University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects - ASEN 4018

Project RiBBIT

River **B**athymetry **B**ased **I**ntegrated **T**echnology

Conceptual Design Document (CDD)

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1 Information

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2 Project Description

2.1 Purpose

Rivers are a critical resource to monitor due to their contributions to agriculture, urban development, hazard monitoring, and environmental monitoring. As global warming persists, the water cycle is a key indicator to track as it links the atmospheric, terrestrial, and oceanic processes [1]. One vital measurement to effectively track this resource is river discharge, or the units of volume per unit time. To calculate this, the river cross-sectional area must be multiplied by the river's velocity [6]. This measurement enables the amount of water available for human consumption or risk mitigation to be quantified. Currently, there is a lack of updated and accurate global data for river discharge, especially in hard-to-access environments. Existing Earth-orbiting satellites simply do not provide the accuracy and precision that in-situ, and UAV-mounted systems can enable [18].

To collect these river measurements, scientists from the United States Geological Survey (USGS) travel the world to collect in-situ river measurements. In the past, these measurements have been collected utilizing a tagline system, pulling a boat across the water with an acoustic depth-sensing instrument and velocity tracker [6]. Alternatively, helicopters towing radar systems have been utilized. However, both of these methods have proven to be expensive and dangerous in certain environments. To solve this problem, a river surveying device shall be designed to enable maximum science output for a portion of the cost of traditional methods.

In correspondence with Steve Nerem, Toby Minear, Jeff Thayer, and the Ann and H.J. Smead Aerospace Engineering Sciences department at CU Boulder, this team shall 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.

2.2 Project Objectives

Project RiBBIT has a number of different project elements that must work in unison to enable a functional and successful project. The levels of success depict the various categories of the project and what constitutes success for each criteria. The levels of success range from level 1 to level 3:

Level 1	Minimum level of success for the project element. If all components reach Level 1 success, the RiBBIT system will be baseline functional.
Level 2	Further development and complexity of project elements, building upon the Level 1 levels of success.
Level 3	Encompasses both Level 1 and Level 2 success criteria. If the project achieves Level 3 success, the project will be fully functional and has achieved all requirements and objectives.

Levels of success are built upon one another, with the mission reaching baseline success at Level 1. In the event of time or budgetary constraints, the higher levels of success may not be accomplished. Each table contains the levels of success for the project subsystems. The rows establish the identified categories for defining levels of success. The columns define the conditions required in order to reach each specified level of success.

Drone

	Level 1	**Level 2**	**Level 3**
Drone Command & Control	- Drone is capable of being flown manually the entire course of the flight.	- Drone is capable of being flown manually the entire flight with commands to correct for wind or other disturbances.	- Drone is capable of using autopilot along a pre-programmed flight path.
Drone Performance	- Drone is capable of carrying payload - Drone is capable of flight time of at least 12 minutes carrying payload	- Drone can fly 12 minutes with 5 minutes of additional flight time for travel	- Drone can fly for 25 minutes.

Figure 1: Drone Levels of Success

Structural and Instrument

	Level 1	**Level 2**	**Level 3**
Depth Sensing	- Instrument system can measure river depths of 0.5m-3m in ideal conditions to an accuracy of <1% of the total depth	- Instrument system can measure river depths of 0.5m-3m in ideal conditions to an accuracy of <0.75% of the total depth. - Instrument can measure river depths to 3-5m in ideal conditions with an accuracy of <1% of the total depth.	- Instrument system can measure river depths to 0.5m-3m in ideal conditions to an accuracy of <0.5% of the total depth. - Instrument can measure river depths to >5m in ideal conditions with an accuracy of <1% of the total depth.
Velocity Measurements	- Instrument system can sufficiently capture surface velocity of 0m/s-4m/s.		
Instrument Positional Measurements	- The instrument system can know its relative horizontal position to an accuracy of +/-3 cm and its vertical position to an accuracy of +/-4 cm using RTK or PPK.	- Inclusion of GNSS receivers on both the drone and sensor suite.	- Inclusion of ground control points or use of advanced base station localization techniques such as truthing to survey landmarks.
Drone Mount	- Instrument suite can be mounted to the selected drone.	- Instrument suite can be mounted to an additional drone with appropriate carrying capacity.	- Instrument suite can be mounted to multiple drones with appropriate carrying capacity.

Figure 2: Structural and Instrument Levels of Success

Software and Electronics

	Level 1	Level 2	Level 3
Data Handling	- All data is stored in on-board memory		
Power	- All onboard sensors shall be powered at minimum for the flight duration of 720 seconds	- All onboard sensors shall be powered for 720 seconds with reserve charge	- Drone shall be able to draw upon reserve sensor suite power under necessary conditions
Velocity Data Post Processing	- The river is modeled as a flat plane. - The velocity of the flow is the horizontal component of true velocity.	- The river is modeled as a 3D surface. - The velocity of the flow is the horizontal component of true velocity.	- The river is modeled as a 3D surface. - The velocity of the flow is the true velocity. [See appendix section 7.1 for schematic of flow velocity components].
Data Verification and Validation	- River velocity and depth profile data shall be compared to in-situ measurements to observe system accuracy.	- Depth profile data shall be compared to that collected by AstraLite.	- Ground control points shall be collected and integrated into the depth profile model to ensure the model is accurately georeferenced (exact accuracy TBD).

Figure 3: Software and Electronics Levels of Success

DEFINITIONS:

- Bathymetry - The study of the beds or floors of water bodies, including oceans, rivers, streams, and lakes.
- Ideal Conditions - According to the USGS, ideal river surveying conditions are defined as "a smooth, mirror-like water surface with steady, uniform, non-varying flow conditions in the stream reach where the discharge measurements will be taken." [6]
  More specifically, the river needs to:
  - be a "reasonably straight channel with streamlines parallel to each other."[6]
  - have a "stable streambed free of large rocks, weeds, and obstructions that would create eddies, slack water, and turbulence."[6]
- Payload - Includes any attachment to the drone including the instrument suite and any additional mounting materials.
- Instrument system - Refers to the instrument and any associated mechanisms being used to capture the measurement defined by the row category.
- Instrument suite - Includes all instruments, electronics, any associated mechanisms, and housing.
- GNSS - Global Navigation Satellite System
- RTK - Real-Time Kinematic
- PPK - Post-Processed Kinematic
- Data - Defined by bathymetric data, velocity capture images, and positional data from GNSS receivers.
- AstraLite - Company which specializes in drone-mounted LiDAR systems used for bathymetric modeling.

2.3 Concept of Operations

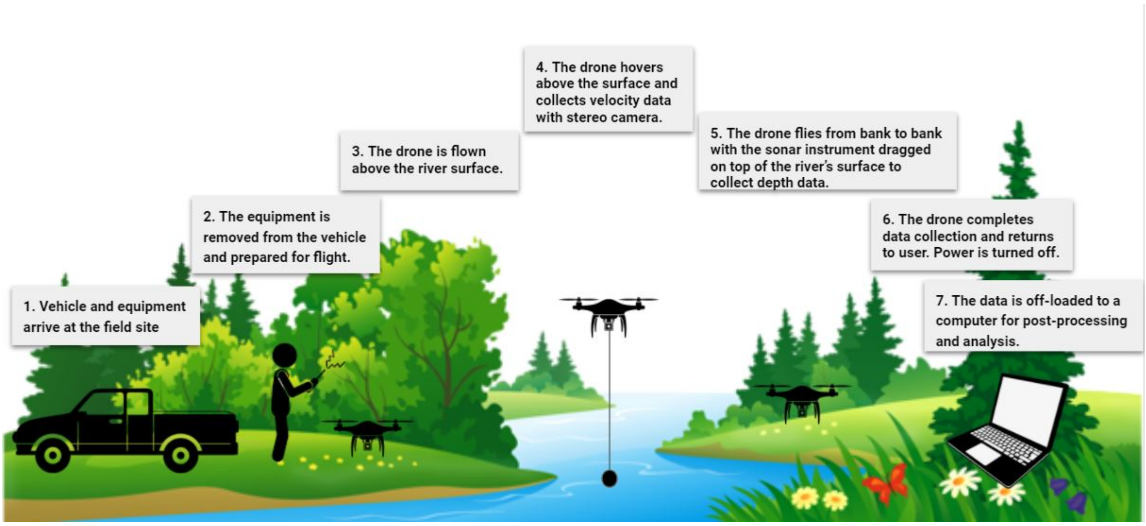

Figure 4: RiBBIT Concept of Operations

The purpose of this mission is to provide a low-cost, light, and long-range drone with mounted sensors to enable river discharge and bathymetric data collection. Figure 4 shows the expected mission procedures of the RiBBIT system. The mission begins with a set-up period where the vehicle and equipment arrive at the river site. The drone and sensor system are then prepared for flight by qualified personnel. The drone shall be elevated to TBD altitude and flown from riverbank to riverbank, perpendicular to the stream flow. While in flight, the sensor package shall collect river discharge and bathymetric data. The collected data will be saved on-board. Once the system has completed the data collection phase, the drone will be flown back to the user, and the system will be powered off. After the data collection has been conducted, the data shall be off-loaded to a computer. Post-processing of the data shall be carried out to ensure the data is in the format necessary for customer use.

2.4 Functional Block Diagram

The functional block diagram in Figure 5 below depicts the connections between the ground segment, drone, and the instrument suite.

The ground segment consists of a stationary GNSS Base Station, a visual observer, and the pilot. The stationary GNSS Base Station will receive positional data from the GNSS satellites. The Visual Observer will have their eyes on the environment surrounding the drone to mitigate the risk of damaging the drone or instrument suite such as hidden tree branches or river debris. The Pilot will be operating the drone through the survey campaign. To do this, the Pilot will use Mission Planner software which comes with the drone. Next, the drone itself will be purchased ready to fly. Shown in this category are the components built in to the drone that the team may need to interface with. There will be a mechanical connection for the instrument suite to mount with the drone.

The instrument suite is broken up into two sections: the On-Board Sensor Unit, and the Deployable Sensor Unit. The On-Board Sensor unit will include an Arduino Mega as the main computer, which is connected to a battery for power supply. The Mega is connected to a stereo camera to capture velocity measurements as well as a GNSS Receiver for positional Data. Additonally, the Arduino Mega will be connected to a wireless data receiver which will receive transmitted data captured by the Deployable Sensor Unit. The Mega will store all the instrument data to an on-board SD card. The On-Board Sensor Unit will have a mechanical connection to the Deployable Sensor Unit which may be controlled by an actuator. The Deployable Sensor Unit will be below the drone in order to safely make contact with the water surface.

The Deployable Sensor Unit will consist of a small micro-controller and battery which will be connected to the SONAR instrument for river depth measurements. The micro-controller will also be connected to a GNSS receiver for additional positional data. Finally, the micro-controller will be connected to a wireless data transmitter which will transmit the data to the data receiver on the On-Board Sensor Unit.

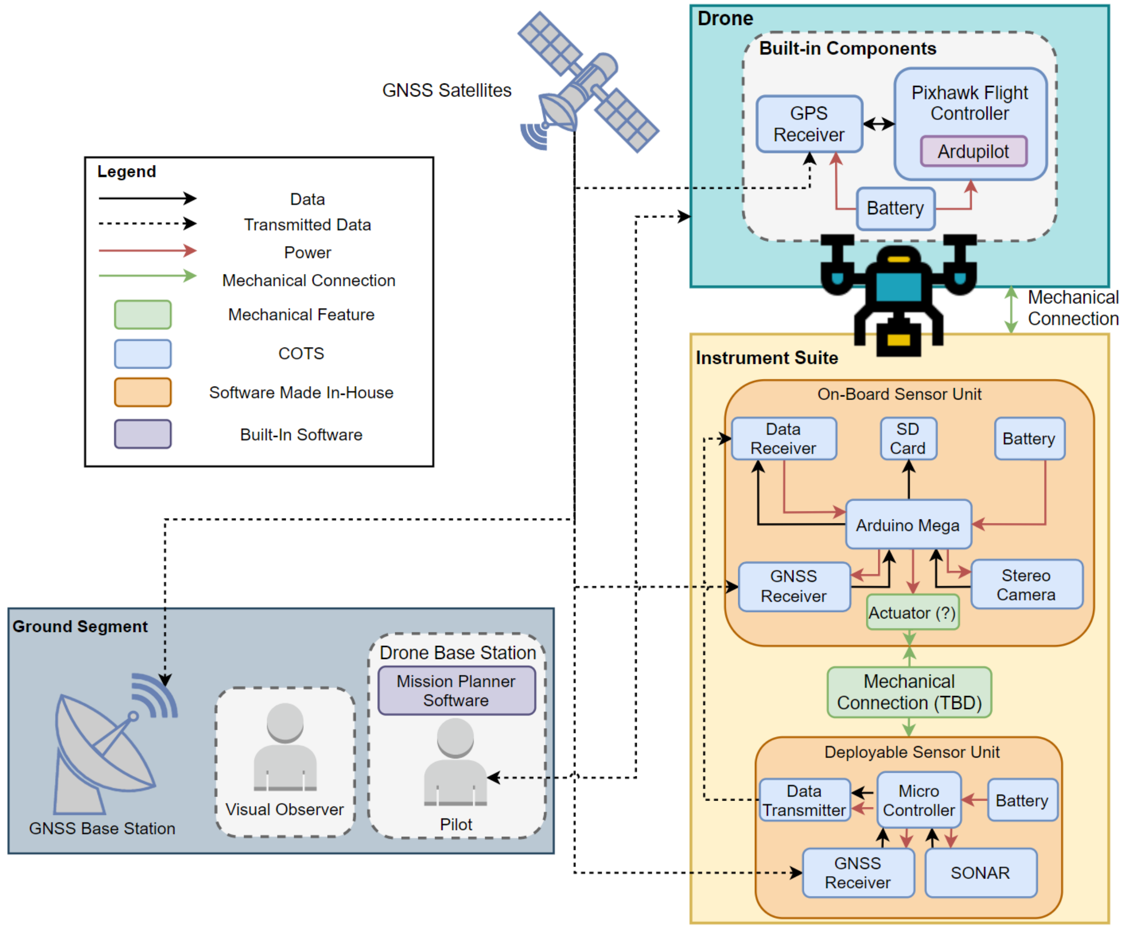

Figure 5: Functional Block Diagram

2.5 Mission (Functional) Requirements

The following outlines the high level functional requirements that were derived from the project objectives. These functional requirements will be the basis of the requirement flow down, steer what trade studies will be conducted, and inform the testing to be completed.

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

Motivation: This comes from the need that the system must be able to travel to various locations via car, helicopter, plane, or on-foot.

FR2. RiBBIT shall be able to operate in difficult to access river locations.

Motivation: This refers to locations that are difficult or dangerous for humans to physically get to the river bank, such as canyons and areas with restricted human access. The drone would avoid these complications by being able to fly over/around obstacles.

FR3. RiBBIT shall include an instrument suite payload that is able to mount with the Tarot 650 V2.1.

Motivation: This requirement is driven by the fact the instrument suite must be able to be mounted to the selected drone.

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

Motivation: In order to measure river discharge, RiBBIT must profile the cross section of the river by measuring water surface level, width, and river depth perpendicular to the current as well as the water flow rate.

FR5. The instrument suite shall be capable of measuring its position.

Motivation: This requirement comes from the need to know where the system is capturing its data for additional correction and error estimation.

FR6. RiBBIT shall include an electronics suite responsible for storing the data collected by all on-board sensors and instruments.

Motivation: This requirement is driven by the need to have a central computer of the instrument suite which controls and stores the data captured by the instruments.

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

Motivation: This requirement is specifies that the on-board computer will not be calculating river discharge simultaneously with the data acquisition.

FR8. The UAV shall comply with all FAA requirements.

Motivation: This requirement ensures that the UAV will be safe to fly for both the community and the team.

3 Design Requirements

The following table specifies the functional requirements and the derived design requirements. The nested structure depicts flow down of the functional requirements to the associated children requirements.

Requirement ID				Requirement	Rationale	Verification Method
FR1				**RiBBIT 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.	Customer informed flight time in order to obtain adequate river data for each survey campaign.	The drone flight is timed with simulated payload weight.
	DR1.2			The flight vehicle shall have a minimum carrying capacity of 1.5 kg.	Vehicle must be able to carry the payload.	The drone operation is tested with simulated payload weight.
	DR1.4			There shall be visual observer to monitor the environment that the drone is flying in.	To reduce risk of damaging or loosing the instrument suite or drone.	An individual is always present to watch the drone surrounding during flight.
	DR1.5			The surveyor shall choose river cross sections with open sky and minimal tree obstruction.	In order to maximize GPS data with minimal interference and multipathing.	The survey location is evaluated prior to survey.
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 650 V2.1.**		
	DR3.1			The payload shall be have a maximum weight of 1.5kg.	In order to not exceed the carrying capacity of the flight vehicle.	The payload is weighed.
	DR3.2			The instruments shall be composed of commercial off the shelf components.	Allows for an affordable system with primary focus on instrument function and integration.	The instruments are bought, not made.
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.	The project will be using SONAR in order to capture the depth profile of a river cross section.	The depth sensing instument is a SONAR instrument.
		DR4.1.1		The SONAR instrument shall be suspended below the drone for data collection to make contact with the water.	SONAR must be in contact with the water to take measurements and it is a large risk to have the drone too close to the water.	The depth sensing instrument is suspended below the drone when data is being collected.
			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.	To ensure proper data capture.	Dependent on the deployment mechanism and float and will be accomplished through sonar housing design.
			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.	To mitigate the risk of damaging drone.	When simulated excessive force is applied to the drone, the suspended instrument breaks away.
		DR4.1.2		The SONAR instrument shall be capable of sensing depths from 0.5 meters to 3 meters in ideal conditions.	Minimum depth range to encompass many rivers.	The SONAR instrument is tested in control pools with known water depth.
			DR4.1.2.1	The SONAR instrument shall be capable to measure depths to an accuracy of <1% of the total depth in ideal conditions.	Customer provided depth accuracy requirement.	The SONAR instrument is tested in control pools with known water depth.
		DR4.1.3		The angle between the SONAR instrument pointing ray and the gravity vector shall be measured.	In order to properly calculate and calibrate the SONAR data.	The deployable unit shall have a sensor to measure this angle.
	DR4.2			The instrument suite shall use a stereo camera in order to measure river surface velocities.	The project will be using stereo cameras to measure surface velocity.	The velocity measuring instrument is a stereo camera.
		DR4.2.1		The camera shall be fixed to the instrument suite that is mounted to the drone.	The camera will survey the river water from the drone.	The camera is rigidly attached to the mounted instrument suite.

		DR4.2.2		The camera shall be able to sufficiently capture river velocity data between 0-4m/s.	Customer provided river velocity range.	The camera is tested with smooth water and known velocities.
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.	GNSS receivers on-board will enable more accurate models to be generated for river velocity and depth.	Test and validate against ground truth data points.
		DR5.1.1		The instrument suite shall be capable of knowing its horizontal position with an accuracy of +/- 4 cm in ideal conditions.	Desired accuracy to minimize error.	Test and validate against ground truth data points.
		DR5.1.2		The instrument suite shall be capable of knowing its vertical postion with an accuracy of +/- 5 cm in ideal conditions.	Desired accuracy to minimize error.	Test and validate against ground truth data points.
FR6				**RiBBIT shall include an electronics suite responsible for storing the data collected by all on-board sensors and instruments.**		
	DR6.1			The electronics suite shall have a main computer.	In order to distribute power, control sensors, and store data.	The main computer controlls data acquisition for all sensors, data is verified on SD card.
		DR6.1.1		The main computer shall provide power to the instruments and sensors.	In order to distribute power among components.	Power to the instruments is correctly provided.
		DR6.1.2		The main computer shall store the collected data from the instruments.	In order to store captured data in a desired format	Data for instruments on SD card is verified as expected.
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.	The desired accuracy for the calculated surface velocity.	Calculated velocitiy is verified against external sensor measurements.
	DR7.2			The SONAR data shall be post-processed to model the river cross section.	The SONAR data will need to be processed in order to model and calculate tha area of the river cross section.	Verified by known river cross section data by external sources.
	DR7.3			The river discharge shall be calculated by the product of the surface velocity multiplied by the area of the river cross section.	The river discharge is defined by the area of the cross section multiplied by the streamflow.	Verified by known river discharge data by external soures.
FR8				**The UAV shall comply with all FAA requirements**		
	DR9.1			The flight vehicle shall be operated under all FAA safety regulations	In order to make sure that the UAV complies with FAA	Flight procedures will be written and followed for all flight tests and survey campaigns.
		DR9.1.1		The UAV shall be registered if it weighs more than 0.55 lbs (250 grams).	In order to make sure that the UAV complies with FAA requirements.	The UAV shall be registered prior to any usage.
		DR9.1.2		Unmanned aircraft must weigh less than 55 lbs (25 kg).	In order to make sure that the UAV complies with FAA	The UAV system shall be weighed prior to usage.
		DR9.1.3		UAV shall be flown below 400 feet above ground level at all times.	In order to make sure that the UAV complies with FAA requirements.	The UAV shall be monitored and will not fly above 400 feet from the ground.
		DR9.1.4		UAV shall be flown in line of sight.	In order to make sure that the UAV complies with FAA requirements.	The pilot shall not loose view of the UAV.
		DR9.1.5		UAV shall not be flown within 5 mile radius from any active airport/airfield.	In order to make sure that the UAV complies with FAA requirements.	The safety lead shall verify that any survey or test location is not within 5 miles of any active airport/airfield.
		DR9.1.6		UAV shall be flown in daylight-only operations, or civil-twilight with appropriate anti-collision lighting.	In order to make sure that the UAV complies with FAA requirements.	The pilot shall not loose view of the UAV.

		DR9.1.7		The smartphone app B4UFLY shall be referenced before flight to determine airspace restrictions.	In order to make sure that the UAV complies with FAA requirements.	The pilot, visual observer, and safety lead shall reference this app prior to any UAV usage.
	DR9.2			The UAV shall be operated by a person with proper FAA and/or municipal permissions	In order to make sure that the UAV complies with FAA requirements.	The safety lead shall gather all permissions, both univerisity and municipal prior to any UAV usage.
		DR9.2.1		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)	In order to make sure that the UAV complies with FAA requirements.	The pilot shall be a liscened drone pilot cetified to fly the Tarot 650 V2.1.
	DR9.3			The UAV shall not be operated in any way that may cause harm to any person or property	The system cannot injure any teammembers, community members, or property.	Flight procedures will be written and followed for all flight tests and survey campaigns.
		DR9.3.1		UAV shall have a safety control in case of emergency to return to pilot.	In order to make sure that the UAV complies with FAA requirements.	The Tarot 650 V2.1. drone includes this feature.
		DR9.3.2		UAV shall not be flown near or over sensitive infrastructure or property.	In order to make sure that the UAV complies with FAA requirements.	The drone shall only be flow in open spaces with no infrastructure in view.
		DR9.3.3		All personel shall remain clear of the UAV and not interfere with it's flight.	The system cannot injure any teammembers, community members, or property.	Flight procedures will be written and followed for all flight tests and survey campaigns.

4 Key Design Options Considered

4.1 Bathymetry Technique

As previously discussed, calculating river discharge involves two quantities: area and velocity. Bathymetry is concerned with the cross-sectional area of the river. The National Oceanic and Atmospheric Administration (NOAA) defines Bathymetry as "...the study of the "beds" or "floors" of water bodies, including oceans, rivers, streams, and lakes." [11].

When it comes to the technology used to measure the depth of a body of water one has to factor in not only the cost, weight, and size of the sensor unit but also the accuracy and usability. For the application of having a UAS mounted system, three depth sensing technique options were considered. These include LiDAR (light detection and ranging), SONAR (sound navigation and ranging) and ADCP (Acoustic Doppler Current Profiling). ADCP is similar to SONAR in the way it would be implemented, but it has the additional ability to measure flow velocity. The major difference between the three systems is the fact that LiDAR does not require contact with the water while Sonar and ADCP instruments do. The Sonar and ADCP instruments must be immersed under the surface, adding another level of complexity to the whole system. This approach would require developing a method of sensor package deployment, but a LiDAR system could easily be flown over the water while mounted on the drone.

4.1.1 LiDAR

Light detection and ranging, more commonly known as LiDAR, works by emitting pulses of light waves that bounce off of surrounding objects and return to the sensor. The sensor uses the time taken for the pulses to return to the sensor to calculate the distance from the sensor to the surrounding objects. Most commercial LiDAR systems use lasers that operate in the infrared spectrum mainly due to their availability. However, for bathymetric applications it is critical to have a LiDAR system that operates in the correct spectrum of 532 nm (green). This is because water absorbs different colors of light at very different rates. Infrared wavelengths can barely make it past the water's surface because wavelengths in this spectrum are absorbed the fastest. In contrast, green is absorbed the least by water. Systems using this type of laser are able to take accurate measurements up to a depth of 20m.

4.1.1.1 RIEGL BDF-1 Laser Range Finder

The RIEGL BDF-1 is a laser range finder specifically designed for bathymetric surveying. The device is intended to collect river profile data when operated from a UAV at low altitudes. The scanner sends out laser pulses of 532nm at a rate of 4 kHz. Optional features for this device include lens tilt compensation, an embedded GNSS-inertial system, and external digital cameras. The scanner produces highly accurate and reliable data. The downside of this system is the weight and the cost. The sensor weighs approximately 5.3kg and the cost of over 10,000 dollars exceeds the entire project budget. This would be an ideal sensor system to achieve the project's goals, but it is not a realistic candidate.

Figure 6: RIEGL BDF-1

Pros	Cons
Does not require in-situ deployment	Expensive
Integrated IMU, GNSS, and data storage unit	Heavy for a drone to carry
Can measure up to 50m in depth	Can only measure a minimum depth of 1m
Approximate accuracy of 20mm	Measurement accuracy is heavily dependant on water clarity
High data collection rate	
Comes with up to two external cameras	
532nm Laser wavelength	
Designed for UAV/drone mounting	

4.1.1.2 RIEGL VQ-840-G Laser Scanner

The RIEGL VQ-840-G is a laser scanner designed for bathymetric and topographic UAV-based surveying. The device sends out 532nm laser pulses at a rate of 50 kHz to 200 kHz. The scanner is highly accurate and has a number of optional features including an inertial navigation system, an infrared rangefinder, and an integrated digital camera. The downside of this product is that it was made for larger UAVs, weighing approximately 12kg. In addition, this sensor is far out of budget by about eight thousand dollars, and therefore not a sound candidate for the purposes of this project.

Figure 7: RIEGL VQ-840-G

Pros	Cons
532nm Laser Wavelength	Expensive
Integrated inertial system navigation	Heavy
Accuracy of approximately 20mm	Minimum depth measurement range of 20m
Optional integrated digital camera	

4.1.2 SONAR

SONAR, also known as sound navigation and ranging is an acoustic technique primarily used to measure distances underwater. There are two main types of sonar. One being passive and the other active. The difference between them is that the passive sonar only listens while the active sonar sends out bursts of sound known as 'pings' and then listens for the echo. Distance is calculated by starting a timer when the ping is sent and stopped when the echo is received. Given the time and the speed of sound in water, the distance is calculated inside of the unit. Active sonar is most useful for bathymetric applications as a ping is required for distance measurements.

4.1.2.1 BlueRobotics Ping Sonar

The Ping sonar by BlueRobotics is a great option for applications in bathymetric surveys for a multitude of reasons, the first of which being its price. Coming in at under 300 dollars, it is a sensor package comfortably within budget. Furthermore, with its measurement range being from 0.5m-30m, this device is able to cover the set levels of success for depth as well as accuracy according to the manufacturers value of 0.5%, as a function of depth. In addition, it does not employ any optical techniques. Therefore, the system is nearly unaffected by turbid water. Due to its small size and weight, this sensor only requires a smaller drone to lift. Finally the unit can also interface with Arduino, C++ and Python libraries, allowing for simple data handling and analysis.

Figure 8: Blue Robotics Sonar

Pros	Cons
Highly accurate and large depth measurements (up to 30m)	Requires surface level in-situ deployment
Minimally dependant on water clarity	Cannot measure flow velocity
Cost efficient	
Extremely light weight	
Easy data handling with provided libraries	
Fully Water proof up to 300m	
Included bottom tracking	

4.1.2.2 Allied SICK UM-30

Similar to the ping echo sounder, the Allied SICK UM-30 also uses SONAR to take distance measurements. The one advantage that it has over the Ping sonar is a minimum measurement threshold of 0.1m. It also has a low purchase price of $370 as well as a light weight and form factor. That being said, after consulting with the manufacturer it became apparent that the maximum depth it can measure is approximatly 1m.

Figure 9: Allied ultrasonic sensor

Pros	Cons
Highly accurate	Requires surface level in-situ deployment
Minimally dependant on water clarity	Cannot measure flow velocity
Cost efficient	Very limited underwater range
Extremely light weight	Only IP67 rated (water proof for 30 min at 1m)
	Unknown difficulty for data handling

4.1.3 ADCP

An Acoustic Doppler Current Profiler (ADCP) uses active sonar to measure the depth of the river. An ADCP contains additional transducers to emit sound pings and measures the Doppler shift of the returning pings to calculate the instantaneous velocity of the entire column beneath the instrument [12],[14]. An ADCP is the preferred method of the US Geological Society for preforming Bathymetric surveys as it is essentially an 'all in one' instrument [6]. ADCPs come in a wide variety of sizes, some of which can measure depths of 6000+ meters for surveying of the ocean floor from boats. Some are designed to withstand immense pressures and are attached to buoy's that are sunk to various depths in the ocean. Project RiBBIT is interested in ADCPs that are normally attached to Unmanned Surface Vehicles that are traditionally used in bathymetric river surveys.

4.1.3.1 Sontek RiverSurveyor M9

The RiverSurveyor M9 is an extremely powerful, compact ADCP. It comes with a built in temperature sensor, compass/tilt sensor, and internal storage. It weighs approximately 2.3kg in air with a velocity profiling range of 40m. This is under its own power supply which consists of standard AA batteries that give it up to 8 hours of continuous operation. The cost of this device ccosts over $15000.

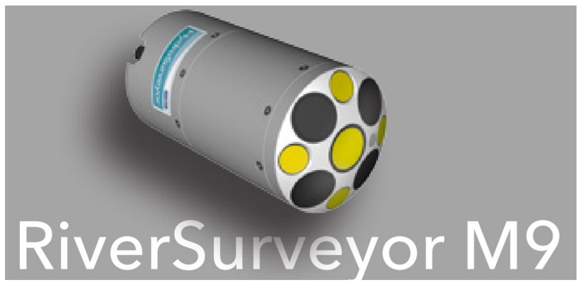

Figure 10: The Sontek RiverSurveyor M9

Pros	**Cons**
Large depth range [80m]	Requires in-situ deployment
No post-processing analysis required	Expensive [$15k+]
Can measure column flow velocity below device	No measurement of surface velocity
Low minimum depth measurement threshold [0.2m]	2.3kg

4.1.3.2 Rowe Technologies OEM

The OEM is a customizable ADCP package from Rowe Technologies and was likely the best candidate for this project were it in budget. Many ADCPs have capabilities that far exceed what is realistically needed for our project. Since the OEM is customizable it could have been tailored much more closely to our requirements. This also makes it the cheapest option as it wouldn't come with anything that wasn't specifically for our mission. However, this package is out of our budget and costs a minimum of $12000.

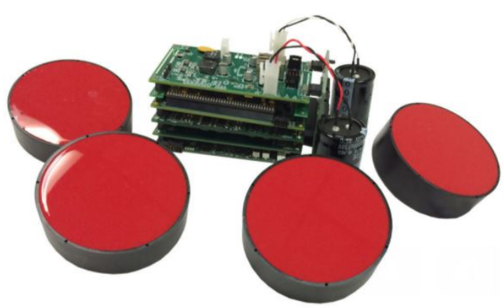

Figure 11: The Rowe OEM package

Pros	Cons
Customizable	Expensive [$12k after student discount]
Low minimum depth measurement threshold [0.2m]	No measurement of surface velocity
Can measure column flow velocity below device	
No post-processing analysis required	

4.2 Deployed SONAR Float Angular Displacement Correction Technique

Following the trade study of various bathymetry techniques, it was clear that sonar is the most affordable and realistic option to pursue with regards to the project requirements. As this technique requires contact on the river surface, a deployable sensor unit shall be developed. This floating sensor unit needs to enable effective data collection of the sonar instrument, which requires the instrument to be partially submerged in the water, pointing downwards. The floating mechanism can either be weighted to ensure direct downward facing of the instrument, a gyroscope can be installed to enable post-processing to get the proper depth measurements, or the sensor could be installed inside of a gimbal that is attached to the float in order to keep it pointing downward.

4.2.1 Weighted Float Technique

This design option considers weighing the float in a way similar to how a sailing boat is, increasing its stability in the water. This specifically being a weighted keel device underneath the float which lowers the system's center of gravity, therefore increasing its stability and resistance to waves and other disturbances that may change the float's relative angle to the gravity vector. While this system is simple, affordable and passive in its function, there are certain drawbacks to using it. The advantages and disadvantages are shown in the table below.

Pros	Cons
Cheap	Very Heavy (sailing boat's keels are 40% their overall weight)
Passive	Only dampens angular displacement
	Creates more drag due to higher surface area

4.2.2 Post-Processing Technique

In this approach, there is no extra weight added to the float with an exception of a 2-axis gyroscope that can interface with the same data logging computer that the sonar is communicating with. If the angle of the sonar unit is known at all times, any gravity vector angle deviation that it may experience during data collection could be corrected for in post-processing, using simple trigonometric relations.

Pros	Cons
Cheap and light (<5g)	Adds extra step to post-processing
Provides full solution	
Low complexity	
Produces no extra drag	

4.2.3 Gimbal Technique

This solution considers the sonar sensor mounted inside of a gimbal that is attached to the float. The gimbal would be able to correct, in real time, any disturbances that the sensor may be subjected to by the flow. This would require no extra work during post-processing the data. The down side, however, is that the gimbal would have to be water proofed and would be rather heavy, weighing approximately 250g.

Pros	**Cons**
Is a complete solution	Heavy Complex Expensive Produces extra drag Has to be actively controlled

4.3 Sonar Deployment Mechanism Technique

Following the science instrument trade study, it was identified that the sonar instrument is most optimal for collecting river depth measurements. To enable data collection, the sonar needs to be deployed from the instrument suite mounted on the drone to contact the river's surface. The mechanical and software interfacing necessary to command this mechanism is also an important consideration. The options for the deployment mechanism are outlined below. All of the options, except for the last, would require a line connecting the sonar suite to the mounted instrument suite. The material options for this feature are presented in the table below, acknowledging there are many other options and thicknesses that could be pursued.

Figure 12: Deployment Line Material Options

Material	**Weight**	**Cost**	**Diameter**	**Max Weight Capacity**
Fishing Line	1.14 g/m	\$0.21/m	0.26mm	6.8kg
Cable	23.3 g/m	\$0.98/m	2.38mm	45kg
Rope	153 g/m	\$0.78/m	9.52mm	167.98kg

4.3.1 Hanging Cable System

This option outlines if RiBBIT decides to have the sonar hanging from a cable with no controlled deployment mechanism on the primary instrument-suite. The cable would be connected to the main instrument payload with a carabiner attached to a custom hook. The hook would have the ability to be commanded by the drone pilot (through connection to the on-board flight controller) to release the attached payload in case of emergency. The arrow in the figure below depicts the opening of the hook once the flight pilot has deemed the situation dangerous, thus sending a command to the on-board flight controller to drop the payload. This option would remove the additional complexity required if a mechanical rappelling system were pursued.

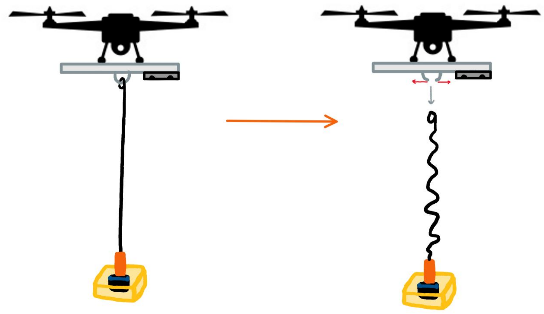

Figure 13: Hanging Cable Deployment Mechanism

Pros	**Cons**
Cheap Mechanically simple, not much design work necessary	Not compact for flight Potential of getting snagged May get in way of stereo camera data collection Uncertain cost

4.3.2 Cable Rappelling System

Another option to be pursued would be a mechanical system to coil the cable connected to the sonar float so that it is initially compact with the instrument unit. After the drone has flown over the river, the drone pilot would flip a switch to initiate a command to smoothly deploy the cable to drop the sonar suite to the water's surface. The drone would fly bank to bank to enable data collection and then the switch would be flipped to coil the payload back up to the main instrument suite. This sonar deployment mechanism would be a more mechanically challenging system to pursue.

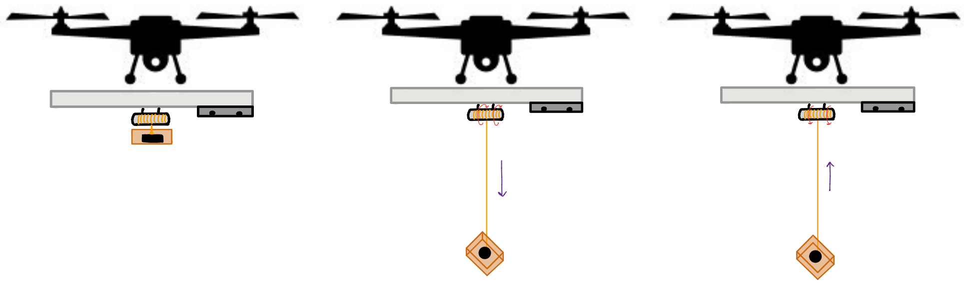

Figure 14: Cable Rappelling Deployment Mechanism

Pros	Cons
Enables compact payload during flight to field site	Mechanically complicated
Would enable sonar float to not be in FOV of stereo camera	Uncertain cost

4.3.3 Tarot X6 Payload Release Drop Mechanism

The Tarot X6 Payload Release Drop Mechanism is designed for dropping payloads carried on the Tarot X6 drone. The payload drop is initiated with the click of a button on the Tarot X6 remote controller. If this option were pursued, the drop would likely not be a gradual descent into the water but a free fall. Once the unit was dropped, bringing it back up would not be easily pursued, so the flight vehicle would need to return to the pilot with the sonar unit deployed below. This option would only be utilized if the Tarot X6 drone is chosen as the flight vehicle. The product includes the payload release drop mechanism, mounting onto the drone, the setup, and the configuration with the controller. The cost of this mechanism is $249.99 USD.

Figure 15: Tarot X6 Payload Release Drop Mechanism

Pros	Cons
Easy to integrate with Tarot X6 Drone	Fully dependant on drone choice
Controlled via Tarot X6 controller	Mechanism is only foundation, more components would
High weight carrying/drop capacity (5kg)	need to be added for smooth sonar release/retrieval

4.3.4 Rigid Sonar Deployment System

A rigid deployment option, unlike the others previously mentioned, would not include a line being dropped from the main payload to the river surface with the attached float. Instead, it would consist of a retractable pole with the sonar instrument at the end of the mechanism. The drone pilot would flip a switch and a command would result in the pole to retract down to the river surface. The drone would fly from bank to bank and once adequate data has been collected the mechanism would retract back up for the return flight.

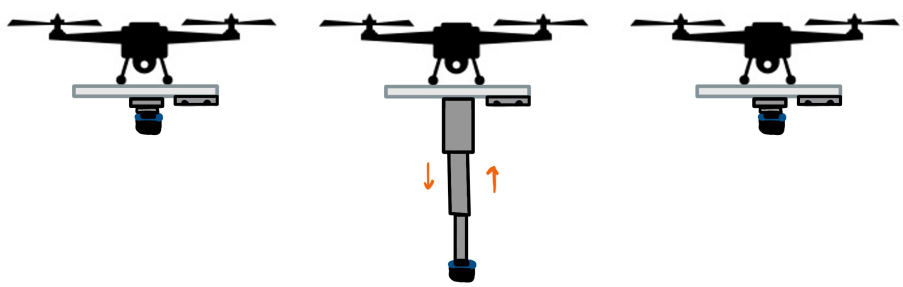

Figure 16: Rigid Sonar Deployment Mechanism

Pros	Cons
Would keep sonar payload steady	More complications in moment generation
Removes need for float	Likely heavier than line
	Complicated mechanical system

4.4 Velocimetry Technique

With ADCPs being very expensive, the velocity calculation of river discharge must still be addressed. However, this left the team with a predicament; if the velocity can't be known as a function of depth then how can discharge be accurately calculated? Luckily, non-contact methods for river discharge have been an active area of research in recent years. The methods primarily revolve around relating the river surface properties to an assumed depth averaged flow velocity to yield the velocity component of discharge [10],[8].

There are three techniques that were considered; the simplest was a optical camera to record the height of the river at a given cross section. The other two fall within what seems to be the direction of industry and use Large Scale Particle Image Velocimetry (LSPIV) to calculate the surface flow velocity. Essentially these work by taking a series of images at a known distance and angle above the water's surface. These images are then post processed where specific points on the waters surface are tracked to find the difference from each frame. The displacement of tracked particles coupled with the camera's viewing angle and distance above the water allows for a velocity calculation to be made across the width of the river [10],[8]. Three LSPIV techniques were analysed; a thermal technique, a stereoscopic technique, and a stereoscopic/structured light RGB camera combo.

Technique	Pros	Cons
Optical	Simple data collection Low power Inexpensive	Large systematic error Low resolution Manual Post-processing
Thermal	Creates time average surface velocity field Software, customer support for post-processing	Expensive Heavy No surface depth information
Stereo	Inexpensive Light weight Creates time averaged surface velocity field Measures surface depth characteristics More accurate for mountain rivers	No native LSPIV software Relatively new technique

4.4.1 Optical Camera

In researching non-contact discharge calculations the team came across a study by the University of Southampton published in Computers Geosciences (see [25]). The purpose of the study was to test the use of cameras for monitoring discharge in a glacial river. The scientists used an older line of the Brinno Time Lapse cameras, the TLC100, to take images of the river. Their choice in cameras was justified by the fact that it was inexpensive and designed to be used for unattended battery operation. The study utilized edge detection software to find image coordinates of the water margins, and combine those coordinates into a flow estimate. The image processing and camera calibration introduced large amounts of systematic error; however, the findings of the study determined that cameras could be used to make meaningful discharge estimates. The measurements taken for one river, however, could not be accurately compared to measurements collected for another river. But collected data could be compared over time for the same river location in order to detect relative changes in discharge.

4.4.1.1 Brinno Time Lapse Camera

The Brinno TLC200 is a lightweight camera that can capture time lapse videos and still photos. The camera has a rotatable lens and can be set to perform unattended. Both of these output formats have a resolution of 1280x720. The entire camera weighs approximately 120g, requires 4 AA batteries, and comes with weatherproof housing. The images would be stored on an SD card during operation. This camera does not provide any depth sensing or image analysis software, so the images collected would require a heavy amount of image processing in order to extrapolate a water velocity estimate. The total cost of this camera is $120.

Figure 17: Brinno TLC 200

Pros	**Cons**
Small	Cannot sense depth
Light weight	Would require edge finding software and heavy image processing
Inexpensive	Resolution is >1Mp
Rotatable lens	Large systematic error
Weather proof housing	
Long battery life	

4.4.2 Thermal Camera

Infrared thermal cameras provide a non-contact temperature measurement using an invisible wavelength that is far right on the electromagnetic spectrum. The wavelengths corresponding to infrared are about 750nm and greater. Infrared energy (IR) is the part of the spectrum that we perceive as heat. Everything with a temperature above absolute zero emits infrared and will be picked up by the camera. The heat energy data taken is converted into an illustration showing heat patterns and is used to create a thermograph. This thermograph is then fed into LSPIV software and different patches of temperature are tracked to yield the velocity of the flow [24].

4.4.2.1 FLIR Vue Pro R

The FLIR Vue Pro R radiometric drone thermal camera makes non-contact temperature measurements with Long Wavelength Infrared (LWIR) techniques using a 6.8mm lens with a 45(H) x 35(V) field of view. The sensor resolution of 336 x 256 pixels, and the entire device only weighs 4 ounces. The dimensions of the camera are 2.26" x 1.75", including the lens. It is highly compatible with other devices and can be controlled from a provided app. It operates within the spectral band 7.5μm - 13μm and has an export frame rate of 9Hz or less. This device is physically versatile, having a wide range of operating temperatures and locations and a necessary input voltage of only 4.8 V. There is an abundance of support and additional products for the FLIR brand, as it is the standard for lightweight, mountable thermal imaging devices. There is a zoom capability provided on the user interface. This device costs $3149.

Figure 18: Radiometric Drone Thermal Camera

Pros	Cons
Low mass	Outside of budget
Ease of integration	Cannot measure surface depth characteristics
Highly accurate [24]	

4.4.2.2 VuIR Lepton

The VuIR Lepton is one of the cheapest systems available, and it is only recommended for beginners and those doing "simple works". For example, this camera is often used to detect moisture in obscure places. It is not suggested that to use Lepton thermal camera for any professional use where the data must be extremely reliable. The VuIR products are meant to be sold as cheaper versions of the FLIR products, which typically cost thousands of dollars. The software is compatible with android and Black Pearl monitors. The resolution is 160 with a 9Hz rate. The VuIR Lepton model is extremely versatile and easy to mount and dismount from a UAV. The product is prepared for use on many of the typical drones used for thermal imaging and comes with a complete system ready to mount, such as the DJI Mavic 1, Mavic 2, Phantom 4 Pro, Inspire 1, and other drones. The cost of this device is $699.[22]

Figure 19: Drone Thermal Imagine System

Pros	Cons
Inside budget	High mass
Accessory inclusive package	Medium size
Self Powered	Lower resolution
Self contained	Medium range (49m)
Quick attachment/detachment from UAV	
High battery life	

4.4.2.3 Seek Micro Core

The Seek Micro Core thermal imaging system is compact yet contains 30,000 temperature pixels. The resolution is 200 x 150, and the size is less than that of a dime. In combination with the Dual-Gain and 12 micron pixel pitch, this makes an accurate, lightweight device that is suitable for UAV applications. The imaging is uninterrupted because it is completely shutter-less. The frame rate is similar to the previous thermal cameras at 9Hz with a low power input. There is excellent image clarity and sensitivity due to the dual-gain smart pixels, which automatically adjusts the gain states of each pixel to maximise contrast on the thermograph output by the camera. The cost of this device is $499.

Figure 20: Shutter-less OEM Thermal Camera

Pros	Cons
Low mass	High cost
Low power	No housing included
Low size	
Uninterrupted imaging	
USB interface [23]	

4.4.3 Stereo Camera

Another technique to collect river flow data would be through use of a stereo camera. Stereo image sensing works both indoors and outdoors and utilizes two cameras to calculate depth. This is done by extracting the differences in image location of an object in a process called triangulation. This is similar to how humans perceive depth through binocular vision.

4.4.3.1 Intel RealSense D455 Camera

The Intel RealSense D455 boasts a very complete and capable sensor package that allows the camera to not just capture HD RGB video at 30fps but also HD depth data at 90fps. This being a crucial and neglected ability compared to the thermal and optical cameras as this depth data coupled with the camera's field of view and resolution is absolutely crucial for obtaining an precise pixel to

Figure 22: Stereo Lab ZED 2

distance calibration. This coupled with its depth sensing range of 0.4 to 20m, weight of 72g and standard 0.25 inch mounting screw makes the RealSense a strong contender for Velocimetry data acquisition operations. This camera costs $239.

Figure 21: Intel RealSense

Pros	**Cons**
Cheap	No internal storage
Precise with long range	Needs to be connected to data logger
Light weight	
Good technical documentation	
Pre-installed mounting hardware	

4.4.3.2 Stereo Lab ZED 2

The ZED 2 from Stereo Labs is a high resolution state of the art stereosonic camera. It is the first camera to employ neural networks to attempt to reproduce human vision to bring a new level to stereo perception. It has an industry leading 110° FOV as well as thermal management to reduce lens distortion and allow for more light capture. Lastly, it also utilizes AI to detect objects and improve the users spatial awareness. This camera costs $449.

Pros	**Cons**
Wide FOV	No internal storage
Live camera control	Needs to be connected to data logger
UHD Resolution	High post processing Requirements
Thermal control	

4.5 On-Board Computer

In order for all sensors included in the sensor suite to produce meaningful data, they all require some sort of mechanism to store their data. The best way to store all collected data is to send data from all different sensors to one main computer. Having a computer will allow for the storage of large amounts of data as well as keeping a uniform timestamp across all incoming data.

4.5.1 Arduino Mega with SD Module

The Arduino Mega is offered at a low cost and weight. Compared to the single serial port in the Arduino Uno, the Arduino Mega has four serial ports in addition to the larger flash memory capacity that reaches $256kB$. Another important feature is the Integrated Development Environment (IDE) which allows users to interface with the Arduino and upload code through a text editor that is easy to edit and understand. The cost of this device is about \$40.

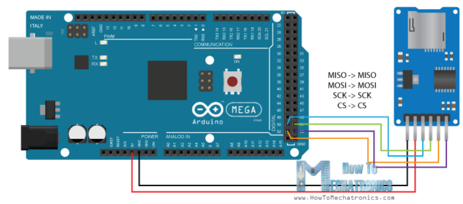

Figure 23: Arduino Uno with SD card attachment

Pros	Cons
Four serial ports	Requires integration with SD card shield
Arduino IDE is easy to understand	Limited by number of data collection ports
Robust	Only one USB port
Simple and easy to use design	
Low average power consumption	

4.5.2 Raspberry Pi 4

The Raspberry Pi 4 is a micro-computer that has four USB ports and a mounted Micro-SD card slot. It is offered at a low price and low weight making it a viable contender for RiBBIT's on-board computer. The Raspberry Pi 4 operates on a Linux system meaning it requires a reasonable understanding of the Linux operating system and how to boot the operating system on the micro-computer. This micro-computer costs about \$50.

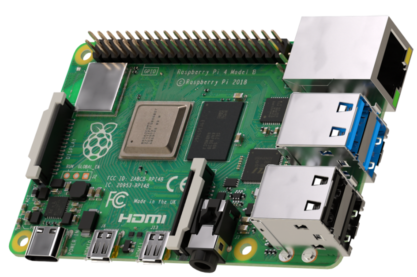

Figure 24: Raspberry Pi 4

Pros	Cons
On-board Micro-SD card slot	Learning curve to understand software
Four USB ports	Easily damaged
	High average power consumption

4.5.3 Odroid XU4

The Odroid XU4 is a micro-computer that has three USB ports and also has a Micro-SD card slot mounted on it. It is slightly more expensive than other listed products which also makes it a viable contender for the on-board computer. Like the Raspberry Pi 4, it operates on Linux. The cost of this micro-computer is $80.

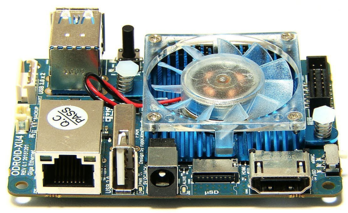

Figure 25: Odroid XU4

Pros	Cons
On-board Micro-SD card slot	Learning curve to understand software
Three USB ports	Easily damaged
	Relatively expensive
	High average power consumption
	Heavy relative to other options

4.5.4 Arduino Fio with XBee

The Arduino Fio is a micro-controller with one serial port and an XBee socket, allowing it to communicate using an XBee device. It is light and inexpensive; however, it is discontinued which could lead to difficulties so there is no support for this product and the documentation is not up-to-date. The cost of this device is roughly $30.

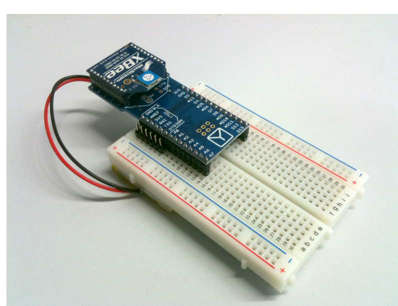

Figure 26: Arduino Fio with XBee attachment

Pros	**Cons**
Good for communicating with another computer Has XBees socket for communication Simple Arduino interface	Discontinued so documentation not up-to-date Easily damaged

4.6 UAV

One of the most essential elements of this project is selecting the appropriate drone that will be responsible for lifting and towing the instrument suite across the water. Leading drone manufacturers such as DJI and Yuneec provide a variety of drones with unique specifications that meet the consumers' desires. The drones are evaluated by the team based on multiple factors including cost, whether or not it has a built in GPS or camera, its carrying capacity, and its flight software. However, the budget of the project highly limits the drone options. Therefore, the team has the option to either buy their own drone with the specifications that they desire or borrow one from research labs such as The Research and Engineering Center for Unmanned Vehicles (RECUV) or The Integrated Remote and In Situ Sensing (IRISS).

4.6.1 Buy

4.6.1.1 Swellpro

The first option to buy is a drone called SplashDrone 3 manufactured by SwellPro[2]. The drone is shown below in Figure 27. In terms of cost, SplashDrone 3 is a low cost drone priced at $1,200. It includes a night camera for operations in the dark and reports a flight time up to 24 minutes. Additionally, the drone has a maximum wind resistance of 28 km/h. However, the SplashDrone 3 only has a payload capacity of 1 kg which is a lower payload capacity than desired.

Figure 27: SplashDrone 3 by SwellPro

Pros	**Cons**
Low cost	Low carrying capacity
Waterproof	Short flight time relative to carrying capacity
Night camera	No built in GPS available
Wind resistance	No autopilot

4.6.1.2 Tarot 650

The Tarot 650 is a US based drone specifically designed to accommodate payloads[3]. It has a carrying capacity of around 1.5kg which is a bit of a low margin to fit the instrument suite in. Also, the Tarot 650 costs around $2,300 which would take up nearly half of the budget for the team. One thing to keep in mind is that the company does provide discounts for students but that is something that shouldn't be counted on. The Tarot 650 uses the Pix4 flight controller with ArduPilot, which is an open source software and is approved for government use.

Figure 28: Tarot 650 by UAV Systems

This drone comes with the Taranis CX7 Transmitter.

Figure 29: Taranis Q X7 Transmitter

For an additional $1000 USD, the Hex Herelink Ground Station can be added on. The Herelink includes the controller and one HD camera installed on the Tarot 650 or Tarot X6. The camera feed can stream live to the Herelink Transmission System. This upgrade replaces the Taranis QX7 Transmitter with the Herelink transmitter. This addition is desirable if the budget allows as it enables easier drone navigation and obstacle avoidance.

Figure 30: Hex Herelink Ground Station Add-On

Pros	Cons
Low cost RTK option Ardupilot/Open source flight software	Low carrying capacity FPV camera is $1000 Lower flight time Wind resistance unknown

4.6.1.3 Tarot X6

The third option that remains in the team's budget is the Tarot X6[4]. The X6 has the same Pixhawk flight controller as the 650 but has a lot more power available. It can lift 5kg for 25 minutes and 35 minutes without a payload. This makes it an ideal candidate for the mission, but it comes with a high price tag of $3300. The Hex Herelink Ground Station can also be added-on on, increasing the price to $4,300. This high cost would require the instrument suite and remaining purchases to be very inexpensive.

Figure 31: Tarot X6 by UAV Systems

Pros	Cons
High carrying capacity	Mid-High Cost
Decent flight time	FPV camera is $1000
Designed for payload	Wind resistance unknown
RTK option	
Ardupilot/Open source flight software	

4.6.2 Borrow

To reduce costs, RiBBIT considers the option to borrow the drone from on-campus laboratories such as RECUV and IRISS. Borrowing a drone would allow more funds to go towards the instrument suite. However, there is only one drone available to borrow which has only half the payload capability of the Tarot X6.

4.6.2.1 DJI S900

Figure 32: S900 by DJI

Pros	Cons
Mid carrying capacity	Can't use whenever desired
Decent flight time	No RTK
Designed for payload	Complicates logistics
Vibration Dampeners	Wind resistance unknown
Ardupilot/Open source flight software	
FPV camera system included	
Low cost	

4.7 Positional Determination and Geo-referencing Technique

While UAV-based remote sensing techniques enable low-cost and quick high resolution data, the data must be validated with geo-referencing techniques to ensure accuracy and reliability. This can be done through direct geo-referencing using on-board position and orientation data or indirect geo-referencing using Ground Control Points (GCP)[10]. The different options for capturing accurate data are laying Ground Control Points, Real-Time Kinematic and Post-Processing Kinematic methods. In Figure 33, the three methods can be visualized. To address the requirement necessitating the system's ability to access difficult locations, the ground control point option was not prioritized. However, GCPs could be collected in outdoor testing to further validate the data.

Figure 33: Different Geo-Referencing Methods

4.7.1 U-blox C94-M8P RTK Package

The $399 U-blox C94-M8P RTK Application Board Package contains two antennas and receiver modules with NEO-M8P high precision GNSS modules, each of which may act as either a base station or rover. This package is able to offer up to 2.5cm accuracy using Real-Time Kinematic positioning.

Figure 34: U-blox NEO-M8P

Pros	Cons
Included antennas Integrated chips	$399 cost

4.7.2 Custom Sensor Fusion

One option is to purchase separate IMU and GPS modules and fuse their data together ourselves. This option allows us to obtain accurate sensors without the overhead cost of pre-programmed components. The standalone $220 Sparkfun GPS board is capable of providing positional accuracy up to 2.5m. The $25 Arduino IMU is capable of providing orientation corrections, but the fusion of GPS and IMU data presents an unknown time cost of software development.

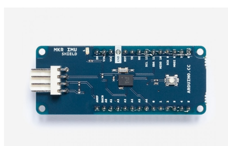

Figure 35: Micro-controller compatible IMU

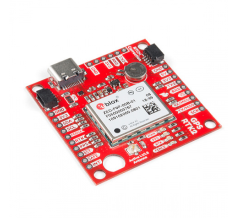

Figure 36: Micro-controller compatible GNSS

Pros	Cons
Parts cost	Unknown time cost of software implementation Inaccuracy of standard positioning service

4.7.3 Emlid Base Station RTK/PPK Configuration

The Emlid RS2 RTK GNSS Receiver is a ground based system used for surveying, mapping and navigation. The cost of this product is $1899, however, it can be borrowed for no cost from the University NAVSTAR Consortium (UNAVCO) located in Boulder. This base station's 1cm accuracy, allows a larger budget for a comparably accurate on-board UAV receiver.

There are multiple options for the on-board GNSS receiver. Two leading contenders being the Aceinna OpenRTK330 ($150 chip and up to 3cm accuracy) and the U-blox C94-M8P. Their key difference is the U-blox package's contains a pre-integrated chip and antennas.

Both pieces of hardware have built-in sensor fusion algorithms that leave room for customization. These devices allow the use of either Real-Time Kinematic (RTK) or Post-Processed Kinematic (PPK) localization methods.

RTK and PPK are different methods of correcting the location of a drone. For our purposes, they each require the same hardware, but differ in their respective implementations. They each require a GNSS capable receiver ground station and drone receiver, and both require those devices to receive GNSS communications throughout the mission. There difference lies in additional required connections and when the data is processed. RTK requires the base station and drone to maintain constant communication with a drone base station, and the data is processed real–time. PPK does not require these extra signals, and thus the data must be post–processed after the flight. As these implementation do not require distinct hardware configurations, they shall be grouped together as a single key design option, which, if selected, can be used in either arrangement.

Figure 37: Emlid RS2 GNSS Receiver

Pros	**Cons**
Can rent from UNAVCO Proven accuracy RTK and PPK options	Need to coordinate borrowing logistics

5 Trade Study Process and Results

5.1 Bathymetry Technique

Criteria	Weight	Rationale
Cost	20%	Instrument cost is a limiting factor. Sensors can be expensive, and there needs to be enough budget to cover drone and manufacturing.
Mass	10%	The instrument needs to be drone/UAV mountable. The weight of the instruments will affect drone selection.
Size	5%	The instrument's footprint must be small enough to be mounted on a drone with minimal issue.
Power	5%	The power source required to function may affect the weight of the sensor suite as well as how easily it can be flown on a drone.
Integration	5%	The sensor suite will need to be mounted onto the drone and should not take an excessive amount of additional hardware to do so.
Data Handling	10%	The ease of which data can be of loaded in a use full format to local storage and then later analysed is central to the success of this project since getting meaning full scientific conclusions is the objective. The ease of this is evaluated based on the instrument connector types, the instrument data format, storage compatibility and software support.
Minimum Depth	7.5%	The sensor must be able to take measurements in shallow waters.
Maximum Depth	7.5%	The sensor must be able to take measurements at least 3m deep.
Accuracy	20%	The sensors should be able to collect accurate data in order to meet the science requirements and provide meaningful results.
Water Performance	5%	The sensor should be able to perform well in clear to mildly dirty water since the water quality of rivers can vary for different locations.
Water Contact	5%	A non-contact sensor would be ideal as it does not require a sensor package hanging below the UAS

Criteria	**1**	**2**	**3**	**4**	**5**
Cost	>$3000	3000-2000	2000-1000	1000-500	<500
Mass	>5 kg	5kg-3kg	3kg-1kg	1kg-0.5kg	<0.5kg
Size	>20*10$^6mm^3$	20-10*10$^6mm^3$	10-1*10$^6mm^3$	10-1*10$^5mm^3$	<1*10$^5mm^3$
Power	>40 W	40W-30W	30W-15W	15W-5W	<5W
Integration	1	2	3	4	5
Data Handling	1	2	3	4	5
Minimum Depth	>2m	2m-1.5m	1.5m-1m	1m-0.5m	<0.5m
Maximum Depth	<1m	1m-3m	3m-10m	10m-20m	<20m
Accuracy	>5%	5%-3%	3%-1%	1%-0.5%	<0.5%
Water Performance		considerable		negligible factor	
Water Contact	Contact required				non-contact

Table 1: Bathymetry Criteria Definitions

Criteria	**Weights**	**LiDAR**	**Sonar**	**ADCP**
Cost	0.2	1	5	1
Mass	0.1	1	5	2
Size	0.05	1	5	3
Power	0.05	2	5	4
Integration	0.05	4	4	4
Data Handling	0.1	3	5	5
Minimum Depth	0.075	3	4	5
Maximum Depth	0.075	5	5	5
Accuracy	0.2	5	4	3
Water Performance	0.05	2	5	5
Water Contact	0.05	5	1	1
Total	1	**2.9**	**4.475**	**3.1**

Table 2: Bathymetry Criteria Levels

From this it became abundantly clear that SONAR is the best depth measuring option available to the group given the constraints and requirements that the team is operating on. For this instrument the group needed one that is small, light, accurate, easy to work with both in regards to power and data, can perform in sub optimal water conditions and finally would ideally be non-contact. All but one of these requirements were met by sonar and because of this it became the clear winner and first choice.
That being said, it now becomes important to down select the final unit to be implements by the group from the two choices outlined above. To do this another trade study was conducted with the two units using the same criteria and weights. This being shown below.

Criteria	**Weights**	**Ping SONAR**	**SICK UM30**
Cost	0.2	5	5
Mass	0.1	5	5
Size	0.05	5	5
Power	0.05	5	5
Integration	0.05	4	3
Data Handling	0.1	5	3
Minimum Depth	0.075	4	5
Maximum Depth	0.075	5	1
Accuracy	0.2	4	5
Water Performance	0.05	5	4
Water Contact	0.05	1	1
Total	1	**4.475**	**4.15**

Table 3: Bathymetry Trade Study

Given this it becomes clear that while both sensors may be good options the Ping echo sounder by BlueRobotics is the better choice and will be the instrument the group will use going forward.

5.2 SONAR Float Angular Displacement Correction Technique

Criteria	**Weight**	**Rational**
Cost	15%	Cost is always a driving factor in a project but given the relatively low cost of these specific systems it is values less in this case.
Mass	20%	Given that this system has to be carried by the UAS it is of the up most importance the its weight be minimised so it has a minimal impact on UAS selection and flight time.
Integration complexity	30%	The solution should be as simple to integrate as possible as creating specialty mounting solutions or having it negatively influence the function of the overall system is to be avoided.
Effectiveness	35%	Given that the collecting valid and useful data is the driving motivation in this project it was decided to place a high amount of importance on this criteria.

Table 4: SFADCT Criteria Definitions

Criteria	**1**	**2**	**3**	**4**	**5**
Cost	>$80	80-60	60-40	40-20	<20
Mass	>100 g	100g-70g	70g-30g	30g-10g	<10g
Integration	1	2	3	4	5
Effectiveness	1	2	3	4	5

Table 5: SFADCT Criteria Levels

Criteria	**Weights**	**Gyroscope**	**Weighted Float**	**Gimbal**
Cost	0.15	5	5	1
Mass	0.2	5	2	1
Integration Complexity	0.3	5	3	3
Effectiveness	0.05	5	3	5
Total	1	**4.7**	**3.1**	**2**

Table 6: SFADCT Trade Study

Thus we can see that based on the sub-systems mass, cost, integration complexity and effectiveness the gyroscope is the winner and will be the instrument the group will use to correct SONAR data moving forward.

5.3 Velocity Technique

Criteria	Weight	Rationale
Cost	20%	Instrument cost is a limiting factor. Sensors can be expensive, and there needs to be enough budget to cover other essential aspects of the project.
Weight	5%	The instrument needs to be drone/UAV mountable. The weight of the instruments will affect drone selection due to payload contrains and required flight time. The weight will also effect the center of mass and other flight characteristics and thus a light instrument is preferred.
Size	5%	The size of the instrument will effect how difficult it is to mount to the drone as well as effect the drag of the drone.
Power Requirements	5%	An instrument that has high power requirements may require additional batteries adding weight or limit the data collection period if extra batteries cannot be afforded.
Integration complexity	5%	An instrument that requires communication with other onboard systems will not only create additional points of failure, but also present the team with additional challenges and constrains (such as making sure the other onboard systems have common programming languages to the instrument).
Velocity Calculation Complexity	15%	The instruments investigated came with varying levels of COTS post-processing software. The easier the post-processing is the more time and effort this will save later in the project
Altitude Measurement	5%	It is advantageous to know the drones height above the water while collecting depth measurements and enables the water height of the river to be determined with lower uncertainty than would be enabled with GPS.
Max Field of View	15%	This has implications for how high the drone will need to be to above the river for data collection but also the range of rivers possible to survey. A larger FOV also means the camera can be closer to the river, and since accuracy is a function of distance also means the camera will likely be able to obtain more accurate results.
Frame Rate	10%	Frame rate will be set the upper limit on how fast of flow can be measured as well as how accurate the velocity calculation can be.
Data collection Resolution	15%	The ability of post-processing to discretize the flow and yield velocities that are more representative of true values will be dictated by the resolution of the collected data.

Table 7: Velocity Criteria Definitions

To compare techniques a 'middle of the road' product from the instruments presented in the key-design section were used. The raw value selection for the qualitative criteria was guided by the score guides shown below.

Criteria	**1**	**2**	**3**	**4**	**5**
Cost	>$3000	3000-2000	2000-1000	1000-500	<500
Mass	>5 kg	5kg-3kg	3kg-1kg	1kg-0.5kg	<0.5kg
Size [mm^3]	>20*10^6	20-10*10^6	10-1*10^6	10-1*10^5	<1*10^5
Power	>40 W	40W-30W	30W-15W	15W-5W	<5W
Integration	Many interfaces		Few interfaces		No interfaces
Velocity Calculation	No COTS		3rd party COTS		Native COTS
Alt Measurement	No Alt				Alt
Max FOV [deg]	<55	55-65	66-75	76-85	85<
Frame rate [FPS]	<25	25-45	46-65	66-85	85<
Data Resolution	<480p	480-720p	720-1080p	1080p-2k	<2k

Criteria	**Weights**	**Optical**	**Thermal**	**Stereo**
Cost	0.2	5	1	5
Mass	0.1	5	5	5
Size	0.05	4	4	5
Power Requirements	0.05	3	5	5
Frame Rate	0.05	1	2	5
Ease of Integration	0.05	5	4	4
Velocity Calculation Complexity	0.15	2	4	3
Altitude Measurement	0.05	1	1	5
Max Field of View	0.15	2	1	5
Data Collection Resolution	0.15	2	1	2
Total		2.9	2.25	**4.2**

Table 8: Velocity Technique Trade Study

Thus it can be seen that the stereo camera is the winning technique and given the affordability of the stereo cameras, this will be the technique to be used to measure flow velocity. But, that still leaves the specific stereo instrument to be determined. Below is the trade study to determine which type of stereo camera project RiBBIT will employ.

Criteria	Weights	Intel RealSense D455	Stereo Lab ZED 2
Cost	0.2	5	5
Mass	0.05	5	5
Size	0.05	5	4
Power Requirements	0.05	5	5
Frame Rate	0.1	5	5
Ease of Integration	0.05	4	4
Velocity Calculation Complexity	0.15	3	3
Altitude Measurement	0.05	5	5
Max Field of View	0.15	5	5
Data Collection Resolution	0.15	2	5
Total		4.2	**4.6**

Table 9: Stereo Camera Trade Study

5.4 On-Board Computer

The on-board computer will be used to store data collected from the sensor suite and to send commands that start and stop data collections on sensor suite instruments. As all candidates for the on-board computer are relatively inexpensive and lightweight, these criteria in down-selecting a computer are given little weight, as they do effect the project as a whole, but not greatly. The computer power consumption is a main criteria because the mission operating time is great enough such that computers with different power requirements will greatly effect the sizing of the battery, which could lead to overall increased payload weight. It is also very important that the computer's hardware can interface with all necessary sensors in the suite. If the computer's hardware is not compatible with all sensor hardware, then the computer cannot achieve it's main objective of storing data collected from the sensor suite.

Criteria	Weight	Rationale
Cost	10%	We need to minimize the amount of money spent on a computer so we can better afford more expensive instruments. However, a computer won't break the bank so we shouldn't sacrifice cost for quality.
Weight	10%	The drone will have a limited payload capacity and most of that is reserved for larger sensors. Computers are generally very light but ideally weight will be minimized.
Power	30%	Throughout the duration of the mission the computer will be drawing power from the battery. We want to minimize the power consumed so that we can minimize the size of the battery.
Compatibility	30%	The chosen computer needs to have the ability to interface with the hardware for all chosen sensors.
Programmability	20%	The computer must be able to efficiently program the mission and store necessary data. A simplistic IDE is preferred as it will save a lot of time.

Criteria	**1**	**2**	**3**	**4**	**5**
Cost	$> \$100$	\$80 - \$100	\$60-\$80	\$40-\$60	$< \$40$
Weight	> 100g	75g-100g	60g-75g	50g-60g	< 50g
Power	> 4W	2-4W	1W-2W	0.5W-1W	< 0.5W
Compatibility	Cannot interface with any sensor	Can interface with one sensor			Can interface with all sensors
Programmability	Not programmable		Steep learning curve	Slight learning curve	No learning curve

Table 10: On-board Computer Criteria Levels

Criteria	**Weights**	**Arduino Mega**	**Raspberry Pi 4**	**Odroid XU4**	**Arduino Fio**
Cost	0.1	4	5	4	4
Weight	0.1	5	5	4	4
Power	0.3	5	2	1	5
Compatibility	0.3	5	5	5	5
Programmability	0.2	4	3	3	4
Weighted Total	1	4.7	3.7	3.2	4.6

Table 11: On-board Computer Trade study

From the results of the trade study, the Arduino Mega will be the on-board computer. Arduino's are robust and simple to use compared to other computers in the trade study. The Arduino Mega is a great choice because it is very versatile in its capabilities. While the Arduino Fio is a close second, it may be considered as a secondary computer that can be used to communicate data from the deployed sonar unit to the main (on-board) computer, the Arduino Mega.

5.5 UAV

Criteria	Weight	Rational
Cost	30%	The cost is the most limiting factor, if the team were to buy an expensive drone there would be less resources for the instruments.
Payload	20%	The drone must be capable of carrying the instrument suite, also having extra payload capabilities can increase the flight time.
Logistics	20%	Having to workout when and where the drone can be flown complicates the testing process. This can lead to delays but it won't be mission ending.
Flight Controller	10%	The flight controller is a limiting factor when dealing with government agencies. So if the drone is unusable with its default controller that would complicate things for the user.
Flight Time	10%	The minimum flight time is relatively easy to achieve, but additional flight time is very beneficial to users of the instruments suite.
FPV Camera	10%	An FPV camera is useful for piloting a drone from a distance and being able to keep an eye out for debris in the river. It also significantly improves safety of the drone. But isn't required

Table 12: Drone Criteria Definitions

Criteria	1	2	3	4	5
Cost	>$4000	$4000-$3000	$3000-$2000	$2000-$1000	$1000-$0
Payload	1kg		1kg-2kg	2kg-4kg	>4kg
Logistics	Need to schedule pilot and drone		Need Pilot		Don't need pilot
Flight Controller		Default banned by government			Can be used by government
Flight time	<12min	12min-16min	16min-20min	20min-25min	25min-30min
FPV Camera	No				Yes

Table 13: Drone Criteria Levels

The selection of a drone depends entirely on our budget, if it is too expensive it won't even be possible to buy. So, the cost is weighted at 30% where anything above $4000 was heavily penalized. The obviously preferred option is the most powerful drone available, this generally increases flight duration and the margin of safety in operating in adverse conditions. With that, a drone that can't lift the minimum payload would heavily penalized, but a drone that heavily exceeds the minimum would be preferred. Logistics are important for the testing and integration phase, having to schedule a pilot and/or drone are the main logistical issues.

Criteria	Weights	Swellpro	Tarot 650	650 w/FPV	Tarot X6	X6 w/FPV	DJI S900
Cost	0.3	5	3	2	2	1	5
Payload	0.2	1	3	3	5	5	4
Logistics	0.2	5	5	5	3	3	1
Flight Controller	0.1	5	5	5	5	5	2
Flight Time	0.1	1	2	2	5	5	3
FPV Camera	0.1	5	1	5	1	5	5
Total	1	**3.8**	**3.9**	**3.7**	**3.6**	**3.4**	**3.5**

Table 14: Drone Trade Study

5.6 Positional Determination and Georeferencing Technique

Criteria	Weight	Rationale
Cost	10%	Cost should not prohibitively bar sensors capable of delivering necessary performance given the critical role of positional determination.
Weight	20%	Given the limited carrying capacity of drones, it is essential to maintain the lowest possible weight profile where possible to allow for maximum flexibility when selecting inevitably heavier components.
Horizontal Position Accuracy	15%	Accurate localization is of paramount importance, as positional awareness allows the bathymetry measurements to be accurately placed in relation to each other.
Vertical Position Accuracy	15%	Accurate localization is of paramount importance, as positional awareness allows the bathymetry measurements to be accurately placed in relation to each other.
Software Complexity	20%	A proper full scale implementation of a sensor fusion algorithm such as the Kalman Filter exceeds our skill and time budgets.
Hardware Complexity	20%	A localization unit requiring an extensive network of auxiliary devices should be strongly discouraged, given the limited spacial and skill budgets.

Table 15: PDG Criteria Definitions

Criteria	**1**	**2**	**3**	**4**	**5**
Cost	>$400	$350–$400	$300–$350	$250–$300	< $250
Weight	>100g	75g–100g	50g–75g	25g–50g	< 25g
Horiz. Positional Accuracy	>5cm	4cm–5cm	3cm–4cm	2cm–3cm	< 2cm
Vert. Positional Accuracy	>6cm	5cm–6cm	4cm–5cm	3cm–4cm	< 3cm
Software Complexity	Requires custom sensor fusion implementation		Requires software modification		Provided API
Hardware Complexity	Requires extensive supporting hardware				Integrated with existing hardware

Table 16: PDG Criteria Levels

Criteria	**Weights**	**U-Blox C94-M8P**	**Custom Sensor Fusion**	**Emild RS2 + Aceinna**	**Emild RS2 + U-Blox**
Cost	0.1	2	3	5	2
Weight	0.2	4	4	5	4
Horiz Positional Accuracy	0.15	4	1	4	5
Vert Positional Accuracy	0.15	4	1	5	5
Software Complexity	0.2	4	1	2	4
Hardware Complexity	0.2	4	2	1	4

Table 17: PDG Trade Study

5.7 Future Trade Studies

This document was predominantly to conduct trades on our critical project elements, with an emphasis on the scientific data being captured by adequate instruments. With this in mind, additional trade studies for future design decisions have been identified. In the future, the holding and deployment mechanisms for RiBBIT's instrument suite will be explored. The deployment mechanism uncertainty also adds uncertainty in power requirements, so for this reason the on-board battery will be a future trade. Additionally, the post-processing for velocity calculation (Particle Image Velocimetry) and depth profile will also continue to be areas of research as the semester progresses.

6 Selection of Baseline Design

6.1 Bathymetry Technique

Based on the above completed evaluations, the most optimal Bathymetric survey sensor for this groups application and project constraints is the Ping SONAR by BlueRobotics. It managed to excel in all categories with exception of the contact vs. non-contact section. That being said, the only other system that scored well in that section was the LIDAR system which was far out of the groups budget and also under performed in the mass, size and water performance sections. All in all, the Ping SONAR is a sensor that is able to full fill the needs of the project in a cost effective manner ($309 including shipping and taxes), offers great range and accuracy in the measurements it takes and also has the lowest mass of all sensors considered which in tern will improve the flight time of the UAS due to it having to carry less weight.

6.2 SONAR Float Angular Displacement Correction Technique

Based on the evaluations completed above, it was determined that having an additional qyroscope sensor installed on the float with the SONAR sensor would be the optimal solution for tracking and then later correcting the angular displacement from the gravity vector the SONAR may experience during its time in the water. The reason as to why this solution was selected was due to it being not only cheap(<$20), simple and affordable but also because it was highly accurate and easy to implement.This being due to its small size, light weight and ability to communicate the the selected computer (ardunio).

6.3 Velocity Technique

Given the results of the stereo-camera trade study and initial research on Particle Image Velocimetry (PIV), the team will proceed with the Stereo Lab ZED 2 for velocity calculation. Its 2.2k video resolution, high frame rate, and in flight adjustable camera settings made it a strong candidate for accurate velocity calculation. It also has a slightly higher quoted stereoscopic accuracy (consistent with its larger distance between cameras) than the Real Sense and a wider FOV meaning it can take more accurate and further measurements from the river. Lastly it includes video streaming capabilities and documentation for post-processing and analysis in MatLab. The ZED 2 retails for $449.00.

6.4 On-Board Computer

Through conducting a trade study on multiple on-board computers, it was determined that the most suitable product is an Arduino Mega with an SD card module. Through analyzing all criteria described in the trade study portion of this document, the Arduino Mega had the highest weighted score. While other products such as the Raspberry Pi 4 and Odroid UX4 have superior processing power to the Arduino Mega, they both consume more power and have more complexity associated with programming the mission of RiBBIT project. The Arduino Mega is superior to other mentioned products because it is very robust, meaning that it is less likely to break when it is set up incorrectly. This trait is certainly desirable among a group of aerospace engineers who have limited experience with micro-controllers and micro-computers. The anticipated cost of the Arduino Mega with an SD card module is $50. To conclude, the Arduino Mega provides a simple platform that surpasses all requirements necessary for the RiBBIT's on-board computer.

6.5 UAV

After consideration of all criteria, as indicated in table 13 ,the most optimal flight vehicle for RiBBIT's system is the Tarot 650 followed by the Swellpro. The primary reasons why the Tarot 650 is chosen are its cost, payload capacity, and availability. The Tarot 650 base cost is $2300, and an additional $1000 with HD camera and Herelink upgrade. The team is willing to buy the Tarot 650 without the Hex Herelink Ground Station add-on since the total cost, along with the cost of the other instruments, would increase to \$4,800. Buying the Tarot 650 alone still leaves enough money to be spent on additional instruments, their mounting, and battery. Moreover, the Tarot X6 is too expensive to purchase even though it has better performance. The estimated total wight of the instruments is $500g$ and at this stage of the project the payload is being limited to 1.5kg, this disqualifies the Swellpro since the final expected payload will be too large. In addition, buying the Tarot 650 is preferred over borrowing the DJI S900. Although it would cut costs, the simplified logistical problem, and similar flight time would allow for better testing and similar performance in adverse conditions. Ideally, and in the event of securing additional funding, the team would buy the Tarot X6 with the camera option.

6.6 Positional Determination and Geo-Referencing Technique

From the results of the completed trade studies, the highest quality and most viable option for localization is the combination of the Emlid RS2 Base Station and the U-Blox C94-M8P set of two receivers. The ability to borrow the Emlid RS2 for free provides a professional quality base station with funds to purchase a high quality receiver for the instrument suite. The best receiver was determined to be the U-blox C94-M8P due to its accuracy and ease of use. The cost of this product is \$399. Each application board contains an integrated NEO-M8P high precision GNSS module, antenna, and data transfer cable. The package's containing of two application boards also allows the placement of a receiver on both the instrument suite and drone, which does not significantly impact the weight budget (each module weighs 35g), and the redundancy may be necessary if the instrument suite receiver is attenuated by foliage surrounding the river banks. Each roaming receiver will store its data, which will be post-processed along with the base station's using **P**recise **P**oint **P**ositioning software (such as RTKLIB or JPL's Automatic Precise Positioning Service) to achieve centimeter-level accuracy.

7 Appendix

7.1 SI-LSPIV Velocity Components

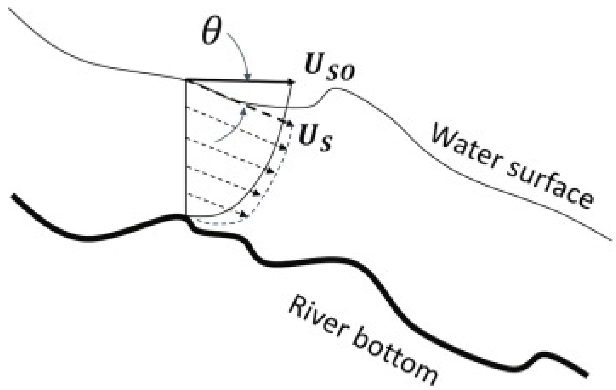

Figure 38: Schematic of velocity components of non-uniform water surface

Figure 38 from [8] shows the different components of flow velocity that can be measured from SI-LSPIV. Level 1 and 2 success of Streamflow measurements use U_{so}, the horizontal component, and level 3 will attempt to calculate U_s which is the true flow velocity.

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