University of Colorado Denver

NIST Unmanned Aerial Systems Flight and Payload Challenge
Conceptual Design

Program	Public Safety Communications Research (PSCR) Program
Proposal Title	Lighter-Than-Air Drone
Proposer Organization	University of Colorado Denver
Technical Point of Contact (POC)	Name: Wendell H. Chun, Research Faculty Mailing Address: College of Engineering & Applied Science University of Colorado Denver Campus Box 110, P.O. Box 173364 Denver, CO 80217-3364 Telephone: 720-877-1184 Email: Wendell.Chun@ucdenver.edu
Administrative POC	Name: Annie Bennet, Dept. Administrator Mailing Address: College of Engineering & Applied Science University of Colorado Denver Campus Box 110, P.O. Box 173364 Denver, CO 80217-3364 Telephone: 303-315-7524 Email: ANNIE.BENNETT@ucdenver.edu
Award Instrument Requested	Award
Total Proposed Cost	Stage 1: $20,000 Stage 2: $10,000 Stage 3: $4,000
Other Team Members	Technical POC Name: Suraj P. Rawal Organization: Lockheed Martin Space Systems Organization Type: Industry Technical POC Name: Geoffrey L. Bland Organization: NASA Wallops Flight Facility Organization Type: Government Technical POC Name: Anthony Jacobs Organization: Quadquestions.com Organization Type: Commercial
Submittal Date	January 25, 2018

Abstract

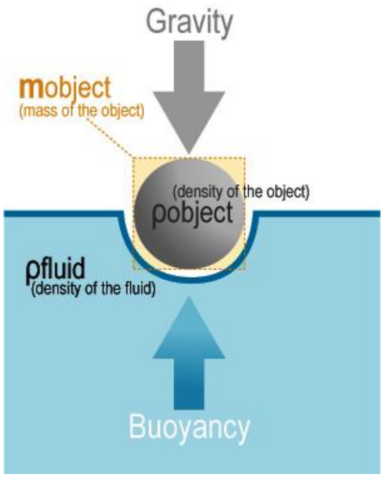
Today's quadcopters are battery powered with flight times ranging between 15 minutes and thirty minutes, with some models lasting for as long as 45 minutes. These aircraft have limited payload capability and as the weight of the payload increases, operational flight time are reduced dramatically. To change the current paradigm, the University of Colorado Denver (UC Denver) is proposing a hybrid lighter-than-air aircraft using buoyancy to stay afloat, and rotorcraft technology for propulsion to enhance ascent/descent and during translation. For example, the rotors are used for station-keeping when the payload is a communication repeater in support of firefighting activities or search & rescue operations, especially in the high altitudes of the Colorado outdoors. The rotors are tilted using a simple gimbal mechanism similar to those used on aerospace gyroscopes (yolk and cradle mechanism) to move the vehicle horizontally.

The buoyancy component is a helium or hydrogen balloon that could be filled on demand, and controlled through active ballast by adjusting the pressure within the balloon. The payload and avionics are packaged next to each other on the bottom of the airframe, and the vehicle is gravity stabilized. Station-keeping is a practical approach to hovering, but using less energy. The baseline is a battery power source with an option to add a gas powered RC engine to recharge the batteries on demand. To keep the drone lightweight, we are investigating the use of a multi-functional structural/wiring/avionics design for lightweight optimization. For manufacturing, our UC Denver students have hands-on experience in using the SolidWorks CAD package, MATLAB simulation and analysis package, and having access to 3D printing of structural elements such as for a quadcopter frame as from a previous UC Denver robotics class. The Qualcomm Snapdragon processor that we plan to use is equipped with a precision GPS receiver, and can support both autonomy and manual operations.

The team is uniquely qualified to design and produce the drone, and have plans to eventually commercialize this aircraft. We combine the best talents of select aerospace subject matter experts (SMEs) with engineering students during the design, development, and test phases of the project. And by teaming with a commercial drone company, we will have quick access to drone components and have an avenue to sell this aircraft world-wide to get the product quickly into the hands of the users. Our team believe in the Keep It Simple or KIS principle, and we will prioritize our effort by using a Risk Radar tool to reduce any uncertainties in the design.

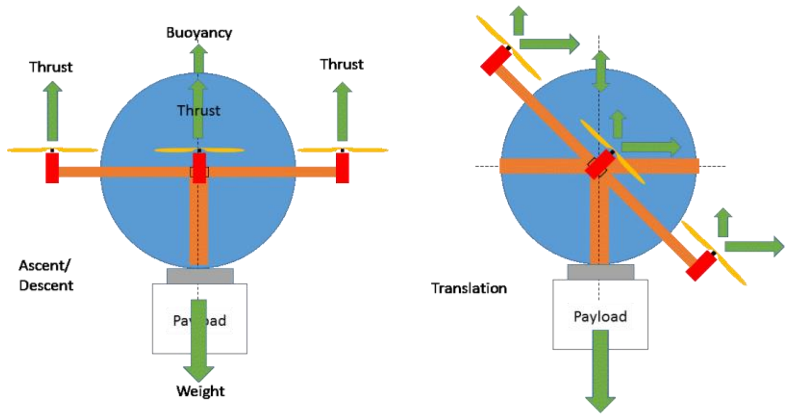
Project Description

Our core team is led by Prof. Chun, an expert in robotics, engineering design, and mechanism design/control at the University of Colorado Denver (UC Denver). He is supported by a materials and flexible solar energy expert from Lockheed Martin Space Systems Company (Dr. Rawal), and a drone expert (G. Bland) from Wallops Flight Facility, the lead center for dirigibles (lighter-than-air) at NASA. The fourth core member, A. Jacobs, is a former electrical engineering student at UC Denver who owns a state-of-the-art drone company (Quadquestions.com) with expertise in racing platforms. If this proposal is selected, we will have access to a class of electrical engineering students who are in a senior design class (EE4309) for this spring semester that aligns with the solicitation's Stage 2 and Stage 3 schedule. In order to align our effort to potential users in the state, we are coordinating our effort with the designated aerospace champion within the Colorado Office of Economic Development and International Trade (OEDIT).



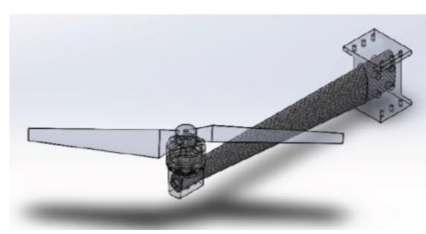
This project follows the classical design process, starting with the problem of maximizing flight time and payload for a hypothetical forest fire application in which the payload is a communication repeater (using commercial model RCA RPX8100 weighing 1.3 kg and measuring 56 mm x 170 mm x 165 mm as a baseline for analysis). This fits within the payload requirements of the 10 in. x 10 in. payload adapter. There is existing work on gasoline-powered quadcopters with the German Yearir drone (1 hour flight time), Nitro Stingray, Goliath Quadcopter, and the Heavy Lifting Quadcopter. However, gas-powered quadcopters tend to be larger and heavier than their electric counterparts. We follow the Keep it Simple (KIS) principle in design. Our approach is to use buoyancy with "lighter-than-air" technology to stay afloat (right figure), and supplement this capability with multi-rotor technology such as those found on quadcopters and hexcopters. Lockheed Martin Corp. has experience with lighter-than-air vehicles at our Akron, OH facility with large aerostats. Based on experience, our baseline is to use a 30-inch diameter to possibly a meter-diameter, observatory balloon. Dr. Rawal has a spare balloon available for immediate use. G. Bland's work at NASA in alternative platforms include tethered blimps and kites that provide valuable lessons learned, even though our platform will be tetherless. A balloon this size can stay afloat for potentially ten days or longer. Our approach is to keep the entire weight of the platform as light as possible, minimizing the number of components and by using aerospace techniques to lighten the aircraft's Master Equipment List (MEL).

The balloon will be assisted by drone quadcopter technology. Quadcopters are desirable for their simplicity in design and control. Opposing rotors use clockwise and counter-clockwise propellers for simple control of an aerial vehicle. Each of the rotors on the quad-copter produces both thrust and torque. Given that the front-left and rear-right motors both rotate counter-clockwise and the other two rotate clockwise, the net aerodynamic torque will be zero. Individual motors (typically AC motors for outdoor applications) are operated in a speed control mode. Quadquestions.com has a complete inventory of drone parts, and selected drone components will be available for quick prototyping. Team member A. Jacobs has designed, manufactured, and continue to sell all things drone-related. When our product reaches the market, we will use the Quadquestions.com internet shop to sell and deliver our lighter-than-air vehicles to emergency response organizations that will need this capability.

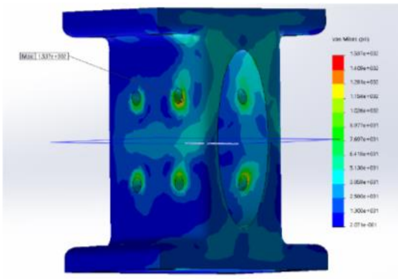


Following the classical engineering design process, we started with the problem, captured our requirements (both functional and non-functional) and design constraints (e.g. FAA rules such as 14 CFR Part 107 if our vehicle weighs less than 55 pounds, Cost, Schedule). The lighter-than-air concept is the result of brainstorming activities using innovation techniques such as mind mapping, six-hats, and SCAMPER to arrive at our conceptual design as shown in the above figure. We used a simple CONOPS to bridge operational scenarios with the design effort (e.g. inflate the balloon body and lift the drone into place in either a manual mode using a human operator with a radio transmitter, or in an autonomous mode using robotic behaviors, a state machine, or GPS waypoints).

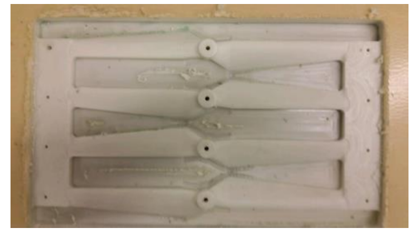
As part of our conceptual design, we developed an initial MEL, a preliminary weight budget, and an initial power profile based on the CONOPS. In parallel, we used a risk radar tool to understand any uncertainties in the design. It is important that we not confuse a risk with good design practices. For example, the meter diameter balloon is shown in the left figure, but we will also trade commercial balloons in the detail design option trade space. The trade study that has the highest priority is the drone's power source. Our preference is to use a battery-only solution. Quadquestions.com carries the Gens ace 4000mAh 11.1V 25C 3S1P Lithium Polymer Battery Pack with Deans plug. We have a design option to use multiple batteries as needed. Dr. Rawal has access to flexible solar cells that we can cover the upper balloon with, but this product has only an 11% efficiency. There are other multi-junction microcells that are less flexible with better efficiency at about 30%, but may not be available to us and may not conform to the balloon. As a backup, we can supplement our power subsystem with a small gasoline engine designed for RC aircraft with a remote electric starter. As we progress from conceptual design to detail design, we will trade our power subsystem options as we refine our requirements.



In a previous bridge inspection application, former UC Denver students designed, analyzed, and manufactured a custom quadcopter for a Senior Design project. In this example, students produced some structural arms that attached the propeller motor to its aircraft frame, shown to the right. This arm has an oval cross sectional shape with a taper along its length to compensate for larger moments near the vehicle's body. In this case, the arms were composed of FOAMULAR 250 polystyrene insulation foam, wrapped in 2 layers of carbon fiber with grain angles at 45 degrees to one another. The arm fits into an arm fixture that was designed using SolidWorks where we performed finite element analysis to determine von Mises stresses. The finite element analysis



took into account maximum lift, drag, and bending moments that can be factored into the analysis. The resultant stresses in the arm fixture fell within safe range of 3D printing the bracket in ABS plastic, which has a yield strength of 4500 psi. Even though our analysis indicated that this design was strong enough, we determined a redesign would further reduce this part's weight. This same team also designed, analyzed, and built custom quadcopter propellers for higher performance (shown to right).



The typical quadcopter propeller configuration allows the drone to rotate in place. To translate a normal quadcopter, it tilts its airframe and travels at an angle to separate its translation vector from its lift or vertical force vectors in order to move. Since the gravity vector points to the ground through the payload and balloon, we need a way to tilt the propeller plane. Our design uses a gimbal and frame mechanism to tilt the rotor plane. Prof. Chun has designed and built aerospace gimbals in the past as a mechanism engineer at Lockheed Martin Space Systems Company. To keep the mechanism's weight down, we plan on using impregnated bushings instead of bearings for rotating surfaces. We will use a simple stepper motor to tilt the rotor plane by counting steps or a small DC motor (pancake or gearhead) in position mode using a PID control loop. We will investigate the use of 3D printing to manufacture the gimbal frame as shown in the above figure with students at UC Denver. Prof. Chun also teaches the controls lab, using an electric DC servo motor with a tuned-PID controller with various non-linearities such as backlash or elastic elements. In the left figure, we depict a UC Denver student implementing a position control loop for a planar LIDAR sensor. The plan is to control the propellers in rate mode, while we control the gimbal in position mode.

For the flight controller, our previous drones have used a Pixhawk unit. This processor is adequate for most manual operations, but for autonomous mode and greater flexibility, we are baselining a Qualcomm Snapdragon processor. The Snapdragon (shown on the next page) is a highly sophisticated flight controller board which integrates features such as sensors (IMU, GPS, cameras, etc.), the main processor, power management systems, and memory all on one open source platform. Qualcomm pioneered Electronic Speed Control (ESC), a closed loop system that monitors and regulates motor speeds, ensuring safety and responsiveness. ESC is critical for reporting each motor's RPM to the flight controller, and allowing it to take corrective action if needed. For example when we are station-keeping, the flight controller receives rotation speed data from the ESC and could direct another motor to perform a counter-yaw rotation to control the drone's yaw and keep it stable. Current FAA rules dictate that the drone must operate below the 500 feet altitude and be no faster than 100 mph. We leverage Qualcomm's research on 4G LTE, who is optimizing LTE for safe drone operation in "real world" conditions such as this. And by accelerating 5G technology development, Qualcomm is supporting 5G specifications within 3GPP for deployments of mission-critical drone use cases such as firefighting or search & rescue. UC Denver senior Alex Grand has over a year's experience programing on the Snapdragon processor using tensor flow in order to demonstrate obstacle detection with machine vision. Incidentally, Prof. Chun has a spare Snapdragon processor available for immediate use.

We continue with the design process by continuing with the trade studies and analysis as the team moves from conceptual design towards detail design. There are still additional trades to be completed, such as to validate the quality of the GPS or if we need a separate altimeter. We will complete the design of a Flight Termination System and integrating the FHSS radio communication hardware with the vehicle. In parallel, we will continue risk reduction by developing a prototype aircraft to be demonstrated in Stage 2, and eventually in Stage 3.

Technical Outcome – The lighter-than-air drone that we are proposing represents a 500x improvement to flight time as compared to conventional drone technology, depending on the balloon's material and the amount of gas utilized. We understand that this platform will not be as maneuverable as the traditional drone due to the added drag of the balloon, and we will investigate the capability to inflate and deflate the balloon on demand that could aid aerodynamic agility. There are still several technical hurdles to overcome, but no high risk items. Forest fires will burn as long as both a fuel supply and oxygen exists. Average forest fires can last anywhere from weeks to months. It is conceivable that our drone will someday be comparable to the Lockheed Martin 74K Aerostat that has a duration of 30 days, but this would only be a long-term design goal. Our project still has to be proven, but would result in a significant improvement over commercially available technology, and will potentially result in a technical solution which makes considerable progress towards the challenge goals.

Team - The team consist of the University of Colorado Denver, Lockheed Martin Space Systems Company, Wallops Flight Facility who is a Part of the NASA Goddard Space Flight Center, and Quadcopters.com (a commercial quadcopter retailer). It is our intent to utilize University of Colorado Denver engineering students (mechanical, electrical, computer science) as appropriate.

Plan – We will judiciously manage resources such as budget (majority allocated to hardware), people, and time with a tight schedule that incorporates adequate margins or reserves. That is the reason why our team will start with existing parts to avoid long lead times on critical items. Our plan for Stage 2 is to aggressively manage the limited schedule by starting with a balloon and multi-rotor plane prototype without articulation for ascent and descent testing using batteries-only to demonstrate station-keeping. In a follow-on test, the lighter-than-air drone will be retrofitted with the gimbal (may be actuated at this point or at a slightly later date) for translational testing. The team will travel to NIST by May 14 for video testing and evaluation at the NIST Robotics Test facility. As part of Stage 2, we will support the hardware component reviews, provide UAS specifications for checkout, and complete a safety review. The lighter-than-air drone will be judged for minimum flight time and payload achievement (using the metrics of hours and pounds-mass for metrics). We plan to continuously improve the drone, adding features in an incremental manner until the live tests and evaluation at the Stage 3 competition, scheduled for May 20-24, 2018 at NIST. Similar to Stage 2, we will support the UAS specification and safety reviews. Assuming that we pass each stage gate, we will support the PSCR Annual Stakeholders Meeting in June 2018. This is one step closer to commercialization.

Resume Information for Key Members

Key Member	Qualifications	Relevant Experience	Commit-ment
Wendell H. Chun	Univ. of Colorado Denver/Univ. of Denver, Lecturer and Research Professor (39 years Engineering/33 years Lockheed Martin Space Systems Co.)	Robotics, Systems Engineering, Mechanism Design, Controls, Performance Testing, Drones, Mechatronics, Electrical Engineering, Design Theory	~ 80%
Suraj P. Rawal	Lockheed Martin Space Systems Co., Engineering Fellow (30 years)	Materials, Thermal Dynamics, Solar Panels, Manufacturing, Structural Design, Multi-functional Structures	~ 20%
Geoffrey L. Bland	NASA Goddard Space Flight Center - Aerospace Flight Systems, Manager and Research Engineer (39 years)	Unmanned Aerial Vehicles, Tethered Kites, System Design, Fabrication, Testing, Electric Propulsion, Miniaturization, Sensors, Blimps	~ 10%
Anthony Jacobs	CEO of Quadquestions.com (4 years)	Electrical Engineering, Drones, Unmanned Air Vehicle Design, Quadcopter Operations	~ 20%

Detailed Biographies:

1) Wendell H. Chun

He has 33 years of experience with Lockheed Martin Space Company in Denver, Colorado, performing a wide and diverse range of engineering disciplines from mechanical engineering, electrical engineering, and systems engineering. Wendell is currently on the faculty at the University of Denver since 2003, teaching both undergraduate and graduate classes in robotics, design, innovation, and entrepreneurship. He is also lecturer and research professor at the University of Colorado Denver since 2014, teaching engineering design, controls lab, and robotics. Having worked extensively in the robotics field for over 35 years, he has been a member of the following world-leading robot research and development projects at the former Martin Marietta and now Lockheed Martin: Autonomous Land Vehicle, Intelligent Task Automation, Unmanned Ground Vehicle Demo II, Walking Beam (an alternate Mars Rover with legs), Automated Highway System (self-driving car), Flight Telerobotic Servicer (space humanoid robot), SuperBot (polymorphic robot), and the Unmanned Ground Combat Vehicle (advanced mobility platform). Wendell Chun was the Vehicle Systems Management Architect on the Orion Crew Exploration Vehicle (CEV) program (a replacement for the US Space Shuttle), having responsibility for automation & autonomy, health & status, fault detection & isolation, mission planning, and resource management technologies. In his last assignment at Lockheed Martin, he supported NASA Goddard Space Flight Center on a robotic satellite demonstration and a future GEO satellite servicing robot. Since leaving Lockheed Martin, he has worked on industrial work cells using robots and mechatronic projects at Adaptive Innovation Corp. (Lakewood, CO), Smart Motion Robotics (Sycamore, IL), and Swisslog, a KUKA robotics company (Denver, CO). He is currently a senior advisor to the Office of Environmental Management, Department of Energy, in its effort to include robotics as a promising new technology for maintenance and cleanup of nuclear waste.

Wendell Chun is a former editor/chairman of the SPIE Mobile Robot conferences (1985 – 1995), and a Board of Trustee at the Association of Unmanned Vehicle Systems International (AUVSI), the largest organization in the World dedicated to all unmanned vehicles (1996-1999). He is a founding member of the AIAA Unmanned Systems Program Committee, who represents and serves the broad interests of the unmanned & robotic systems community, encompassing aerial (UAS), space (robotic), ground (UGV), surface water (USV), underwater (UUV), and other unmanned and robotic systems, their components, and their myriad of applications. He is a member of UAS Colorado, an organization committed to promoting and improving the aerospace industry in Colorado, particularly supporting the safe integration and use of unmanned aircraft systems throughout the state. His other activities include supporting the National Science Foundation as a reviewer, a former reviewer of SBIR/STTR proposals for the US government, and a reviewer of proposals for NASA Headquarters. He holds over ten patents and over sixty publications, and was featured on the History Channel Modern Marvel's episode on Remotely Operated Vehicles (2000). His personal interest include research in autonomy, artificial intelligence, complexity theory, and innovative engineering design techniques.

2) Suraj P. Rawal, PhD

Dr. Suraj Rawal is the Technical Fellow in the Advanced Technology Center, Lockheed Martin Space Systems Company. Dr. Rawal received his B. Tech. at Indian Institute of Technology, Kanpur, India; and PhD at Brown Univ., RI in Materials Science and Engineering. He has over 30 years of experience in the advanced materials and structures technologies. He has been program manager and principal investigator of several contract research and development (CR&D) programs including thermal protection materials and structures, advanced aeroshell technologies, and additive manufacturing.

Dr. Rawal has successfully transitioned several components related to thermal management, advanced composites, nanocomposites, additive manufacturing, and multifunctional structures technologies into DoD/NASA spacecraft. He represents Lockheed Martin in the advisory panels of the Mechanical Engineering Department of Colorado State University, University of Denver, and University of Colorado (Boulder). Currently, he is the Vice-chair at Rocky Mountains SAMPE chapter. Dr. Rawal has received numerous Lockheed Martin awards, including inventor, author, and technical achievement. He holds nine patents and four trade secrets in the areas of thermal management, lightweight ablators, and multifunctional structures technology. Dr. Rawal has also authored chapters entitled, 'Composites for Space Applications', and 'Multifunctional Materials and Structures' in the 'Comprehensive Composite Materials' handbook edited by A. Kelly and Carl Zweben.

3) Geoffrey L. Bland

Geoff Bland began development of small unmanned aircraft and instrument systems for Earth science research since 1993. His activities have included platform and systems design, fabrication and test, including several pioneering unmanned aircraft utilizing then-unique electric propulsion. He has led the development of unique instrument packages that have focused on miniaturization, and several of his remote sensing and in-situ sensor systems have been, or will be flown, on NASA and commercially provided platforms in support of several collaborative research projects.

Bland is also active in the development of alternative platforms such as this project, and associated instrumentation. Tethered blimps and kites have been incorporated in research and educational activities, and Bland is actively engaged in collaborative activities in a growing community of users and system developers. Education is also a core focus of Bland's work, including the recent introduction of a series of novel aquatic surface craft for hands-on training in technology, operations, and scientific investigation. On the AREN Cooperative Agreement education project, Bland focused on introducing NASA's science activities using novel technologies and hands-on experiences. For example, kite-borne instrumentation is used to simulate satellite and aircraft based observations, and robotic instrumented surface crafts are used to introduce new engineering concepts and develop mission operational skills.

As another example, the Volcanic Retrievals Emissions Experiment was a field experiment focused on sensor system development as compared to the ASTER observations at Kilauea HI, with instrumented flights of NASA's Dragon Eye unmanned aircraft and kites. As a Small Business Innovation Research (SBIR) program sub-topic manager for Airborne Measurement Systems, Surface and Sub-Surface Measurement Systems, and Unmanned Aircraft and Sounding Rocket Technologies, Bland works closely with numerous NASA centers and companies. University collaborations are also a key component in the effort to bring new capabilities to in-situ and remote sensing research.

4) Anthony Jacobs

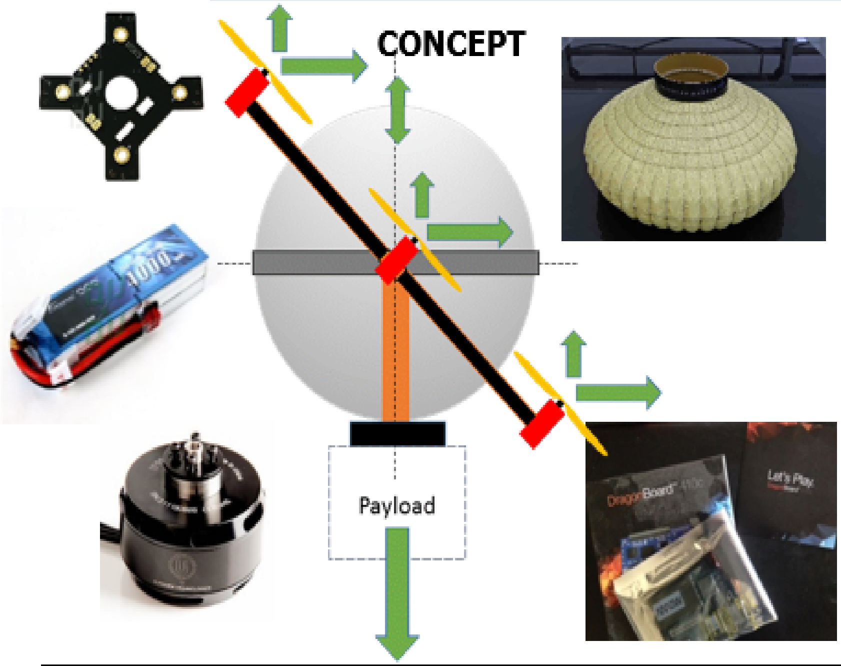
Jacobs is a former electrical engineering student at the University of Colorado Denver and an entrepreneur. While in college, he founded Quadquestions.com with tremendous success. He loves quadcopters, and his company sponsors race events, develop products, and work closely with pilots around the world. His mission is to simplify multi-rotors, and his company is constantly asked when flying, what his machines are, where to get one, and how to build one. He works hard to source the newest, most forward thinking designs in Racing Quads to make them available to his customers. He and his company also develop products that help people build quadcopters.

Summary Slide

Lighter-than-Air Drone

University of Colorado Denver; POC: Wendell H Chun

CONCEPT



APPROACH

Today's quadcopters have short battery operational times. Drones also have limited payload capability and as the weight of the payload increases, operational flight times are reduced dramatically. To change the current paradigm, the University of Colorado Denver' and its Team is proposing a hybrid lighter-than-air aircraft using buoyancy to stay afloat, and rotorcraft technology for propulsion to enhance ascent/descent and during translation. Instead of hovering, this new drone will station-keep.

IMPACT

The impact is a revolutionary new drone that promises to be a 500x improvement to flight time as compared to conventional drone technology when carrying a payload such as a communication repeater to support firefighter radios during forest fires. The goal is to make this vehicle available on the commercial market to all humanitarian and emergency response missions, e.g. firefighting and search & rescue efforts. This vehicle could add meaning to the notion of "perch and stare" in surveillance and security applications.

TEAM

LOCKHEED MARTIN

QuadQuestions.com

NASA Wallops Flight Facility GSFC WFF

College of Engineering and Applied Science
UNIVERSITY OF COLORADO DENVER | ANSCHUTZ MEDICAL CAMPUS