ELECTRONICS AND AUTONOMISATION OF AN ELECTRIC WING IN GROUND-EFFECT DRONE FOR SHIP CHANDLING

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Abstract
Early attempts to purpose the ground effect for technological use in the form of novel aircraft in the 1920s demonstrated clear room for improvement in this area. The same can be said about the fledging autonomous robotics technology, which has yet to see widespread use in industries such as ship chandling. Ship chandling is one domain in which the use of autonomous ground effect vehicles could be applied to possibly boost productivity, and as such, this is a report of an investigation into the potential application of ground-effect vehicles for ship chandling through the design and analysis of a scaled down model, with the focus on electronics and programming. As this integral phase of the project comes to a close, extensive research and literature review has been conducted on how autonomous technology and software can be integrated into the mechanics surrounding ground effect vehicles. Another notable achievement is the building of the entire electronics system on which a prototype is heavily dependent on to achieve its functions, laying the groundwork for future expansion and research in this project.

1. Literature Review
The invention, introduction, and continuous development of autonomous vehicles (hereafter 'AVs') heralded a new age in the world of technology and transportation. Quickly becoming one of the most iconic indicators of the global shift towards creative, futuristic solutions, AVs are among the latest to promote efficient, no-hands systems[1]. Aircraft, cars, ships, and drones are in the midst of a technological revolution orchestrated by corporate giants across the globe, and transitioning into full autonomy. While this concept is relatively new and mostly in a stage of infancy, steady progress is being made toward the objective of fully autonomous vehicles[2].

1.1.1. Autonomy eradicates human error, allowing for more effective transport
AVs' autonomous nature eliminates human input, thus drastically reducing human error[3]. The continued use of AVs will lead to far less frequent accidents, hence improving transport systems' effectiveness[4][5].

1.1.2. Autonomy allows for greater precision, paving the way for innovation and new technology
Introducing AVs maximises the precision of navigation and travel, as well as hazard avoidance. Their capacity to instantaneously make use of valuable, specific, and precise data from onboard electronic sensors allows them to predict potential hazards and navigate based on empirical data[6]. With rapid, pragmatic, and consistent adjustments to their surroundings with little margin of error, AVs allow for safer travel and shorter response time to road hazards, evident in immediate re-routing and obstacle avoidance systems. As AVs play a major role in reinventing transport to be more precise, efficient, and innovative, further refining AV technology paves the way for novel applications of future technologies. Mass AV development creates more room for innovation, benefitting future technological advances.

1.2. Uses of autonomy in ship chandling

The latest advancements in AV technology are a hopeful indicator of the future of industries such as transportation[7][8][9]. Since semi-autonomous systems that partially control vehicle movement are widely used, establishing the new improvements AVs can bring to the freight industry is vital. Having examined the benefits of AVs in society, the discussion can progress to a closer inspection of the role that AVs play in the future in the military. With limited space for docking on Singapore's shores, ship chandling at sea can increase her capacity to resupply her naval fleet, increasing efficiency and combat potential.

1.2.1. Greater capacity for supplies allows for more efficient operation

Without the need for human input for navigation and locomotion[10], the cockpit of the AVs, now mainly used for communication rather than navigation and steering, can be sized down to allow for greater carrying capacity, allowing for the same amount of cargo to be transported with fewer trips. In the case of the navy, maximising fast resource supply to where it is most needed and meeting the demands of the modern military machine is a priority. Removing the need for human operators via autonomy can lead to larger scale ship chandling activity, which optimises the supply of resources to Singapore's naval fleet.

1.2.2. AVs are able to handle complex functions, navigation, and commands with ease

With quantitative evidence and past missions, AVs are able to rapidly adapt to stimuli beyond human control quicker than any human operator. AVs operate based on a wider, more informed perspective, due to their reliance on empirical data, and are thus more inclined to make wiser decisions when it comes to navigation. Evidently, AVs can function at levels beyond a human's potential, and will greatly enhance the performance of Singapore's naval fleets.

1.2.3. Larger scale operations are made possible via multiple unmanned vehicles

The application of autonomy in freight vehicles minimises the manpower required to operate each vehicle, increasing the number of vehicles that can be dispatched at any given time. This greatly eases the burden on supply systems during large scale operations, such as drills that are far from shore. With AVs, provision supply can easily meet demand, improving naval fleets' support system. Deploying AVs would also mitigate, if not solve, the greatly pressing issue of an "impending manpower crunch" due to "a 30% reduction in its enlistees by 2030[11]" in the Singapore Armed Forces. The autonomy AVs offer lowers the navy's ever-growing demand for manpower, ensuring that the supply of enlistees will not be greatly dwarfed by manpower needs.

1.4. Conclusion

To summarise all that has been discussed, this literature review offers a comprehensive insight into the universal benefits that the development of AVs can bring about to society and industries. AVs offer humanity a world that is more convenient, hands-free, and, perhaps most importantly, more productive and efficient as a result of novel technology[12]. These new classes of transport, if properly utilised, can revolutionise the technology-military industrial complex. Such a revolution will be inevitably accomplished through the elimination of human error, the encouragement of innovation, and the exponential increase in efficiency and productivity of Autonomous Vehicles.

2. Project Materials and Methods

2.1. Aims and Objectives of Project

With the limitations of little prior experience in robotics and autonomy, as well as resource and time constraints, the project focus was shifted to semi-autonomy rather than a fully autonomous vehicle. The vehicle was programmed to reliably navigate the shortest path from its starting position to its desired end point, as well as communicate via telemetry to a ground unit so as to regulate values such as altitude, rotation, and position.

2.2. Project Flow

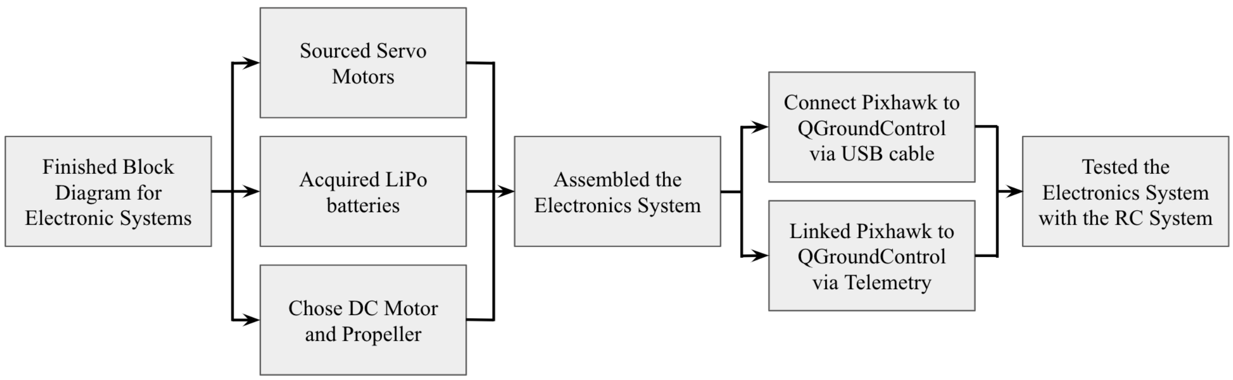

Fig. 1. Important milestones achieved in the duration of the project

2.2.1. Block Diagram and Introduction of Electronics System

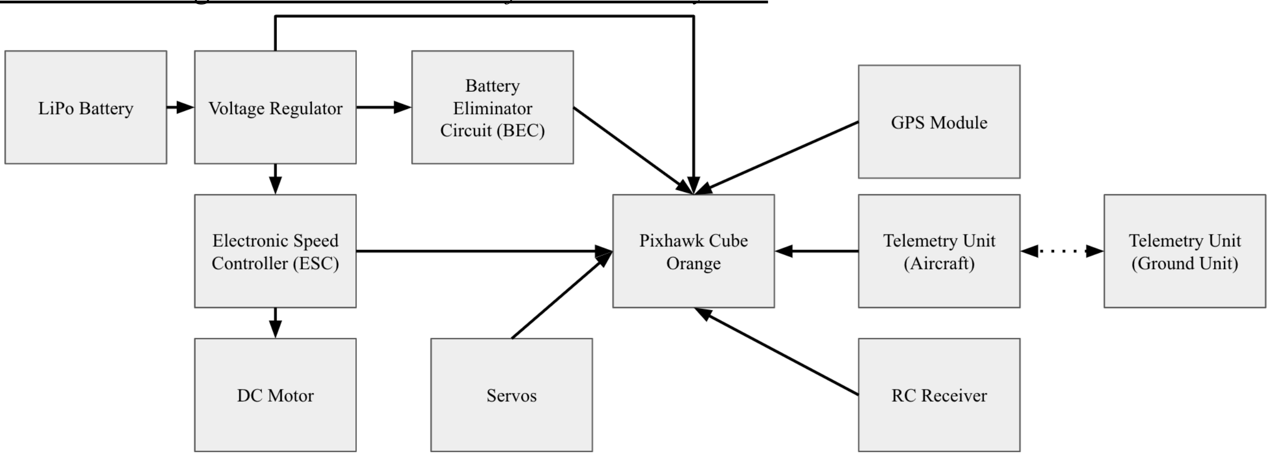

Fig. 2. General Outline of the Electronics System

The block diagram (above) maps out connections between components, which allows for ease of reference during wiring later on. Each component in the electronics system has a purpose that warrants further discussion below, including the following:

2.2.1.1. Pixhawk Cube Orange

The role of the flight controller is to act as the base of communications for the entire system. It is equipped with numerous ports that are compatible with a host of electronic devices. Out of other commercially available options such as CUAV Autopilot, the Pixhawk Cube Orange was deemed most suitable - not only is it a competent and consistent flight controller, it is distinctive in that it is designed for manufacturers who wish to fully integrate an autopilot into their system. In terms of practicality, it also happened to be most accessible for this research investigation.

2.2.1.2. Here2 Global Positioning System (GPS) Module

Due to the semi-autonomous nature of the project, it was inevitable that a GPS module had to be procured. The GPS is necessary as it assists the GEV in pinpointing its geographical position, and subsequently, navigating the prototype towards the intended destination. In this regard, the Here2 GPS Module is simple yet effective, allowing for accurate location tracking. The Here2 GPS module can be connected to the flight planner QGroundControl (to be discussed further) via the Pixhawk, allowing the software to receive the instantaneous geographical information of the GEV during flight.

2.2.1.3. 3DR Radio Telemetry System

The 3DR Radio Telemetry System serves as the primary mode of communication between the prototype and the QGroundControl software. When connected to the Pixhawk, the telemetry system coordinates with the aforementioned GPS module and other sensors built into the Pixhawk to transfer sensory and geographical data about the prototype to the ground unit. The QGroundControl display will thus be able to reflect information such as altitude, velocity, position, airspeed, roll, pitch and yaw. Constant updates of the prototype's progress during flight will be useful for operators, as they will be situationally aware and hence be able to respond accordingly should plans go awry.

2.2.1.4. Motors, Servos, and Electronic Speed Controller (ESC)

In order to manually alter physical variables such as roll, pitch, yaw, and velocity during flight, actuators are necessary. Hence, the prototype features several PWM servo motors, a DC motor, as well as an ESC. These actuators directly manipulate the ailerons, elevator, rudder, steerable rear landing gear, and propeller of the GEV. While the PWM servo motors are equipped with piano wires to increase the degree to which control surfaces can be manoeuvred, the DC motor is directly connected to the propeller of the GEV and produces forward thrust. In turn, the DC motor is linked to the electronic speed controller, which adjusts the speed of the motor.

2.2.1.5. Lithium-polymer (LiPo) Battery and Voltage Regulator

As required in every circuit, a power source is necessary to provide sufficient voltage so that all electrical components in the system can perform their respective functions. The LiPo battery was selected over alternatives such as alkaline batteries, even though the latter are more commercially available. LiPo batteries have a much higher power output, ergo, allowing it to deliver enough power to the DC motor, so it would produce sufficient thrust. In this set-up, a voltage regulator is also equipped as a precaution, ensuring that a sufficient amount of voltage is supplied consistently to each component of the electronics system. Any malfunction can cause unregulated flow of current throughout the system, resulting in the devices working erratically, or damaging the components altogether.

2.2.2. Parts Sourcing

After all the electronics that were required were compiled in the form of the block diagram, specific models of electronic components were chosen, taking into consideration the criteria of efficiency, cost and accessibility. This was to ensure that the prototype was fabricated quickly, produced under budget constraints, and with the parts easily procured.

2.2.2.1. Servo Motors

Four servo motors were required for the two ailerons, one elevator, one rudder, and one steerable rear landing gear. In each case, the torque required was less than 1kg/cm as the control surfaces were light and easily moved, except for the servo controlling both the steerable rear landing gear and rudder, which required 2kg/cm of torque due to its greater mass and the additional force it needs to overcome friction between itself and the ground. Hence, four 1kg/cm servos and one 2kg/cm servo was used.

2.2.2.2. DC Motor and Propeller

The components that are directly responsible for producing a forward thrust are the DC motor and the propeller. To propel the plane forward, at least 2N of thrust must be produced by the DC motor and the propeller. As such, it was imperative that the selected DC motor spun at a sufficiently high speed and the propeller was of the appropriate size. It was under these circumstances that the highly efficient KDE2315XF-885 brushless motor was used alongside a 10 inch by 6 inch propeller.

2.2.2.3. LiPo Batteries

A balance between size and power capacity had to be reached so that the battery could be compact and easily stored while still being able to sufficiently power the prototype. As the DC motor chosen required 11.1 V (3S LiPo) - 26.1 V (6S LiHV) of voltage to spin at a fast rate, and the battery had to be as light as possible and small enough to be contained in the fuselage of the prototype, a 11.1V 3S LiPo battery was chosen.

2.2.3. Use of QGroundControl for flight

QGroundControl is an open source mission planner that supports autopilots such as the Pixhawk series for many types of aircraft, as well as autopilot systems such as Ardupilot and PX4 Pro. QGroundControl was selected due to its intuitive interface and versatility. For the purposes of this project, PX4 Pro was used in this investigation due to the appeal of familiarity and the high appraisal from supervisors.

2.2.3.1. Functions that QGroundControl offered for aircraft setup

QGroundControl has a built-in flight map that tracks the flight of the aircraft based on its position located by the GPS module, which allows for monitoring of the GEV during flight even without a USB connection. In addition, the flight planner allows for autonomous flight from waypoint to waypoint. It also allows for sensor calibration, remote control tuning, and other parameters that allow for easier manoeuvre of aircraft.

2.2.4. Connecting Pixhawk to the QGroundControl Software

To connect the Pixhawk to the QGroundControl Software, two methods were tested.

2.2.4.1. USB Connection

To ensure that the Pixhawk was in working condition and was compatible with the software, the Pixhawk was connected directly to the computer through a USB cable, enabling

QGroundControl to download relevant firmware into the Pixhawk. ESC calibration and motor testing was also carried out to ensure that servos and motors were working and provide the range of throttle inputs to the ESC.

2.2.4.2. Telemetry

Via the radio telemetry system, where one antenna was connected to the aircraft and the other connected to the computer, the Pixhawk could receive arming and disarming signals from QGroundControl, and the software could receive real-time sensor values from sensors such as gyroscope, compass, altimeter, and GPS.

2.2.5. Remote Control System Testing

Once all components of the electronics system was confirmed to be in working condition, a remote control transmitter was used to test the movement of all control surfaces and propeller both synchronously and asynchronously.

3. Results (Final Model)

3.1. Use of Remote Control Transmitter for flight

Using the remote control transmitter, the aircraft could manoeuvre around obstacles, and change its velocity and direction of movement with human remote input.

3.2. Use of GPS module with QGroundControl

By using the GPS module together with the QGC software, the location of the Pixhawk could be tracked in real time, and the path of movement of the plane could also be drawn out on the map.

Fig. 4. Launch position of the plane

Fig. 5. Movement and final position of the plane

3.3. Use of proportional–integral–derivative (PID) controller for flight

The proportional–integral–derivative controller, also known as the PID controller, allows for the computation of an actuator output based on a sensor input, via calculating the proportional, integral, and derivative errors and summing them using the formula:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt} e(t),$$

where:

K_p, K_i *and* K_d are the respective proportional, integral, and derivative constants,

u(t) is the actuator output at time *t*,

e(t) is the error computed at time *t*, defined by $x_{setpoint}$ - $x_{measured}$, the difference between the setpoint and measured input.

3.3.1. Use of PID controller in PX4 Pro

PX4 Pro uses said PID controller to allow for fast response rate to changes in altitude, velocity, and axes (roll, pitch, and yaw) for smoother and more efficient flight. By adjusting K_p, K_i, and K_d accordingly, the process oscillation around its intended setpoint is minimised as much as possible, which results in a minimised response time to disturbance.

3.3.2. Importance of PID controller in flight

In flight, fast responses to external stimuli will greatly affect the stability of flight, the ease of control of aircraft movement, and the efficiency of waypoint navigation. Not only would a quicker response rate allow for less oscillation leading to minimised back-and-forth value adjustment via PWM outputs, thus resulting in more stable flight, it would also navigate between waypoints at a faster rate as the GEV can turn more sharply and accurately towards the direction of the waypoint it is heading to.

4. Discussion (Assessing the Effectiveness of the Prototype)

4.1. Prototype movement

Each test run of the prototype consisted of the servo test, propeller test, and the drive test. This is a safety precaution to ensure that the control surfaces and propeller are able to function properly and can be controlled by the remote control transmitter before the prototype begins movement.

In the testing phase, over 20 test runs were conducted in less than a week on the latest prototype. Despite initial setbacks in the internal configuration of the prototype, it has been generally observed that the DC motor and propeller had produced ample thrust. The remote control transmitter throttle controls the speed at which the DC motor turns, producing thrust which consistently propels the prototype forward in a straight line, given that all control surfaces are in their initial zeroed positions. This had confirmed that the centre of gravity of the plane was in the correct position, as there were no instances of the aircraft tipping over during motion. The prototype was thus able to consistently respond to signals from the remote control transmitter and travel in a straight line even at maximum throttle.

4.2. Prototype manoeuvrability

After the forward motion of the prototype was ensured to be consistent, the focus turned to ensuring its steerability and ability to turn via the manoeuvring of the various control surfaces. After multiple tests, the prototype was deemed to be moderately steerable, with the rudder and rear gear performing their function the best. It must be noted for the record that given that the prototype is not developed enough to achieve stable flight, changes in roll and pitch affected by the ailerons and the elevator could not be effectively examined.

4.3. Prototype flight

While manoeuvrability and steering was achieved to some degree, the prototype was regrettably unable to take off even at maximum throttle. This can be fundamentally attributed to two reasons; firstly, the imperfect mechanical structure of the prototype, due to equipment inaccessibility; and secondly, the significant weight of the prototype because of the electronics system.

4.4. Software and Navigation

While autonomy and self-navigation was an objective from the beginning of the project, it is unfortunate that the circumstances posed a great obstacle. While the software aspect of the project is not sufficiently developed at this phase of the project, the mechanics department has bolstered the foundation for further progress in this area. With a tangible prototype on hand, the team now has the means to efficiently test software. In other words, this project is now well-positioned for further substantial improvement.

5. Limitations and Further Improvements

Due to the nature of the project, as well as the resource and time constraints present, much of the programming aspect of the project was not achieved. The electronics and programming aspects heavily relied on the mechanical and aerodynamics team to produce a tangible, working prototype to test on, therefore, the majority of the time, manpower, and budget were spent on those two areas. This led to a deficiency in time and resources to sufficiently cover all aforementioned aspects of electronics and programming that were previously outlined.

However, this project is to be continued in the future, with improvements to the software aspect being the main focus. Possible improvements include (but are not limited to) using PID to regulate velocity, axes, and altitude values; using cameras to detect, recognise, and avoid obstacles in its path; and using MAVLink to communicate between the aircraft and the ground unit and send commands to the aircraft.

6. Conclusion

To recapitulate the mass of information discussed, this report is a collection of the learnings and progress accumulated from the research conducted from July to October, and the tireless construction and experimentation carried out between November and December. The vital importance of preliminary research was thoroughly demonstrated in the initial phase of the project so that all team members had the skills and expertise to carry out their respective roles. In the specialised area of electronics and programming, technical knowledge of electrical components and familiarity towards coding syntax were of particular importance. While the entire electronic system was firmly established, constraints on time and manpower greatly hindered progress, and compromises had to be made in certain areas. It is thus worth concluding that the project is in the position and phase for further development in the near future.

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