DESIGN, DEVELOPMENT, AND FIELD TESTING OF THE GLACIERHAWK: AN UNMANNED AERIAL SYSTEM FOR GEOSCIENCE DATA RETRIEVAL

A Thesis in
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by
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Abstract

The GlacierHawk Unmanned Aerial System (UAS) serves as a data retrieval platform in support of the geoPebble sensor system developed at the Pennsylvania State University. The mission of the distributed sensor network is to wirelessly collect seismic and movement data across areas of interest on glacial surfaces over a multi-day deployment period. Due to the cragginess and volatility of the ice, the sensors are inaccessible except by air and may not be recoverable at the end of the defined deployment period. Should a sensor be lost to ice calving or system failure, some or all of its data may be lost, so the ability to retrieve data on demand during a deployment is of significant value. Furthermore, beyond serving as a backup, mid-deployment retrieval provides earlier access for analysis during longer deployments. The cost, risk, logistics, and required expertise of helicopter-based access to the geoPebbles makes such a method infeasible except for sensor installation and removal, so the concept of a drone-based solution quickly becomes attractive. This thesis outlines the design, development, and concept of operations of the GlacierHawk UAS, from initial concept generation to field testing over Helheim Glacier in southeast Greenland.

The importance of endurance to the geoPebble mission, coupled with Helheim’s remote, austere operating environment, make battery selection and rugged, modular design two of the most critical factors in this application. To accommodate transport and field assembly, the GlacierHawk’s thin-walled composite airframe consists of a square-section fuselage tube and two cylindrical arm tubes, both of which are durable and easily removable. Battery storage and most cable routing are internal, whereas the Pixhawk autopilot, sensors, and Wi-Fi access point payload are externally mounted. The construction process leverages conventional production methods and materials with composites and additive manufacturing. Commercial-off-the-shelf components and systems are also leveraged with custom fabrication whenever suitable.

During field testing with a deployed sensor array, the resulting 11.6-kg, 30+-minute-endurance quadcopter demonstrated the capability of flying glacier transit profiles and facilitating geoPebble data retrieval. Insights gained from the Greenland proof-of-concept mission are presented as concepts for implementation in future vehicle designs and field deployments. Identified areas for improvement include, among others, robustness of the positioning system and data links, redesigned landing gear, motor tilt for improved maneuverability, and increased endurance to support longer, more complex mission profiles.
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Last but certainly not least, to my family and friends, both at home in Buffalo and here in State College — thank you for always having my back. You are the wind to my wings.
Dedication

To all who have looked up and dreamt of flight.
Chapter 1
Introduction

Geosciences field research often requires data collection in remote, austere environments by small, interdisciplinary teams. This places significant constraints on the design, transportation, and operation of deployable experimental equipment. Recent advances in small-scale electronics, such as sensors, data storage, radios, and power systems, have enabled development of compact networked instrumentation capable of making \textit{in situ} measurements of distributed parameters throughout large regions of interest. Much of this same technology has also contributed to the evolution and rapid growth of unmanned aerial systems (UASs), which have enabled new capabilities across a variety of technical fields. UASs offer effectively unrestricted mobility of compact payloads over complex, rugged, or otherwise hazardous terrain while avoiding most of the cost, energy, and training requirements of full-scale aircraft, all without placing aircrews at risk. Research at Greenland’s Helheim Glacier, shown in Figure 1.1, exemplifies an application of UAS technology for data retrieval from nodes of a distributed sensor network deployed across inhospitable terrain. After introducing Helheim and its relevance in ongoing climate change research, this chapter describes the geoPebble sensor system and motivates the role of UAS development in support of data retrieval.
1.1 Geosciences Mission Overview

In recent years, UASs have come to occupy an ever-expanding range of roles across a variety of applications; from military intelligence, surveillance, and reconnaissance (ISR) to agriculture, construction, law enforcement, and many more. Regardless of field, the ability to fly a camera, laser scanner, or other sensor payload on-demand and at low cost presents a compelling alternative to using full-scale manned aircraft or non-flight-based means of acquiring data. UAS implementation is especially beneficial when these other methods would put human crews at risk, be cost-prohibitive, or otherwise infeasible due to other factors such as noise, emissions, public perception, logistics, or existing regulations.

The increasing capability, accessibility, and affordability of compact electric remotely-piloted and autonomous flight vehicles further expands their utility. As flight times, payload masses, and vehicle performance increase, UASs are capable of taking on more
advanced mission sets in more challenging environments. Furthermore, widespread availability of commercial-off-the-shelf (COTS) components and open-source autopilot systems enables developers to design, construct, and automate a specialized UAS for a given mission profile and constraint set. University-led field research, especially in the geosciences, is well-suited to bespoke UAS development and implementation in support of distributed sensing missions in remote, austere environments. Ice sheets and glaciers are prime examples of such settings, as they require modular, robust, and internationally portable UAS designs capable of endurance-focused flight over long ranges.

1.1.1 Motivation

While it may be a common misconception to view glaciers as quasi-static, nigh unchanging objects, they are actually governed by dynamic processes and forces of nature ranging in timescale from minutes to thousands of years. As the condition of Earth’s climate becomes an increasingly prevalent and urgent field of study and action, there is much to gain in seeking better understanding of glacier dynamics and their relationship with broader environmental factors.

Helheim Glacier is Greenland’s third-largest outlet glacier, and is known for its high rate of calving and seismic activity in the form of glacial earthquakes [4]. Calving is the process by which sections of freshwater ice break off a glacier and become icebergs floating in a salt water fjord. As a tidewater calving glacier (TWG), Helheim’s ice dynamics and their relation to broader atmospheric and oceanographic trends are more complex than those of terrestrial glaciers, which can serve as more straightforward indicators of climate change. Figure 1.2 presents a cutaway illustration of Helheim’s location and anatomy, including flow direction, ice depth, terminus, and the interplay between fresh Arctic and oceanic salt water in the fjord. The volatility of churning water at the center of the terminal front precludes ice formation there and results in an exposed pool called a polynya that is visible from the surface. A number of research installations and the nearest town, Tasiilaq, are also shown.

Classical TWG behavior is cyclical in nature, comprising three primary stages: advance, retreat, and dynamic instability [5]. During the advancing stage, ice flow speeds are typically moderate and iceberg calving is low as the glacier lengthens while still receiving support from rocks and sediment below the terminus. Favorable basin geometry and terminus stability play larger roles in driving TWG advances than do external climate factors. Eventually, however, the glacier extends to the point at which its area of mass loss, or ablation zone, grows relative to its accumulation zone, where mass is gained.
As this progresses, advance becomes less favored, transition to retreat begins, and the glacier’s climatic sensitivity increases.

Compared to advances, retreats are much quicker and more severe. Whereas advances may last centuries and yield tens of meters of growth per year, retreats can drive a terminus back hundreds or thousands of meters per year over the course of decades. Dramatic increases in ice flow and calving couple to form a feedback loop that results in significant mass loss both to the glacier and the ice field from which it feeds. These losses have been shown to be far more severe than surface melting due to increased air temperature. Yet, while atmospheric conditions alone may not exert strong influence on individual TWG cycles in the short term, analysis of global trends over centuries and millennia may be informative as to the extent of and balance between advance and retreat across many cycles for multiple glaciers.

Due to the complex dynamics of TWGs, the exact mechanisms of instability and transition between advance and retreat are not yet well understood, especially when viewed with respect to broader climatic factors. The presence of multiple asynchronous TWG systems around the globe demonstrates that, within a given region, all three
phases of the cycle may be occurring at once; in other words, all glaciers in an area need not advance or retreat together, despite being in the same general climate. This suggests that there exist additional drivers of glacial health and behavior beyond those traditionally considered — namely snowfall, air temperature, and other atmospheric processes. Ocean water temperature is now being recognized as one such additional driver that has significant influence over the stability of calving glaciers. Further investigation into the relationships between ocean forcing, atmospheric factors, and calving will be vital to better understanding and modeling TWGs as significant contributors to global sea level rise [5].

Prior research at Helheim has correlated abrupt accelerations in ice flow with major calving events and glacial earthquakes, which highlights the relevance of investigating short-timescale phenomena in developing deeper understanding of glacial dynamics [4]. Measuring the propagation of seismic wavefronts through the ice and their reflections off the underlying rock at multiple locations can help better characterize the glacier’s structure, history, and behavior [6]. While seismic reflectometry studies traditionally require artificial generation of seismic sources, the high degree of calving and naturally-occurring seismic activity at Helheim may preclude such a necessity. Nonetheless, the demand exists for an accurate, practical, and affordable means of capturing this data.

1.1.2 geoPebble Sensor System

Investigation of short-timescale glacial processes requires the placement of precise, high-resolution instrumentation at multiple locations of interest over multiday deployment periods. The geoPebble system developed at the Pennsylvania State University is a wireless network of self-contained electronic seismometers aimed at increasing sensing capabilities while reducing the practical challenges, costs, and complexity of performing experiments in the extreme environments of glaciers and ice sheets in Greenland and Antarctica. Figure 1.3 depicts an individual unit, while Figure 1.4 illustrates the network’s concept of operations. The top of a geoPebble is approximately the size of a dinner plate.

Each geoPebble contains a GPS unit capable of centimeter-level precision for recording position and movement data, along with a suite of seismic sensors for recording the propagation of wavefronts below the glacier surface. To prevent erroneous inter-unit timing that would compromise seismic indications, each geoPebble contains a custom GPS-Disciplined Oscillator (GPSDO) to maintain wireless network synchronization. Three-axis magnetometers and accelerometers allow for orientation determination, while temperature and humidity sensors measure ambient conditions. A 7 amp-hour lithium
Figure 1.3. geoPebble CAD model. (Source: “Penn State geoPebble system: Design, Implementation, and Initial Results” [2])

ion battery powers each geoPebble, and 16 GB of internal storage facilitate up to 16 days of continual data recording. Wi-Fi connectivity facilitates communication between individual units and a control station computer, while Wi-Fi access points act as range extenders. The system is designed to support over 100 geoPebbles across randomly placed arrays that may expand over multiple square kilometers [2, 6].

1.2 Role of UAS in Data Retrieval

Although the geoPebbles are mounted to poles drilled into the ice, the glacial surface’s crevasses and dynamic natural processes carry the possibility that geoPebbles may be overturned or completely lost at any point prior to their planned removal. This poses a threat to the network’s overall data integrity and motivates the need of a mid-deployment data retrieval system. The inherent inaccessibility of the glacier surface renders any ground-based approach infeasible, if not impossible, to implement in a safe, cost-effective, and frequent manner. While a manned helicopter is required for geoPebble installation and removal, the cost, scheduling, risk, and expertise required for this process precludes frequent revisiting of the sensor sites. This scenario naturally lends itself to a UAS
The design mission for the geoPebble support UAS, dubbed the GlacierHawk, is to take off from a small campsite alongside the glacial fjord, fly over the ice to the sensor array, and loiter over a specified geoPebble for as long as necessary to download data before returning to the campsite for recovery. All of these tasks are to be performed while carrying a 1-kg payload consisting of a Wi-Fi access point, ODROID computer, and dedicated payload battery. Upon return, flight batteries will be swapped for newly charged units, and the vehicle will be sent to the next geoPebble in the array. This is to be repeated for each geoPebble over each day of the deployment period. Regularly retrieving data from the entire array not only provides a backup in case of lost geoPebbles, but also provides data access for earlier analysis during longer deployments.

With limited information on — and no prior access to — the specific site to be used, the vehicle itself, crew, and operating concept must be adaptable to actual conditions during field testing, as opposed to those planned for or anticipated. Table 1.1 lists the key mission parameters around which the GlacierHawk was designed and operating concepts were planned. While specifics as to the UAS launch and recovery site were unknown until arrival at Helheim, the farthest geoPebbles were expected to be up to 5 km from
the UAS launch point.

<table>
<thead>
<tr>
<th>Mission Parameter</th>
<th>Value</th>
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<tr>
<td>Maximum round trip distance (Required range)</td>
<td>10 km</td>
</tr>
<tr>
<td>Altitude above mean sea level (MSL)</td>
<td>100–200 m</td>
</tr>
<tr>
<td>Payload mass</td>
<td>1 kg</td>
</tr>
<tr>
<td>Average wind speed</td>
<td>3 kts</td>
</tr>
<tr>
<td>Air temperature</td>
<td>50–60°F</td>
</tr>
<tr>
<td>geoPebble-to-payload data transfer rate</td>
<td>1 MBps</td>
</tr>
<tr>
<td>File size</td>
<td>1 GB/geoPebble-day</td>
</tr>
<tr>
<td>Deployed array size</td>
<td>15 geoPebbles</td>
</tr>
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</table>

A UAS designed to support the geoPebble system must emphasize a blend of endurance and payload capacity, while also incorporating ruggedness and simplicity of operation and repair in a remote and austere environment. Furthermore, such a vehicle must be modular or otherwise easily collapsible to facilitate durable packing for multimodal international transport — travel from Penn State to Helheim Glacier involves moving equipment by road vehicle, airliner cargo hold, helicopter interior, and external sling load.

Even amongst UASs in the same broad vehicle category, varying mission requirements and constraints cause initially similar design concepts to result in vastly diversified final products. While this has always been true for traditional aircraft and engineering in general, the rapid emergence and evolution of small electronics, sensors, and batteries make UAS technology all the more agile, scalable, and flexible overall. The development of and rapid expansion of multirotors (rotary-wing aircraft with at least two, but commonly four or more, relatively simple rotors, as opposed to traditional helicopters with a single, more complex main rotor system) as platforms for cameras and other sensors exemplifies this dynamic. While simple and straightforward in principle, the intended application, available resources, and operational environment quickly complicate the design and development process. For the GlacierHawk, endurance (dependent primarily upon available battery technology) and airframe modularity for transport and field operations are the central design drivers.
1.3 Contributions

The primary contributions of this thesis are a field-validated UAS design and an initial knowledge base regarding geoPebble support operations in an actual mission environment, as seen in Figure 1.5. The resulting 11.6-kg, 30+-minute-endurance quadcopter demonstrated the capability to fly a Wi-Fi access point payload on glacier transit profiles and successfully facilitated geoPebble data retrieval. Key design tradeoffs and operational challenges are discussed both as context for the initial vehicle development and as a basis for future system improvements. These considerations, coupled with a detailed description of the UAS operating area at Helheim Glacier and general insights from the field, comprise a valuable foundation for subsequent efforts.

Figure 1.5. The GlacierHawk overlooking Helheim. (Author photo)
1.4 Reader’s Guide

The remainder of this thesis is organized as follows:

Chapter 2 describes the UAS development process as divided into the three traditional phases of aircraft design: conceptual, preliminary, and detail design. Initial sizing and performance calculations are presented and discussed in comparison to the as-built GlacierHawk.

Chapter 3 outlines the key tools, equipment, and processes used in constructing the GlacierHawk vehicle and integrating the mission payload. The assembly process and transport configuration are also described.

Chapter 4 reviews GlacierHawk flight planning, operations, and key mission concepts generated and developed during field testing over Helheim Glacier. Mission results are presented and discussed.

Chapter 5 presents conclusions and provides concepts for potential implementation on future UAS designs and flight operations in support of the geoPebble data retrieval mission.
Chapter 2  
Design of the GlacierHawk UAS

This chapter outlines the conceptual, preliminary, and detail design phases of the GlacierHawk’s development, responsible for bringing the vehicle from an idea on the proverbial drawing board to a detailed compilation of components and systems to buy, build, and assemble. Given a set of mission requirements, conceptual design selects a broad aircraft category, generates potential vehicle configurations, and predicts performance using initial sizing and operating parameters. Preliminary design narrows the focus to a single airframe configuration, defines the primary systems, and selects major components. The detail design stage brings the design to build-ready status by defining all custom parts, modifications, fastener arrangements, and other such refinements.

For any electric UAS, available battery technology is a major factor that drives not only the propulsion system design but that of the entire vehicle, and places fundamental limits on its size, weight, and performance characteristics. The intended operating environment and associated transportation requirements are also central to all stages of the design process. Rigorous battery selection and modular airframe design for transport to and use in the remote and austere setting of Greenland’s Helheim Glacier stood at the core of the GlacierHawk’s development. Figure 2.1 shows multiple CAD views of the final design with several basic dimensions.

2.1 Conceptual Design

Conceptual design is the first of the three traditional phases of aircraft design. It is during this stage that the broadest variety of ideas is considered as the designer seeks to establish a general vision of what form the vehicle will take. Rather than focusing on individual components and other details at the nuts and bolts level, conceptual design generates and evaluates potential aircraft configurations, which provides high-level vehicle definition.
2.1.1 Vehicle Configuration

2.1.1.1 Fixed-Wing vs. Rotorcraft

Among the first configuration decisions was that between a fixed- or rotary-wing design. While fixed-wing aircraft offer significant advantages in speed, range, endurance, and payload capacity for a given vehicle weight and power, rotorcraft possess remarkable versatility with regard to precise positioning and the ability to take off and land in confined or otherwise restrictive environments.

Uncertainty over the campsite’s suitability for fixed-wing flight operations was a primary factor favoring development of a rotorcraft. Even if hand launch of a fixed-wing vehicle was possible, a conventional landing would likely incur more risk, pilot workload, and difficulty than a vertical landing, in addition to requiring more space. Not only would a larger area be necessary, but also clear approach paths from a number of angles to allow for variability in wind direction and safe execution of a go-around. Surface smoothness, uniformity, and other characteristics would be another major concern affecting the feasibility of belly and/or wheeled landings. While optimizing the design for short takeoff and landing (STOL) capability may improve feasibility, it would also likely
begin to erode the advantages of speed, range, and endurance of a fixed-wing design over a rotorcraft. Adding secondary flight control surfaces and high lift devices such as flaps and slats would further complicate and weigh down the design, as would ruggedized landing gear with its attendant drag penalty. If the hypothetical fixed-wing UAS was too large to either hand launch or land conventionally, then specialized launch and recovery equipment would need to be designed. Development of such equipment would add cost and complexity to both the technical and logistical processes associated with the mission.

The requirement for maintaining payload proximity to a specified geoPebble was the second major factor favoring a rotary-wing platform. Hovering would allow on-demand positioning of the payload directly over a given geoPebble, and would avoid potential lost connections or other complications arising from an airplane’s need to fly an orbit about the geoPebble’s location. For instance, if there were an ice formation obstructing line-of-sight between the sensor and payload, or if the sensor was not level, there could be signal degradation or dropout at one or more azimuthal stations in the orbital pattern.

A rotorcraft’s ability to hover was thus deemed more valuable than the performance benefits of a fixed-wing design due to substantial advantages in launch, recovery, and on-station functionality for the geoPebble support mission. Although a vertical takeoff and landing (VTOL) fixed-wing aircraft would, in principle, combine the performance advantages of an airplane with the hovering ability of a rotorcraft, in practice it would represent a significant developmental and operational risk, especially with regard to the transitional flight regime between hover and wing-borne forward flight. While both traditional fixed- and rotary-wing UAS technology has reached a notable degree of maturity and accessibility, a hybrid design would be at a disadvantage in this regard.

2.1.1.2 Multirotor Selection

A variety of configuration options exists within the broad category of rotorcraft. While a traditional helicopter with a large single vertical-axis main rotor and smaller lateral-axis tail rotor may be the first to come to mind, this is far from the only, or best, layout for any given application.

Helicopters with a single main rotor need a lateral-axis perpendicular tail rotor to counteract the torque imbalance caused by spinning the main rotor from a central shaft. Yaw control is achieved by varying the collective pitch of the tail rotor, such that the side force and corresponding yaw moment produced is either greater or less than the equilibrium value. This equilibrium value changes based on the flight condition, so transitioning between climb, descent, and hover will each require anti-torque inputs. For
example, a climb requires an increase in main rotor collective pitch, which will in turn demand a greater torque output from the aircraft’s powerplant in order to maintain constant rotor speed. This introduces a torque imbalance that will yaw the aircraft without application of a simultaneous increase in tail rotor pitch. The converse is true for descending flight [8].

Coaxial and tandem helicopters each feature two counter-rotating main rotors to avoid the need for a tail rotor. In a coaxial design, the rotors are vertically stacked and share a common axis, whereas those of tandem configuration are either side-by-side or longitudinally inline on separate hubs. While these designs eliminate tail rotors, they still require cyclic pitch control mechanisms for maneuvering.

Lacking discrete lifting and control surfaces, traditional rotorcraft rely on their main rotor systems for simultaneous lift, thrust, and maneuvering forces and moments. This necessitates the ability to change rotor blade pitch in both collective and cyclic manners. As these names suggest, collective pitch control changes the pitch of all blades simultaneously so as to increase the vehicle’s total lift output. Collective pitch inputs do not change the orientation of the tip path plane, only the magnitude of the lift vector. Cyclic pitch control is used to generate pitching and rolling moments by only manipulating blades passing through specified azimuthal regions. This changes the angle of the tip path plane, but not the rotor’s total force output [8]. Main rotor assemblies must be able to simultaneously facilitate both types of pitch control in a responsive, reliable, and resilient manner. While the swashplate mechanism is the proven standard for large-scale and human-occupied rotorcraft, it involves multiple actuators, linkages, bearings, and other flight-critical moving parts requiring careful inspection and regular maintenance for safe, reliable operation. This mechanical and control complexity presents a challenge to implementation on smaller scale, lower cost, and non-maintenance-intensive UAS designs.

Multicopters with four or more fixed-pitch rotors powered by direct-drive electric motors have become the standard for many UASs. Such vehicles now span numerous roles and industries, from $25 micro-scale recreational quadcopters in the consumer hobby space to professional heavy-lift octocopters capable of carrying LIDAR scanners, DSLR cameras, or other equipment and potentially costing tens or hundreds of thousands of dollars.

Relative to traditional helicopter designs, quadcopters offer significant reductions in mechanical and control complexity, in addition to being easier to fly. Thrust and maneuvering forces and moments are controlled solely through individual motor speeds,
which eliminates the need for blade pitch control and thus any swashplate mechanisms. Rather than altering the tip path plane of a single main rotor to induce, for example, a forward aircraft pitch, the two rear rotors simply spin faster than those in front to produce more thrust and generate a nose-down pitching moment. Torque modulation from alternating motor directions provides yaw control and eliminates the tail rotor. To climb or descend, all four rotors uniformly accelerate or decelerate, respectively, and the pairing of clockwise and counter-clockwise motors inherently balances torque and, thus, does not require additional pilot input or automation to prevent undesired yaw.

Although they cannot autorotate after power failure as traditional helicopters can, quadcopters are generally more damage tolerant, which may be highly beneficial for initial flight testing, pilot training, and other operations with increased likelihood of sustaining damage. When crashes do occur, restorative measures are often limited to replacing individual broken rotor blades or landing gear components. These swaps generally can be done on-site in the field, as opposed to more involved structural work or mechanical repairs that may arise from a broken tailboom or swashplate assembly. Additional motors and rotors can provide a degree of redundancy should one or more fail, depending on aircraft configuration and which motor(s) fail. The power gained may also benefit heavy-lift and other high performance applications. Designs offering this added power and protection nonetheless present tradeoffs with cost, weight, complexity, and efficiency. Due to the vital importance of endurance in the geoPebble mission, construction of a quadcopter design with spare parts and an extra airframe was selected over a single vehicle with redundant propulsion.

2.1.2 Initial Sizing, Power, and Performance Estimates

A MATLAB code written by Langelaan [9] was used to predict multirotor performance based on initial and subsequently refined estimates of vehicle design parameters. The code loads a vehicle-specific input file containing basic component mass and aerodynamic characteristics, then runs a series of computations to estimate key performance metrics.

2.1.2.1 Momentum Theory, Ideal Hover Power, and Figure of Merit

Momentum theory provides the theoretical lower limit for power required to hover. As an approximation based on a number of simplifying assumptions, the ideal hover power is unattainable in practice, though it offers an easy-to-calculate baseline for later comparison
with more rigorous estimates [8]:

\[ P_{\text{ideal}} = \sqrt{\frac{m^3 g^3}{2 \rho A}}, \]  

(2.1)

where \( m \) is vehicle mass, \( g \) is acceleration due to gravity, \( \rho \) is air density, and \( A \) is rotor disk area. Vehicle total rotor disk area is computed using the equation for area of a circle of rotor radius \( r \), multiplied by the number of rotors \( N \):

\[ A = N \pi r^2. \]  

(2.2)

Incorporating the figure of merit into the hover power calculation accounts for inherent losses preventing achievement of the idealized theoretical limit. Figure of merit serves as a measure of rotor hover efficiency, and is the ratio of ideal to actual hover power required:

\[ \text{FM} = \frac{P_{\text{ideal}}}{P_{\text{actual}}}. \]  

(2.3)

The hover power equation thus becomes:

\[ P_{\text{hover}} = \frac{1}{\text{FM}} \sqrt{\frac{m^3 g^3}{2 \rho A}}. \]  

(2.4)

Note that, in the conceptual design phase, a specific vehicle’s actual hover power, and thereby figure of merit, is not yet known; this introduces a degree of empiricism to the process, whereby performance of existing designs informs selection of an estimated FM value.

### 2.1.2.2 Hover Time and Takeoff Mass as Functions of Disc Loading

Estimated hover power and battery parameters can be used to bound hover time and takeoff mass as functions of disc loading \( \frac{mg}{A} \), the ratio of vehicle weight to rotor disc area. This quantity is analogous to wing loading for a fixed-wing aircraft; lower values translate to higher efficiency and capability in low-speed flight, so for rotorcraft it is particularly relevant to hover performance. Multiplying hover power by the desired hover time \( t_{\text{hover}} \) yields the required battery energy capacity \( E_{\text{batt}} \), which is the product of battery mass \( m_{\text{batt}} \) and gravimetric energy density \( e_{\text{batt}} \):

\[ t_{\text{hover}} P_{\text{hover}} = E_{\text{batt}} = m_{\text{batt}} e_{\text{batt}}. \]  

(2.5)
Rearranging to solve for hover time and substituting the expression for hover power yields:

$$t_{\text{hover}} = \frac{m_{\text{batt}} e_{\text{batt}}}{P_{\text{hover}}} = m_{\text{batt}} e_{\text{batt}} \text{FM} \sqrt{\frac{2 \rho A}{m^3 g^3}}.$$  \hspace{1cm} (2.6)

Removing $m^2 g^2$ from the square root term and further rearranging:

$$t_{\text{hover}} = \frac{m_{\text{batt}} e_{\text{batt}} \text{FM}}{g} \sqrt{\frac{2 \rho A}{mg}}.$$ \hspace{1cm} (2.7)

Note that this expression contains the battery mass fraction $\frac{m_{\text{batt}}}{m}$ and the inverse of disc loading $\frac{A}{mg}$:

$$t_{\text{hover}} = \frac{e_{\text{batt}} \text{FM}}{g} \sqrt{\frac{2 \rho A m_{\text{batt}}}{mg m}}.$$ \hspace{1cm} (2.8)

Figure 2.2 plots the relationship between hover time and disc loading for a number of FM, $\frac{m_{\text{batt}}}{m}$, and $e_{\text{batt}}$ ranges and values. The dashed curve represents an unattainable theoretical limit based on FM and $\frac{m_{\text{batt}}}{m}$ values of 1.0, which are physically impossible. The solid curves serve to bracket more realistic FM and $\frac{m_{\text{batt}}}{m}$ ranges for achievable rotorcraft designs. The disc loading domain corresponds to takeoff masses between 7–15 kg for lithium–polymer (LiPo) powered quadcopters with rotor diameters of 30.5", which is among the larger sizes of readily available UAS rotor blades. In addition to the curves, data points for the final LiPo-powered vehicle as built and a projected lithium–ion (Li–Ion) design are included for comparison. The plot reaffirms that maximizing hover time requires minimizing disc loading for a vehicle of given FM and $\frac{m_{\text{batt}}}{m}$. Increasing the rotor and power system efficiencies would improve FM and lead to further hover time gains, as would increasing $\frac{m_{\text{batt}}}{m}$. Increasing battery capacity, removing empty and/or payload weight, or a combination of the two measures would affect this latter change. Regarding the vehicle-specific data points, converting the as-built GlacierHawk’s power source to a Li–Ion battery pack with an $e_{\text{batt}}$ of 250 Wh/kg would add approximately 20 minutes of hover time, for a total of 55 minutes, assuming total takeoff weight and all other parameters were unchanged. Attainable weight reductions would likely enable a slightly lighter, Li–Ion-powered future design to meet or surpass the 1-hour hover mark.

Takeoff mass represents the sum of the vehicle empty mass $m_e$, payload mass $m_p$, and battery mass. Empty mass refers to that of the airframe itself and any components other than the payload and batteries.

$$m = m_p + m_e + m_{\text{batt}}.$$  \hspace{1cm} (2.9)
Figure 2.2. Hover time vs. disc loading for varying figure of merit, battery mass fraction, and energy density.

The contributions from the empty and battery masses can be expressed in terms of their ratios with respect to the takeoff mass, multiplied by the takeoff mass:

$$m = m_p + \frac{m_e}{m} m + \frac{m_{\text{batt}}}{m} m.$$  \hspace{1cm} (2.10)

Rearranging to solve for $m_p$ and factoring out $m$:

$$m_p = m \left(1 - \frac{m_e}{m} - \frac{m_{\text{batt}}}{m}\right).$$  \hspace{1cm} (2.11)

Solving for takeoff mass:

$$m = \frac{m_p}{1 - \frac{m_e}{m} - \frac{m_{\text{batt}}}{m}}.$$  \hspace{1cm} (2.12)
Equation (2.8) can be rearranged to solve for battery mass fraction:

\[ \frac{m_{\text{batt}}}{m} = \frac{gt_{\text{hover}}}{e_{\text{batt}}FM} \sqrt{\frac{mg}{2\rho A}}. \] (2.13)

Substituting Equation (2.13) into Equation (2.12) yields an expression for takeoff mass as a function of empty mass fraction, disc loading, and hover time:

\[ m = \frac{m_p}{1 - \frac{m_e}{m} - \frac{gt_{\text{hover}}}{e_{\text{batt}}FM} \sqrt{\frac{mg}{2\rho A}}}. \] (2.14)

Figure 2.3 plots the semi-logarithmic relationship between takeoff mass and disc loading for a number of empty mass fraction values, with a data point for the as-built GlacierHawk UAS. This plot of Equation (2.14) assumes a hover time of 36 minutes and FM of 0.52, corresponding to the as-built vehicle. The curves demonstrate the role of \( \frac{m_e}{m} \) as a major performance driver, which restricts the maximum possible disc loading to achieve a desired hover time for a given vehicle configuration. Reducing empty mass fraction not only shifts the mass curve downward, but also significantly reduces its slope and increases the maximum possible disc loading value.

### 2.1.2.3 Total Power Required and Its Components

A more refined estimate of total power required combines multiple components arising from more detailed vehicle and rotor aerodynamic parameters, and is also capable of addressing forward, climbing, and descending flight:

\[ P_{\text{total}} = P_{\text{body}} + P_{\text{extra}} + P_{\text{gravity}} + P_{\text{induced}} + P_{\text{profile}}. \] (2.15)

\( P_{\text{body}} \) and \( P_{\text{extra}} \) represent power required to overcome drag from the airframe and additional components, respectively. \( P_{\text{gravity}} \) corresponds to power required for altitude changes, and will therefore be positive for ascending flight, negative for descending flight, and zero in hover. \( P_{\text{induced}} \) scales with lift production, while \( P_{\text{profile}} \) counteracts drag incurred by the rotor blades’ physical forms passing through the air at a given speed. Computation of these components requires a number of preliminary calculations based on the vehicle configuration and flight condition [9].

Since a pure rotorcraft has no lifting surfaces or propulsive mechanisms other than its rotors, rotor thrust must simultaneously counteract vehicle weight, body drag, and drag incurred during forward flight. For vehicles with purely horizontal rotors, such as
the GlacierHawk, the thrust and lift vectors are coincident and vertical in hover. This necessitates rotation of the entire aircraft to generate longitudinal and/or lateral thrust forces, which increases effective frontal area and body drag in forward flight, assuming the fuselage sits level in hover. Motors may be angled in a desired direction or combination thereof to augment forward flight performance and/or controllability, with the latter generally coming at the cost of hover efficiency, as complementary non-vertical thrust components cancel one another. In the former case, the vehicle body would no longer sit level in hover, as its thrust vector would not align with the body’s vertical axis. As maximum hover endurance is the dominant factor in this performance analysis and the overall geoPebble support mission, purely horizontal rotors aligned with the airframe are assumed. Figure 2.4 depicts the coordinate axes, angles, and vectors characterizing the force balance of such a vehicle in flight:

\[
T = \sqrt{(mg)^2 + D_{\text{body}}^2 + 2D_{\text{body}}mg \sin \gamma},
\]  

(2.16)

Figure 2.3. Takeoff mass vs. disc loading for varying empty mass fraction.
Figure 2.4. Forces and inertial, body, and flight path reference frames in unaccelerated flight.

where $D_{\text{body}}$ is vehicle body drag and $\gamma$ is flight path angle measured relative to the horizontal. From the definition of drag,

$$D_{\text{body}} = qS C_{D,\text{body}} = \frac{1}{2} \rho v_a^2 S C_{D,\text{body}},$$

(2.17)

where $q$ is freestream dynamic pressure, $S$ is body reference area, and $C_{D,\text{body}}$ is body drag coefficient. Multiplication of the airspeed $v_a$ by its corresponding body drag force yields the body drag contribution to power required:

$$P_{\text{body}} = D_{\text{body}} v_a. \quad (2.18)$$

Power required contributions from additional component drag forces follows the same process:

$$P_{\text{extra}} = D_{\text{extra}} v_a. \quad (2.19)$$

Gravitational power required depends on the vertical component of the velocity vector:

$$P_{\text{gravity}} = mgv_a \sin \gamma. \quad (2.20)$$
Vehicle angle of attack is calculable with knowledge of the drag force and flight path angle:
\[ \alpha = \arctan \frac{-D_{\text{body}} - mg \sin \gamma}{mg \cos \gamma}. \]  
(2.21)

Pitch angle represents the sum of the flight path angle and angle of attack:
\[ \theta = \gamma + \alpha. \]  
(2.22)

Downwash is computed based on angle of attack, but first uses the hover downwash value as an initial estimate:
\[ w_0 = \sqrt{\frac{T}{2\rho A}} = \sqrt{\frac{mg}{2\rho A}}. \]  
(2.23)

This hover downwash value is then substituted into the following equation, the solution of which provides a more accurate downwash speed:
\[ 2\rho A w \sqrt{(w - v_a \sin \alpha)^2 + (v_a \cos \alpha)^2} - T = 0. \]  
(2.24)

Induced power is the product of the thrust force, downwash speed (also known as the induced velocity), and induced power factor, which is an empirical corrective scaling factor:
\[ P_{\text{ind}} = \kappa_{\text{ind}} T w, \]  
(2.25)

where \( \kappa_{\text{ind}} \) is the induced power factor, generally set equal to 1.15.

Rotor solidity represents the ratio of blade area to disk area; in other words, it is obtained by dividing the blades’ cumulative upper surface area by that of the circle one blade would scribe in one complete revolution:
\[ \sigma = N_b \bar{c} \frac{\bar{c}}{\pi r}, \]  
(2.26)

where \( N_b \) is the number of blades per rotor and \( \bar{c} \) is the mean rotor blade chord, or average distance between the rotor’s leading and trailing edges. The rotor solidity and an initial estimate of blade sectional lift coefficient are used to compute a nominal thrust coefficient value for the hover condition:
\[ C_{T,\text{nom}} = \sigma \frac{\sigma}{6} c_{l,\text{nom}}, \]  
(2.27)

where \( c_{l,\text{nom}} \) is the nominal blade section lift coefficient in hover. As a sectional value, \( c_{l,\text{nom}} \) quantifies the theoretical lifting performance of a two-dimensional airfoil or constant-
geometry rotor blade of infinite span, thereby devoid of induced drag and other three-dimensional flow effects. From the definition of thrust coefficient:

\[ C_T = \frac{T}{\rho A v_t^2}, \]  

(2.28)

where \( T \) is thrust force, \( \rho \) is air density, and \( v_t \) is rotor tip speed. Recognizing that hover thrust is equal to the product of mass \( m \) and gravitational acceleration \( g \), and rearranging to solve for \( v_t \):

\[ v_t = \sqrt{\frac{mg}{\rho AC_T}}. \]  

(2.29)

Knowledge of the rotor tip speed allows computation of the advance ratio in forward flight conditions:

\[ \mu = \frac{v_a}{v_t}. \]  

(2.30)

Mean blade section lift coefficient in forward flight is then calculable using thrust coefficient, rotor solidity, and advance ratio. Note this computation is based on the assumption that \( C_T \) remains constant irrespective of airspeed:

\[ \bar{c}_l = \frac{6C_T}{\sigma(1 + 3\mu^2)}. \]  

(2.31)

The \( \bar{c}_l \) value and Reynolds number, which represents the ratio of inertial to viscous forces in a flow, can be used to calculate \( \bar{c}_d \), the mean blade section drag coefficient. If not calculated, \( \bar{c}_d \) may already be known from blade airfoil data. Once determined, it is used in computation of the profile power, a key component of the total power required estimate. As a rotor blade passes through air, a portion of its total aerodynamic drag is due primarily to its airfoil shape, or profile, and skin friction, whether or not it is producing lift. This component is known as profile drag, and is regarded separately from induced drag, which is also referred to as drag due to lift. Profile drag and the corresponding power required to overcome it are highly dependent upon airspeed, as evidenced by the cubic velocity term in the profile power equation:

\[ P_{\text{profile}} = \frac{1}{8} \rho A v_t^3 \sigma \bar{c}_d(1 + 3\mu^2). \]  

(2.32)

With all components calculated, total power required can be computed and used for performance estimates.
2.1.2.4 Flight Endurance and Range

Endurance is computed by dividing the battery energy capacity by the total power required and multiplying the quotient by drivetrain efficiency:

\[ t_{\text{max}} = \eta \frac{E_{\text{batt}}}{P_{\text{total}}}, \tag{2.33} \]

where \( \eta \) is drivetrain efficiency and \( E_{\text{batt}} \) is battery energy capacity. The flight condition for maximum endurance corresponds to that of minimum total power required, and will occur at non-zero airspeed. Hover time is computed with the same formula, using the total power required for zero airspeed.

Range is computed by multiplying the ground speed by its corresponding endurance. Note that in this formulation a zero-wind condition is assumed, such that the ground speed is equal to the airspeed:

\[ R = v_a t_{\text{max}}. \tag{2.34} \]

The code computes these power required and performance calculations over a predefined range of airspeeds and altitudes, beginning with hover at sea level. This allows for graphical performance predictions across a prospective flight envelope, as opposed to analysis of a single operating point. Figure 2.5 plots total and componentiated power required, and Figure 2.6 plots endurance and range vs. airspeed for a prospective LiPo-powered quadcopter with projected mass of 8 kg and rotor diameter of 30.5".

2.2 Preliminary Design

Following selection of a general aircraft concept, the objective of preliminary design is to freeze a single configuration and develop it at a major component and system level of detail [7].

2.2.1 Airframe Definition

Thanks to their relative simplicity, quadcopters offer a substantial degree of design flexibility with regard to airframe layout and construction. Lacking a traditional helicopter’s large main rotor, swashplate mechanism, and thin tail boom, quadcopter designs may take on a variety of shapes and structures while remaining compact and resilient. Most designs generally contain a central frame and one arm for each motor/rotor assembly. These arms are often arranged in an X configuration, with the battery (or batteries),
power distribution board, and flight controller in the center. On smaller quadcopters, such as those used in racing, the arms are relatively short and integral to the airframe, which results in a very compact and durable structure. Clearances between rotor sets, and between rotors and surrounding structure, tend to be low. In such configurations, the arms are extensions of a flat plate forming the primary structural member. As vehicle size increases, however, the structural feasibility of using integral flat plate arms diminishes, and the arms generally become discrete tubes or box beams that fasten to the central frame.

Switching from the common X frame to an H shape offers advantages in several key areas for the GlacierHawk design: namely structural integrity, manufacturability, modularity, and systems/payload integration. Rather than four individual arms converging at a point, this layout features a central fuselage with arms mounted at either end. As there

Figure 2.5. Total and componentated power required vs. airspeed.
is no central intersection, the front and rear arms are parallel to one another and can each be a single member. Instead of acting as two separate cantilevered beams, this arm arrangement preserves the structural integrity of a single, continuous centrally-mounted member supporting end loads. There is thus no need for additional reinforcements or coupling mechanisms to join port and starboard arm sections, only fuselage mounts for the fore and aft arms. This design feature saves structural weight, reduces complexity, and streamlines the assembly/disassembly process, all of which are crucial factors for international transport and operations in remote, austere environments.
2.2.2 Major Component Selections

2.2.2.1 Power and Propulsion

Proper selection of a battery, motor, and rotor combination is the most critical factor in determining whether or not the GlacierHawk would have sufficient endurance to complete its design mission. Integration of these components drives the rest of the airframe’s development.

Original plans called for a battery pack composed of Lithium-ion 18650 cells due to the potential benefits of such a chemistry and form factor. 18650 refers to the dimensions, in mm, of an individual cylindrical cell: i.e., $18 \times 65.0$. These cells may be arranged in a variety of configurations within a pack to best fit a given application. Increased gravimetric energy density (measured in watt-hours per kilogram) is their primary advantage over Lithium-polymer (LiPo) batteries, which are regarded as the standard for most electric UAS designs. LiPo batteries have come to dominate this space thanks to their substantial power density (measured in W/kg), which allows for higher performance in smaller packages relative to older Nickel-based chemistries. Whereas LiPo’s excel in high current draw applications, Li–Ion packs promise endurance gains at the cost of continuous and burst current capacity.

This current-supporting capability is quantified in a battery’s C-rating, which represents the ratio of allowable current draw to total energy capacity. For example, a battery with an energy capacity of two amp-hours (2 Ah) capable of supplying 10 amps continuously or 20 for short bursts would have a 5C continuous and 10C burst rating. A 10C rating is generally considered low for a UAS LiPo pack, whereas this value would be essentially unheard of in an 18650 Li–Ion pack. Thus arises the challenge of properly configuring a Lithium-ion battery for satisfactory flight performance. Compensating for a low C rating requires additional cells configured in parallel to increase total amp-hour capacity. This comes at the cost of added weight without a commensurate increase in voltage, which results in a reduction of maximum excess thrust. These tradeoffs between amp-hour capacity, current support, and voltage capabilities became central to the selection of potential batteries for the GlacierHawk.

At 3500 mAh and 10 A, the LG MJ1 was selected as the prime candidate due to its unusually high 3.5C rating and capacity for an 18650 cell. KDE Direct was selected as the motor and rotor supplier for the GlacierHawk based on the company’s selection of large UAS propulsion offerings and the Penn State Air Vehicle Intelligence and Autonomy (AVIA) Laboratory’s prior experience using such products. Manufacturer-
provided performance specifications and use of the rotorcraft performance MATLAB code facilitated meaningful assessment and comparison of multiple propulsion configurations and iteratively informed the selection process.

Based on anticipated vehicle gross weights of 7–10 kg, the pairing of KDE7208XF-110 motors with 30.5" diameter rotors and an 8S power system facilitates hover near 50% throttle, a key design objective for efficiency [10]. 8S refers to 8 banks of cells connected in series, to produce an approximate nominal voltage of 30 V. This quoted value varies based on the assumed nominal voltage per cell, which may range from 3.65–3.85 V depending on the data source. For this configuration, an estimated full-throttle total current draw of over 90 A means that an 8S Li–Ion pack built from MJ1 cells would need at least 10 parallel banks, for a total of 80 cells.

![Figure 2.7.](image) CAD model of 8S/10P LG MJ1 Li–Ion pack design (~ 26" × 3" × 1.5").

The desired layout for such a pack features horizontal cells arranged four wide, two tall, and ten deep, as shown in Figure 2.7. This configuration complements fuselage design and overall vehicle layout by limiting frontal area and side profile height without extending vehicle length beyond what is required for adequate fore/aft rotor separation and longitudinal/lateral symmetry. The battery pack could be centrally mounted in a fuselage box beam of constant cross section and relatively low frontal and side profile, and thus make efficient use of the area between the arms, as opposed to a more concentrated pack arrangement requiring a taller, wider central fuselage section not spanning the distance between the arms.

Procurement of this battery pack, however, ultimately proved infeasible due to the
desired quantity being lower than that required for custom production by a professional manufacturer. Furthermore, a lack of access to battery welding facilities and training precluded in-house production. Although weld-free cell assembly kits exist, the added weight of 80 sets of plastic cell holders and metal fasteners would nullify the energy density gains of using the Li–Ion chemistry over a COTS LiPo pack, concerns about parts count and pack integrity notwithstanding. Table 2.1 lists, in descending order, the estimated energy densities for a number of potential flight battery solutions, with a single LG MJ1 cell included as a benchmark. Each product’s estimated $e_{batt}$ was calculated using manufacturer dimensions and mass specifications [11–14]. The selected battery is emphasized in bold text and pictured in Figure 2.8.

<table>
<thead>
<tr>
<th>Battery Pack</th>
<th>Estimated $e_{batt}$ (Wh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single LG MJ1 Li–Ion cell (reference)</td>
<td>261</td>
</tr>
<tr>
<td>Professional custom 8S/10P LG MJ1 Li–Ion</td>
<td>251–219&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>MaxAmps 11-Ah 8S LiPo</td>
<td>190</td>
</tr>
<tr>
<td>DIY weld-free 8S/10P LG MJ1 Li–Ion</td>
<td>180</td>
</tr>
<tr>
<td>MaxAmps 12-Ah 8S XL LiPo</td>
<td>170</td>
</tr>
<tr>
<td>MaxAmps 9-Ah 8S XL LiPo</td>
<td>167</td>
</tr>
<tr>
<td>MaxAmps 8-Ah 8S LiPo</td>
<td>155</td>
</tr>
<tr>
<td>Turnigy 5-Ah 8S LiPo</td>
<td>137</td>
</tr>
</tbody>
</table>

<sup>a</sup>Based on respective 150–750-g allowances for wiring, connectors, and other non-cell parts mass.

Regarding the Li–Ion packs, note their decreased energy density relative to the individual cell; this is due to mass contributions from all non-cell components, such as wiring, connectors, welded parts, and packaging. Battery management boards or other accessories would further reduce $e_{batt}$. The energy density of the selected LiPo surpassed all but the professionally-produced custom Li–Ion pack, and even slightly bested that of the weld-free kit.

A set of two 11-Ah LiPo packs was chosen to replace the originally planned 35-Ah Li–Ion pack. While total capacity decreased by 13 Ah, the purpose of the Li–Ion pack having 10 parallel banks was to support a potential full-throttle current of over 90 A, as each parallel bank would add 10 A of continuous current support. With 40C capability, however, the LiPo alternative would not be current-limited, even if flown on only a single pack. While adding a third LiPo pack would rival the capacity of the Li–Ion design,
the projected hover endurance gains of doing so were not deemed worthwhile. A third pack was projected to yield approximately half the gain of moving from one to two packs. The added weight of additional battery supports, wiring, connectors, and any extra required structure would threaten to offset the capacity gains, while complicating systems integration and the logistics of recharge cycles between flights. This last concern could increase turnaround time without an additional charger. Furthermore, if total vehicle size needed to expand, transportation provisions and costs likely would as well, especially with international operations in mind.

### 2.2.2.2 Airframe

Using pre-fabricated thin-walled carbon fiber tubes for the fuselage and arms simplifies manufacturing and allows for internal battery storage and cable routing. Most construction processes, therefore, can focus on cutting simple holes for access panels, cable management, and fasteners, rather than forming complex part geometries or bespoke mechanisms. Furthermore, such a scratch-built airframe precludes dependence on the
availability (and potential limitations) of a properly-sized quadcopter kit accommodating the selected components and payload.

The fuselage box beam was selected around the chosen battery’s axial cross-section to accommodate internal storage and provide adequate clearance for support structures, cable management, and general hand accessibility. Arm tube size was selected for bending strength and compatibility with COTS motor mounts. COTS carbon components meeting these requirements were sourced from DragonPlate based on available selection and prior AVIA experience with the company’s products. Dimensions of the chosen carbon members are listed in Table 2.2.

<table>
<thead>
<tr>
<th>Component</th>
<th>Cross-Section</th>
<th>ID (in)</th>
<th>OD (in)</th>
<th>t&lt;sub&gt;wall&lt;/sub&gt; (in)</th>
<th>L (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuselage tube</td>
<td>Square</td>
<td>3.75</td>
<td>3.875</td>
<td>0.0625</td>
<td>48</td>
</tr>
<tr>
<td>Motor arms (2)</td>
<td>Circular</td>
<td>1.25</td>
<td>1.375</td>
<td>0.0625</td>
<td>48&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Later shortened to 42” to fit in transport cases.

2.2.2.3 Avionics

A Pixhawk 4 kit manufactured by Holybro and Futaba R3008SB radio receiver were selected as the GlacierHawk’s avionics package, which operates on the capable and developer-popular PX4 open-source autopilot system. The Holybro kit was chosen primarily because its included power distribution board (PDB) could support up to 12S LiPo batteries and 120 A, more than adequate for the GlacierHawk’s 8S power system and anticipated maximum current draw. A combined GPS/compass module supports location and heading determination, while a pair of telemetry radios facilitates real-time over-the-air communication between the vehicle and ground station. The R3008SB’s S.BUS functionality ensures radio control (R/C) compatibility with the autopilot so as to facilitate manual and assisted flight modes, which is vital in all stages of development and operation.

2.3 Detail Design

With the high-level configuration, major systems, and suitable COTS components defined and identified in the preceding conceptual and preliminary design stages, detail design represented the third and final phase of refinement before construction could begin. This
consists of developing bespoke or modified components to facilitate vehicle assembly and systems integration, including a means of supporting, securing, and removing the arm tubes, motors, landing gear, and flight batteries.

2.3.1 Fabricated and Modified Components

2.3.1.1 Fuselage Access Panels

Easily-accessible internal battery storage and cable management requires access holes cut into the top of the fuselage box beam, which, in turn, necessitates design of removable panels both to cover the ports and provide mounting for battery supports and avionics components. Figure 2.9 depicts the sheet aluminum access panel design, which is common for all three bays: one for each battery and one for the avionics mounting.

![Figure 2.9. CAD model of fuselage access panel (dimensions in inches).](image)

2.3.1.2 Motor Mount Plates

Although the selected Tarot 35-mm motor mounts fit the arm tubes as-is, their fastener hole geometry was not compatible with the selected motors. New plates were designed to facilitate the required hardware pattern and replace the provided carbon fiber mounting plates. Figure 2.10 depicts the sheet aluminum motor plate design.

![Figure 2.10.](image)
2.3.1.3 Landing Gear Legs

Dowel-reinforced foam landing gear legs were designed to facilitate energy absorption and accommodate flight test operations in tall grass. Selection of insulation foam as the primary material helped ensure the legs are lightweight, rigid, inexpensive, and easy to fabricate and repair.

2.3.2 Design for Additive Manufacturing

Additive manufacturing, more commonly referred to as 3-D printing, played a key role in the GlacierHawk design. The ability to prototype and implement custom part geometries reduced dependency on conventional machine shop processes while enabling precise production of more complex three-dimensional components. Such precision and complexity were vital to ensuring secure proper part alignments, such as for fastener arrangements, arm tube mounting, and acceptable tolerances for the flight battery retention system. This latter assembly required a fit sufficiently snug to prevent undesired battery motion, while still allowing for slight variation in battery sizes due to unit-to-unit discrepancies and/or minor swelling after multiple cycles.
2.3.2.1 Arm Mounts

The motor arms mount to the top face of the fuselage via a sandwich arrangement of 3-D printed beds with plywood backing plates above the top bed and below the fuselage surface. The upper and lower beds are identical for simplicity and interchangeability. A set of four 50-mm M5 machine screws fasten each assembly and hold the arm tubes in compression. When the screws are fully tightened, friction prevents axial translation or rotation of the mounted arm tubes without requiring pins, locking mechanisms, or other modifications to the arms themselves. In addition to simplifying construction and assembly, this also allows for mounting of the arms at any angle if a fixed motor tilt is desired. Forward motor tilt would enable the fuselage to remain horizontal in forward flight at an airspeed corresponding to the tilt angle, which would reduce drag and improve endurance for that specific flight condition. Figure 2.11 depicts the arm bed design.

![Figure 2.11. CAD model of arm mount bed (dimensions in inches).](image)

2.3.2.2 Landing Gear Brackets

The landing gear brackets are derived from the arm mounting arrangement. Identical upper and lower 3-D printed beds are held in compression between plywood plates by two M5 machine screws. The lower plywood plate is directly bonded and taped to a
dowel-reinforced foam landing gear leg. Screw tightening and a layer of electrical tape between the arm surface and the printed beds ensures that in-flight vibrations do not result in axial translation or rotation of the landing gear. This arrangement allows for easy removal of the landing gear for transport or repositioning inboard so that the airframe can stand on a table, workbench, or other platform of limited size. Figure 2.12 depicts a single landing gear bracket part.

![Figure 2.12. CAD model of landing gear bracket half (dimensions in inches).](image)

### 2.3.2.3 Battery Supports

Each flight battery is held by a two-part 3-D printed support system designed specifically for the selected batteries. A lower tray with rear and side walls acts as a backstop during installation and helps hold the battery in place at any vehicle orientation. The front end of the bottom channel is wider than the battery for ease of installation, and narrows rearward for a snug fit. Lightening holes save material without snagging on the battery edges, and ribbed supports reinforce the walls. A flange on the bottom surface allows
the lower tray to laterally self-center within the fuselage box beam. Figure 2.13 depicts
the lower battery support.

Upper supports on the underside of each battery access panel complement the lower
trays to hold the batteries in all three dimensions. A rib-supported back wall restrains
the pack longitudinally while vertical side panels provide lateral support. Cutouts on
either side of where these panels would meet the back wall serve as pass-throughs for the
battery leads. This component, as shown in Figure 2.14, also features lightening holes in
noncritical locations for material savings. Figure 2.15 shows a battery within the upper
and lower supports, and Figure 2.16 depicts the supported battery assembly integrated
within the fuselage box beam, along with a number of other integrated components.
These components include a mounted arm and motors, autopilot board, two ESCs forward
of the arm mount, all three access panels, and the radio receiver at the fuselage’s aft end.
Plywood backing plates for the arm mount are also shown.
Figure 2.14. CAD model of upper battery support (dimensions in inches).
Figure 2.15. CAD model of battery within supports.

Figure 2.16. CAD assembly of selected component integration.
Chapter 3  
Construction of the GlacierHawk UAS

This chapter explains the GlacierHawk build process, which involved machine shop fabrication of custom parts, modification of COTS components, and additive manufacturing. Primary systems integration is described and illustrated, and total vehicle mass is broken down by component and category. The GlacierHawk’s modularity is emphasized in explaining the field assembly process and ability to fit disassembled in a rugged transport case.

3.1 Construction Process

3.1.1 Fuselage

A rotary tool was used to cut three access holes in the upper face of the fuselage beam: a central one for the avionics bay, and one forward and one aft for the flight batteries. An end mill was then used for precision placement of fastener holes. The access panels were secured with M4 screws threaded into tee nuts within the fuselage. These tee nuts were set in plywood backing plates epoxied to the inside upper face of the fuselage beam. Two such plates, each containing two tee nuts, accommodated each panel. The fore and aft arm mounts each required four holes to accommodate M5 tee nuts set in a backing plate. These plates were epoxied to the fore and aft ends of the upper inside face of the fuselage beam. Smaller plywood backing plates were mounted above the 3-D printed arm mounts to complete the sandwich assembly. All plywood backing plates and aluminum access panels were cut with a band saw and smoothed on a belt sander. The same mill was used for fastener hole placement in these components. Four 3/4-inch-diameter holes
were milled into the top fuselage face for cable routing to each ESC. Two 1-inch-diameter holes were milled near the center of the starboard face to accommodate tool-free external manipulation of the aircraft power connectors. The lower battery supports were epoxied to the inside bottom surface of the fuselage beam, whereas the upper supports were epoxied to the bottom of the battery bay access panels. Sanding was used to prepare all epoxied surfaces for bonding and to smooth edges of cuts and large holes. All other milled holes were smoothed with a chamfer drill bit.

3.1.2 Motor Arms and Mounts

Motor cable routing slots were cut via rotary tool near the inboard ends of either side of each arm tube. After initial tuning and vehicle validation, the arm tubes were shortened using the rotary tool to fit with the remainder of the airframe in a commercially available ruggedized transport case.

The motor mount plates were cut from sheet aluminum using a band saw, milled, then smoothed using a belt sander. The original fasteners were replaced with larger hardware and lock nuts to secure the plates to the motor mounts.

3.1.3 Landing Gear

The landing gear legs were cut from insulation foam on a band saw, and a vertical hole was drilled into the top center of each leg to accommodate a wooden dowel. The dowel was cut to the desired length with a band saw and mounted in the lower plywood backing plate. Both upper and lower plywood backing plates were cut on a band saw, milled, then smoothed on a belt sander.

3.1.4 Electronics, Payload, and Systems Integration

The GlacierHawk’s onboard electronics consisted of two flight batteries, a power distribution board (PDB), four electronic speed controllers (ESCs), four motors, a radio control receiver (RX), Pixhawk 4 autopilot board, GPS/compass module, and telemetry radio. Figure 3.1 provides a condensed visual representation of the system connections and layout.

The PDB was centrally installed on the bottom surface of the fuselage beam interior. Insulation foam served as a barrier between the PDB and carbon surface. This foam was secured to the fuselage floor via hook-and-loop fasteners. The internally-mounted flight
batteries connected to the PDB via a parallel adapter using Castle Creations 6.5-mm connectors. ESC connections to the PDB used Castle Creations 4.0-mm connectors for the main power wires and servo-type triple wires for the signal connection. The ESCs were externally mounted with hook-and-loop fasteners and heavy-duty zip ties to the fuselage’s upper surface, between the arm mount assemblies and the battery access panels. The ESC-to-PDB connections routed through holes into the fuselage and ran along the top edges of its inner walls, clear of the flight batteries. Internal cable management was achieved using thin zip ties with adhesive holders applied to the inner walls, which kept the battery bays unobstructed for straightforward and consistent battery installation and removal. ESC-to-motor connections were routed into the arm tubes via slots near the arm mounts and out through the open tube ends.

Figure 3.1. Illustrated primary systems arrangement.

The Pixhawk, GPS/compass module, and telemetry antenna were all mounted to the avionics access panel, which sat on spacers allowing for Pixhawk-to-PDB wiring to run through the gap between the panel and the fuselage. The RX was mounted to the aft end of the fuselage floor using an arrangement of insulation foam and hook-and-loop fasteners. The foam housing held the RX antenna wires in the desired orientation and extending outside the vehicle, while the hook-and-loop fasteners permitted easy movement of the RX completely inside the fuselage for transportation. RX-to-Pixhawk wiring was routed internally past the aft battery bay and out of the avionics access panel gap. When mounted, the payload was externally secured to the fuselage underside via hook-and-loop fasteners and a heavy-duty zip tie. The payload battery was internally secured to the underside of the avionics access panel with hook-and-loop fasteners, and the payload power connectors ran through the same fuselage holes as the aircraft power connectors. An accessory strobe light system was later added partway through field testing in Greenland; all wiring and components, including a 4×AA battery holder and power switch, were mounted externally.
3.2 Component Mass Breakdown

Table 3.1 breaks down the GlacierHawk’s total mass by component and category.

<table>
<thead>
<tr>
<th>Component/Category</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor &amp; wiring (×4)</td>
<td>1920</td>
</tr>
<tr>
<td>Carbon fiber fuselage tube</td>
<td>941</td>
</tr>
<tr>
<td>Rotor assembly (×4)</td>
<td>584</td>
</tr>
<tr>
<td>Upper &amp; lower battery supports (est.) (×4)</td>
<td>500</td>
</tr>
<tr>
<td>Carbon fiber arm tube (×2)</td>
<td>478</td>
</tr>
<tr>
<td>Landing gear assembly (×4)</td>
<td>460</td>
</tr>
<tr>
<td>Motor mount (×4)</td>
<td>420</td>
</tr>
<tr>
<td>ESC &amp; wiring (×4)</td>
<td>400</td>
</tr>
<tr>
<td>Arm mount assembly (est.) (×2)</td>
<td>300</td>
</tr>
<tr>
<td>PDB &amp; wiring</td>
<td>273</td>
</tr>
<tr>
<td>Strobe light system w/ 4×AA batteries (est.)</td>
<td>250</td>
</tr>
<tr>
<td>Fuselage access panel (×3)</td>
<td>240</td>
</tr>
<tr>
<td>Plywood fuselage backing plates &amp; hardware (est.)</td>
<td>200</td>
</tr>
<tr>
<td>Parallel battery wiring adapter</td>
<td>148</td>
</tr>
<tr>
<td>Pixhawk kit &amp; R/C RX</td>
<td>126</td>
</tr>
<tr>
<td><strong>Empty mass (est.)</strong></td>
<td><strong>7240</strong></td>
</tr>
<tr>
<td>Flight battery (×2)</td>
<td>3380</td>
</tr>
<tr>
<td>Payload mass (est.)</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Takeoff mass (est.)</strong></td>
<td><strong>11620</strong></td>
</tr>
</tbody>
</table>

3.3 Assembly Process

The GlacierHawk’s modular design allows for straightforward assembly, teardown, and swapping of key components as needed for repairs, replacement parts, or modifications. Two sizes of metric Allen screwdrivers facilitate the basic airframe assembly. A 3-mm screwdriver is used to secure the fuselage access panels, arm mounts, and landing gear brackets, whereas a 2.5-mm screwdriver is used to fasten a rotor assembly directly to each motor. Additional tools including a 2-mm Allen screwdriver, open-end wrench, and
torque wrench from the rotor manufacturer are used to verify proper tightness of other fasteners not manipulated during routine assembly. Visual markings on the arms and the use of geometric references preclude mandatory use of a level or measuring tape to verify proper centering and angular alignment of the arms. For example, when viewed end-on from the side of the vehicle, the metal motor mount plates will be level with the top edges of the fuselage. Landing gear are also vertically aligned visually. While unnecessary for routine field assembly, a level and measuring equipment is beneficial when adjusting operationally fixed components such as motor mounts. Figures 3.2 and 3.3 show the assembled and transport configurations, respectively.

In the transport configuration, the fuselage beam fits centrally in a rugged, internally padded case, with one arm arranged lengthwise on either side of the beam. The fuselage and arms are separated by foam padding, and the rotors and landing gear are stored detached from the arms. Undetected shifting of components during transport is not a concern, as the aircraft’s assembly and preflight procedures involve setting and verifying proper fits and alignments, and all parts are well-contained within the transport case. Furthermore, all components are readily accessible, both visually and by hand and/or tool, for inspection of secure mounting and assembly prior to flight operations.

Figure 3.2. Fully assembled GlacierHawk quadcopter. (Author photo)
Figure 3.3. Disassembled GlacierHawk in transport case. (Author photo)
Chapter 4  
GlacierHawk Flight Operations

This chapter presents the GlacierHawk’s operational history, from its initial indoor tuning flights to the final day of field testing over Greenland’s Helheim Glacier. Detailed descriptions of the Helheim flight area, ground station equipment, and crew roles are provided, along with an extensive operational narrative from the field featuring each day’s testing, technical challenges, troubleshooting measures, other relevant events. It is here that the efforts documented in the preceding chapters culminate, and insights for the final conclusions and future concepts are formed.

4.1 Initial Flight Testing

The objectives of the GlacierHawk’s flight testing were to tune the vehicle for stable, responsive handling, characterize flight performance, and verify proper functionality of multiple flight modes and autonomy functions. To achieve any of these goals, however, it was first necessary to develop an understanding of multirotor control architecture and tuning methodology.

4.1.1 Controller Structure and Flight Modes

Proportional, integral, and derivative (PID) feedback control is the dominant form of multirotor flight control design. This method is implemented in the PX4 system, an open-source autopilot suite used in a variety of developmental UASs, including the GlacierHawk [15]. This arrangement consists of three nested loops, each of which controls a separate aspect of the vehicle’s flight condition, and in the case of the second and third loops, builds upon the previous layer(s). The inner and most fundamental loop is the rate controller, which controls the vehicle’s angular rates about its roll, pitch,
and yaw axes, each of which has an independent set of PID gains. The roll, pitch, and yaw angles themselves are controlled by the next layer, comprised of a P gain for each respective angle. This type of gain generates a control response proportional in magnitude to the error so as to counteract and reduce it. The outermost loop controls velocity and/or position, depending on the active flight mode and pilot inputs on PX4-controlled vehicles [16].

Figure 4.1 shows a block diagram for a similarly-structured multirotor attitude and velocity controller. Given a velocity command, the system compares this setpoint to the vehicle’s current velocity, computes the error, and generates an acceleration command based on this discrepancy and the outer loop gains. The greater the error and the higher the proportional gains, the larger and more abrupt this acceleration will be. Comparison of the current vehicle attitude and that required to initiate the desired acceleration results in an angle command from the second loop. An angular velocity setpoint similarly cascades from the innermost loop, whose gains then compute a desired angular acceleration. The vehicle’s control mixer then receives this angular acceleration setpoint and any vertical acceleration commanded from the attitude control loop. The mixer combines and processes these setpoints to allocate throttle commands for each motor independently, which then results in the rotor speed changes that produce flight maneuvers.

The GlacierHawk primarily used three PX4 flight modes when not engaged in autonomous flight: manual/stabilized, altitude mode, and position mode. Each successive mode incorporates a greater degree of autonomy to reduce the pilot’s manual workload and compensate for environmental factors. In manual/stabilized, the simplest mode, manual pitch and roll inputs command their respective angles (as opposed to angular rates or vehicle translation speeds), the vehicle will auto-level when pitch and/or roll inputs are neutralized, and the pilot has direct throttle control for climbs, descents, and accelerations. This mode is independent of GPS and barometer indications.

Figure 4.1. Example of a multirotor attitude and velocity feedback control loop structure. (Tomás Opazo)
Altitude mode replaces the pilot’s direct throttle control with vertical speed control by incorporating barometric changes into the control logic. Pitch and roll control logic are unchanged from manual/stabilized, such that altitude mode remains independent of GPS measurements. In this mode, the vehicle will automatically adjust for vertical disturbances and seek to maintain constant altitude when the left control stick is kept at the configured hover setting. Maximum climb and descent rates are also configurable, with the latter being critical to the avoidance of entry into a vortex ring state, a hazardous flight condition that may result in rapidly increasing uncontrolled descent rates if not recovered from quickly. Descending at the rotors’ downwash speed is a primary trigger for the vortex ring state, so calculating this value in advance and setting controller limits accordingly provides a level of protection not offered in manual/stabilized mode.

Position mode replaces the pilot’s direct pitch and roll angle control with translational speed control, and incorporates GPS measurements to lock in vehicle position, which enables autonomous wind and drift correction. Combined with altitude mode’s vertical control logic, this enables hands off hovering. When manual translation inputs are within a specified deadzone, control logic shifts from speed to position control for fine adjustments [16]. Being GPS dependent, position mode is generally unusable indoors.

4.1.2 Tuning Flights, Envelope Expansion, and Autonomy Testing

Tuning strategy involved beginning at the innermost control loop while flying in the least automated flight mode; in this application, adjusting PID gains for the rate controller while flying in manual/stabilized mode. Best practice was to change one gain at a time, typically by no more than 20-30% initially, with smaller adjustments for subsequent refinement. Control inputs used to assess tuning were similarly discretized, and included, for example, gradual or step inputs in individual directions, then returning to neutral inputs and observing the vehicle’s response. While ideal handling traits for a given vehicle and mission are somewhat subjective and may vary from pilot to pilot, satisfactory performance generally demands prompt, non-oscillatory control responses with minimal delay or overshoot. As tuning progressed, maneuvers became more demanding and sometimes involved simultaneous inputs in more than one control axis. Once baseline handling quality was established, performance characterization and flight envelope expansion could begin. Figure 4.2 shows the GlacierHawk in an indoor hover endurance test.

Tuning deemed satisfactory in one setting sometimes required revisiting in other environments; this was exemplified by the transition between indoor and outdoor flight.
Longer distances, higher altitudes, faster speeds, and the presence of external disturbances all represented expansions of the flight envelope, and as such required gradual, regimented exploration. A similar dynamic applied when implementing autonomous flight functions. For example, gains setups that resulted in crisp, immediate handling during manual indoor flight were sometimes found overly aggressive in outdoor flight, especially in position mode or during autonomous navigation. In more severe cases, poorly and/or over-tuned gains resulted in vehicle instabilities, or upsets, in certain flight modes and conditions, such as position mode flights in strong winds or automated navigation requiring significant heading changes between waypoints. Following an upset, other in-flight anomaly, or crash, review of onboard flight data logs frequently provided insight as to the causality and/or mechanism of a given issue, and thus informed subsequent troubleshooting measures.

Once the vehicle’s tuning enabled reliable manual, assisted, and autonomous flight throughout as much of the anticipated operating envelope as was feasible (range testing, for example, could not replicate the actual distances over the glacier), testing shifted to a full-system focus. This began with payload integration testing to verify that the mounting arrangement was secure, did not interfere with other vehicle components, and did not compromise flight performance or handling qualities. Subsequent flights with the payload running and a geoPebble transmitting in the field assessed connection ranges
and data transfer rates from varying aspects, altitudes, and distances.

### 4.2 Greenland Field Testing

Field testing was conducted in August 2019 at Helheim Glacier by a team of two from Penn State (the author and geosciences professor Dr. Sridhar Anandakrishnan) traveling and camping alongside a group of researchers from the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) and associated personnel. The group shared a common main campsite on the south side of the glacial fjord, approximately 2 km east of Helheim’s terminus. The teams and equipment were transported via helicopter from the town of Tasiilaq, located 85 km south of Helheim.

#### 4.2.1 Helheim Glacier Operations Area

##### 4.2.1.1 UAS Campsite

GlacierHawk flight operations were based out of a dedicated UAS launch and recovery campsite situated approximately 80–100 m above the glacier surface. The UAS site was roughly 1 km west of the main camp, and about 200 m lower in elevation. All required equipment was transported from the main camp via helicopter and stored in a six-person tent that was used as a hangar and workspace. The team slept at the main CRREL site and hiked to the UAS camp for each day of testing. On the satellite map of Figure 4.3, the green triangles represent campsite locations, and the array of blue circles denotes the intended geoPebble deployment points. The centermost southern camp is the UAS site, the main CRREL camp is located to its southeast, and the northernmost site is another CRREL camp not visited or used by the Penn State team.

The UAS camp, shown in Figure 4.4, consisted of a launch and recovery zone, hangar tent, ground station overlook, gravel pit, and generator area. The launch and recovery zone was a relatively level patch of soft foliage clear of rocks or other obstructions. Beyond takeoffs and landings, this area was large enough to accommodate short-distance functional check flights incorporating legs of about 30 m without leaving the immediate camp area. While this zone was fairly level compared to the surrounding dropoffs and rock formations, the foliage surface itself was uneven, with ruts and small gaps present throughout. This required special care in positioning the vehicle prior to takeoff to ensure a level attitude and prevent any landing gear legs from being caught in a gap during liftoff. These surface details are visible in Figure 4.5.
A gravel area approximately 10 m in diameter was located in the northwest corner of the camp. The gravel pit offered a more level and consistent surface than the soft foliage, which made the gravel preferable for sensor calibrations and other tasks. This region was slightly elevated relative to the launch and recovery zone, and was ringed by a low outcrop of rock. This outcrop provided an overlook of the campsite, glacier, and surrounding terrain; an ideal vantage point leading to its selection as the ground station position.

A 2.2-kW gasoline-powered generator was positioned downwind and downhill of the ground station. Being roughly centered on the north side of the camp area and separated by rock from both the ground station and the takeoff and landing zone, the generator did not pose an obstruction or distraction during flight operations. Extension cords allowed for convenient flight battery and computer charging in close proximity to the ground station.
A six-person tent on the south side of the foliage area served as a UAS hangar and workshop, which permitted indoor assembly and troubleshooting in a more controlled setting than the foliage area or gravel pit could provide. This simplified setup by precluding the need to disassemble and pack the airframe at the conclusion of each
day of testing. Strategic stacking of transport cases approximated a workbench, while a miniature camping table and stools facilitated comfortable working in a variety of positions within the tent. Furthermore, having a floor and enclosed space reduced the likelihood of losing small components and provided a barrier from wind and flying insects.

Obstacles and hazards to UAS operations surrounding the campsite included the uphill section behind the south side, and dropoffs beyond the other three edges of the area. While a convenient source of drinking water, a river running down to the glacier from west of the camp represented an additional feature to be mindful of in flight.

4.2.1.2 geoPebble Array

A reduced-scale array of 15 geoPebbles was deployed slightly upglacier of the terminus and about halfway across the fjord width. In future field operations, a full-scale array may include as many as 200 of the networked sensors. One unit was kept at the UAS campsite as a control. The deployed geoPebbles were secured to 5-ft poles augered into the ice by a helicopter-borne installation team. In addition to providing stabilization for the sensors, the mounting poles featured orange flags for improved visual acquisition, as shown in Figure 4.6. While elevated surface ice structures obstructed visual line of sight to some of the flags, a number of them were observable from the UAS campsite via spotting scope.

![Figure 4.6. Aerial photo of a deployed geoPebble. (Ananda Fowler, US Army Cold Regions Research Engineering Laboratory, Remote Sensing / GIS Center of Expertise)](attachment:image)
4.2.2 Ground Station and Crew Roles

The ground control station (GCS), shown in Figure 4.7, was comprised of a laptop computer running the Ubuntu operating system, a USB telemetry antenna, and a 22 – 66 × 100 mm spotting scope. QGroundControl (QGC), an open-source UAS control software program, was used for mission planning, live over-the-air telemetry, and general vehicle setup including sensor calibrations and parameter settings. This GCS arrangement provided a live feed of mission-critical data including aircraft attitude, ground track, ground speed, altitude, flight mode, and estimated battery level while also enabling detailed visual monitoring at long ranges.

![Figure 4.7. The ground station computer, antenna, and spotting scope. (Author photo)](image)

The minimum required GlacierHawk crew consisted of a Remote Pilot in Command (RPIC) and Visual Observer/spotter (VO). Most preflight setup, including aircraft assembly, could be completed by one person, though a second was useful for faster assembly and sensor calibrations, especially the compass, which required holding up and rotating the vehicle through a number of orientations. Radio range checks also required two people; the pilot walked away from the vehicle and GCS while manipulating the radio control (R/C) transmitter in a low power setting, while the VO monitored the computer for input tracking and signal dropouts.
During launch and recovery operations, the pilot flew manually while the VO read back select telemetry as requested by the RPIC, such as altitude, ground speed, and estimated battery percentage. After landing, the VO verified from the computer display that the vehicle was disarmed after the pilot made the corresponding R/C input.

After transitioning from manual to autonomous control during a mission, the RPIC alternated between monitoring telemetry and visually tracking the vehicle in case of the need to revert to manual control. During this phase, the VO would acquire the vehicle with a spotting scope for the remainder of the long-range autonomous portion of the mission.

Whereas a minimum crew of two could accomplish the primary mission, additional personnel added capability and expanded situational awareness in a number of non-routine scenarios. For example, during a low-altitude test flight over the takeoff and landing zone, a third person standing at the camp’s southwest corner provided visual verification that the vehicle remained well clear of the hangar tent and did not exceed the bounds of the soft foliage area. In this test, the RPIC and VO operated in close proximity to one another at the usual GCS position due to the requirement for frequent telemetry reading and easy verbal communication. Accurately judging distance between the vehicle and tent from such a perspective was not feasible, so having a second observer provided an additional safeguard. On another occasion, an additional team member flew a commercially available camera UAS as an air-to-air chase videography platform to document a mission over the glacier.

This same member also had an aviation hand radio which the RPIC used to contact and deconflict with a manned helicopter that entered the fjord area unexpectedly prior to one of the UAS missions. In addition to the importance of having communications equipment and coordinating with full-scale aviation operations as needed, this event highlighted the lack of a sense of scale at Helheim. With no buildings, trees, or other familiar objects to provide visual reference, one cannot intuitively judge distance over the glacier and fjord.

The general lack of man-made or other loud, sustained noise at Helheim meant that the helicopter’s sound carried over long distances and did not lend itself to precise location estimation until the aircraft was visually acquired. At the spotting scope’s maximum 66× magnification, the 212’s nearly 20-m length occupied roughly one quarter of the field of view, as shown in Figure 4.8. Based on calculations using the scope geometry, the helicopter was approximately 4.2 km away from the UAS camp, despite it sounding much closer. Reading the tail number through the scope and using the hand radio, it
Figure 4.8. The unexpected Bell 212 as seen through the spotting scope. (Author photo)

was determined that the helicopter pilot would not be flying near or upglacier of the terminus, and would thus be no factor for the continuance of UAS operations in the area.

4.2.3 Flight Planning, Mission Profiles, and Execution

The Penn State team occupied the UAS camp for three days of field testing, with helicopter extraction back to Tasiilaq in the afternoon of day four. The following operational narrative summarizes each day’s tests, discusses technical issues that arose, and describes troubleshooting attempts and solutions.

4.2.3.1 Day 1: Sunday, August 4

The team performed initial airframe assembly inside the hangar tent while one of the CRREL members accompanying the group for the day located a number of deployed geoPebbles using the spotting scope. Once assembly was complete, Dr. Anandakrishnan configured the payload software and the control geoPebble kept at the UAS camp.
The RPIC performed a compass calibration and flew initial check flights to assess basic functionality in the new environment. The first of these flights consisted of a manual takeoff and hover followed by a climb, descent, and translation in each direction. These maneuvers were then repeated in altitude control mode and then in position control, with the addition of yaw commands. Descent and landing were completed in position mode without issue.

A series of three endurance verification flights followed the handling checks. To ensure the vehicle retained its baseline hover time of 30 minutes in the new environment, the RPIC took off and hovered in position control mode for three 10-minute intervals, landing to check battery levels at each interval. While Helheim’s lower elevation and colder, denser air, in theory, would improve aircraft performance over flight in State College, these endurance checks were necessary to ensure overall system integrity, especially the LiPo batteries, avionics, and hardware connections, for extended flights after extensive multimodal transport and field assembly. Endurance and vehicle integrity were as expected.

The next objective was to verify functionality of the Return to Launch (RTL) mode. For this check, the RPIC intended to take off in position mode, translate to the east end of the foliage area, climb, then activate the RTL sequence, which was configured to autonomously descend, fly the aircraft back to the takeoff point, descend further and hover for a set period in a pre-landing loiter, then descend at a lower rate to complete the autonomous landing. The vehicle behaved as expected through the pre-landing loiter; however, upon transition between the loiter and final landing descent, power to one motor suddenly cut and the vehicle crashed in a nose-high, left-bank attitude from approximately 5 m. From this low of an altitude, there was insufficient time or space to execute a manual recovery. The left half of the rear arm tube snapped on impact, which was the most severe damage the aircraft had yet sustained, with past breakages limited to rotor blades and/or landing gear legs. Review of the flight logs did not reveal a clear cause to this upset, though the data do indicate that the controller attempted to counteract the uncommanded sharp pitch and roll. At the moment of departure, the pitch and roll rate setpoints spiked to their maximum allowable values in the opposite directions of the sudden motion. Without being able to pinpoint a hardware, software, sensor, or autonomy fault, it was determined that the lowest risk option on subsequent missions would be to eliminate autonomous landings. The RTL was thus configured to terminate in the pre-landing loiter phase, at which point the RPIC would revert to position control and perform a manual landing. This failure mode did not reappear
during subsequent testing.

After replacing the broken arm with one from the secondary airframe, the team worked up to performing a basic autonomous waypoint navigation mission. This entailed an autonomous takeoff, climb, and translation to the first waypoint. The vehicle was then meant to stop and perform a 180° yaw while translating to a second waypoint in the opposite direction of the first, then initiate the RTL sequence. Approaching the first waypoint, however, the vehicle began to yaw during its climb and flew in a circle rather than yawing about the point, and continued this excessive, uncommanded behavior through the translation towards the next point. As flight behavior worsened and transitioned to an upset, the RPIC reverted to manual control and attempted the recovery procedure developed during initial testing in State College; namely, switching to the stabilized flight mode and neutralizing any pitch, roll, and yaw inputs while simultaneously applying full throttle. In most prior yaw-related upsets, this would re-level aircraft attitude while minimizing or eliminating altitude loss. This recovery procedure was largely successful in past events, provided it was initialized before actuator saturation could set in during autonomous or assisted flight modes. In this case, however, the vehicle did not respond as expected during the recovery attempt. While pitch and roll oscillations were reduced and a catastrophic attitude divergence did not appear imminent, directional control was compromised as uncommanded yawing persisted and the RPIC could only effectively control the climb or descent rate. The vehicle was brought to the ground in as controlled and expedient a manner as possible before it could drift far from the camp or endanger any of the crew. The UAS set down hard onto the rocks just beyond and below the outcrop on the west end of the campsite, out of view of the RPIC and VO. The vehicle was quickly recovered, and damaged rotors and legs were replaced.

Although yaw upsets and recoveries were not uncommon during initial testing in State College, this form of errant heading behavior had not yet been experienced. Two potential causes were identified: degraded magnetometer function due to geographic/geological factors, or the decision not to perform all pre-flight sensor calibrations. Regarding the sensors, typically only the magnetometer would need calibration for use in a new location, while other calibrations, such as for the accelerometer, level horizon, and gyroscope, would persist between testing days and locations. While this may have been sufficient for short, low-impact surface-only trips in relatively consistent conditions in State College, the widely varying conditions of international air travel (particularly temperature and pressure changes in flight and accelerations during handling) may have affected these other calibrations. To account for this possibility, potentially worsened by the day’s crash
and hard landing, the full calibration sequence was carried out prior to flight the next day.

4.2.3.2 Day 2: Monday, August 5

The objective for the second day’s initial flight testing was to re-establish baseline functionality following the previous day’s events and continue with envelope expansion toward a glacier transit mission. The first test involved a manual takeoff, transition to altitude hold mode, and translation between a number of designated points before returning to the starting point, yawing to face forward, and descending to land. In this flight, travel between waypoints was pure translation, such that the vehicle was not yawed to point the nose on course. Following completion of this and several subsequent altitude mode flights, the team performed a basic position mode check flight in which the RPIC flew the vehicle with heading on course around the foliage area. With the manual, altitude, and position control modes again performing as expected, the team transitioned back to autonomous waypoint navigation tests.

The RPIC configured a polygonal flight path over the foliage area for the UAS to navigate autonomously. Angles between waypoints were intentionally less than 180°, as such directional reversals had historically been problematic in autonomous missions. Manual takeoff, transition to mission mode, and autonomous flight to the first point were uneventful; however, instead of flying to each subsequent waypoint, the vehicle returned directly to the starting point and concluded the mission. The waypoint acceptance radius, a Pixhawk autonomous navigation parameter, was identified as the most likely cause of this behavior. The waypoint acceptance radius sets the maximum allowable lateral distance between the exact waypoint position and the actual UAS trajectory. So long as the vehicle enters this circle around a given waypoint, it will proceed to the next programmed action rather than attempt to home in closer to the waypoint’s precise coordinates. Suitable values for this setting depend upon the nature of the mission, vehicle size and characteristics, operating area, wind conditions, and other potential factors. While the 10-m radius previously established for the GlacierHawk during initial tuning was satisfactory for navigation in large fields and maintaining connection with geoPebbles, this setting was likely too large for precise flight path definition within the relatively confined dimensions of the UAS camp’s soft foliage area. It was suspected that the waypoint tolerance zones overlapped one another, so by reaching the first waypoint’s radius, the vehicle had also satisfied the criteria for the other points and thus initiated the mission-ending RTL mode. It was decided that the lower risk option would be to
extend the distance between waypoints to eliminate this overlap, rather than reduce the waypoint acceptance radius from its known satisfactory value and risk another in-flight upset condition. The tradeoff for this decision was the requirement to leave the relative safety of the foliage area and fly over rock and beyond the drop-off on the camp’s east end. Mission altitude was also increased to improve the probability of a successful manual recovery should another upset occur. Expanding the mission area proved successful, as the UAS autonomously navigated between waypoints, including a 180° turn, without issue. This test was then repeated with a transition to RTL mode as the mission completion action, which was also successful.

The final check before sending the GlacierHawk over the ice was an in-flight R/C signal loss test. QGC was configured to initiate the RTL sequence upon R/C loss, and the RPIC flew the vehicle in position mode east of the camp, then shut down the R/C transmitter (TX). As expected, the GCS issued an audible manual control lost warning and announced as the vehicle entered RTL mode. The RPIC turned the TX back on as the UAS approached and regained control for landing after the prescribed RTL descent and loiter were complete.

The first flight over ice was configured for RTL upon telemetry signal loss, and was meant to test data link range in the actual mission environment. A waypoint was set for geoPebble P6, located 3.5 km from the UAS camp. The telemetry link was lost at a quarter of this distance, and the vehicle returned autonomously. Review of the vehicle’s onboard flight log indicated that while the GCS telemetry link cut out and triggered the RTL sequence, the UAS never detected an R/C signal loss. This is noteworthy for future implementations in that a switch or other input on the R/C TX should be configured for RTL, so that the GCS is not the only way to externally activate RTL on demand. While the system performed as desired for this failsafe test, both the telemetry and R/C lost link procedures would need to be disabled so that the GlacierHawk could traverse the full distance to the geoPebbles in spite of intermittent or total link losses.

The second over-ice flight was intended as the first data retrieval mission. The payload was mounted and configured to connect with P6 once in range, and the lost link failsafes were disabled to prevent undesired mission termination en-route. Performance and autonomous navigation appeared satisfactory as the GlacierHawk approached the halfway point to P6, until it unexpectedly yawed 90° to the right and appeared to slow or stop in flight. Intermittent degradation and cutouts of the telemetry feed and Helheim’s lack of scale made it appear, both visually and on the GCS display, as though the UAS had halted and was hovering uncommanded halfway to its destination. These factors,
coupled with the sudden rotation, led the RPIC to initiate the RTL procedure through the GCS as soon as link integrity allowed. Onboard flight logs indicated that the vehicle did not actually stop, but had only slightly slowed as it translated sideways along the correct ground track towards P6.

The subsequent attempt represented the first successful glacier transit mission, as the UAS not only reached P6 but also achieved a payload–geoPebble connection and facilitated data retrieval. Upon transition to autonomous navigation, the UAS climbed to 20 m above the launch site elevation, which resulted in an estimated on-station altitude of approximately 100 m above ground level (AGL). The transit was flown, again sideways due to suspected magnetic effects, at 10 m/s, and the GlacierHawk hovered as planned over P6 for 30 seconds before initiating the RTL sequence. The planned on-station time was brief to preserve battery capacity since a full-distance mission had not yet been completed. With this in mind, the objective was only to reach the geoPebble and potentially connect; an appreciable amount of data retrieval was not anticipated due to the 100-m AGL altitude and brief loiter time. During testing in State College, altitudes above 30-m AGL did not support the minimum useful data transfer rate of 1 MBps. The actual mission defied expectations, with the payload not only establishing a connection with P6 but retrieving approximately 6 hours of recorded data. While an en-route and/or on-station descent was considered to improve data rate, such a maneuver was not included in this initial attempt so as to minimize mission complexity. The first successful geoPebble mission covered 7.12 km, lasted 14 minutes and 42 seconds, and used an estimated 43% of the flight battery capacity. Figure 4.9 shows the GlacierHawk on station over P6, and Figure 4.10 displays the ground track of the flight to and from the geoPebble over a satellite map.

4.2.3.3 Day 3: Tuesday, August 6

The third day of testing saw additional transit attempts to P6 and other geoPebbles, the implementation of aircraft strobe lights, and efforts to correct the vehicle’s off-course heading tendencies. While they did not extend the range from which the vehicle could be seen, the strobes did significantly assist visual orientation determination, both at short ranges during manual flight and through the spotting scope when flying over the ice.

Regarding the heading error, firmware and hardware troubleshooting measures included changing the Pixhawk parameter for magnetic declination and mounting the GPS/compass module higher on the airframe. Multiple changes of the declination setting had no apparent effect on performance, and indicated headings continued to exhibit
Figure 4.9. The GlacierHawk on station retrieving data from P6. (Ananda Fowler, US Army Cold Regions Research & Engineering Laboratory, Remote Sensing / GIS Center of Expertise)

Figure 4.10. P6 mission ground track over satellite map. (PX4 Flight Review online tool using Mapbox satellite imagery [3])
major deviations from their actual values. Raising the GPS/compass module, which contained the magnetometer, as high as its cable length allowed gave promising results in ground testing, but fabricating and securing a mount of this height was not feasible with the tools and materials available in the field.

The mission planning approach to the heading issue was to alter the point at which the RPIC handed off control of the vehicle to the autopilot. Previously, the RPIC would take off, climb, and establish a hover in the position control mode, then transition to mission mode from directly over the takeoff point. Rather than have the vehicle directly overfly the GCS and crew on departure, a post-takeoff waypoint was defined off the east end of the campsite to increase clearance from personnel. This would add two more autonomous turns to the flight plan, which the team saw as potential starting points for the heading errors. It was thought that, if the vehicle were instead manually flown to the hand-off point and rotated to face the proper direction, the heading error en route could be reduced or eliminated by avoiding the need for autonomous yaw.

This approach was tested in a short-range mission within the UAS camp vicinity. Immediately following hand-off, the vehicle’s heading error appeared to have decreased significantly compared to prior flights. Upon reaching its waypoint approximately 30 m away from the hand-off point, the UAS entered a severe pitch/roll oscillation and uncommanded yaw requiring an immediate manual recovery. The RPIC landed in stabilized mode once the oscillations settled and the vehicle returned to controlled flight. While the initial en route heading behavior seemed to improve during this test, the short distance between the hand-off point and waypoint precluded identification of the upset’s cause. Unwilling to risk inducing another upset from further troubleshooting the on-course heading error, a non-mission-critical issue, the team decided to continue flying geoPebble missions using the same hand-off procedure as the previous day’s over-ice flights.

The objective of the day’s first glacier transit was to replicate the previous day’s successful data retrieval flight, but with the on-station loiter extended tenfold to 5 minutes. While the autonomous navigation to P6 proceeded as planned, the team realized that the payload was powered off upon the vehicle’s return, and no data had been retrieved. The mission was repeated following replacement of the payload’s power board, but the device was again powered off upon return and had not acquired any data. The team reinforced the payload’s power connections and sent the UAS on a third flight attempt, which resulted in uninterrupted payload power but still no geoPebble data. This led the team to conclude that P6 had somehow gone offline, perhaps due to a power failure,
other system malfunction, or a change in orientation due to ice movement preventing
data transmission.

With P6 assumed no longer serviceable, the following transit was to the next closest
geoPebble, P7. Besides the destination, the main change for this mission was a gradual
en route descent from 20 m above to 50 m below the UAS campsite elevation, which
resulted in an estimated on-station altitude of approximately 30 m AGL. This flight
successfully connected to and retrieved 12 hours of recorded data. The P7 transit covered
7.25 km, lasted 19 minutes and 39 seconds, and used an estimated 48% of the flight
battery capacity. Of note is that, despite hovering at less than half the altitude and for
ten times as long, this flight retrieved only twice as much data as the previous day’s
successful flight to P6. This indicates that factors beyond loiter time and altitude exert
strong influence on actual mission data rates. Such factors may include differences
between individual geoPebbles, their mounting orientations, power levels, surrounding
ice geometry, the UAS approach path, and any number of unknown unknowns. For
example, if approaching from a higher altitude, the UAS may establish a connection and
begin data transfer from farther away, which may eclipse the progress of a lower-altitude
approach, which does not connect until the UAS is significantly closer to the geoPebble.

The remainder of the third day’s flight operations included two more geoPebble
transits and two more upsets. The longest flight covered 8.12 km, lasted 23 minutes and
31 seconds, and used an estimated 55% of the flight battery capacity. The first upset
occurred between the transit flights, and required an immediate manual recovery following
hand-off to mission mode. The second upset occurred after the vehicle passed the post-
takeoff waypoint and began flying towards P20, the farthest geoPebble. Approximately
100 m after the post-takeoff waypoint, the vehicle experienced a yaw departure and began
to oscillate in pitch and roll. The RPIC unsuccessfully attempted a manual recovery, and
the UAS went down hard out of sight; forward, below, and on the other side of the river
west of the camp. Once located, the RPIC flew a camera UAS to inspect the downed
GlacierHawk. Damaged appeared limited to the landing gear legs, a subset of the rotor
blades, and the payload. The river’s water level precluded recovery of the vehicle that
night, so the team hiked down the following morning with screwdrivers, disassembled the
airframe on-site, and returned it to the UAS camp. Figure 4.11 shows the GlacierHawk
as seen by the camera UAS shortly after the final hard landing, with the main airframe
and electronics intact, and the strobe lights still running.
Figure 4.11. Primary airframe and electronics intact after the final hard landing. (Author photo)
Chapter 5  |  Conclusions and Future Work

This chapter presents the key findings and takeaways of the GlacierHawk’s design, development, and field testing. Multiple system improvements and new operating concepts are discussed for consideration in future implementations. Although the first-generation design encountered a number of challenges in the field and demonstrated room for improvement in several areas, the GlacierHawk UAS ultimately proved capable of reaching, connecting to, and retrieving data from deployed geoPebbles in a real-world mission environment.

5.1 Conclusions

The Greenland field testing served as a proof-of-concept for the use of a quadrotor UAS leveraging commercially available components and open-source software to retrieve geoPebble data over a tidewater calving glacier. Following initial system development in State College, Pennsylvania, the team adapted to operations in the actual mission environment over Helheim Glacier and addressed conditions and challenges not encountered in prior testing. While some system elements performed at or beyond expectations — for example, satisfactory GlacierHawk flight endurance and much greater data link ranges than anticipated, both for the aircraft and WiFi access point payload — other factors presented unforeseen challenges, namely the aircraft’s off-course heading tendencies and new upset modes. Furthermore, the relationship between the payload and the geoPebbles defied expectations. In the most successful mission to P6, link and data transfer were established from far higher than was thought possible, yet a substantially lower flight over P7 with ten times the loiter period yielded only twice as much data. This phenomena indicates that factors yet to be characterized exert strong influence over performance of the payload-to-geoPebble data link, some or all of which may be beyond the UAS crew’s
and/or system’s control, at least in its current form. Having integrated the GlacierHawk, payload, and geoPebbles in their actual mission environment and achieving data retrieval, the team has successfully demonstrated baseline feasibility of the system’s design mission at the proof-of-concept level. The GlacierHawk can be seen mid-transit over Helheim in Figure 5.1.

![The GlacierHawk en route to a geoPebble over Helheim. (Ananda Fowler, US Army Cold Regions Research & Engineering Laboratory, Remote Sensing / GIS Center of Expertise)](image)

**Figure 5.1.** The GlacierHawk en route to a geoPebble over Helheim. (Ananda Fowler, US Army Cold Regions Research & Engineering Laboratory, Remote Sensing / GIS Center of Expertise)

### 5.2 Future Work

A number of potential modifications to the vehicle design and system equipment were identified to improve performance, expand mission capabilities, and enable new operational concepts.

#### 5.2.1 Heading Error Correction and Improved Positioning

Increasing the height of the GPS/compass unit mount was identified as the most straightforward and lowest-cost potential solution to the off-course heading problem. Further elevating this component containing the magnetometer from the surrounding electronics
and airframe would reduce magnetic interference and in theory improve heading detection and tracking performance. The lack of this heading error when flying in State College suggests that magnetic field effects are of much greater prevalence in Helheim’s environment, primarily due to the glacier’s higher latitude and thereby significantly greater magnetic inclination. With the Earth’s magnetic field having a greatly diminished horizontal component at higher latitudes, compass errors will be far more frequent and pronounced during operations in these regions [17]. These concerns are exacerbated by unanticipated shifts in the Earth’s magnetic field, which may outdate the World Magnetic Model (WMM) configured in a particular instrument prior to its planned update. One such shift, or “magnetic jerk,” occurred soon after the release of the 2015 WMM and precipitated an early out-of-cycle update to the model [18].

Should increasing the GPS/compass mounting height not substantially reduce or eliminate the heading error, transition to a dual-antenna GPS unit would offer the next level of capability and preclude dependence on a magnetometer for heading data. These systems implement two antennas on a single receiver to provide velocity, position, and heading angle estimates based solely upon GPS signals. The estimates are thereby independent of magnetic field conditions and vehicle ground speed. While it would require a precise GPS fix (and thereby clear areas and relatively level flight attitudes) at all times, a dual-antenna unit would offer improved accuracy over the current setup of a paired single-antenna GPS and magnetometer [19]. The GlacierHawk application may be well suited to a dual-antenna GPS system, as the vehicle operates in clear, unobstructed airspace, flies at low tilt angles and spends a significant portion of its mission in hover.

Regardless of the on-board method of heading determination, the challenges of navigation at high latitudes remain. Should difficulties persist after implementation of the aforementioned corrective measures, augmentation of the GPS signals via one or more ground-based pseudolites may offer further improvements. Although GPS signals are consistently available from multiple satellites in the field, Helheim’s high latitude means that the satellites’ maximum elevation, and thereby vertical accuracy, is reduced compared to operations at lower latitudes. This results in increased Vertical Dilution of Precision (VDOP), which, in turn, increases the overall Geometric Dilution of Precision (GDOP) and thereby diminishes positioning accuracy [20]. While navigation difficulties during field testing appeared to primarily involve heading discrepancies from magnetic field effects, decreasing GDOP would nonetheless improve performance, especially if a dual-antenna GPS-only system were adopted. Implementation of one or more ground-based pseudo-satellites, or pseudolites, would offer a means by which to improve positioning.
A single, fixed, GPS-connected pseudolite of known location may act as a reference point to augment GPS, whereas a network of them throughout an operating area could eliminate satellite dependence altogether, provided the vehicle maintains line-of-sight to the transmitters [21]. Given Helheim’s scale, terrain, and availability of satellites, however, GPS augmentation rather than replacement would likely be the preferred pseudolite approach. One or more devices could be installed on either side of the glacial fjord, at high elevations, and near the UAS launch and recovery site.

5.2.2 Long Range Radios, Video Feed, and Payload Telemetry

Although the maximum connection distances of both the R/C and telemetry links far exceeded expectations over Helheim, their integrity at these ranges was inconsistent and often intermittent at best. Implementation of long-range radio equipment would greatly improve system reliability and situational awareness (SA) while enabling intervention at even the farthest points in the mission envelope. Addition of a first-person view (FPV) live-feed camera system would further improve SA, especially if mounted on a tilt-controllable gimbal so that the RPIC could either look forward in transit flight or down at a geoPebble once hovering on-station. This would also enable the RPIC to ascertain details of the ice surface immediately surrounding a given geoPebble and safely descend as desired to improve the data retrieval rate. Integrating these upgrades on the vehicle and GCS display could leverage existing COTS solutions with limited impacts to overall system cost, weight, and complexity.

Development of an over-the-air payload telemetry interface would further expand SA and in-flight flexibility. If the GCS could receive and display the payload-geoPebble connection status, the crew would know in real-time if and when a geoPebble is acquired and transmitting data to the payload. If the GlacierHawk does not receive data or establish any geoPebble link once on-station, the RPIC could visually inspect the geoPebble and surrounding area via the FPV camera to determine if the sensor was overturned, missing, or otherwise physically compromised. The crew could then update the flight plan, configure the payload to communicate with the next closest geoPebble, and immediately fly to it, rather than finishing the original profile, returning with no data, and needing to launch an entirely new mission. Implementing an over-the-air payload telemetry feed would require direct communication between the payload’s ODROID computer and the GlacierHawk’s Pixhawk autopilot unit for transmission to the GCS via the aircraft’s on-board telemetry radio. Ideally, passing payload metrics through the aircraft’s telemetry system would enable integration of payload status messages directly
onto the QGC interface and thus keep the GCS software as streamlined as possible. If an integrated payload data feed through the Pixhawk were not feasible, however, the payload would need a separate radio system, GCS software interface, and display, which would add to system cost, weight, and complexity.

5.2.3 Skid-Type Landing Gear

A lightweight skid-type landing gear design could improve the GlacierHawk’s ground stability on uneven surfaces such as the UAS camp’s foliage area. With the existing setup of four individual vertical legs, the vehicle does not always sit level or securely when individual legs are placed over ruts or gaps on the surface. This often results in the need to re-situate the vehicle before takeoff and after landing. A pair of taller, unified skids would mitigate this issue while providing additional ground clearance for the attached payload. Whether mounted to the airframe arms or fuselage beam, a skid-type design would ideally feature thin members for minimal drag, a wide stance to prevent tipping and/or rotor strikes on the ground, and a degree of compliance for absorbing energy should a hard landing or crash occur.

5.2.4 Tool-Free Design and Systems Integration

Transition from traditional fasteners to tool-free and/or quick-release mechanisms for the airframe’s access panels would significantly streamline the assembly process and reduce turnaround time between missions. In its current form, each access panel is secured by four screws, so a minimum of eight must be removed, retained, and reinstalled between missions, as the two flight batteries are each secured beneath a separate panel. Payload installation and removal requires manipulation of the central avionics panel since the payload battery is carried internally, with a power connection running to the externally mounted payload. If the payload and its battery were completely self-contained in a common quick-release housing, cable management and overall system integration would be simplified at the cost of a small increase in drag, dependent upon the size and orientation of the payload battery. This drag penalty, however, could be mitigated or eliminated with aerodynamic design of the payload fairing. Internal cable routing for the aircraft strobe lighting would also streamline systems integration.
5.2.5 Improved Yaw Authority

Tilting the front motors aft and the rear motors forward at fixed angles would create longitudinal rotor thrust components complementary to the moment imbalances induced for directional control, and thus augment the vehicle’s yaw authority. For example, to initiate a clockwise yaw without any motor tilt, the counterclockwise motor speeds must increase relative to their clockwise counterparts so as to generate a clockwise torque imbalance and vehicle rotation. For a props-in vehicle such as the GlacierHawk, this corresponds to the front right and rear left motor speeds increasing for clockwise yaw. Longitudinal thrust components from tilting the front right motor backwards and the rear left motor forward would form a clockwise couple about the center of gravity adding to the torque-induced moment. Backward motor tilt on the front arm and forward tilt on the rear arm results in the same complementarity for counterclockwise yaw inputs, so left-to-right symmetry is maintained. Thanks to this symmetry, only the arm and landing gear mounting angles would need to change, so the motors on a given arm would remain in-plane with one another. This relationship is illustrated in Figure 5.2.

Figure 5.2. Illustrated yaw control and motor tilt directionality.

The GlacierHawk’s hardware mounting design means that implementing such a
change would require only an assembly adjustment rather than a fundamental airframe modification. Since the arm tubes and landing gear are secured via compression and friction in clamps rather than pins, ratchets, or other mechanisms, any angle may be set so long as rotor tip ground clearance and primarily vertical thrust vectors are maintained. The anticipated tradeoff of this motor angling for yaw authority is a decrease in flight endurance and efficiency, especially in hover, since a portion of the total thrust will be lost to the longitudinal components. A potential compromise could be to angle only the rear arm forward and leave the front arm level, as this may reduce losses in forward flight, though the longitudinal thrust imbalance would mean the vehicle would no longer be able to yaw purely about its center of gravity or sit level in hover.

5.2.6 Increased Flight Time

If possible to procure, the originally planned Li-Ion battery pack could offer significant endurance and range gains to an updated vehicle designed around this power source. Although the first-generation GlacierHawk proved capable of reaching a deployed geoPebble and gathering an appreciable amount of data in a single mission, the ability to hover longer on-station and/or visit multiple geoPebbles in a single flight would drastically improve system performance and viability for longer deployments of larger sensor arrays. A more involved and higher-risk option with the potential for even greater performance gains would be to develop a VTOL fixed-wing aircraft capable of significantly faster, more efficient forward flight during the en route stages of a mission.

5.2.7 Roll Call and Traveling Salesman Mission Concepts

With increased range and endurance, the GlacierHawk could overfly the entire array in a single pattern, such that the payload could verify each geoPebble’s ability to establish link, as well as its signal strength, battery level, and other sensor health metrics. If implemented, an onboard camera could photograph each sensor site for visual confirmation. Upon return, this data would provide the crew with valuable information for use in planning subsequent flights. This “roll call” mission, while not a primary data retrieval flight itself, would increase operational efficiency by eliminating flights to inactive, inaccessible, or otherwise compromised geoPebbles. The crew could then choose to either visit geoPebbles with the lowest battery levels to attempt data retrieval before power loss, or immediately focus on the sites most likely to provide the largest quantities of data at the fastest rates.
This roll call concept, combined with an additional on-board ODROID communicating with the Pixhawk and running a path planning algorithm, could partially automate flight planning using a solution to the traveling salesman problem (TSP), a classical combinatorial optimization problem [22]. Given a list of active geoPebble coordinates, the TSP algorithm would order the waypoints to minimize, for example, total flight distance, mission time, or estimated battery energy expenditure. Although the basic problem definition is straightforward, computation of the optimal route quickly becomes intractable as the number of stops increases. The extreme computational demands of a brute force approach, both in terms of processing power and run time, preclude use of an exact solver and necessitate implementation of a faster, yet still effective approximation. Implementation of a genetic algorithm (GA) represents one such approach. Rather than computing every possible combination of stops and returning the optimal one, a GA simulates natural evolution by iteratively breeding and mutating the fittest routes arising from an initial population [23]. Whereas an optimal solution for even a modest number of geoPebbles may require hours of processing and/or a powerful computer, a GA’s approximate solution would be much faster and more practical for repeated use in the field, especially if incorporated into an on-board vehicle computer. Depending upon the algorithm’s level of sophistication and available computing power, this solution could also be expanded to incorporate wind speeds, geoPebble signal strength, or other more advanced variables. However, greatly increased endurance and range are the key barriers to implementing a TSP approach to data retrieval flights, as the first-generation GlacierHawk only has sufficient performance to service a single geoPebble per flight.

Coupled with the preceding design and equipment upgrades to the vehicle, payload, and GCS, these mission concepts would offer a generational increase in overall GlacierHawk system performance in support of Penn State’s geoPebble research effort.
Appendix A
GlacierHawk UAS Checklists

A.1 In-Lab Procedures
To be completed at least 24 hours in advance of planned flight operations.

A.1.1 Flight Planning and Preparation
1. Secure flight approval(s) as required
2. Create test matrix and identify test points
3. Compose flight briefing cards
4. Design, simulate as needed, and verify flight plans (Pixhawk mission files)
5. Charge batteries (aircraft, TX, payload, ground power box)
   (a) Log flight battery charge metrics (date, charge added, charger used, charge mode, elapsed time, final internal resistance, and application)
   (b) Tape over connectors and place in LiPo-safe storage
6. Assemble airframe, except rotors
7. Connect ground station telemetry radio and open QGroundControl
8. Verify rotors not mounted
9. Power on R/C transmitter
10. Power on aircraft
11. Verify R/C, telemetry radio connections and R/C calibration
12. Set and verify kill switch setting
13. Set and verify flight mode switch settings
14. Calibrate sensors as required
15. Verify attitude and heading indication sense correct
16. Verify manual/stabilized flight mode control directionality correct
17. Verify GPS lock and ability to switch to mission mode (may need to move outside)
18. Disarm vehicle and disconnect aircraft batteries
19. Check TFRs, NOTAMs, and weather for test period; adjust plans or cancel as required

A.1.2 Packing and Required Equipment

1. Airframe: fuselage, arms, and arm mounting brackets
2. Rotor sets: at least 2 CW and 2 CCW, plus any available spares
3. Landing gear: legs, mounting brackets, any available spares
4. R/C transmitter (verify charged), manual, case, spare batteries (4×AA)
5. Charged aircraft batteries, Y adapter (Castle 6.5-mm parallel), LiPo-safe bags
6. Strobe lights, switch, wiring, batteries (4×AA) and holder
7. Voltage checkers
8. Ground station
   (a) Laptop and charger
   (b) Telemetry radio and USB cable
   (c) Ground power box (verify charged)
   (d) Pixhawk USB cable
9. Aluminum tape, double-faced tape, electrical tape, Velcro, zip ties, scissors
10. Foam saw, foams-safe glue, X-Acto knife
11. Soldering iron, solder, wire cutters
12. Pliers: needle-nose and regular
13. Screwdrivers: 3-mm Allen, 2.5-mm Allen, 2-mm Allen, large Phillips head
14. KDE torque wench 6030, size 7 and 8 wrenches, Loctite (low and medium strength)
15. Bubble level
16. Safety glasses, hats, sunscreen
17. Drinking water and food
18. Folding table and chairs
19. All flight test and other required documentation

A.2 Field Procedures

To be completed on the day of planned flight operations.

A.2.1 Field Assembly and Preflight Checks

1. Ground station laptop connected to ground power box as needed
2. Ground telemetry antenna set up and connected to ground station laptop
3. QGroundControl running
4. Verify airframe assembly and equipment mounting complete and correct
   (a) Front/rear arms centered, level, and secure
   (b) Landing gear legs vertical and secure
   (c) All electronics and wiring connections intact and secure
   (d) Payload battery secure under avionics lid
5. Verify rotors not mounted
6. Install flight batteries and connect to Y cable
7. Secure battery lids
8. Power on R/C Transmitter
9. Power on aircraft (connect Y cable to power board)
10. Perform sensor calibrations as needed, i.e., after shipping, new location, etc.
11. Perform radio range check (procedure given for Futaba 10J)
   (a) Hold jog button (hat switch) while powering on TX and select Power Down Mode. Beeps every 3s and red LED flashes.
   (b) Press END button to exit Power Down Mode. Red LED becomes constant.
12. Verify compass indication, recalibrate if incorrect
13. Verify GPS lock and satellite count

14. Ensure correct QGroundControl mission profile and geofence uploaded
   (a) Geofence configured and uploaded
   (b) Mission profile configured and uploaded — review and verify with VO/crew
   (c) Home/lost comms waypoint and actions configured — review and verify with VO/crew
      i. DO NOT SET ANY FAILSAFE AS HOLD MODE

15. Test arming functionality; troubleshoot/recalibrate as needed if vehicle will not arm
   (a) Power on R/C TX, disengage kill switch, pre-arm aircrfat, arm from TX

16. **Disconnect aircraft power**

17. Mount and secure rotors, verify directionality correct (front right/rear left are CCW — a.k.a. props in)

18. Move aircraft to takeoff location
   (a) Nose pointed downrange
   (b) Vehicle placed **DOWNWIND** of people

19. Power on R/C TX and verify switch mappings correct
   (a) R/C kill switch - *engage* (switch A to bottom position)
   (b) Flight mode switch - *stabilized* (switch G to top position)

20. **Move to front of aircraft and remain clear of rotor arcs**

21. Connect power cable and hold pre-arming switch **from front of aircraft, well clear of rotor arcs** until pre-arm tone heard

22. **Move well clear of aircraft - behind and away**

23. Brief crew on flight plan

24. Verify mission area clear (ground and air, including weather)

25. R/C kill switch - *disengage* (switch A to top position)

26. Arm motors vis R/C TX - rotors will spin up

27. Launch and proceed with mission
A.2.2 Post-Mishap Checklist

1. **Disarm** via R/C TX, confirm via GCS
2. R/C kill switch - **engage**
3. **Disarm** via onboard aircraft switch
4. **Disconnect** aircraft power

A.2.3 Shutdown and Packing

1. Disarm and kill vehicle
2. Disconnect aircraft power
3. **Disconnect ground power box batteries**
4. Disassemble and pack aircraft
5. Pack all tools and equipment
Appendix B
Non-Default Pixhawk Parameters

B.1 Tabulated Parameters

The final GlacierHawk firmware configuration used the following non-default parameters within the PX4 autopilot suite. Airframe type was set as Quadrotor X, vehicle was set as Generic Quadrotor X, and firmware version was 1.8.2 on the Pixhawk 4 board.

Table B.1: Non-default Pixhawk parameters.

<table>
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<tr>
<th>Parameter Name</th>
<th>Description</th>
<th>GlacierHawk Value</th>
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<tr>
<td>BAT_A_PER_V</td>
<td>Current per volt (A/V)</td>
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<td>BAT_CAPACITY</td>
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<td>Emergency threshold (%)</td>
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<td>Low threshold (%)</td>
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<td>Number of cells</td>
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<td>BAT_V_DIV</td>
<td>Battery voltage divider</td>
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<td></td>
<td>Landing auto-disarm</td>
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<td></td>
<td>timeout (s)</td>
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<td>COM_DISARM_LAND</td>
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<td>4th flight mode slot</td>
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<td>6th flight mode slot</td>
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<td>COM_LOW_BAT_ACT</td>
<td>Battery failsafe mode</td>
<td>Return mode</td>
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<td>Magnetic declination (°)</td>
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<td>Parameter Name</td>
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<td>NAV_GPSF_TR</td>
<td>GPS failure loiter&lt;br&gt;thrust setting (%)</td>
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<td>GF_ACTION</td>
<td>Geofence violation action</td>
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<td>Max. vertical distance (m)</td>
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<td>COM_TAKEOFF_ACT</td>
<td>Action after accepted takeoff&lt;br&gt;Max. horizontal distance from home to 1st waypoint (m)&lt;br&gt;Max. horizontal distance between waypoints (m)</td>
<td>Mission (if valid)</td>
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<td>Roll rate P gain</td>
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<td>Roll P gain (rad/s)</td>
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<td>Yaw rate I gain</td>
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<td>Max. yaw rate (°/s)</td>
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<td>MC_YAWRAUTO_MAX</td>
<td>Max. yaw rate in auto mode (°/s)</td>
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<td>Yaw P gain (rad/s)</td>
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<td>MPC_ACC_DOWN_MAX</td>
<td>Max. downward accel. in velocity-controlled modes (m/s²)</td>
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<td>Max. horizontal accel. in velocity-controlled modes (m/s²)</td>
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<tr>
<td>Parameter Name</td>
<td>Description</td>
<td>GlacierHawk Value</td>
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<td>------------------------</td>
<td>-----------------------------------------------------------------------------</td>
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<tr>
<td>MPC_ACC_UP_MAX</td>
<td>Max. upward accel. in velocity-controlled modes (m/s²)</td>
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<td>Landing descent rate (m/s)</td>
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<td>MPC_MANTHR_MIN</td>
<td>Min. manual thrust (%) Max. tilt angle in manual or altitude mode (°)</td>
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<td>Max. manual yaw rate (°/s)</td>
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<td>MPC_XY_CRUISE</td>
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<td>Horizontal velocity error differential gain</td>
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