta = 45°$,

$\Sigma F_y = 0 = F_{tA} + F_{tB} - T\sin(\theta) - W$ $\quad F_{tA} = 11.5\ N$

$+\circlearrowleft \Sigma M_{cg} = 0 = -F_{tA}\frac{D}{2} + F_{tB}\frac{D}{2} + T\cos(\theta)H$

$F_{tB} - T\sin(\theta) = -F_{tA} + W$

$F_{tB}\frac{D}{2} + T\cos(\theta)H = F_{tA}\frac{D}{2}$

$$\left[\begin{array}{cc|c} 1 & -\frac{\sqrt{2}}{2} & -2.43 \\ \frac{1}{2} & \frac{0.0414\sqrt{2}}{2} & 5.75 \end{array}\right]$$

RRef

$F_{tB} = 10.4\ N$

$\boxed{T = 18.2N}$

$\theta = 0$

F_D

$W = .727g \cdot 9.81$

$\Sigma F_y = T\sin(\theta) - W = 0$

$T = \frac{W}{\sin(\theta)} = \frac{.727 \cdot 9.81}{\frac{\sqrt{2}}{2}} = 10.086N$

$\boxed{T_{max} = 10.086N}$

Payload Housing Feasibility

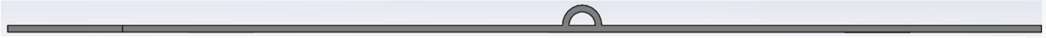
FR3. RiBBIT shall include an instrument suite payload that is compatible with the *Tarot 680 Pro*.

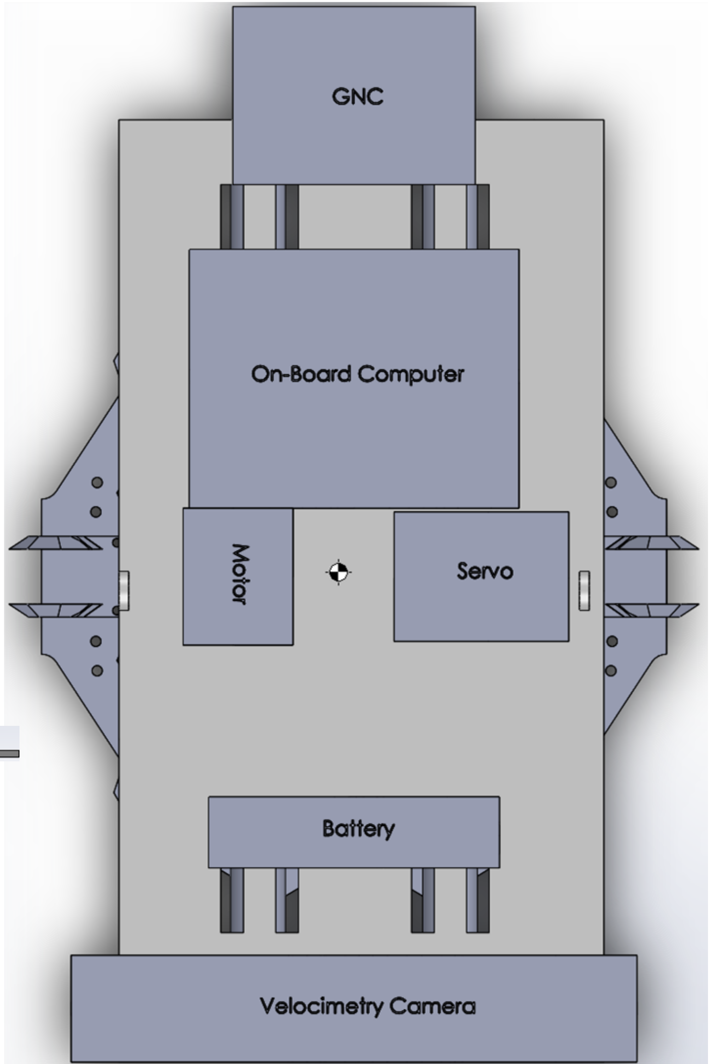
DR3.3 The payload shall be designed such that it minimizes the external applied moments on the drone.

DR4.2.1 The camera shall be fixed to the instrument suite that is mounted to the drone.
DR 4.1.1.1 The SONAR instrument shall be suspended below the drone for data collection to make contact with the water.

Payload Housing Feasibility

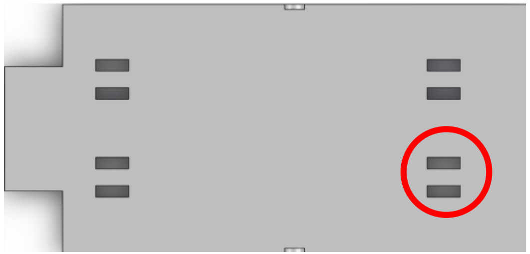
- The payload housing has to be capable of allowing the CG to remain inline with the Drone's CG
- This initial distribution shows that the payload housing can fit all the necessary components and maintain the CG

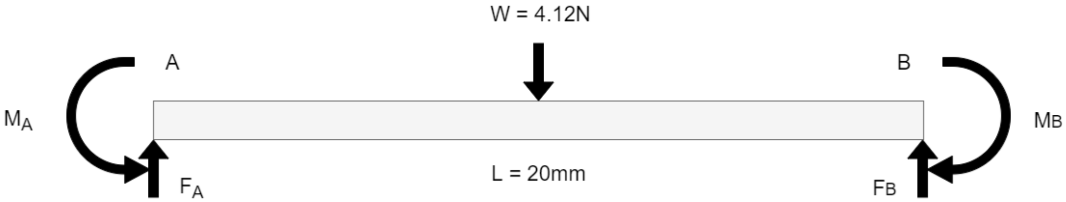




Drone Mounting Technique Feasibility

DR3.4 The payload shall be mounted such that it minimizes the external applied moments on the drone.





Drone Mounting Technique Feasibility

M_{max}= Maximum Moment achieved

σ_{max}= Maximum Strain achieved

I = Moment of inertia of a rectangle

c = Distance from midpoint to edge of cross-section

$$M_{max} = \frac{W \cdot L}{8}$$

$$I = \frac{1}{12} \cdot (w \cdot h^3)$$

$$\sigma_{max} = \frac{M_{max} \cdot c}{I}$$

σ_{max} = 1.545 MPa
$\sigma_{allowed}$ = 100 MPA

Sonar Deployment Mechanism Feasibility

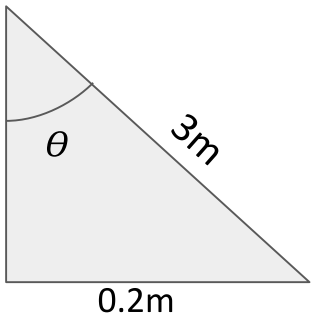
FR4. The instrument suite shall be capable of measuring the bathymetric profile and stream flow of a river cross section from one bank to the other, perpendicular to the current.

DR4.4.1.1 The SONAR instrument shall be suspended below the drone for data collection to make contact with the water.

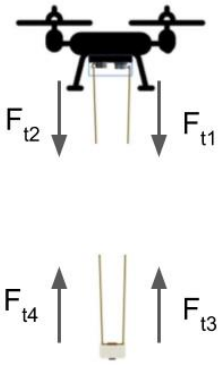
DR4.1.1.2 The attachment between the SONAR instrument and the drone shall include a failsafe option shall be put in place to drop the payload in case of emergency.

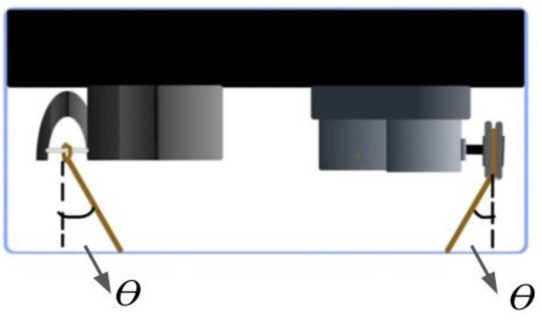
Sonar Deployment Mechanism Feasibility

- Total mass of payload is 727g
- Motor rated torque is 4.5kg*cm
- Torque on motor due to payload is 0.65kg*cm
- Max tension force sustained by servo is 98.1N
- Using Newton's 1st Law: F = mg
- Tension force on each rope is 7.13N
- Using pythagorean theorem for:



So, θ = 3.82°

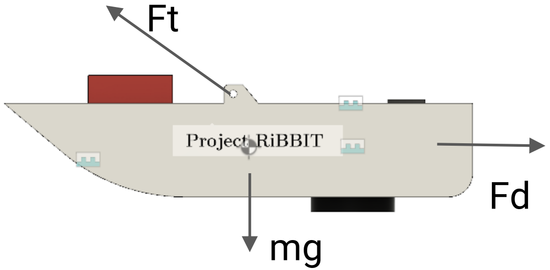




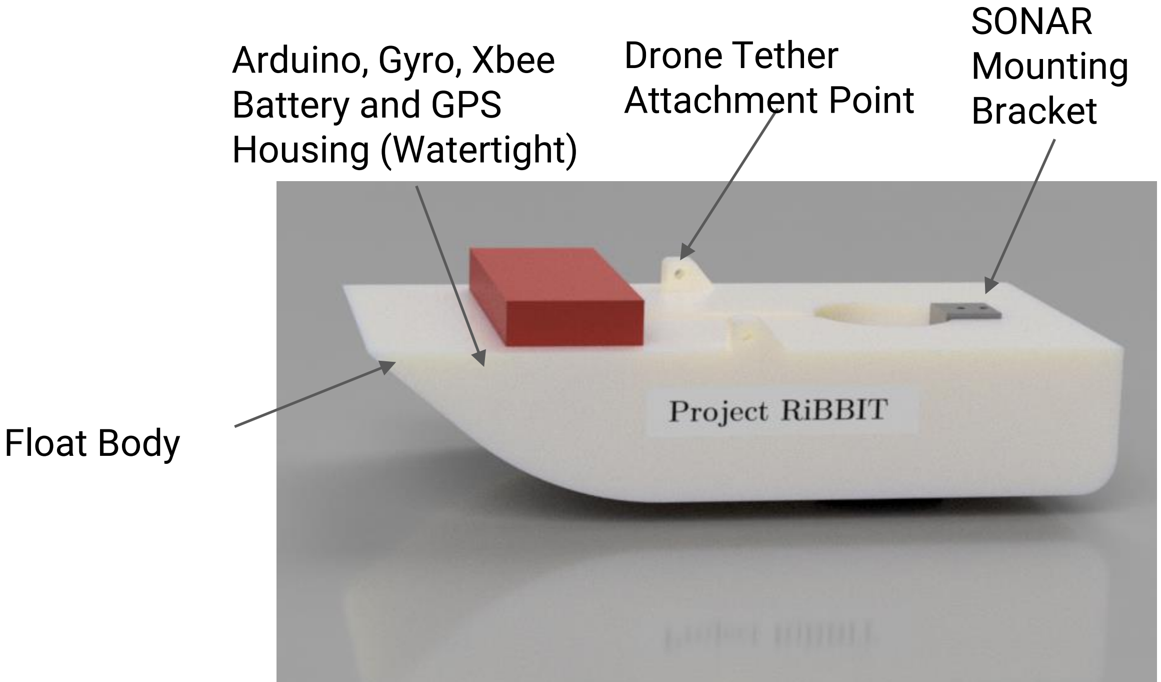
*The angle θ is exaggerated for clarity

Sonar Float Feasibility

- As shown on the FBD below the float may be inclined to pitch and roll so a gyroscope will be mounted to it to track the floats angle and correct the data in post.



- Float Mass = 400g (PLA)
- Total Mass = 727g



Sonar Float Force Calculations

- R = Reynolds Number
- L = Length of Waterline
- v = kinematic viscosity of water (10℃)
- C_f = Coefficient of Friction
- F_d = Drag Force
- ϱ = Density of Water
- V_0 = Flow Velocity (5m/s)
- S = Wetted Area
- α = Tether angle (30°)
- F_t = Tether Tension

$$R = V_0 * \frac{L}{v}$$

$$C_f = \frac{0.075}{(log_{10}(R) - 2)^2}$$

$$F_d = \frac{1}{2} * \varrho * V_0^2 * S * C_f$$

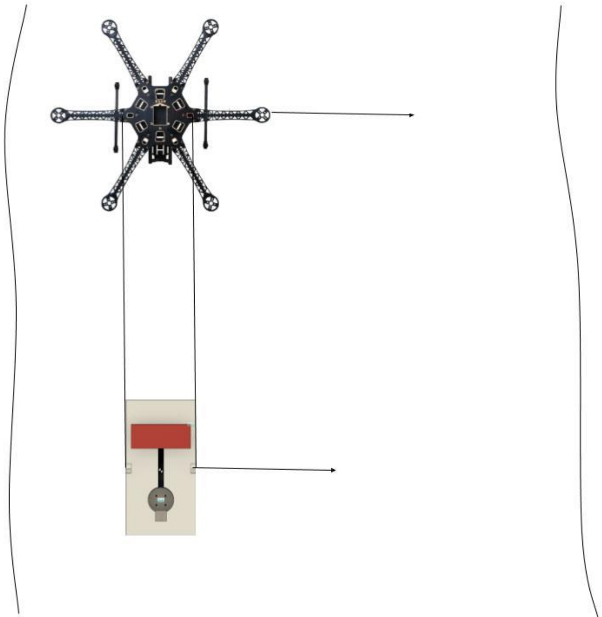
$$F_t = \frac{F_d}{cos(\alpha)}$$

- R = 841622
- C_f = 0.004868
- F_d = 2.5N
- F_t = 2.66N

Sonar Float Feasibility

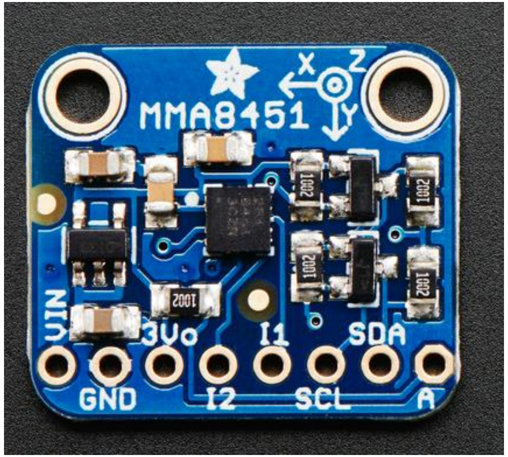
DR4.1.1.1 The SONAR instrument shall float on top of the water surface with the bottom 2.5 cm of the instrument submerged.

- Float max. Lateral speed 0.5 m/s
- Float weight (total) = 727 grams
- Sonar Submersion = 3.55 cm
- Required SONAR Power 0.55W
- Arduino Power <1W
- GPS Power = 0.09W
- Total power = ~1.5W



Sonar Float Feasibility

DR4.1.3 The angle between the SONAR instrument pointing ray and the gravity vector shall be measured.



- Adafriut-MMA8541
  - Interfaces with onboard arduino
  - Measures acceleration in 3 axis
  - Weighs 1.3 grams

The sensor will collect data parallel to the sonar unit which can then be used to correct any gravity vector deviations in regards to the depth measurement in post.

Stereo Camera System Feasibility

DR4.2 The instrument suite shall use a stereo camera in order to measure river surface velocities.
DR4.2.2 The camera shall be able to sufficiently capture river velocity data between 0-4m/s.

Discharge Calculations from [6]

How to translate Surface-water Velocities into a Mean-vertical or mean-channel Velocity

Regardless of the method (LSPIV or velocity radars) used to measure surface-water velocities, computing a discharge requires:

- Mean-channel velocity
- Cross-sectional area

This post offers methods for translating surface-water velocities into a mean-vertical (u_{vertical}) or mean-channel (u_{avg}) velocity either directly (USGS Surface-water Method, Probability Concept) or indirectly (Index Velocity Rating). Future posts will address steps for (1) assessing the quality of surface-waters scatterers, (2) correcting for wind drift, which can bias measurements and alter surface-water velocities, (3) schemes for filtering instantaneous velocity measurements, (4) computing area, and (5) computing real-time discharge.

It is important that when reporting u_{avg}, the method should account for the velocity distribution that exists at the transect or cross-section-of-interest. For example, if the maximum velocity occurs at the water surface, a logarithmic or or power law can be assumed; however, if the maximum velocity occurs below the water surface, a non-standard velocity distribution equation (e.g., Chiu velocity equation) should be used.

Discharge calculations from [6]

Direct Measurement:

USGS Surface-water Method for estimating the mean-vertical velocity

If surface-water velocities (u_D) are measured directly (LSPIV or velocity radars) and at multiple stations (25-30) from the left edge of water (LEW) to the right edge of water (REW), $u_{vertical}$ at a station can be computed using equation 1:

- $u_{vertical} = u_D$ *x coefficient (typically ranging from .84 to .90)* *Eq. 1*

This assumes the vertical-velocity profile can be characterized by a logarithmic or 1/6th or 1/7th power law (Mueller, 2013). Rantz et al. (1982) and Turnipseed and Sauer (2010) recommend a coefficient is necessary to convert a surface-water velocity to a $u_{vertical}$; however, these coef-ficients are generally difficult to determine reliably because they may vary with stage, depth, and position in the measur-ing cross section. Experience has shown that the coefficients generally range from about 0.84 to about 0.90, depending on the shape of the vertical-velocity curve and the proximity of the vertical to channel walls, where secondary currents may develop causing the maximum velocity to occur below the water surface. During these conditions, the coefficient can exceed unity (1.0). Larger coefficients are generally associated with smooth streambeds and normally shaped vertical-velocity curves; whereas, smaller coefficients are associated with irregular streambeds and irregular vertical-velocity curves.

In many instances, the velocity distribution is non-standard or the maximum velocity occurs below the water surface. In these cases, an alternative velocity distribution equation is needed to translate a surface-water velocity into a u_{avg} (Chiu, 1989; Chiu and Tung, 2002; Fulton and Ostrowski, 2008) or $u_{vertical}$ (Guo and Julien, 2008; Jarrett, 1991; Kundu and Ghoshal, 2012; Wiberg and Smith, 1991; Yang et al., 2006).

Discharge calculations from [6]

Probability Concept Method for estimating the mean-channel velocity

The Probability Concept was pioneered Chiu (1989) and offers an efficient platform for computing u_{avg} at a cross-section-of-interest. Two parameters, and the maximum-instream velocity (u_{max}), are needed to compute u_{avg} The variable is derived by measuring point velocities along a very important and single vertical as a function of depth beginning at the channel bottom and concluding at the water surface or by collecting pairs of u_{avg} and u_{max} for a variety of flow conditions. The vertical is called the "y-axis" and all data collection efforts should focus on that station, which is that vertical that contains the maximum information content (minimum velocity, maximum velocity, and depth) to derive the parameters u_{max}, h/D used to compute u_{avg} (equations 2 and 3). Research suggests (Chiu et al., 2001; Fulton and Ostrowski, 2008; Fulton et al., in preparation) the location or stationing of the y-axis is generally stable for a given transect and does not vary with changing hydraulic conditions including variations in stage, velocity, flow, flow, channel geometry, bed form and material, slope, or alignment; however, field verification of these parameters must be conducted periodically and a stage-area rating must be maintained. The y-axis rarely coincides with the thalweg in open or engineered channels. Computing is accomplished through a Python or R-script (**will pr ovide link**); u_{max} can be computed or measured directly using LSPIV or velocity radars.

- $u_D = u_{max}/M \times \ln [1+ (e^M-1) \times 1/(1-h/D) \times \exp(1- 1/(1- h/D))]$ *Eq. 2*

- $= u_{avg} / u_{max}$ *Eq. 3*

Where = function of M (2 to 5.6) and generally ranges from ***.58 to .82*** *and*

u_{max} *= maximum in-stream velocity*

u_{avg} *= mean-channel velocity*

M = entropy parameter and is related to $= e^M / (e^M-1) - 1/M$

u_D *= surface-water velocity*

h/D = location of u_{max} *below the water surface at the y-axis/water depth at the y-axis*

Indirect Measurement:

Index Velocity Rating for estimating the mean-channel velocity

The protocol for establishing index velocity ratings are described by Levesque and Oberg (2012) where an index such as u_D can be paired to a measured discharge for a variety of flow conditions.

Discharge calculations from [6]

References

Chiu, C.-L., and Tung, N.C., 2002. Velocity and regularities in open-channel flow. Journal of Hydraulic Engineering, 128 (94), 390-398.

Chiu, C.-L., Tung, N.C., Hsu, S.M., and Fulton, J.W., 2001, Comparison and assessment of methods of measuring discharge in rivers and streams, Research Report No. CEEWR-4, Dept. of Civil & Environmental Engineering, University of Pittsburgh, Pittsburgh, PA.

Chiu, C.-L., 1989, Velocity distribution in open channel flow, Journal of Hydraulic Engineering, 115 (5), 576-594.

Fulton, J.W., Cederberg, J.R., Best, H.R., Fulford, J.M., Mills, J.T., Jones, M.E., and Bjerklie, D.M., *in preparation*, SWOT-based River Discharge: Ground-truthing using the Probability Concept and Continuous-wave Velocity Radars.

Fulton, J.W. and Ostrowski, J., 2008, Measuring real-time streamflow using emerging technologies: Radar, hydroacoustics, and the probability concept, Journal of Hydrology 357, 1–10.

Guo, J. and Julien, P.Y., 2008, Application of the Modified Log-Wake Law in Open-Channels, Journal of Applied Fluid Mechanics, 1 (2), 17-23.

Jarrett, R.D., 1991, Wading measurements of vertical velocity profiles, Geomorphology, 4, 243-247.

Kundu, S. and Ghoshal, K., 2012, Velocity Distribution in Open Channels: Combination of Log-law and Parabolic-law, World Academy of Science, Engineering and Technology, International Journal of Mathematical, Computational, Physical, Electrical and Computer Engineering, 6 (8), 1234-1241.

Levesque, V.A. and Oberg, K.A., 2012, Computing discharge using the index velocity method: U.S. Geological Survey Techniques and Methods 3–A23, 148 p.
(Available online at http://pubs.usgs.gov/tm/3a23/).

Mueller, D., 2013, extrap, Software to assist the selectin of extrapolation methods for moving-boat ADCP streamflow measurements, Computers & Geosciences, 54, 211-218.

Rantz, S.E. and others, 1982. Measurement and computation of streamflow: Volume 1. Measurement of stage and discharge. Water-Supply Paper 2175, U.S. Geological Survey.

Turnipseed, D.P. and Sauer, V.B., 2010, Discharge measurements at gaging stations: U.S. Geological Survey Techniques and Methods book 3, chap. A8, 87 p. (Also available at http://pubs.usgs.gov/tm/tm3-a8/).

Wiberg, P.L. and Smith, J.D., 1991, Velocity distribution and bed roughness in high-gradient streams, Water Resources Research, 27 (5), 825-838.

Yang, S.-Q., Xu, W.-L., and Yu, G.-L., 2006, Velocity distribution in gradually accelerating free surface flow, Advances in Water Resources, 29, 1969-1980.

River Profile, Gyroscope, and GNSS Data Integration

Integrating Gyroscope Data with Sonar Data

- Use interpolation to match up data points
- Use trigonometry to incorporate gyroscopic data into sonar data

Integrating GNSS Data with Sonar Data

- Use interpolation to match up data points
- Software package to fuse data sets together

River Velocity Data Processing Feasibility

FR7. The collected data shall be post-processed after data acquisition.

DR7.2 The stereo camera data shall be post-processed to calculate river velocity to an accuracy of <10% of the true surface velocity.

Positional Determination Feasibility

FR5 The instrument suite shall be capable of measuring its position.
DR5.1 The instrument suite (both drone fixed and suspended units) shall have a GNSS receiver with the depth measuring instrument for positional data.

Base Station:

- ~1hr observation time prior to mission commencement
- Raw data UBX logs stored

Rover:

- Log UBX data from GNSS module through micro-A USB interface

Post Processing:

- Download raw logs from base and receivers into RTKLIB
- Convert UBX to RINEX 3.03 with RTKCONV
- Process in RTKPOST

Positional Determination Feasibility

DR5.1.1 The instrument suite shall be capable of knowing its horizontal position with an accuracy of +/- 4 cm in ideal conditions.

- With PPK, the Emlid REACH RS2 base station has a horizontal accuracy of 5 mm + 0.5 ppm
- With PPK, the C94-M8P receivers have a horizontal accuracy of 25mm + 1 ppm

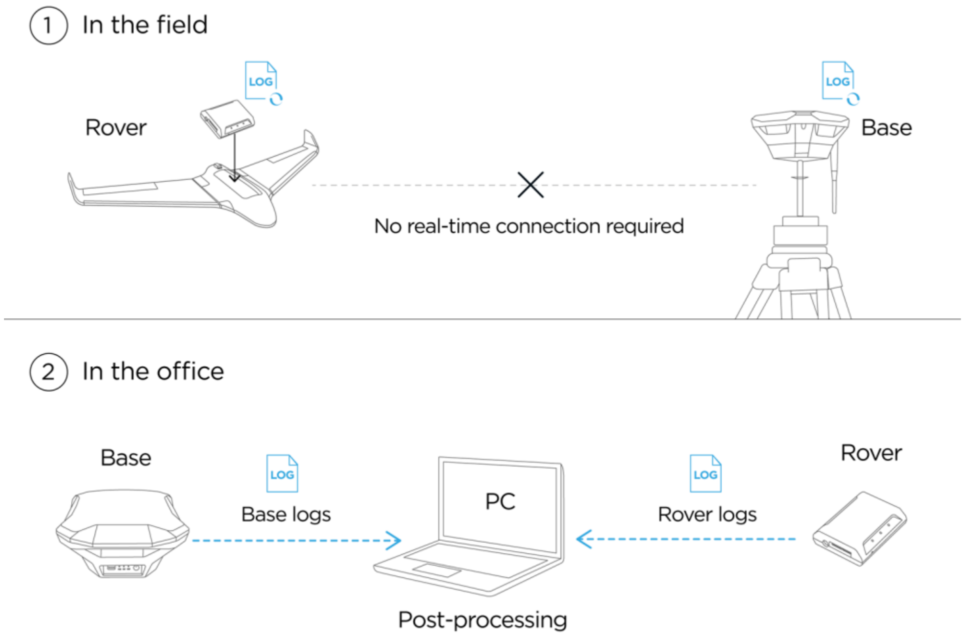
DR5.1.2 The instrument suite shall be capable of knowing its vertical position with an accuracy of +/- 5 cm in ideal conditions.

- With PPK, the Emlid REACH RS2 base station has a vertical accuracy of 10 mm + 1 ppm
- With PPK, the C94-M8P receivers have an estimated vertical accuracy of 37mm*

* By amateur studies, the official documentation only contains horizontal accuracies

Positional Determination

Post-Processed Kinematic is a GNSS correction method that allows centimeter-level accurate position data. As our mission does not require live position updates, this offline option (instead of Real-Time Kinematic) is opted for.



Testing Feasibility

Testing Location:

- ASPEN Lab
- CU South Boulder

Data Validation:

- Set-up water testbed in flight lab/outside

Testing Contact:

- Dan Hesselius
- Bobby Hodgkinson

Testing Plan

- Test each component individually before integration:
  - Test all instruments alone to understand data and begin post-processing scripts
  - Integrate each component successively to easily identify errors
- Drone:
  - Mount with simulated weight to estimate flight time
  - Mount with simulated tether to test performance with suspended attachment
- Data Verification and Validation
  - Team will work with company AstraLite for data V&V.

Requirements (1/4)

FR1				**RiBBIT shall be a transportable unmanned aerial vehicle (UAV) system.**
	DR1.1			The combined flight vehicle and payload system shall have a minimum operational flight time of 12 minutes.
	DR1.2			The flight vehicle shall have a minimum carrying capacity of 2 kg.
	DR1.4			There shall be visual observer to monitor the environment that the drone is flying in.
	DR1.5			The surveyor shall choose river cross sections with open sky and minimal tree obstruction.
FR2				**RiBBIT shall be able to operate in difficult to access river locations.**
FR3				**RiBBIT shall include an instrument suite payload that is compatible with the Tarot 680.**
	DR3.1			The payload shall be have a maximum weight of 2 kg.
	DR3.2			The instruments shall be composed of commercial off the shelf components.
	DR3.3			The payload shall be designed such that the translated forces and moments do not exceed the drone's performance capabilities.

Requirements (2/4)

FR4				**The instrument suite shall be capable of measuring the bathymetric profile and stream flow of a river cross section from one bank to the other, perpendicular to the current.**
	DR4.1			The instrument suite shall use SONAR to capture depth measurements.
		DR4.1.1		There shall be a mechanism which lowers the SONAR to the the water surface.
			DR4.1.1.1	The mechanism shall include a failsafe option to release the payload if the translated forces and moments to the drone exceeds its flying ability.
		DR4.1.2		The drone shall fly no higher than 3 meters while the SONAR instrument suite is deployed.
			DR 4.1.2.1	The SONAR instrument shall be connected to the drone through a non-rigid material.
			DR4.1.2.2	The SONAR instrument shall float on top of the water surface with the bottom 2.5 cm of the instrument submerged.
		DR4.1.3		The SONAR instrument shall be capable of sensing depths from 0.5 meters to 3 meters in ideal conditions.
			DR4.1.3.1	The SONAR instrument shall be capable to measure depths to an accuracy of <1% of the total depth in ideal conditions.
		DR4.1.4		The angle between the SONAR instrument pointing ray and the gravity vector shall be measured.
	DR4.2			The instrument suite shall use a stereo camera in order to measure river surface velocities.
		DR4.2.1		While collected velocity data, the drone shall fly no higher than 3 meters above the river surface.
		DR4.2.2		The camera shall be fixed to the instrument suite that is mounted to the drone.
		DR4.2.3		The camera shall be able to sufficiently capture river velocity data between 0-4m/s.

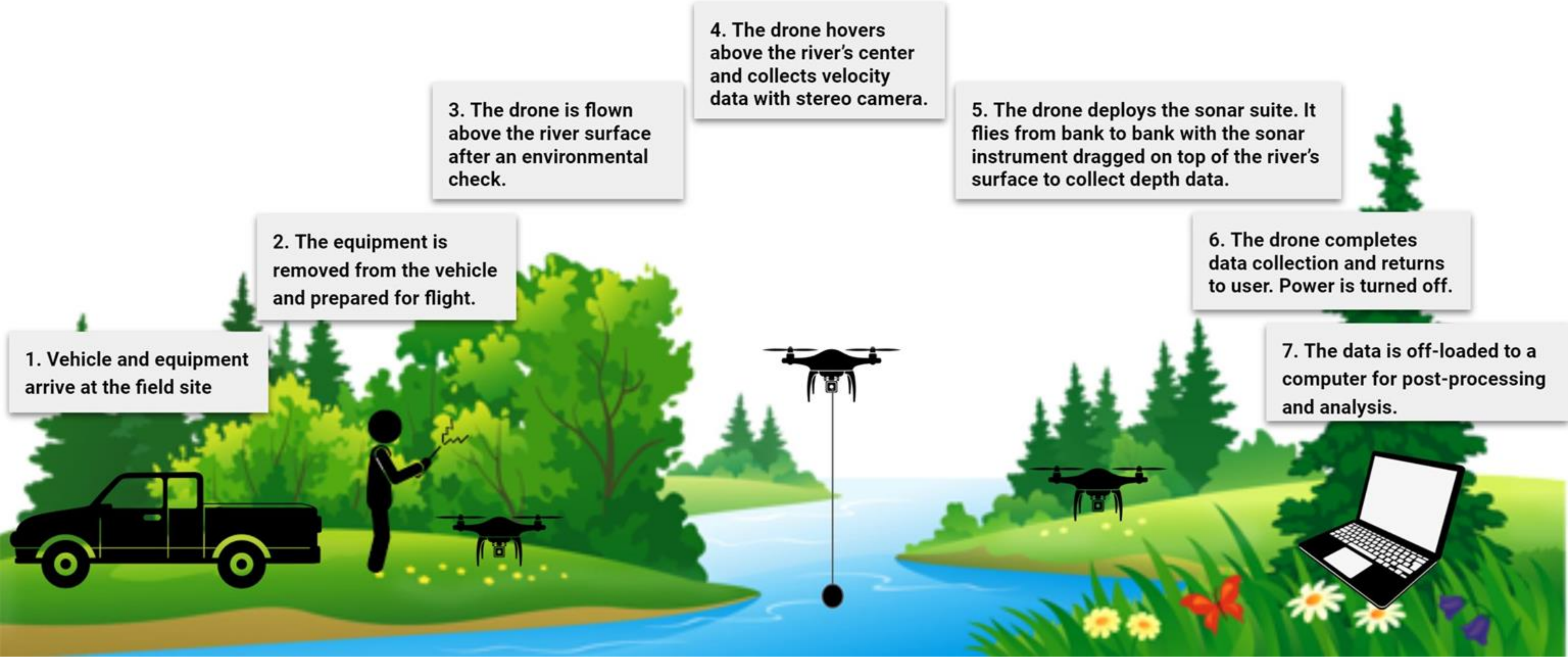
Requirements (3/4)

FR6				**RiBBIT shall be able to power and command all instruments and sensors.**
	DR6.1			There shall be a main computer on the on-board which commands and directs power to all on-board instruments.
		DR6.1.1		The main computer shall be responsible for storing the data collected by the on-board instruments.
	DR6.2			There shall be a micro-controller on the deployed sensor unit which commands and directs power to all deployed instruments.
		DR6.2.1		The micro-controller shall be responsible for storing the data collect by the deployed instruments
	DR6.3			Both the on-board and deloyed sensor units shall include batteries to provide enough power for 5 minutes of continuous data acquisition.
FR7				**The collected data shall be post-processed after data aquisition.**
	DR7.1			The stereo camera data shall be post-processed to calculate river velocties to an accuracy of <10% of the true surface velocity.
	DR7.2			The SONAR data shall be post-processed to model the river cross section.
	DR7.3			The river discharge shall be calculated by the product of the surface velocity multiplied by the area of the river cross section.

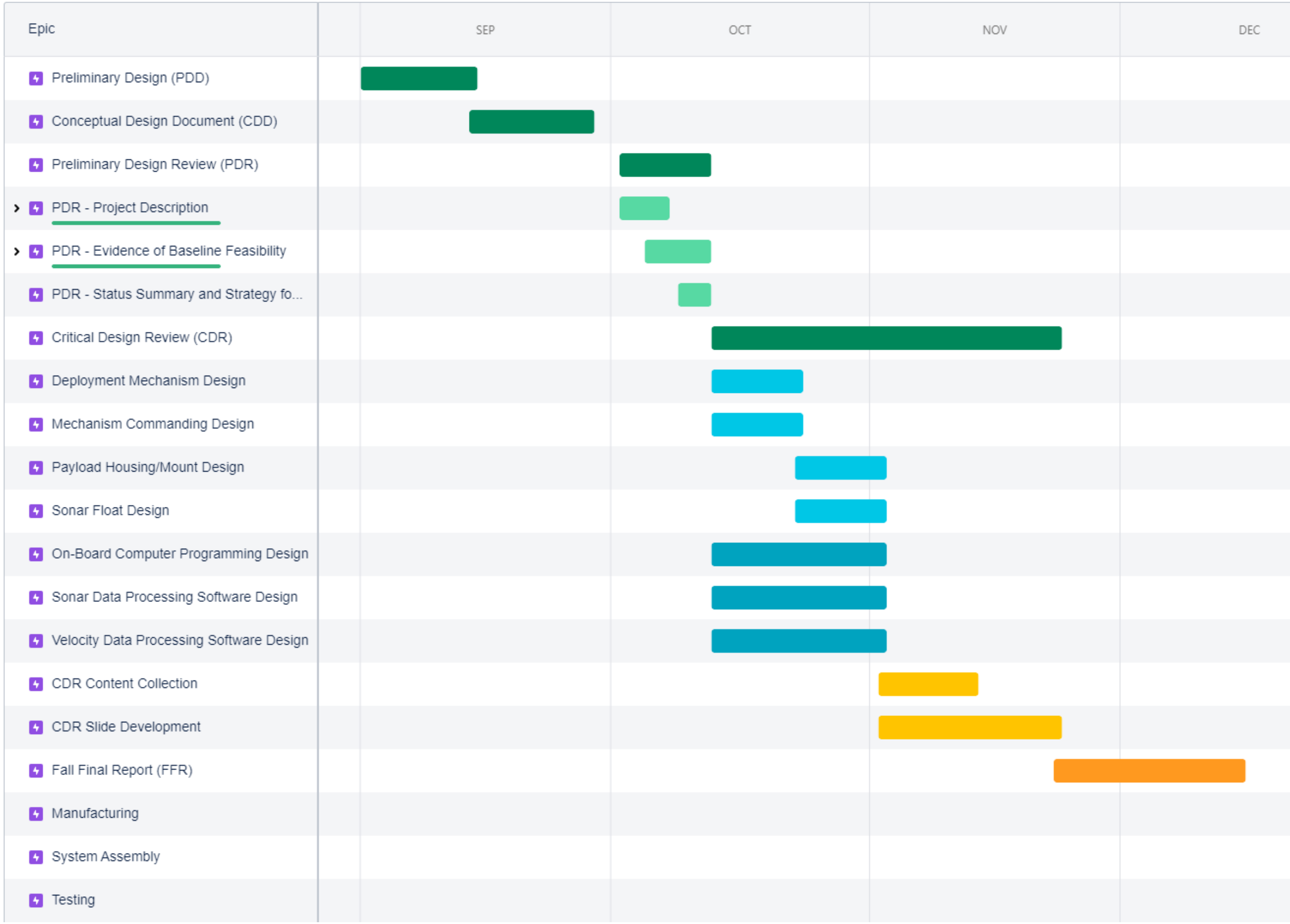
Requirements (4/4)

FR8				**The UAV shall comply with all FAA requirements**
	DR8.1			The flight vehicle shall be operated under all FAA safety regulations
		DR8.1.1		The UAV shall be registered if it weighs more than 0.55 lbs (250 grams).
		DR8.1.2		Unmanned aircraft must weigh less than 55 lbs (25 kg).
		DR8.1.3		UAV shall be flown below 400 feet above ground level at all times.
		DR8.1.4		UAV shall be flown in line of sight.
		DR8.1.5		UAV shall not be flown within 5 mile radius from any active airport/airfield.
		DR8.1.6		UAV shall be flown in daylight-only operations, or civil-twilight with appropriate anti-collision lighting.
		DR8.1.7		The smartphone app B4UFLY shall be referenced before flight to determine airspace restrictions.
	DR8.2			The UAV shall be operated by a person with proper FAA and/or municipal permissions
		DR8.2.1		A person operating a small UAS must either hold a remote pilot airman certificate with a small UAS rating or be under the direct supervision of a person who does hold a remote pilot certificate (remote pilot in command)
	DR8.3			The UAV shall not be operated in any way that may cause harm to any person or property
		DR8.3.1		UAV shall have a safety control in case of emergency to return to pilot.
		DR8.3.2		UAV shall not be flown near or over sensitive infrastructure or property.
		DR8.3.3		All personel shall remain clear of the UAV and not interfere with it's flight.

CONOPS Backup



Fall Schedule



RiBBIT Organizational Chart

Position	**Lead**
Project Manager	Megan Jones
Lead Systems Engineer	Mikaela Dobbin
Manufacturing Lead	Andy Benham
Safety & Regulations Lead	Abdullah Almugairin
Financial Lead	Courtney Gilliam
Avionics Lead	Phil Miceli
Science Lead	Paul Andler
Structural Dynamics	Samuel Razumovskiy
Mechanisms Lead	Abdullah Almugairin
GNC Lead	Daniel Crook
Science Interface and Post Processing Lead	Jessica Knoblock

RiBBIT Organizational Chart

Subsystem	Members
Avionics	**Lead:** Phil Miceli Jessica Knoblock Samuel Razumovskiy Daniel Crook
Science	**Lead:** Paul Andler Courtney Gilliam Andrew Benham Abdullah Almugairin
Structural Dynamics	**Lead:** Samuel Razumovskiy Andrew Benham Abdullah Almugairin
Mechanisms	**Lead:** Abdullah Almugairin Courtney Gilliam Andrew Benham
GNC	**Lead:** Daniel Crook Phil Miceli Megan Jones