Autonomous UAVs as Highly Efficient Seed Spreading Robots

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Introduction

With global temperatures in 2018 1.5F above the previous mean measured from 1915 to 1980[1], it is no secret that climate change is a rapidly developing problem threatening our way of life. Carbon emissions are a significant factor in global warming, as carbon gases blanket our atmosphere, trapping solar heat that would otherwise be radiated into space.[2] A large contributor to carbon emissions is the agricultural sector of the U.S., which makes up a total of 9.9%[3] of total carbon emissions in our country. With agriculture becoming less and less small farms and more large plantations governed by heavy machinery with the average U.S. farm size at 443 acres in 2018[4], there is much space to reform these heavy and inefficient machines. One efficient solution to this problem is to replace seed spreading and gas powered fertilizer spreaders with unmanned aerial vehicles which spread seeds and map farmland to verify equal growth on a large field. Fixed Wing UAVs are best suited for this problem because their payload capacity allows for easy transportation of seeds, fertilizer and other spreadable farming materials. A high cruising speed allows a UAV to traverse one of these farms in just over a day, with average distance intervals of 15 inches, the recommended width of a wheat row[5]. At this same cruising speed, a UAV could map the entire farm of this size in 30-45 minutes. To conserve manpower and minimize pathing

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1 https://climate.nasa.gov/news/2865/a-degree-of-concern-why-global-temperatures-matter/

2 https://www.ucsusa.org/resources/global-warming-faq#:~:text=Global%20warming%20is%20caused%20primarily,be%20radiated%20out%20into%20space.

3 https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#:~:text=In%202018%2C%20greenhouse%20gas%20emissions,by%2010.1%20percent%20since%201990.

4 https://www.statista.com/statistics/196106/average-size-of-farms-in-the-us-since-2000/#:~:text=Average%20size%20of%20farms%20in%20the%20U.S.%202000%2D2019&text=The%20average%20size%20of%20farms,from%20418%20acres%20in%202007.

5 http://www.mafg.net/Files/Wheat%20Row%20SpacingHyIWtH.pdf

inaccuracy, an autonomous flight system can be implemented. An autopilot system will create a path for the UAV to map the field and drop payloads while avoiding obstacles in real-time and preset boundaries. To simulate this mission, a UAV will complete the AUVSI SUAS 2021 competition. The payload is not seeds; it is a Unmanned Ground Vehicle, which allows for ground support to flying missions. Completion of the AUVSI SUAS course with complete autonomy indicates a UAV of level 5 autonomous action, the highest level possible. With level 5 autonomy, the UAV can complete its mission with no contact to ground station or any human intervention[6]. A UAV of this level will save farmers thousands of dollars, and save our environment from the abundance of carbon emissions that agriculture currently produces.

1. Systems Engineering Approach

1.1. **Mission Demonstration Analysis** - An analysis of the Mission Demonstration requirements was necessary for development of optimal UAV, UGV, Imaging, Obstacle Avoidance, Object Detection, Localization, Classification (ODCL), Control, and Autopilot Systems. See Table 1. The Mission Demonstration requires the successful execution of a variety of tasks. To navigate these outlined tasks, a table was created to delineate relative significance of each task. Significance is indicated by two variables: attainability and point value, where an attainable task is defined as one most likely to be completed. Tasks with low point values and low attainability are least significant, and tasks with high point values and high attainability are most significant.

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6 https://www.govinfo.gov/content/pkg/GOVPUB-C13-cbc9faa25f6d651e046c9df607d40d59/pdf/GOVPUB-C13-cbc9faa25f6d651e046c9df607d40d59.0.pdf

Table 1

Mission Task	**Mission Requirements**	**Necessary System**
I. Timeline 10% **A. Mission Time 80%** **B. Timeout 20%**	❏ Fly 4 mi, image 250,000 m^2, drop payloads, process images within 40 min ❏ Execute mission without timeouts	❏ UAV with reliable connection, flying health, and air time ❏ Reliable hardware and software for mission execution
I. Operational Excellence 10%	❏ Professional communication and conduct	❏ Pre-flight safety checklist, professional and safe habits
I. Obstacle Avoidance 20%	❏ Avoid static obstacles and upload telemetry at 1Hz	❏ Path planning with obstacle avoidance implemented
I. Object Detection Classification Localization 20% **A. Characteristics 20%** **B. Geolocation 30%** **C. Actionable 30%** **D. Autonomy 30%**	❏ Recognize ground targets ❏ Record geolocation ❏ Transmit object to GCS ❏ Transmit without GCS information request	❏ Software detects images and saves actionable information ❏ Software stores object and geolocation ❏ System links to communication to plane during flight ❏ Imaging system requires no prompt from GCS
I. Air Drop 20% **A. Drop accuracy 50%** **B. Drive to location 50%**	❏ Deliver UGV and payload to geolocation ❏ Drive to destination, with error of 10ft	❏ Gentle drop mechanism ❏ UGV lands in drivable state and contains autopilot and GPS
I. Autonomous Flight 20% **A. AutonomousFlight 40%** **B. Waypoint Capture 10%** **C. Waypoint Accuracy 50%**	❏ Avoid manual takeovers and crashes ❏ Autoflight for 3 min ❏ Fly within 100ft of 4mi waypoints	❏ Reliable Autopilot and airframe ❏ Airframe with sufficient range ❏ Precise and accurate GPS

1.2. **Design Rationale** - Tables 1 were employed to determine the optimal UAV, UGV, Imaging, Obstacle Avoidance, Object Detection, Localization, Classification (ODCL), Control, and Autopilot systems.

1.2.1. **UAV System Rationale** - To complete the mission with high accuracy and allow for completion of each task, Obstacle Avoidance, ODCL, Mapping, Payload, four airframe designs were considered for the UAV System. Each design varied in assembly time, flight speed, fuselage volume, lift, thrust, and stability control. With each of these constraints in mind, the MFD Crosswind was selected. The Crosswind is quick to assemble and rebuild, which is integral in our testing.The MFD Crosswind boasts a long wingspan of 1.9 meters, making it ideal for stable flight with a high cruising speed. The MFD Crosswind also has an abundance of usable volume in its fuselage for comfortable storage of each component for our UAV, UGV, Imaging, Obstacle Avoidance, Object Detection, Localization, Classification (ODCL), Control, and Autopilot systems.

1.2.2. **Autopilot System Rationale** - The Autopilot System controls the continued trajectory of our UAV without support from manual human operators or Ground Control System (GCS). However, our Autopilot System does not replace human operators; Safety Pilots remain on standby throughout the duration of the flight in the case of Autopilot System failure. The Autopilot System consists of two main parts: a flight control board and its firmware. A flight control board is the “brain” of the UAV, as it contains a variety of sensors such as ACC (accelerometer), GYRO (gyroscope), and BARO (barometric pressure). The flight control board's firmware is what accepts sensor input and outputs flight information. As outlined by Table 2, an Autopilot System with capabilities autonomous flight control, GPS link, GYRO, ACC, Compass, Telemetry, and bus for I2C and CAN communication was necessary. A controller which satisfies each of these requirements is a Pixhawk Cube Orange board with ArduPilot firmware. ArduPilot runs in real-time, on top of a ChibiOS, a small RTOS. ArduPilot is a mature firmware, and its RTOS makes efficient use of the flight control board's small processors resulting in increased stability during control loops. ArduPilot is a superior alternative to ROSPlane, as high customization benefits are outweighed by its low developer support and bug-prone environment. PX4 firmware is another popular alternative to ArduPilot.

1.2.3. **Imaging System** - The Imaging System is responsible for input for mapping and ODCL capabilities. For mapping, the imaging system is responsible for capturing images of the entire mission location within the mission boundaries. The imaging system also provides image input for ground level objects to be analyzed for the ODCL requirement. Two separate tasks require two separate cameras. An airframe cruising altitude between 150 and 750ft requires a high resolution camera for recognizing objects, whereas a low resolution camera saves post processing time and can recognize changes in color on a 1ft by 1ft object from cruising altitude. To detect objects, a low latency and low quality monoscopic camera, the Caddx Nebula Pro was selected. The Caddx Nebula Pro records 120fps at 720p, making it optimal for a fast-cruising plane to have a reliable image of the ground and objects on the ground. To take high resolution images, a Sony A6000 was selected.

1.2.4. **UGV System** - The UGV System requirements indicate the UGV will be dropped or lowered from the UAV in-air to the ground. When dropped, the UGV must land precisely and accurately in the specified location avoiding breakage during its descent and landing. A fixed wing design allows for a smooth landing of the UGV. A viable UGV must be dropped from a height of at least 150 ft. Such a drop height requires a parachute to smooth the landing. Attached to the parachute is a UGV. The UGV is a modified LaTrax Teton, capable of carrying the mission specific payload of 16floz. The Teton was selected due to its reliable suspension and powerful gear ratio. Its shaft driven 4WD drive system and large wheelbase allows for stable traversing of rough terrain, like high or wet grass.

2. Systems Design

2.1. UAV System

2.1.1. Airframe - As rapid and frequent testing is a necessity, the UAV Airframe selected was the MFD Nimbus Pro, also known as the MFD Crosswind. This plane is made entirely of foam, and is simple to assemble. This makes the plane optimal for testing, as crashes are anticipated. The body is sturdy and made completely of polystyrene with carbon fiber spars which support the wings as well as the fuselage. The front camera bay is supported by a ⅛ inch thick plywood fortification, which is useful as batteries are likely to be stored there throughout the flight. The battery is connected to a series of other components in the plane by XT90 connectors. XT90 connectors allow for quick wing replacement in the incident of a crash. To find a desirable lift-to-drag ratio, flight software was used to ensure low stalling risk.

Steady level flight of the MFD Crosswind is difficult to achieve as the angle of incidence in the tail is zero. Significant up elevator is required to keep the Crosswind upright to mitigate this angle of incidence. The battery storage in the front of the plane allows for the center of gravity to be placed at the wing spars, which is the best place as the battery is the heaviest object of the plane. An optimal center of gravity will ensure total steady flight without risk of common aircraft drag and airflow issues like porpoising and stalling. To find the best center of gravity, the point at which the sum of the longitudinal pitching moments equal zero was considered. To maximize lift-to-drag ratio while minimizing pitching moments to zero, a center of gravity at 6.2 cm aft the leading edge of the wing was optimal.

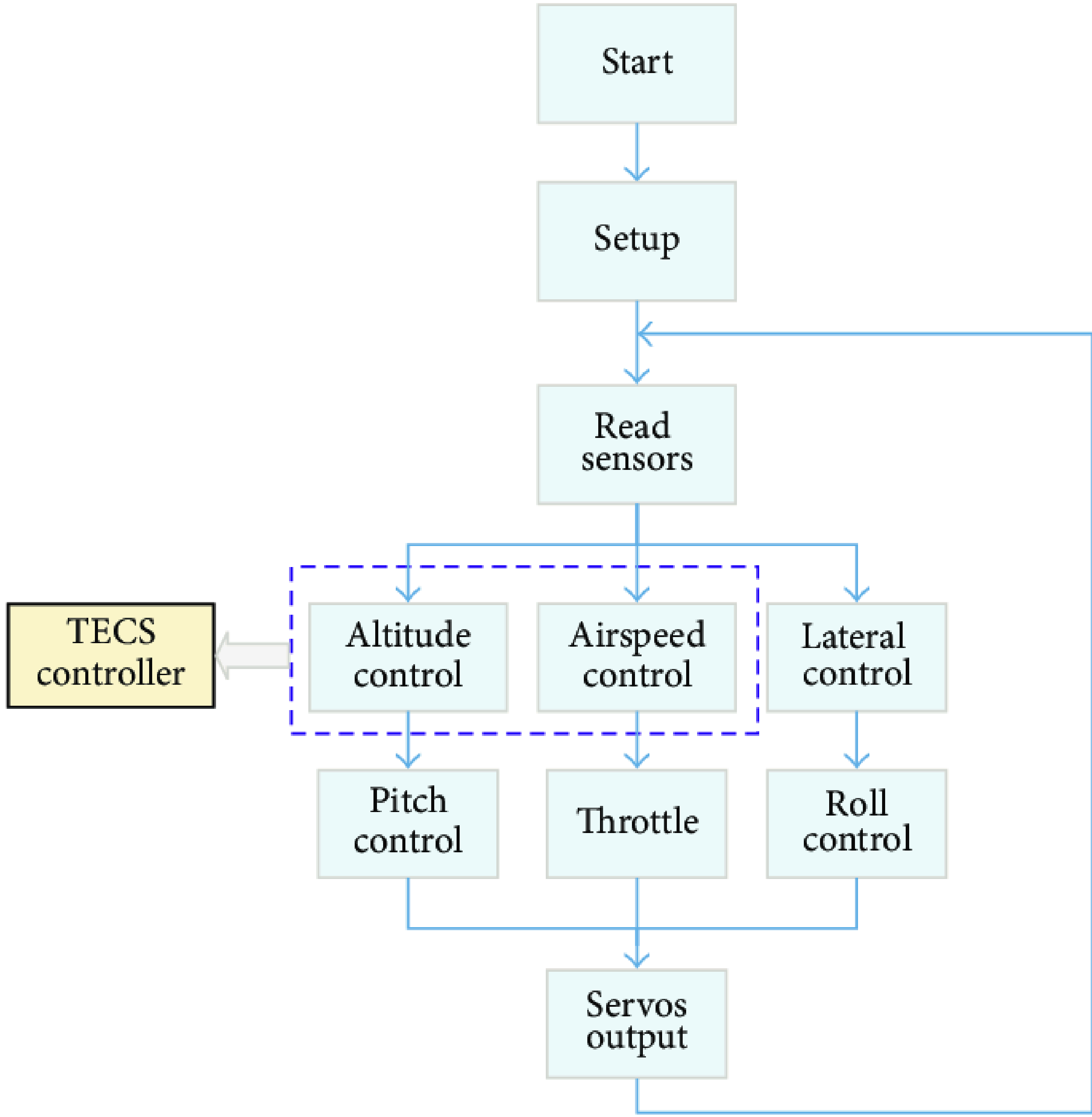
For propulsion of the airframe, two SunnySky 800Kv 2820 motors were implemented. A motor of this size and kilovoltage was selected based on its extremely efficient performance as combined with the correctly pitched propeller and a six cell lithium polymer battery of 6000mAh Using propeller performance data published by UIUC, the optimal propeller was GWS Slowflyer 8x6.

A Hobbywing Skywalker 80A ESC was selected to handle each of the motors. A 800Kv motor with a 6 pitch propeller draw close to 30A at cruising speed, and if the plane accelerates a lot in a short amount of time, the ESC may experience up to 65A draw as calculated by (Watts) = K X Pitch X RPM^3 X Diameter^4 X 5.33 X 10^-15 to an EPC 4.1 x 4.1 propeller and this engine with 4300Kv, watts = 0.7 * 4.1 * (4300kv*11.1v = RPM)^3 * (4.1)^4 * 5.33 * 10^-15 = 470.022703041 watts, and 62 amps. Counting efficiency loss and other marginal factors, the amperage draw may be between 2 amps above or below this estimate.

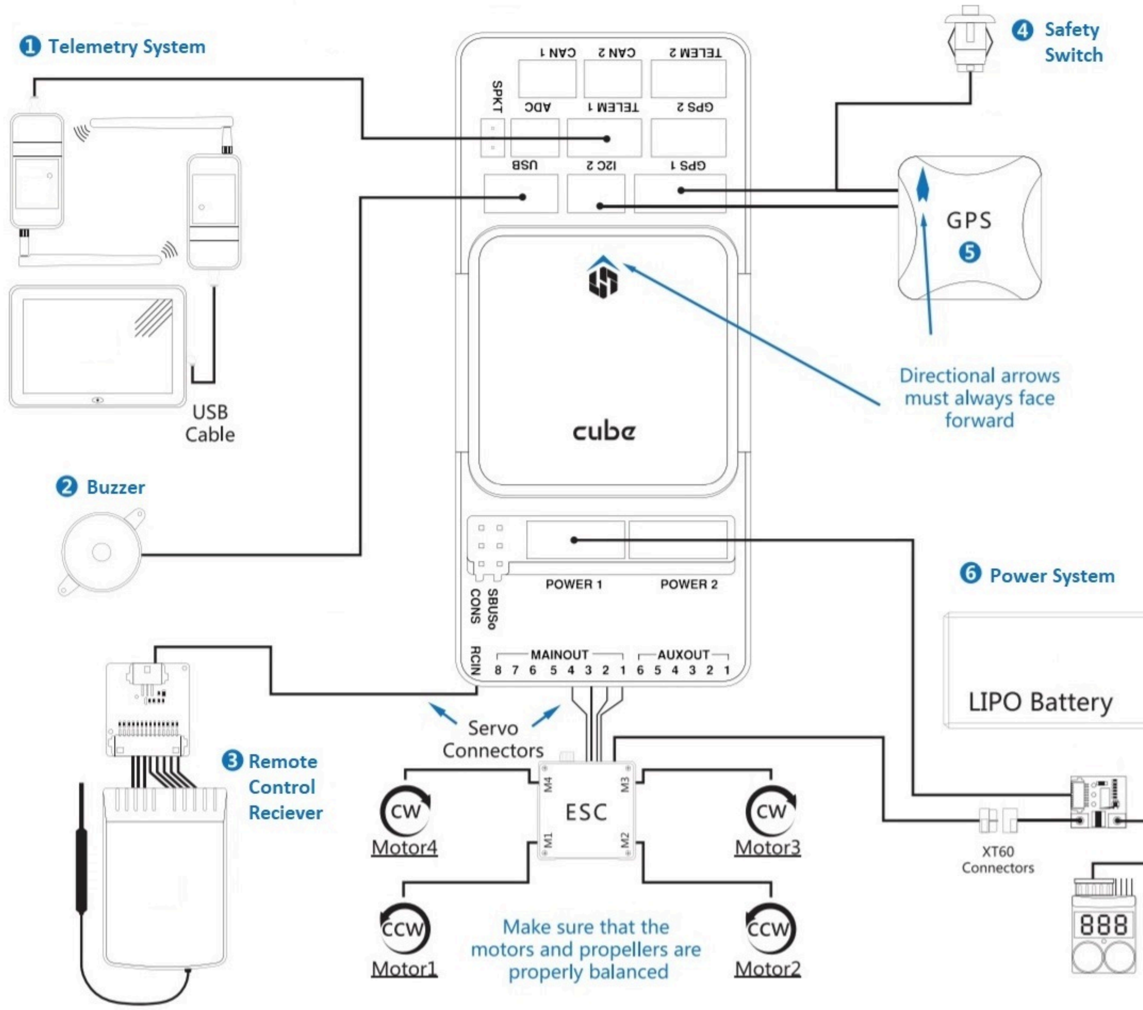
Model Nimbus Pro by My Fly Dream
Material Expanded Polystyrene
Wing Span 1.9 m
Wing Area 0.473 m2
Length 1.283 m
Gross Weight 5.2 kg
Tail Incidence 7.5 deg
Motor (× 2) Rimfire .15 1200 kV
Propeller (× 2) GWS Slow Flyer 8×6

2.1.2.

2.2. Autopilot System - A PX4 Cube Orange with ArduPlane 4.0.3 firmware loaded and 4.0.0 ArduPlane bootloader was selected. The ArduPlane flow is described in figure 2 below.



The ArduPlane autopilot uses a variety of sensors around the plane to compute the optimal flightpath. The autopilot hardware is the PX4 Cube Orange, through which the sensors are inputted to the ArduPlane flight algorithm. The Cube has I2C and CAN bus protocols which allow the user to plug in Telemetry, GPS, LED, Buzzer, ADC, USB Micro 3 as well as power rails for Servo and ESC connectors.



The autopilot determines vital factors, such as airspeed, 3D flight course, flight tasks, and flight control. The autopilot attempts to follow the 3D flight course which is preprogrammed through the CLI at ground control. The flight course can be updated mid-flight. The 3D flight course is programmed using a waypoint system. A pair of GPS coordinates, altitude in feet above ground station (also known as the “home” or “takeoff” point by the autopilot system), and the desired radial path around the waypoint are inputted, and this consists of one waypoint. A map of waypoints is stored in an array and executed by the autopilot system. The autopilot system measures airspeed through an external sensor called a pitot tube. Flight tasks are also controlled by the autopilot and its assistant computer, the Raspberry Pi 3B+. This RB3 processes the task in ROS and executes; our flight task is a payload drop at a certain waypoint. At this waypoint, the plane will drop the payload while maintaining flight course. Finally, flight control is achieved by a variety of systems controllers, but most influenced by a PID controller. The PID controller creates a gyroscopic effect to assist the plane in avoiding mid-air disturbances like heavy wind gusts or vibration. Any noise in the plane's system environment is mitigated by this controller.

2.3. Imaging System - An imaging system able to produce high resolution images at far distances of altitudes from 150ft-750ft was needed. A component to stabilize the camera during flight was also required, as vibration noise is amplified as the camera zoom increases. For high resolution images, a Sony A6000 camera was selected. A gimbal controlled the Sony A6000 in the UAV Crosswind airframe's camera bay. The gimbal mitigated all vibration through a gyroscopic controller similar to the PID Controller in the PX4 Cube Orange Autopilot. The Sony A6000 is stock equipped with a 16-50mm lens and 24 MP sensor. It communicates over a USB 2.0 interface. As the UAV system searches for its flight path, the Sony A6000 takes images and sends them via MAVLink to the GCS. This constant streaming reduces post processing time. Autonomous object detection, classification, and localization utilizes this camera as well as the mapping function.

2.4. UGV System

2.4.1. Frame Design - The LaTrax Teton is the frame for our UGV System. The Teton can withstand large obstacles like stones and high grass, both of which may appear in the competition field. The advanced shock system of the Teton allows it to sustain a large amount of impact on its wheels without breaking the suspension, which is integral, as it will be dropped out of a plane from above 150ft at least. If the parachute or tether release mechanism fails, it needs to sustain such gravitational acceleration without breaking. The Teton's large wheelbase and freestyle purpose allows the Teton to flip back right side up if upon its descent it falls to its back.

2.4.2.

2.4.3. Power and Propulsion - The Teton is powered by a shaft drive 4WD. Its motors are powered by a six cell Nickel Metal Hydride battery, and are controlled by 25A ESCs. Its 4WD mechanism and serrated tire structure allows for a quick escape of rough terrain with low friction constant.

2.5. Obstacle Avoidance

2.5.1. Pathfinding Algorithm - The competition presents obstacles in the form of preplanned static obstacles and non planned dynamic obstacles. Non planned dynamic obstacles require a vision-based obstacle avoidance system. Preplanned static obstacles require a non vision based obstacle avoidance system which relies on an Interoperability system to stream realtime obstacles and their geolocation to the pathfinding system. This pathfinding system receives telemetry signals from the ground station via MAVLink radio, and processes the optimal path on a RB3 assistant computer during the flight. A pseudocode interpretation of our pathfinding algorithm follows.

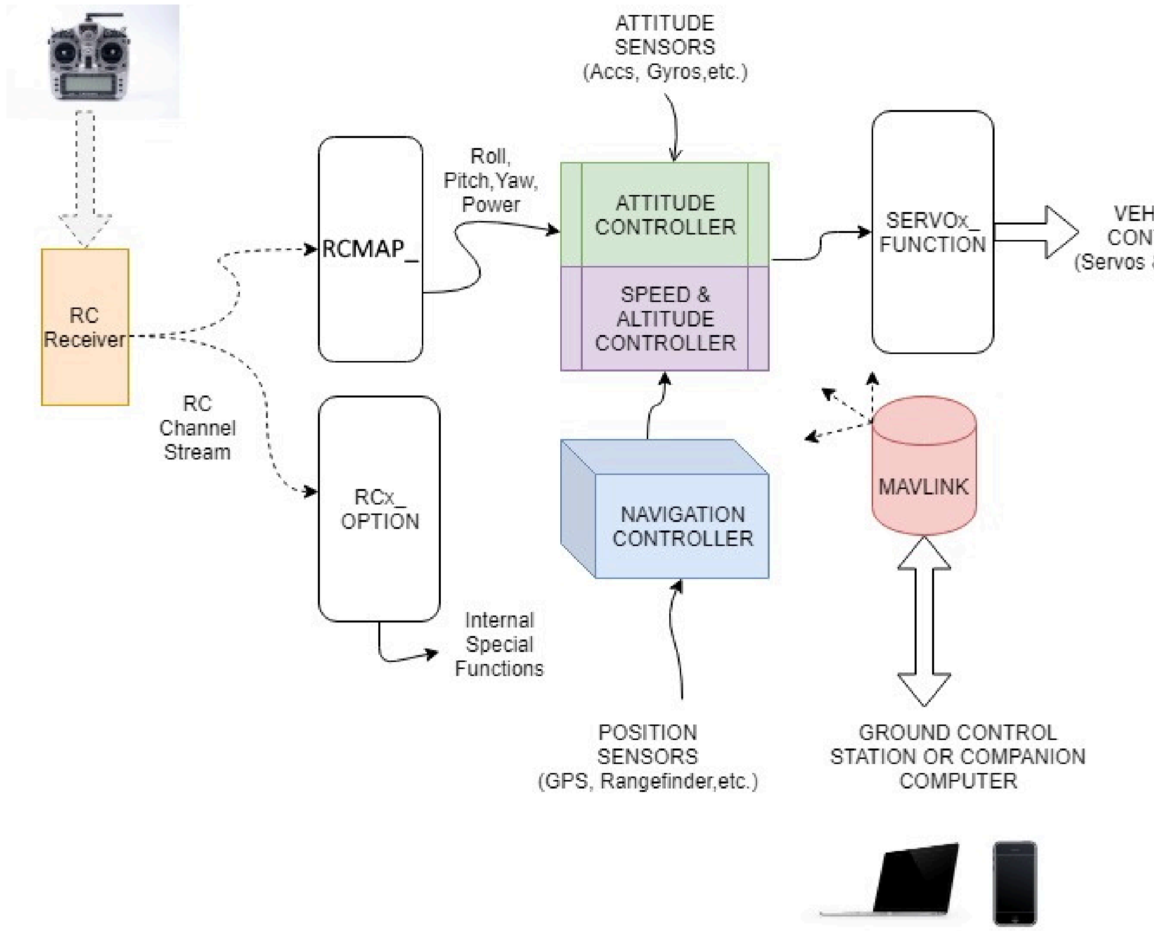
```
Input: Obastacles O, Boundaries B, start point ps, end
point pe, node distance D
Output: Waypoint Path W
successful paths count = 0
Initialize RRT graph as T = {ps}
while count < 5 do
p ← generateRandomNode(B)
i ← findClosestNode(B)
Find segment in direction of P:
pl ← findPath(p, i, D)
if flyablePath(T, i, pl) then
T.append(pl)
end if
if flyablePath(T, pl
, pe) then
mark pl as a complete path
count+ = 1
end if
newP ← P with length < SegLength
T.append(nodee)
end while
paths ← smoothCompletePaths(T)
W ← findShortestCompletePath(paths)
```

2.6. Object Detection, Classification, Localization

2.6.1. Auto Vision - The ground object is a colored square with a character inside the borders of the square. The square is 1ft by 1ft, and the character is lettered one inch thick. The square, the ground, and the character are different colors. The UAV will detect, localize, and classify these ground objects autonomously without assistance from ground control. A high frequency camera was employed to detect when an object lay on the ground beneath the camera. When the camera detected an object, the Sony A6000 activated and zoomed in on the area at which the object lay on the ground. Following, the GPS would record and store the geolocation of the object. The geolocation of the object is determined by the airspeed of the UAV as well as the flight course and time. The UAV can easily localize the ground object as it considers that it is however far along the flight path. The object must be classified by color, letter and shape. The Sony A6000 is deployed for this purpose, it zooms using the stock 16-50mm lens. It captures an image of the ground object, and uses a Sequential Model built with Keras to recognize the letter inside the ground object. Then, the letter, shape of the object, color of the object, and geolocation are stored in the RB3 and streamed back to the ground station by MAVLink radio. Streaming allows for reduced post processing time, but storing allows for a backup copy in the case that the stream takes too long or becomes corrupted.

2.7. Communications

2.7.1. UAV Communications, Figure 2



2.7.2.

2.8. Conclusion

A popular approach among scientists lowering carbon emissions is to reduce commercial vehicle emissions. This has been proven to be less effective than creating an autonomous flight system to reduce industrial emissions. By certification of autonomous flight from the AUVSI SUAS Competition, this UAV will be federally certified for autonomous navigation and flight at the highest level, level 5. The system presented above will not only be able to perform the assigned tasks, but do so admirably. We have designed our system to meet the specific mission requirements, we have proven the effectiveness of our design by testing its hardware and software extensively, and, as much as is reasonable, we have mitigated risk. We look forward to demonstrating the performance of the UAS at the competition this summer.