REQUIREMENTS SPECIFICATION: ICE-THICKNESS MAPPING USING DRONE-MOUNTED SENSOR PACKAGE

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1. Introduction

Ocean Networks Canada (ONC) is interested in the research and development of ice-thickness mapping technology that can be deployed using drone/UAV systems. As part of UVIC's ECE 399 course, the ground penetrating radar (GPR) will be designed to integrate with certain OTS drones to transfer real-time measurements to the ground control unit. The document will cover product function requirements and constraints.

1.1. Purpose

The document will outline the requirement specifications for the Drone Mounted Ice-Thickness Mapping Sensor Package proposed by ONC [1]. The sensor package will be deployed on a drone to measure ice thickness and transfer data to a ground control unit.

Currently, most ice-thickness geospatial maps are created by either satellite or ground-penetrating radars mounted on surface vehicles. Measuring ice-thickness using drones can help commercial ice-breaker ships navigate through the sea as they can only break ice up to a thickness of 4.5 meters. The drone-mounted radar can be deployed for determining the ice-thickness of different areas which can help to choose the best shipping route with the least possible damage to the ice-breaker ships. Also, northern communities can safely navigate their landscapes during changing climate conditions using drone ice-thickness mapping.

1.2. Product Scope

Ocean Networks Canada is interested in developing drone-mounted ice-thickness measuring sensor packages to enable rapid ice-thickness measurement collection of large areas of ice [1]. The developed sensor package will be mounted to a fixed-wing drone which will be launched from the decks of commercial ice-breaker ships. The sensor package will be able to control the drone's flight to measure the ice thickness along a predetermined path set by the users. The sensor package will collect ice-thickness data along the path and communicate it to the ground control unit. The ground control unit will process the data and present the findings to the user in an easily readable format.

The fixed-wing drone will be a commercially available over-the-shelf (OTS) fixed-wing drone which will be slightly modified to allow for the sensor package to be mounted. The drone will connect to the communication subsystem of the sensor package to allow for the drone control data to be communicated to the ground control unit through the sensor package's communication channels. Furthermore, the antennas of the sensor package will have a dual antenna system for data and control links.

The sensor package will use ground penetrating radar (GPR) to measure the thickness of the ice. The reflected signal will be received by the antennas mounted to the wings of the drone and then passed along to the GPR subsystem, the MCU of the sensor package, and then the onboard external SD card storage and the communication subsystem of the sensor package.

1.3. References

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2. Overall Description

The following sections describe the perspective and functions of the sensor package product, the operating environment, and any constraints, dependencies, and assumptions imposed on the sensor package product.

2.1. Product Perspective

Ice-thickness measuring GPR sensor packages have been implemented by many commercial and scientific groups to gather thickness data. However, this GPR sensor package will be manufactured to be mounted on fixed-wing drones. The GPR sensor package is not a standalone product, it requires the fixed-wing drone and base control unit to accomplish this task. To achieve this, the drone-mounted GPR sensor package will work in tandem with the drone and the base control unit. However, the sensor package will contain the central subsystems for drone-mounted ice-thickness mapping such as the GPR, antennas, GPS, and main communication subsystem. The system diagram of the complete system including the GPR sensor package, base control unit, and fixed-wing drone can be seen below in Figure 1.

The GPR sensor package will receive the reflected signal in the wing-mounted antennas and pass the data along to the MCU. The MCU in the sensor package is a Raspberry Pi 4 Model B 8GB. The MCU as well as the other onboard electronic subsystems will be powered by removable lithium-ion batteries. The MCU will record the ice-thickness data to the onboard external storage SD card as well as communicate the data in real time to the base control unit using the communications subsystem of the sensor package. The MCU data and software can also be accessed by connecting the user's computer to the sensor package through the USB ports in the ports subsystem.

The user can chart predetermined paths and measurement locations on the base control unit. These paths and locations will be used to control the movement and operation of the drone-mounted sensor package. The GPR sensor package will control the flight of the fixed-wing drone by receiving inputs from the base control unit through its communication subsystem, processing the inputs in the MCU, developing the drone instructions using data from the GPS, and sending the instructions to the drone's communication subsystem to be used by its control interface.

Furthermore, once the base control unit has received the GPR ice-thickness data using its communication subsystem, it will process the data, store the data in its local storage, and output a clear visualization of the ice-thickness maps created for the user. The user can then observe the ice-thickness measurements and use them to determine the appropriate navigation path of the ice-breaker ship.

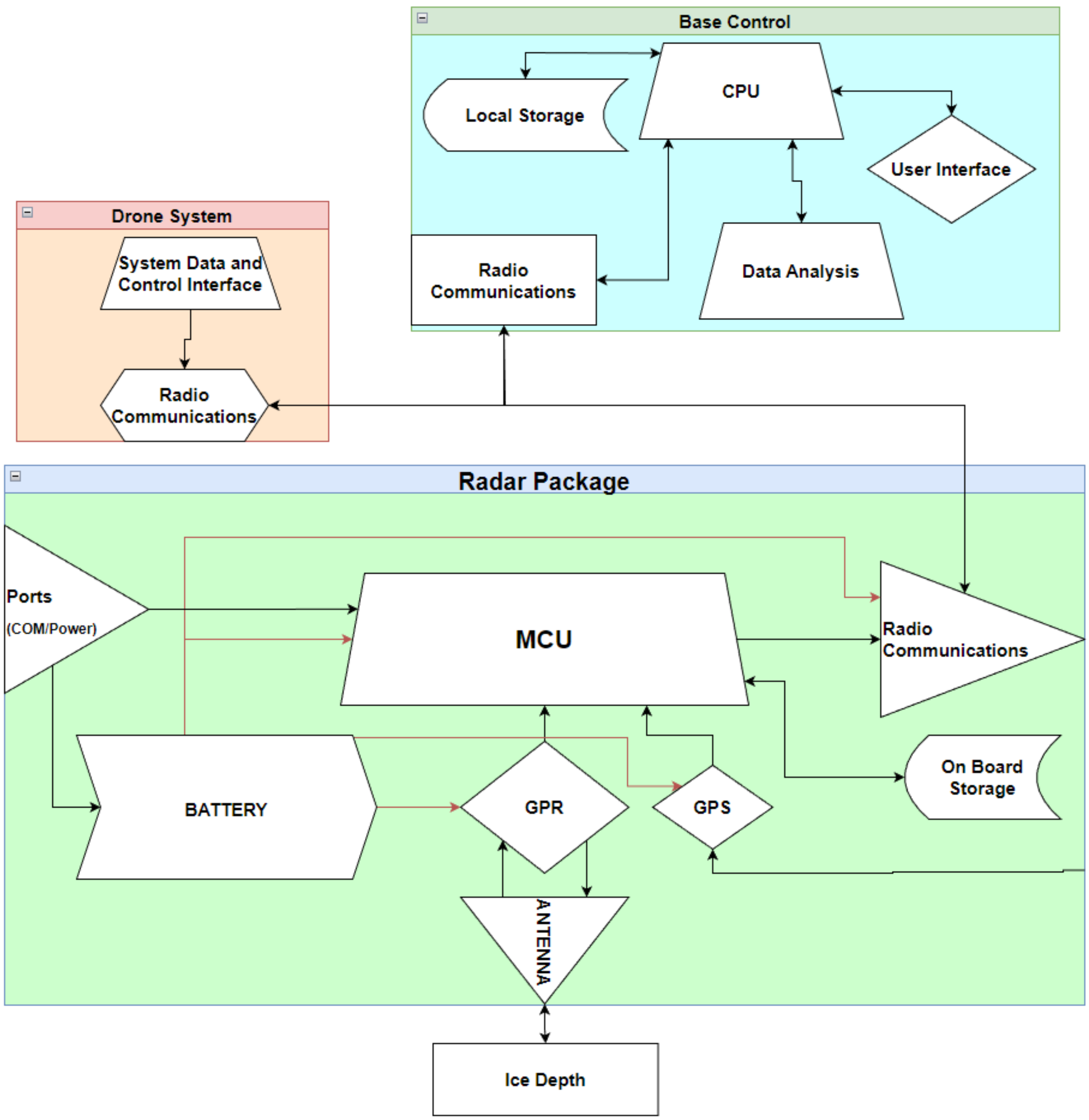

Figure 1: System Diagram of the Ice-Thickness Mapping Sensor System

2.2. Product Functions

The main functions that the drone-mounted sensor package must accomplish are following the programmed route, measuring ice-thickness, and sending that data back to the ground station for review. The complete state diagram for the regular operation of the drone-mounted sensor package system can be seen below in Figure 2.

The system must first takeoff from the ice-breaker ship, then, travel to the first measurement location, send a GPR signal to measure ice-thickness, receive a reflected signal, communicate measurement data to the ground control unit as well as save to onboard storage, and move to the next measurement location. If the sensor package has scanned every specified measurement location and a new scanning route has not been uploaded, the sensor package will then return to the ice-breaker ship so the battery can be recharged, and the drone and sensor package can be resupplied. However, if a new scanning route has been uploaded after the previous one has been completed and there is sufficient battery remaining, the drone will follow the new scanning route.

The state diagram can be divided into three main parts: The travel section where the drone-mounted sensor package is moving to and from measurement locations, the measurement part where the sensor package is sending GPR signals and receiving the reflected signals, and the communication component where the sensor package is storing and transmitting the ice-thickness measurement data to its onboard storage and base control unit, respectively. These three modules are achieved using the system features explained further in the fifth section: the GPR sounding system, independent power supply, microcontroller and data packaging, communication and data link, and housing and drone mounting.

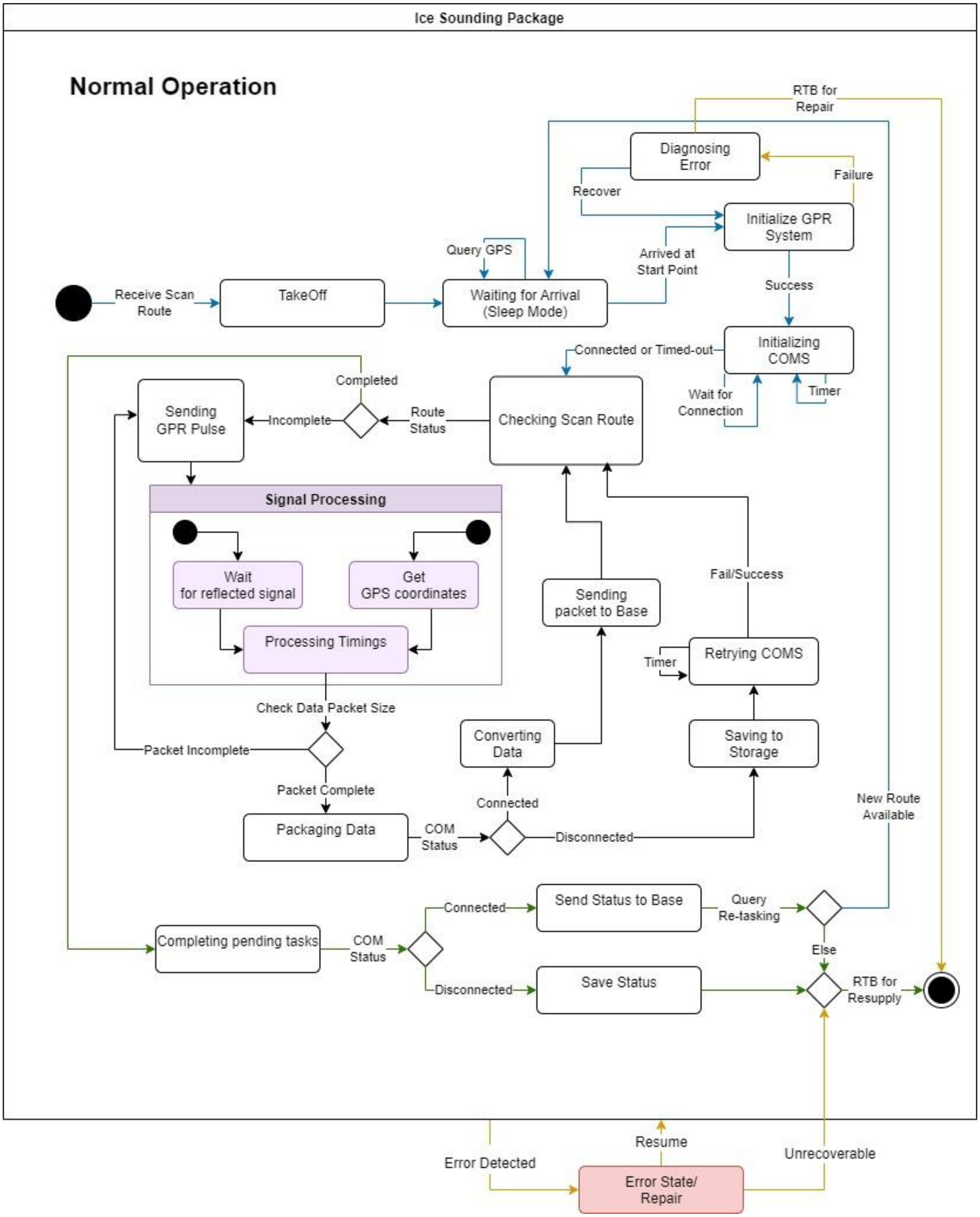

Figure 2: State Chart for Regular Operation of the Ice-Thickness Mapping Sensor Package

2.3. Operating Environment

The sensor package will be controlled by a Raspberry Pi MCU. The MCU will control the data from the GPR and the communication of that data to the ground control unit. The base control unit operating environment is not in the scope of this project.

The physical environment in which the drone with the attached sensor package will be used is the remote Arctic. The drone will be used along shipping routes through northern Canada. Arctic temperatures range from an average of -30℃ in the winter and 10℃ during the rest of the year [2]. The average wind speed is 80km/h and can reach up to 100km/h [3]. This environment is very flat and is therefore free of hazards a drone would encounter in different environments such as trees or buildings which the drone can crash into, or which interfere with control signal transmission between the base control unit and sensor package.

2.4. Design and Implementation Constraints

The purpose of the drone-mounted sensor package is to fly a pre-planned route and measure the ice-thickness at each designated point using GPR. This data is then sent back to the base control system for processing. There are several constraints on the design and implementation of this technology.

The sensor package will need to be securely mounted to a compatible OTS fixed-wing drone that will be launched from a ship. A suitable drone must be chosen as this drone must be able to function in the Arctic's climate as well as carry and interface with the sensor package.

A Raspberry Pi will be used as the microcontroller. The design is constrained by the hardware of this device such as the amount of RAM and its power requirements.

External software compatibility will limit us to certain drone mission control softwares. Our internal drone commands must be able to communicate with the drone's control software. The data processing will also be limited to what the drone mission control software can produce.

The ground control unit (GCU) will have to have sufficient signal processing equipment and antenna gain. The omnidirectional antenna for the data link on the sensor package will require a large high-gain antenna on the GCU to capture the weak signal transmission.

2.5. Assumptions and Dependencies

The following assumptions have been made to limit the scope of the design. All assumptions and dependencies are necessary for a realized system but are not covered within the design of the sensor package.

A-1	An independent drone system capable of carrying the package is available
Rationale	This device is designed to integrate with certain OTS drones. Not all drones will be able to lift/carry the device. Consequently, we assume a suitable and compatible drone to deploy the sensor package on is available.

A-2	The fixed-wing drone has autonomous flight capabilities.
Rationale	The drone must have the ability to complete a flight path at a certain speed and altitude without direct user control for the device to operate in its long-range mode.

A-3	An external computer system is available to analyze the ice-thickness data.
Rationale	The scope of this project does not include the data analysis of the GPR-sounding data. To calculate the ice-thickness, software must be available to compute this value from GPR timing data.

A-4	An existing drone mission control software is available.
Rationale	The scope of this project does not include creating a drone mission control software that controls the movement of the drone. We assume that there is an existing drone mission control software available.

A-5	A base station with radio communication and data processing capability is available.
Rationale	The scope of our system does not include creating the base control unit. Thus, it is assumed that a base control unit which can run the control and communication software for the sensor package is available.

3. External Interface Requirements

This section covers the external interface requirements of the drone-mounted sensor package. The external interface requirements covered are user interfaces, hardware interfaces, software interfaces, communication interfaces, and environmental interfaces.

3.1. User Interfaces

There are two user interfaces required for the GPR sensor package product: A simple power override control on the sensor package, and a software user interface to allow for communication between the sensor package and the base control unit. These interfaces are explained further below.

R-3.1-1	Override power control interface.
Rationale	For installation and microcontroller access, the user must have the ability to disconnect the sensor package power supply. A simple switch or button will effectively serve this purpose.

R-3.1-2	User control and data management application for the base control unit.
Rationale	The user will issue commands and receive data from the sensor package (and drone) via a software interface on the base control unit computer. This application must allow the user to utilize the abilities of the communication hardware and external data processing software.

3.2. Hardware Interfaces

For data collection, firmware upgrades, and debugging purposes, the sensor package requires a USB port to access the microcontroller and onboard storage. The USB should provide power to the microcontroller and the storage device. The battery power supply should be disconnected or disabled during this time.

Additionally, if the drone has an available serial connection, a port should be provided on the sensor package to connect the drone interface to the microcontroller. This should be a data line online but contain a common ground connection to enable reliable transmission.

These requirements are summarized below.

R-3.2.1	A USB port for an external computer connection.
Rationale	A USB interface is required to collect stored data, upgrade firmware, and debug errors in the sensor package. This interface should power the microcontroller and data storage device as well as allow fast communication between the microcontroller and an external computer.

R-3.2.2	An SPI interface for a serial-enabled drone.
Rationale	If the drone has an available SPI interface, the sensor package should connect to the drone via this link to avoid additional complications with wireless communications. This interface should only transmit data but have a common ground. Protective circuits should isolate both devices from power surges.

3.3. Software Interfaces

The software interfaces for the system will include the internal sensor package software and the external software. The internal sensor package software will be the algorithm for ice-thickness measuring and sending/receiving data. The external software will be an existing drone mission control software. For the GPR system calibration and testing, there is existing software that allows you to test the effectiveness and accuracy.

R-3.3.1	Integrate sensor package to existing drone mission control software interface.
Rationale	The internal sensor package software for processing GPR and flight data should be able to integrate with the existing drone mission control software.

R-3.3.2	Linux Shell application interface.
Rationale	Linux shell application for system diagnostics and calibration of radar systems. A diagnostics tool will allow the drone operator to repair the system on-site.

3.4. Communication Interfaces

There will be multiple communication links from the drone flight controller, sensor package, and ground control unit (GCU). The drone flight controller will be linked to the sensor package via USB or other wired serial connection. This will allow the control signals for the drone to be received from the sensor package. The sensor package radio module will be receiving these control signals from the GCU via a 433 MHz communications link as seen in Figure 3. For the data link, there will be a secondary 433 MHz communications link. This allows for constant control of the drone with no data interruptions. The radio module interface will be made up of the Tx/Rx antennas for the control link and a single Tx antenna for data uplink.

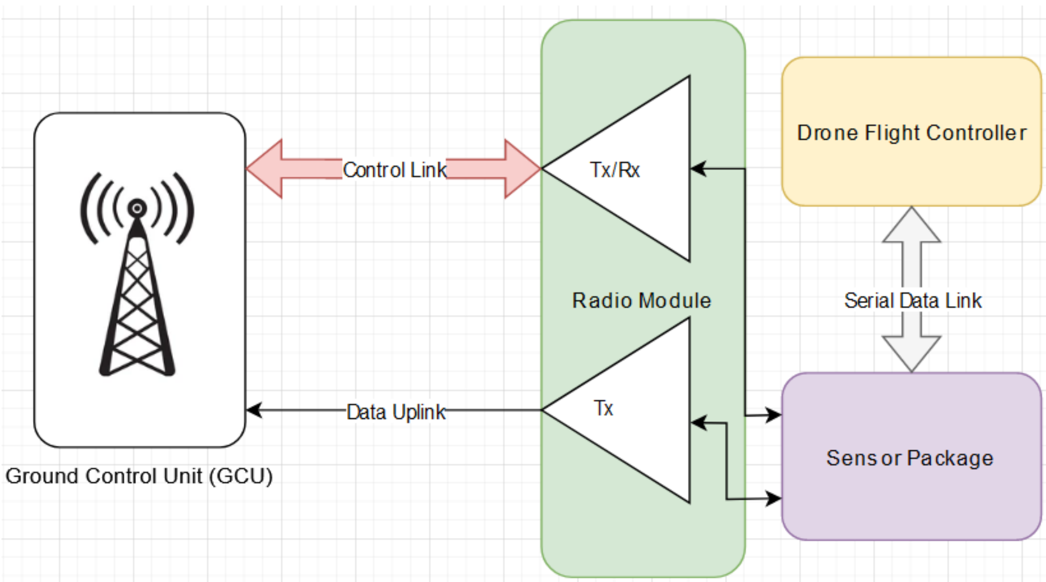

Figure 3: Radio Communication and Data Link of Ice-Thickness Measuring System

The communication interface is summarized below.

R-3.4.1	A centralized communication system between the sensor package and GCU.
Rationale	Full control of the drone and radar package will be available through one ground control unit.

3.5. Environment Interfaces

The environment interfaces for the drone-mounted sensor package system must enable the use of the sensor package in the extreme environment. The Arctic climate requires the drone-mounted sensor package to be able to handle freezing temperatures. Thus, the environmental interfaces are heating systems for the electronics and motors as well as waterproofing in case of accidental exposure to moisture. The environmental interfaces are summarized below.

R-3.5.1	Heating system interface.
Rationale	The heating system interface is needed to maintain the electronics and motors of the drone-mounted sensor package in their operating range.

R-3.5.2	Waterproof case interface.
Rationale	A waterproof case interface is required to prevent water from reaching vital electronics which could damage the functionality of the drone-mounted sensor package.

4. System Features

This section details the intended system features and how they function. The system features described below are the GPR sounding system, independent power supply, microcontroller and data packaging, communication and data link, and housing and drone mounting.

4.1. GPR Sounding System

The GPR system uses high-frequency EMF signals and precise timing to determine the internal topography of ice sheets.

The GPR system requires a large antenna and precise timing circuitry. The GPR antenna is large and must be mounted externally to the rest of the sensor package - most likely on the wings of the drone.

As the main component of the system, the GPR will likely consume the highest power and mass percentage of the device (besides the battery). Based on similar devices, the expected power consumption of the device will be between 250mW and 5W [4], [5]. With these parameters and considering the payload capacity of drones, we may expect at least 30 min of active GPR scanning with a suitable battery.

R-4.1.1	Can detect ice-thickness of up to 10 m.
Rationale	Ice-breaker ships have been known to break through ice up to 7 meters (21 ft) thick [6]. The sensor must measure ice up to this depth plus a safety range to indicate how accessible or inaccessible the area is.

R-4.1.2	Has a precision of +\- 15 cm.
Rationale	While the precision of the device should aim to be as small as possible, having a precision of greater than 15 cm would create a less usable system.

R-4.1.3	Has a mass of less than 1kg.
Rationale	Most fixed-wing drones have payload capacities of 2 kg to 40 kg [7]. Being less than 1kg offers potential compatibility with most applicable drones.

R-4.1.4	Operates at a minimum velocity of 7 m/s.
Rationale	Fixed-wing drones require a minimum speed to remain airborne. Since the GPR will be deployed on these drones, it must operate at least at the minimum speed of the drone.

R-4.1.5	Operate at a minimum of 10 m above the ground.
Rationale	To allow the drone to comfortably fly above the ground, a buffer of 10 m is selected. The GPR must accurately detect the ice thickness at this height.

R-4.1.6	Battery powered.
Rationale	The sensor package must be capable of running off battery power from the integrated battery.

R-4.1.7	Functions in light wind, rain, or snow.
Rationale	To be useful at scanning ice-thickness, the system must be deployable in a range of weather conditions. Extreme weather operation would be a bonus but is not a requirement.

R-4.1.8	Has an operational frequency between 100 MHz to 10 GHz.
Rationale	Based on previous GPR ice-penetration systems [8], [9], to achieve a penetration depth of around 10 m at the required resolution, an EMF signal between 100 MHz to 10 GHz is required.

4.2. Independent Power Supply

The independent power supply will provide power to all subsystems of the sensor package. The power will be supplied by a removable battery which will be charged while detached from the package. Based on the power requirements of the other subsystems, the battery should be able to provide between 5W and 15W of power for 30 minutes to 1 hour. The battery should be lightweight because increasing the payload weight will decrease the drone's flight time. The power subsystem will also include voltage step-up or step-down converters to provide the necessary voltages for each component.

R-4.2.1	Has a swappable battery.
Rationale	The battery must be easily swappable so that a depleted battery can be easily replaced by a charged battery

R-4.2.2	Can function in cold arctic temperatures.
Rationale	The battery must function in arctic conditions. Batteries experience decreased functionality when they are cold. Arctic temperatures range from an average of -30℃ in the winter and 10℃ in the summer [5].

R-4.2.3	Has a lightweight and high-capacity battery of less than 0.25 kg.
Rationale	To increase the range, a high-capacity and lightweight battery will be needed.

R-4.2.4	Can provide a total power of 15 Wh.
Rationale	At most 15W of power will be needed to power the Raspberry Pi, GPR, and communication subsystem for 1 hour.

4.3. Microcontroller and Data Packaging

A Raspberry Pi 4 Model B 8 GB will be used as the MCU because of its small size and lightweight. It will control the GPR and capture measured signals. Thus, the system features of this MCU are as follows below.

R-4.3.1	Communicate data to the communication subsystem.
Rationale	Raspberry Pi will send GPR data to the transmitter module to be transmitted to GCU.

R-4.3.2	Transmit GPR data and GPS data together.
Rationale	Combining GPR data with the current GPS position for transmission will allow for GPR data to be used for the ice-thickness map.

R-4.3.3	The connection between the sensor package and GCU can be verified.
Rationale	The MCU can determine if a connection is possible between the GCU and the sensor package so that control information and data can be transmitted between them.

R-4.3.4	Multiple data routing options are available.
Rationale	Based on the communication status of the package, the controller can route GPR data to the communications array and/or local storage.

R-4.3.5	External peripherals and user interfaces are available.
Rationale	The raspberry pi can communicate via serial connections to external peripherals and a user device for control, calibration, and update purposes.

4.4. Communication and Data Link

Communications features will include two receiving and transmitting antennas for control signals and one transmitting-only antenna for data transmission as seen in Figure 3. The control antenna will be a directional antenna intended to increase antenna gain to the GCU. Since a directional antenna is used, the drone will require line-of-sight and a motorized gimbal. The data link can be an omnidirectional antenna, but the GCU will need a high gain antenna to receive the small data signals from the drone.

R-4.4.1	Transfer real-time ice-thickness data to the ground control unit.
Rationale	To allow the operators to determine the best route based on the ice-thickness data.

R-4.4.2	Store ice-thickness data on external memory for redundancy.
Rationale	The ice-thickness measurements will be stored on an external memory micro SD card in case the communication system fails to transfer the data to the ground control unit.

R-4.4.3	Low power consumption for the communication system.
Rationale	Maximum 2W power consumption to reduce overall system power consumption and preserve battery power for other processes. This will allow for longer GRP measurement time and thus more measurement locations.

R-4.4.4	Long-range data link between sensor package and GCU.
Rationale	A minimum 30 km range to allow for long-range mapping way ahead of the ice-breaker ships.

R-4.4.5	433 MHz transmission frequency band.
Rationale	The 433 MHz frequency band provides a good range and bandwidth. It is also an available frequency under the Canadian Table of Frequency Allocations so there will be little interference from other infrastructure.

R-4.4.6	Serial connection to the drone flight controller.
Rationale	Serial data link via USB from the drone to the mounted sensor package will allow flight control data to pass through to the sensor package. This will create a redundancy in the communication subsystem as the drone will have its own communications link to the GCU.

R-4.4.7	Separate communications link for data and control.
Rationale	The control signals will be sent through one communications link and the data will be sent through another. This is so there are no data interruptions for the drone control.

4.5. Housing and Drone-Mounting

The housing and drone-mounting features will include lightweight and durable mounting, easy access to electronics within the sensor package, a waterproof and weatherproof case, a shock-resilient case, and gyroscopic stabilization. These features are detailed further below.

R-4.5.1	Lightweight and durable mounting fixture.
Rationale	Since the payload capacity on a drone is limited, the material must be as light as possible but robust at the same time to ensure the sensor package doesn't disconnect from the drone.

R-4.5.2	Radar is easily accessible.
Rationale	The radar must be easily accessible for installation and maintenance purposes.

R-4.5.3	Housing for extreme weather conditions.
Rationale	Insulation for the drone will be required to keep it within operating temperatures. Also, waterproof housing is needed to protect electronics from any water damage.

R-4.5.4	Shock-resistant housing.
Rationale	Since radar equipment is sensitive, the sensor package must be capable of withstanding vibrations from a high-velocity flight.

R-4.5.5	Gyroscopic stabilized radar mount.
Rationale	Gyroscopic stabilization for the GPR will increase the accuracy of the ice-thickness measurements.

5. Non-Functional Requirements

This section covers the non-functional requirements of the drone-mounted sensor package system. The non-functional requirements detailed below are the performance requirements, safety requirements, quality attributes, and business rules.

5.1. Performance Requirements

The performance requirements of the drone-mounted sensor package are that it needs a long operating time, has variable precision, and can send a distress signal if it crashes, or the system fails. These performance requirements are described in further detail below.

R-5.1.1	Should have a minimum operating time of 1 hour with 30 minutes of active scanning.
Rationale	Considering the operation speed of drones and the travel speed of icebreaker ships [7], [10]**;** A 1 hour operating time allows for approximately 20 km of ice to be scanned ahead of the ship, which is equivalent to 30 minutes of ice-breaker ship travel time at cruising speed.

R-5.1.2	Has variable precision between 15 cm and 3 cm.
Rationale	To increase use cases, the sensor package should have a programmable precision of up to 15 cm such that, if required, high-precision data may be acquired at the cost of the area covered or power consumed.

R-5.1.3	Crash alert and distress signal.
Rationale	In the event of a crash or other failure which results in a grounded system, the sensor package can use its communication system to issue a distress signal. This signal could aid in the recovery of the drone and sensor package.

5.2. Safety Requirements

This section covers the safety requirements which must be followed to ensure the safe use of the system. The safety requirements are that the electrical standards and safety protocols are followed, and aviation regulations are adhered to.

R-5.2.1	Electrical standards and safety protocols are followed.
Rationale	The electronics of the drone-mounted sensor package adhere to electrical standards and safety protocols to prevent shorts in the sensor package or injury to the user.

R-5.2.2	Adherence to aviation regulations.
Rationale	The device will adhere to applicable aviation regulations regarding radar, power, and communication equipment.

5.3. Quality Attributes

The following sections describe the quality attributes desired for the radar system.

5.3.1. Usability

The radar system must be user-friendly to allow for any user to easily learn the system and be able to control the sensor package features.

5.3.2. Reliability

The radar system must provide accurate measurement data in constant arctic environments without any repair required for a minimum of six months.

5.3.3. Correctness

The radar must output the ice-thickness measurements with a precision error not greater than 15 cm.

5.3.4. Interoperability

The radar system must allow for easy data transfer between the sensor package and the ground control unit.

5.3.5. Diagnosability

The system must have multiple status indicators located on the sensor package and a Linux application for on-site repair/calibration.

5.4. Business Rules

The operation of the drone-mounted ice-thickness mapping package must be done while adhering to the following business rules:

- The package shall be securely mounted to the drone and checked before takeoff.
- The integrity of the drone should be confirmed before launch.
- The drone shall only be launched by trained personnel.
- The drone shall not be flown in restricted areas.

6. Other Requirements

This document outlines all the major requirements needed at this time.

Appendix A: Glossary

The terms used throughout the document are listed below.

Term	Description
ONC	Ocean Networks Canada
UAV	Unmanned Aerial Vehicle
OTS	Over-the-Shelf
MCU	Microcontroller Unit
RAM	Random Access Memory
GCU	Ground Control Unit
EMF	Electric and Magnetic Fields

Appendix B: Analysis Models

No Analysis Models were used.

Appendix C: To Be Determined List

The following lists show the items yet to be determined.

Radar System:

- Sampling rate of the radar.
- Mounting fixture for the radar.
- OTS drone that fits the requirements of the radar and can function in the Arctic climate.

Hardware:

- Size of the external hard drive.
- Independent power supply.
- Large gain antenna for GCU.

Software:

- Open source software for an emulated view of drone path.