High Altitude Balloon with Image Processing Module

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***Abstract*—A High Altitude Balloon will fly *Plant Life Automatic NDVI with Telemetry from a High Altitude Balloon* (PLANTHAB) payload module to altitudes near 100,000ft. The HAB5 and PLANTHAB payload are to be developed in parallel over one year. The vehicle and payload are both designed to be modular so that the HAB is able to support diverse mission payloads on the same platform. PLANTHAB will use multispectral imaging to measure vegetation density, and will demonstrate on-board image processing and computer vision techniques with low cost, consumer level components.**

I. Introduction

High Altitude Balloons (HABs) are autonomous balloons sent up to 100,000 feet and serve as research platforms for a variety of purposes. SPEX has designed, constructed and launched a number of HABs, with HAB4 being the latest iteration. A HAB will usually fly with, at the very least, a power system, one-way communication notifying a ground station of its position and basic electronics. For this purpose a HAB must have a safe and reliable structure capable of providing protection from different atmospheric conditions, including temperature and pressure. It is also preferred if this structure allows for modular payload development and is compatible with cubesat designs. Constraints of mass and volume follow naturally, leading to limitations then on power, processing and memory capabilities and communication rate and range. Essential HAB functions such as position tracking and power delivery should be as weight and volume efficient as possible to optimize payload volume and mass budgets.

Image processing is the application of computer algorithms or digital processing techniques to images. Recent advances have made it possible to carry out image processing on relatively cheap, light and easily interfaceable consumer electronic equipment. Computer Vision (CV) is the automated extraction of information from one or several images. CV allows for autonomous extraction and interpretation of information from an image feed and can be utilized for a variety of applications. Among these are the identification of objects or the detection of a horizon. Many of the algorithms can be trained to recognize particular features or objects, or a combination thereof, to recognize, predict or quantify another feature or quantity.

This Project Definition Document describes a High Altitude Balloon suited to flying imaging and CV payloads as discussed in the "On-Board Image Processing and Computer Vision Techniques on Low-Cost Consumer Electronics for Vegetation Density Mapping and Other Experiments" Project Definition Document [1]. These payloads are designed to be achievable using readily available consumer electronics within a reasonable development budget.

II. Primary Objective

A. Vehicle

Development of a reliable HAB vehicle capable of flying modular payloads, as described in (section V), is a primary objective.

B. Payload

The primary payload, *Plant Life Automatic NDVI with Telemetry from a High Altitude Balloon* (PLANTHAB) is a continuation of *Where U At Plants?* (WUAP), a payload that flew on the SPEX high altitude balloon HAB4 in Spring of 2018 [2]. PLANTHAB shares its predecessor's primary objectives to measure vegetation density using the Normalized Difference Vegetation Index (NDVI) with visible to near-infrared (VNIR) imaging, demonstrate on-board image processing, and gather large datasets of aerial images using low cost, entry-level electronics. NDVI data collected in flight will be validated using NASA NDVI or Enhanced Vegetation Index (EVI) datasets.

WUAP demonstrated the core concepts of image processing and imaging payloads on high altitude balloon missions but did not meet all of its objectives or design goals and encountered unexpected problems in flight [2, Post-Flight Analysis]. Though PLANTHAB will attempt the same mission as WUAP as a follow-on payload, it will place more emphasis and effort on testing, reliability, and system architecture. The priorities for PLANTHAB development are as follows.

1) **Understanding the system.** There should be no surprises in flight, and if goals or target performanceare not met it should be known by how much.
2) **Reliability and stability.** The system should behave the same way every time, and should produce the same output for a given (known) set of inputs.
3) **Performance.** The quality of output data should reach the maximum possible for the system's capability. Realize all the potential of the system.

A list of "essential questions" to be addressed during PLANTHAB's development is given in appendix A.

III. Secondary Objectives

A two-way communication system is desired but may be scaled back due to resource limitations based on the choice of payload. Geofencing and control over the APRS transmitter's frequency is one such pertinent case. Similarly, consistent location information has been an elusive target. As the HAB is trusted with more complex payloads, the tracking becomes of greater importance.

In addition to NDVI studies of vegetation density in the VNIR band, PLANTHAB aims to demonstrate CV techniques such as object detection and image segmentation of populated areas. On the ground, methods of determining and mapping vegetation density from RGB visible images alone will be developed using computer vision and machine learning techniques with public NDVI data and aerial photography, and then applied to PLANTHAB datasets.

IV. Benefit to SPEX

The high altitude balloon system offers a unique environment to develop skills and demonstrate prowess to RIT faculty and staff, potential SPEX members, and potential sponsors. A HAB bearing the mark of RIT SPEX is a declaration that we can confidently launch non-trivial payloads in a system of our making. HAB demands careful planning, intelligent utilization of resources, considerable multidisciplinary engineering and long-term teamwork. A successful HAB is thus linked to a success-ready SPEX, whose members are now better prepared for any task. HAB also serves as a unique testing platform for projects involving different temperatures, altitudes or pressures than those experienced normally. This is particularly useful for lower-altitude rocket payloads, testing them for a fraction of the cost or risk. HABs designed with a payload form resembling a cubesat or combination thereof have an even wider utilization. HABs are also the easiest platform for testing of longer-range communication systems.

The pursuit of HAB is the pursuit of maximizing scientific output using off-the-shelf components and present limitations of SPEX's human capital. Progress here develops SPEX's knowledge base for all future missions, including SPEX's understanding of what can and cannot be achieved. Presently proposed operations include rigorous pre-flight testing for diagnosis and correction of software and hardware components, post-flight analysis and amelioration and inculcation of this into the design cycle.

Documenting training sets and linking them to performance is a potential avenue for exploration. This can be evaluated both to determine which training data results in the best performance and in gauging how resilient methods implemented are to a varied number of incorrect samples in the data set. Also, by incorporating testing and training processes into the design and execution process, SPEX can iterate on more advanced software tools. Specific focus on algorithmic improvisation may also draw in more talent, which in turn advances the scope of possible missions.

As image processing tools advance, ever more useful information can be garnered from the same physical equipment. Progress here automatically increases SPEX's potential to make news, capture imaginations and talent, and grow. This advantage is both due to us maximizing the knowledge gleaned from cheap and readily available hardware, as well as the abundance of open source resources for computer vision. While the entry requirements are non-zero, the acquisition of talent utilizing OpenCV or useful Python libraries broadens SPEX's options for other ventures, such as IREC's SDL Payload Challenge.

Developing the capability to perform Normalized Difference Vegetation Index (NDVI) provides a foundation for a wide range of future imaging payloads. SPEX is yet to use near-Infrared imaging, and this analysis for NDVI serves as a new but relatively simple processing exercise.

Further, this project offers great flexibility in terms of team composition, once beyond a requisite minimum. While the mechanical design of the HAB is quite mature, its electrical systems are not. An gifted electronics team may choose to consider much more advanced imaging equipment or image processing using other factors to control, requiring only a moderate CS investment.

As RIT looks to expand its research endeavors, especially in fields such as Imaging Science where it possesses an advantage, developing a long and mutually beneficial relationship with that department is also a goal unto itself. As a platform for experiments, SPEX has the unique opportunity to be a student body involved in the synthesis, publication and presentation of materials. This can build SPEX's reputation and foster relationships with faculty and research organizations, leading to opportunities for mentorship and funding from sustainable sources.

V. Implementation

A. Deliverables

1) Documentation: HAB5 will require GitHub repositories for all software that is developed. Library dependencies will be listed with references or citations to existing codebases. Duplication of online resources, with citations, will be made to aid in reproduction of results or retracing of errors. Electronic components utilized will be logged in a bill of materials (BoM) and KiCad files for any custom PCBs will be archived. Printed mechanical parts will have files saved and machined components' sketches will be included. Expectations, hurdles and solutions are to be tabled in documents both before and after the flight.

2) Vehicle: The desired product at the end of the development is a modular HAB vehicle capable of reliably, predictably, and safely carrying a payload compatible with a nU cubesat size. The lower limit is a 3U internal volume, with the upper bound not exceeding 8U. The vehicle is defined as the mechanically sound HAB structure and common electronic/software components necessary for payload deployment. Mechanical soundness includes, but is not limited to, protection from disintegration, temperature, winds, pressure, charge buildup and vibration. To this end a power system, APRS transmitter, pressure/temperature/humidity sensor, payload arming/disarming mechanism and all facilitating processing and memory elements are to be included. A data recording system to record flight data and provide information leading to more advanced HABs and missions is aimed for, with measurements from sensors stored to an SD card on the HAB. It is expected that the payload will be modular, fitting both an x-u form factor and having a power supply of its own. This is because optimization of a HAB vehicle capable of handling any modular payload results in selection for a power system dedicated solely to the HAB vehicle board and merely arming/disarming the payload electronics. Past issues have included adhesives melting, batteries breaking apart and damage due to environmental factors. Each of these contingencies is to be specifically tested and solved for.

3) Software and Payload: Python is to be the (payload) language of choice, greatly increasing the talent base which can be drawn upon. Development costs and considerations for quality control also encourage the use of Python over C/C++. Previous HAB teams have considered this question, and given the resources on the team, their findings are restated. OpenCV 3 will continue to be used as a major part.

The primary payload on HAB5 is the PLANTHAB payload. Use of NDVI is to be investigated on the ground and considerable attention paid to how NDVI results may be linked to visual spectrum analysis of vegetation. While specific to the payload mission selected, exploring the linking of different realms of sensor information is a pursuit which will further aid SPEX. An example could be the linking of IMU attitude data to images at the corresponding time, which in turn may allow for correction of apparent areas due to the angle of the camera with respect to the horizon. This in turn prepares SPEX for projects requiring this correction be done on-flight, and for other projects such as horizon detection which could "train" on-flight by comparing analyzed data to known IMU readings. To this end the synchronization of clocks may be pursued. Another consistent challenge has been the processing of information on a stream, without information being skipped or resampled. Raw and processed information should be saved for later evaluation and iteration of systems.

Detailed test plans and test reports will record the method and results from rigorous testing of mechanical and electrical components, software algorithms, telemetry collection, and fault detection. Additional and calibrations unique to HAB5 and PLANTHAB include camera alignment; camera stability; spectral response/quantum efficiency; software processing of simulations; payload NDVI/visual functioning while on ground; an electronics functional test with specific focus on power systems and APRS reliability; electronics environmental testing; and integrated system testing. Time-stamping of information received by different processes may be considered. It is also desired that metrics be included for post-flight analysis.

Among the physical requirements for the payload, it is required that the HAB vehicle and payload system be better capable of protecting from environmental factors such as humidity, winds and temperature. Specific to this payload, the alignment of cameras is a question needing further exploration. An angle and separation optimal for the combination of data acquisition and securedness is required. Vibration or displacement during flights can significantly impair or corrupt all information gathered. Fixing this hurdle is critical for future projects which may look to infer distance data with a combination of two cameras or a radar altimeter setup. While the project doesn't expect that these will all be met as results, it is firmly held that the steps taken to implement these goals as best as possible will transformatively improve SPEX's advanced payload capabilities.

B. Milestones

Development and fabrication milestones are listed in Table I. One key consideration in choosing a time of year to launch HAB5 with PLANTHAB is the abundance of plant life in the area where it will be launched. In upstate New York, plant vitality is at its highest in late spring through early fall.

TABLE I
MILESTONES TO DESIGN AND BUILD HAB5

Task	**Complete Date**
Review and Write Up of Current Systems	September 2nd Week
Mechanical Constraints for Development	September 2nd Week
Sensor Acquisition, Readout Config	October 2nd Week
Power System and Communications Design	October 2nd Week
Mechanical Design [a]	October 2nd Week
Camera Setup and Software	October 2nd Week
Power System Assembly	October 4th Week
Mechanical Construction	October 4th Week
Image Processing Implementation, Testing	December
APRS Testing and Verification[b]	December
Testing of All Subsystems	February 2nd Week
Image Processing Tuning	February 2nd Week
Assembly and Testing, incl. Environmental	February 4th Week
Launch	Imagine RIT

[a]Mechanical deadlines assume rebuilding the box to the HAB4 specification. This work is truncated if the HAB4 structure is not damaged from previous flights.

[b]Assumes the HAB4 power board is supplying power and APRS to HAB5 avionics boards.

VI. EXTERNALITIES

A. Prerequisite Skills

Proficiency in Python (CS 1 or equivalent) is required for implementing PLANTHAB image capturing and processing software. Experience with Python computer vision and machine learning tools is required for developing the advanced CV objectives like object detection and segmentation. A minimum of 2-3 dedicated individuals will be required for the project. Electrical engineering skill set varies greatly based on method of implementation—purchasing ready-to-assemble products to design and fabrication of custom PCBs. A single eiectrical engineer could, with significant effort, design and implement the sysem. A safer approach would be 2-3 with moderate experience; further talent being used to move the project away from premade subcomponents. The result is that we have the opportunity to tune implementation based on the EEs we find. Understanding of basic circuits and connections/interfacing is still required. An understanding of the fundamentals of heat transfer is recommended in order to do basic thermal analysis. A team of 2-3 mechanicals would be required for the project itself. Additional talent can be used to probe the question of camera stabilization and other long-term niceties. The HAB structure leverages HAB4 designs so the brunt of mechanical design will focus on camera mounting and enclosures. University Physics II (with optics) is recommended for imaging systems testing and calibration tasks.

B. Funding Requirements

The budget described in Table II assume the worst case where no material is reused from HAB4, and uses HAB4 and WUAP to baseline costs. From this baseline cost estimate, the components and materials for HAB5 and PLANTHAB module should not exceed \$600.

TABLE II
ESTIMATED COST

Item	**Cost**	**Reused?**
Balloon	\$100	No
Helium	\$120	No
Avionics, sensors & batteries	\$150	Yes
(2x) Raspberry Pi 3	\$100	Yes
Pi Camera V2	\$30	Yes
Pi Camera NoIR	\$30	No
Foam & structural materials	\$50	Yes
Total	\$580	

This estimate is based off of the inclusion of a prior HAB board for baseline functionality, an existing APRS module and some functional WUAP hardware. Significant leeway was left specifically because the exact implementation topology (for processing) and level of pre-fabrication of components scales inversely with availability of time dedicated by advanced electrical engineering students.

C. Faculty Support

The project laid forth doesn't assume that faculty support is guaranteed or that any particular faculty members will be forthcoming. The project is undertaken in part hoping to build these connections without any significant one-way reliance. It is for that reason that specific, informed and meaningful discussions with possible candidates are recommended as the project progresses and substantive results can be shared.

D. Long-term Vision

As laid out in the section II and section IV, this document is tabled with an eye to the future. Data collection will focus not just on raw data but also on how processing develops and compares to the knowns. Cataloguing the progress, as described in subsection V-A, builds on present resources and knowledge in a manner amenable to future growth. Similarly, the potential for much more advanced algorithmic excursions on maintained or minimally modified hardware is substantial. SPEX's in-house ability is developed in line with estimates for skills required for later missions.

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References

[1] P. Linden, T. Tarazevits, and J. Maggio, "On-board image processing and computer vision techniques on low-cost consumer electronics for vegetation density mapping and other experiments," *RIT Space Exploration*, December 2017, Project Definition Document.

[2] P. Linden, "HAB4 post flight report," Tech. Rep., July 2018, URL: https://github.com/RIT-Space-Exploration/hab-cv/blob/master/reports/HAB4%20Post%20Flight%20Report/report_wuap_postflight-hab4.md.

APPENDIX A
PLANT LIFE AUTOMATIC NDVI WITH TELEMETRY FROM A HIGH ALTITUDE BALLOON (PLANTHAB) KEY INVESTIGATIONS.

PLANTHAB is a multidisciplinary effort at the convergence of electrical engineering, imaging science, software engineering, and artificial intelligence. In order to accomplish PLANTHAB's goals, students working on the project must find answers to the questions in section A. Although some of the concepts are somewhat advanced, all are within reach to motivated undergraduate students provided they have guidance from individuals with experience in the respective fields, such as student or alumni mentors or university faculty members.

TABLE III
ESSENTIAL QUESTIONS

Discipline	Essential questions
Imaging	What is the spectral response of the Pi Camera V2? The Pi Camera V2 NoIR?
Imaging	What is the spatial resolution (GSD) of images at 480p? 1080p? How does it vary with altitude?
Imaging	What is the lens distortion for the Pi Camera V2 standard lens?
Imaging	Given the spectral response of the cameras, is NDVI possible without filters? With filters?
Imaging, Image Processing, Mechanical	How precisely do the cameras need to be aligned? How do we align them? Do we align with hardware, software, or both?
Imaging, Embedded Systems	What is the best way to control/command the cameras capture timing?
Image Processing	What framerate is optimal for processing? For image quality? Where's the pareto frontier for framerate/resolution combinations vs processing?
Image Processing	How can image saving and processing operations be more efficient? More reliable?
Image Processing, Computer Vision	How much processing is reasonable to do in flight? How complex? Where's the pareto frontier for usefulness/complexity of operations vs processing capability?
Image Processing, Computer Vision	Can images be preprocessed in flight to make analysis/development on the ground easier?
Image Processing, Computer Vision, System Integration	Can auxiliary data (other sensor data) be combined with image data for useful for Computer Vision algorithms? Which metrics are needed?
Computer Vision	How can vegetated areas and vegetation density be estimated from visible RGB images?
Computer Vision, Imaging	What is the minimum pixel resolution where useful CV can be done? Max altitude?
Computer Vision	Can a vegetation density mapping model trained on NASA datasets be applied to HAB aerial images?
Computer Vision	Can roads and buildings be identified from HAB aerial images? Can this be done in flight?
Computer Vision	Is VNIR imaging (with Pi Camera NoIR, for example) useful on its own or is Visible RGB better for vegetation mapping? Are both required?
Embedded Systems	What is the minimum power needed for payload electronics to operate reliably under load?
Embedded Systems	How does the performance of single-board-computers, camera modules, and other electronics under load change with time? Temperature? Pressure? Power? Used storage space?
Embedded Systems, System Architecture	What is the most precise and reliable method of synchronizing image captures from multiple cameras?
Mechanical	What are the thermal characteristics of the payload electronics under load? Do they overheat in open air? In an insulated enclosure?
Mechanical	What is the best enclosure design for thermal stability/management? For vibrations? For alignment?
Image Processing, Embedded Systems, Software, Test	How can software be tested for functionality on development hardware? Flight hardware?
Image Processing, Embedded Systems, Software, Test	How can software be tested for benchmarking (power, reliability, performance over time)?
Image Processing, Embedded Systems, Software, Test	How can software be monitored during testing? Pre-flight? In-flight?
Image Processing, Embedded Systems, Software, Test	How can software be tuned or calibrated?

APPENDIX B
NOTIONAL PAYLOAD ARCHITECTURES

There are several topologies to address PLANTHAB image capture and processing needs as described in appendix A. This appendix suggests notional payload architecture topologies to be considered during development.

1) **2 SBCs, 1 camera each (like WUAP).** SBCs capture frames based on a master trigger or clock. The SBCs operate completely independently and are not connected.
2) **1 SBC controlling 2 cameras.** Two camera modules are commanded from a single SBC, processing is handled by a dedicated SBC that receives images from the upstream SBC.
3) **1 SBC, 1+ auxiliary boards.** An SBC handles images and processing but timing and frame captures are controlled by to a specialized FPGA or microcontroller daughter board for each camera. The SBC manages on the high level but processing and timing occurs on the daughter boards.

4) **2+ SBCs for each of 2 cameras.** Timing and capturing is handled by any of the topologies above. The processing workload is parallelized between multiple SBCs for each image stream so that processing signal chains can keep up with image capture rates.

The architecture selected for the PLANTHAB payload must balance cost, performance, complexity, and difficulty. While the objectives of PLANTHAB may be trivial to handle on more powerful or more specialized—and thus more expensive—hardware, the intent of the mission is to push the limits of low cost consumer level electronics [1].

APPENDIX C
SUGGESTED TASKS FOR PAYLOAD DEVELOPMENT

This section names some actionable tasks to address the essential questions of PLANTHAB described in section A.

TABLE IV
SUGGESTED TASKS

Discipline	Essential questions
Imaging	Measure camera module average pixel response vs wavelength, targeting 400nm-1100nm.
Imaging	Calculate spatial resolution (GSD) from pixel density, field of view, and altitude.
Imaging	Measure lens distortion by imaging a standard target and generate a distortion correction map.
Computer Vision	Develop NDVI and vegetation density estimation algorithms using NASA aerial photography (Visible and VNIR), and use NASA NDVI/EVI data as ground truth.
Computer Vision	Investigate the effectiveness of these algorithms at very low resolution images, and determine the minimum viable resolution.
Imaging/Image Processing/Mechanical	Develop the most efficient architecture for reliably differencing images from two cameras, including calibration, hardware alignment or mounting, and software alignment techniques.
Image Processing/Software	Develop reliable software for retrieving, saving and processing images.
Software	Develop dev tools for debugging, monitoring, benchmarking, and tuning payload systems.
Embedded Systems	Design a system architecture that reliably and efficiently captures synchronized images. (see section B)