UNIVERSITY OF COLORADO - BOULDER

DEPARTMENT OF AEROSPACE ENGINEERING SCIENCES

ASEN 4018

PROJECT DEFINITION DOCUMENT (PDD)

HERD-CU Phase 1D - TEAM SEVEN

Approvals

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III. Problem or Need

Reliable communications networks are a vital component in emergency response situations. The ability to communicate between multiple response services facilitates the execution of an emergency operation. Here in Boulder, establishing a communications network is often very difficult due to the mountainous terrain and poor lines of sight. The Boulder Emergency Squad (BES) has faced these issues many times in the past and have tasked TEAM SEVEN, along with Professor Mah, with tackling this challenge

The use of aircraft or other flying vehicles is a promising solution to this challenge. By placing an aircraft at altitude, the line of sight issues between response teams can be eliminated by using the aircraft as a temporary communications relay for a variety of missions. Specifically, TEAM SEVEN is responsible for the controls aspect of an Unmanned Aircraft System (UAS) for this exact application.

A successful design of HERD-CU Phase 1D would result in a full micro-controller and sensor suite solution which would allow users to effectively, quickly, and easily launch a fixed-wing autonomous aircraft and instruct it to survey an area, having it return autonomously at the end of the mission.

IV. Previous Work

The goal of HERD-CU Phase 1D is to improve the baseline endurance and operational capabilities of a small UAS by further optimizing HERD-CU Phase 1B's flight trajectory control system. The field of small remote aircraft has expanded dramatically with the invention of low power, low cost, and nanometer process nodes. This has allowed the micro-avionics field to expand into an accessible market for civilian use and development. The number of open source control platforms has greatly expanded, allowing for increasing levels of complexity to be easily developed and implemented across the space. The flight controller software we will be considering and most likely working with is ArduPilot. ArduPilot is an open source low and high level flight software developed by civilians for civilian use.

Path optimization has been a field of research for hundreds of years, with the Euler-Lagrange equation first describing the first order analytic solution to functional optimization problems. These sets of differential equations, $\frac{\partial \mathscr{L}}{\partial q_i} = \frac{d}{dt}\frac{\partial \mathscr{L}}{\partial \dot{q}_i}$, and its derivatives have helped solve a number of problems from calculating the brachistochrone, to describing quantum state of a system, to helping describe fighter jet dynamics. In the 19th century, mathematicians such as Riemann and Gauss developed a new formulation for describing space; combining linear algebra, geometry, and calculus. This developed into what is known today as differential geometry. Differential geometry surrounds developing a metric tensor to describe a surface, or manifold, and using that to help make calculations. By combining these two fields of mathematics, researchers are able to describe multivariate, complex problem spaces, and reliably find solutions.

In HERD-CU Phase 1B, team RALPHIE [1] tackled a similar problem to us, and developed a number of flight profiles to maximize flight time. Namely, these are a circling pattern, and a sweep pattern into the wind. We hope to build off these findings, and fine tune their results so they can be efficiently implemented with TEAM SEVEN's mission.

V. Specific Objectives

CATEGORY	LEVEL 1	LEVEL 2
Ease of Use	The Control System shall be operable by a single user with minimal set up time and no additional ground support.	The Control System shall enable the user to launch from a variety of difficult environments.
Energy Management	The Control System shall increase the endurance of an aircraft by 20% over a standard mission profile with constant altitude, constant airspeed, and orbit radius.	The Control System shall increase endurance for an aircraft by 30% over a standard mission profile with constant altitude, constant airspeed, and orbit radius.
Autonomous Flight	The Control System shall be capable of autonomously navigating to and maintaining a station, relying on operator-controlled take off and landing.	The Control System shall be capable of autonomous operator-launched take off and landing and be capable of autonomously navigating to and maintaining a station.

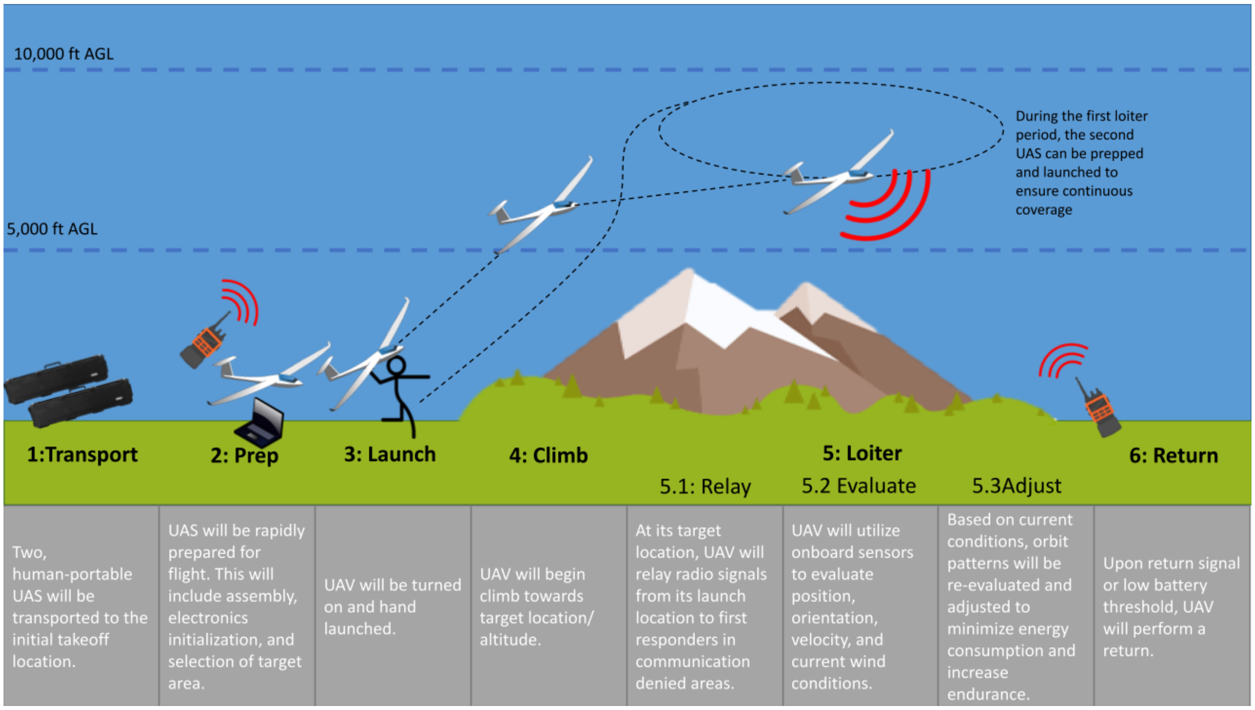
Operating Conditions	The Control System shall maintain a 100% Fully Mission Capable rate with cruise altitude winds of up to 30 mph and launch surface winds of 20 mph.	The Control System shall maintain an 80% Fully Mission Capable Rate under Instrument Meteorological Conditions.
Airframe Dependence	The Control System shall be airframe agnostic, able to operate with any airframe running supported energy and sensor packages.	The Control System shall support modifications to allow for varied energy and sensor packages.
Flight Boundaries	The Control System shall operate at an altitude between 5000-10000ft MSL with a max loiter deviation of 500ft, and have the ability maintain line of sight control with the operator while in autonomous flight.	The Control System shall provide sensor packages to identify, and capabilities to actively avoid obstacles.
Low Cost	The development cost of the Control System, including test platforms as well as System hardware, shall not exceed $4, 000.	The production unit cost of a full Control System package shall not exceed TBD.
Safety	The Control System shall include a manual override of autonomous control and comply with all relevant FAA requirements, as outlined in 14 CFR Part 107.	The Control System shall be capable of operating in trafficked airspace, with Automatic Dependent Surveillance-Broadcast (ADS-B) included in the System package.

VI. High Level Functional Requirements

#	**Functional Requirement**	**Rationale**	**Parent**	**Verification Method**
001	The total cost for full development of the UAS and a technology demonstrator prototype shall not exceed $4000 USD	To achieve our specific objective of Low Cost, the development and technology demonstrator prototype must be competitive in price with currently utilized drones to make the UAS more accessible and reproducible at scale.	Customer Provided	-
002	The UAS shall be fully operational in austere environments with minimal support or equipment and remain in a continual standby posture when unused	To provide a robust system to be utilized during emergency situations the control system must be adaptable to it's environment.	Customer Provided	Testing
003	The UAS shall autonomously manage aircraft trajectory based on energy state in order to improve flight endurance	With a heavy emphasis on prolonged endurance, aircraft energy must be optimized by the control system.	Customer Provided	Simulation/ Demonstration
004	The UAS shall be capable of receiving commands and transmitting telemetry to and from a controller	For safety purposes the UAS needs to have the ability to be controlled manually by an operator at any time.	Customer Provided	Analysis/ Demonstration
005	The UAS shall adhere to FAA regulations outlined in 14 CFR Part 107, SMALL UNMANNED AIRCRAFT SYSTEMS	In order to fly our UAS we must adhere to these FAA regulations.	Customer Provided	Analysis/ Integration
006	Flight operation shall only require a single operator with limited flight experience and will minimize the number of orbital swaps	Personnel are valuable assets during emergency situations and limiting the required operators to a single user allows emergency teams to most efficiently distribute their workforce and minimizing the number of orbital swaps limits the operator's workload.	Customer Provided	Analysis/ Demonstration

007	The controller software shall be completely open-source or team-developed and the hardware shall be available consumer off the shelf (COTS) products	This UAS is meant to be easily constructed and restricting software to open-source and parts to be COTS allows these aircraft to be manufactured by anyone.	Customer Provided	-

A. Mission CONOPS



Two, human-portable UAS will be transported to the initial takeoff location.

UAS will be rapidly prepared for flight. This will include assembly, electronics initialization, and selection of target area.

UAV will be turned on and hand launched.

UAV will begin climb towards target location/ altitude.

At its target location, UAV will relay radio signals from its launch location to first responders in communication denied areas.

UAV will utilize onboard sensors to evaluate position, orientation, velocity, and current wind conditions.

Based on current conditions, orbit patterns will be re-evaluated and adjusted to minimize energy consumption and increase endurance.

Upon return signal or low battery threshold, UAV will perform a return.

Fig. 1 Concept of Operations

VII. Critical Project Elements

Critical Project Element	Constraint Rationale	FR #
CPE1: Energy Management	The design will continuously update the flight path throughout the mission to improve endurance as well as manage subsystems to limit power consumption. This will be done by creating mathematical models to optimize the properties of aerodynamics and energy conservation.	003 006
CPE2: Ease of Use	When in an emergency or on a call, BES must be able to operate the system as quickly and efficiently as possible, especially during setup, launch, and recovery. Since training comes at a premium, creating a system that is intuitive must be a primary objective. This will mainly focus on the user interface, to ensure that a single operator can perform all their tasks. Additionally, an autonomous flight controller will enable minimally trained operators to effectively deploy the system.	002 003 006 007

CPE3: Flight Control	The control law and energy management designs must be implemented as a physical flight controller that will need to be configured and integrated to enable efficient and stable flight throughout the mission profile. In addition, it must be able to handle user flight inputs.	004 006
CPE4: Autonomous Flight	Since the aircraft will be fully autonomous during the loiter phase, the aircraft will require sensors to measure the aircraft's state and feed the data to flight software. The flight software will interpret this data, and send commands to the flight controller according to specified control laws.	002 003 006
CPE5: Safety and Regulation	In flying the UAS, safety is of utmost importance. As such we will rigorously test our models in order to verify that they are sound as well as precise. Furthermore, we will enable the operator to take over control of the UAS in order to make sure that in case of an emergency they have the ability to manage the situation. We will additionally comply with FAA regulations outlined in 14 CFR Part 107, SMALL UNMANNED AIRCRAFT SYSTEMS.	002 005
CPE6: Finances	In order to ensure the design is affordable and reproducible for as many emergency departments as possible, limiting costs will be a significant design consideration. The total design costs must also be within the project $4000 budget.	001 007

VIII. Subsystem Breakdown and Interdependencies

For successful operation of the UAS many subsystems will need to communicate between each other to operate seamlessly from the prospective of the end user. One major subsystem is the airframe and control surfaces themselves. This will be assembled and provided by the other two UAS teams, while the primary focus of TEAM SEVEN is a system agnostic flight control module with a corresponding base station and onboard sensor package. Likewise our system will be divided between the hardware and software on the aircraft, and the hardware and software located with the pilot on the ground station.

On the plane, our system will receive power from the Airframe's Electronic Speed Controller (ESC), and output controls through Servo pulse width modulation (PWM) signals. The corresponding sensor package will be able to determine: location, airspeed, attitude and accelerations of the airframe. The flight controller also needs a radio receiver for manual override from the pilot, and a receiver/transmitter to communicate system and waypoint information to and from the ground station.

In autonomous flight the flight controller will take state information determined by data from the sensor package, compare it to the path information sent from the ground station, and by using custom control laws focused on maximising aircraft efficiencies, will compute the controls needed to pilot the aircraft along the path. These controls will be passed to the ESC and servos through PWM signals, allowing the flight controller to rapidly adjust control surfaces and throttle position to maintain optimal flight.

In manual override mode, which can be engaged at any time by the pilot, they will have manual control of the airplane, but in such a mode we will still use the control laws to maximize stability and ease of flying by dynamically adjusting the control surface deflections using a mixer to combine the pilot's control inputs and the Flight Controllers control inputs. In this case the control laws are adjusted with the objective to keep the aircraft in steady, level, unaccelerated flight, as opposed to following a path.

The ground station will consist of the pilot's radio transmitter and a laptop for interacting with and visualizing the UAS's path and state information. This includes Battery level, Altitude, Heading, Velocity, and Location. The user will be able to path a route for the UAS to follow, by placing waypoints on a map, as well as use these waypoints to define search areas, points, or perimeters for the plane to continually fly through. This laptop will receive and send this information from a RX/TX station with an auxiliary battery, connected to the laptop through USB. The details and protocols TBD.

IX. Team Skills and Interests

Team Member(s)	Associated Skills/Interests	Critical Project Elements
Ty Banach	Matlab, Electronics Design and Manafacturing, Mathematical Modelling, project management	CPE1, CPE2, CPE3, CPE6
Maklen Estrada	Modeling and Simulation, Dynamics/Control, Electronics, UI/UX Software: MATLAB, R, C++	CPE1, CPE3, CPE4
Max Gerber	Electronics, Modeling and Simulation, Pilot, Software: MATLAB, C++, C, Python	CPE2, CPE3, CPE4, CPE6
Samuel Hatton	MATLAB, SOLIDWORKS, electronics soldering, GPS-RTK/CORS, project management, UX/UI, test engineering	CPE1, CPE4, CPE6
Alexander Hubben	Systems Engineering, Dynamics/Control, Signal Processing, C++, Radio Communications, System Integration	CPE1, CPE2, CPE3, CPE4, CPE6
Collin Hudson	Robotics, Dynamic Simulation, UX, Software Development, MATLAB, C, C++, Solidworks	CPE1, CPE2, CPE4, CPE6
Michael Miller	Software Test Engineering, Pilot, Avionics, Embedded Systems, Software: C, C++, Python, MATLAB	CPE3, CPE4, CPE5
Kevin Pipich	Embedded Systems, Serial Communications, UI Design, Software: Python, C++, Matlab	CPE2, CPE3, CPE4
Bennett Spengler	Control System Modeling and Simulation, Robotics, UI/UX, MATLAB	CPE1, CPE2, CPE4
Ethan Temby	AutoCAD/Drafting, Machine Learning/AI, UI/UX, Software: MATLAB, HTML/SCSS, JavaScript, AngularJS, Julia	CPE1, CPE2, CPE4
Alessandro Villain	Matlab, Soldering and Electronics Manufacturing, Algorithms and Math Methods,	CPE2, CPE3, CPE4
Jacob Wilson	Electronics Design and Manufacturing, Altium, MATLAB, C++, Test Engineering	CPE2, CPE3, CPE4

X. Resources

Critical Project Elements	Resource/Source
Flight Computer	ArduPilot
Sensor Suite	ArduPilot Affiliated Stores
Miscellaneous Sensors	SparkFun, Arduino, Digi-Key, Mouser
Test Airframe Platform	PILOT Resources, AES Machine Shop
Motor and Battery Suite	AES Electronics Shop
Safety and Regulations	FAA Standards and FAA Certified Pilot

XI. References

[1] "Rapid autonomous loiter program for highly increased endurance (Ralphie)," Ann and H.J. Smead Aerospace Engineering Sciences URL: https://www.colorado.edu/aerospace/academics/undergraduates/senior-design-projects/past-senior-projects/2021-2022/rapid-autonomous [cited 9/11/2022].