Mission Planning and Manual Control Systems in an Autonomous Fixed-Wing Tailsitter

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1 Abstract

The design of aircraft capable of long duration, long distance missions with the maneuverability of shorter-range craft has been a problem in engineering since the beginning of flight. A type of Aircraft that attempts to bridge this gap by flying in both vertical and horizontal flight modes is known as a tailsitter. While manned tailsitter planes have existed in the past century, current work in the field of autonomous vehicles has had more success due higher tolerance for failure and lighter battery power. In the construction of tailsitters, many recent projects either attempt to brute-force the problem with data from an array of sensors or increase the degrees of freedom in control of the aircraft. Each of these approaches has their own problems, primarily there are complexity issues when applying autonomous models to more general problems. The technical approach to this project is to utilize existing commercial equipment for tailsitter capable autonomous vehicles, but to utilize as simple a control system as possible and apply that simple approach to complex problems that have previously been solved by complex systems. By reducing the number of control surfaces on a flying vehicle, the goal is to reduce the complexity the tailsitter flight control model so that it can be applied to a wider range of aircraft. From a physical perspective, the flying vehicle will take advantage high control authority and of unlimited space in the sky (as opposed to testing in a lab) to perfect its precise movements. Using GPS and internal sensors measuring the orientation of the plane, the end goal is to create a vehicle that can fluidly transfer between hovering and flying horizontally, such that it can hover in a location set by an external controller or predetermined mission.

2 Introduction

Efficient flight in autonomous vehicles is an important issue in military and commercial applications of drones. In flight, it is most efficient for a vehicle to fly horizontally, so that the air passing over and under the lift surfaces can be used to support the craft. In this orientation, horizontal thrust is needed to propel the craft forwards, which conveniently facilitates movement in a particular direction (towards a destination). On winged aircraft (aircraft with translational lift surfaces), the size of the wings determines the amount of lift, so more efficient aircraft have larger wings, and require less forward thrust to generate enough lift to keep flying. Flying over one location, however, is very difficult with large wings, since the airflow over the lift creating surfaces is zero when travelling at zero velocity. Another difficulty is that wings are heavy and have a lot of air resistance, which is usually offset by the fact that they support their own weight. To solve this problem, aircraft without wings that direct all of their thrust downwards can hover most efficiently (maneuver translationally with great precision). In each scenario, adding and removing wing area to increase efficiency for one orientation reduces the ability for the aircraft to perform in the opposite situation. With less wing, a craft can have a smaller load in a horizontal configuration but with more wing, a craft can have a smaller load when hovering. An aircraft that can take advantage of both flight configurations with minimum drawbacks will supersede the precision of horizontal aircraft that require runways but outrun vertical aircraft like helicopters and multirotors.

Previous approaches to this problem attempt to alter the physical properties of wing shape or add more motors to change a vehicle into a tailsitter. Many of these changes enable vertical takeoff and landing (VTOL) by also adding landing gear for the vertical orientation. These changes remove almost all of the beneficial aspects of tailsitter vehicles such as their large wing-to-mass ratio and low drag. By eliminating the landing gear component of VTOL, it is possible to preserve the efficiency of tailsitter aircraft and develop a flight model that is more applicable to traditional fixed wing aircraft.

The technical approach for solving this problem used the open source software for autonomous piloting of remote-controlled aircraft called ArduPilot. ArduPlane is a version of the ArduPilot firmware written for a variety of flight controller chips that are for fixed wing planes. By combining simulated missions and physics models for aircraft movements, a real-world model was developed to be implemented in a real-world plane. This plane will be controlled by a ground station and pilot for backup manual control but will also have the ability to act completely autonomously and complete pre-imputed missions. These missions will specify waypoints with GPS coordinates and commands to complete at points in the mission.

In the experiment a functional model was been created to execute remote commands for plane behavior in software and hardware simulation. Mission planning and complex instructions can be executed by the plane and hovering is possible with smooth transitions. The ground station software (QGroundControl) is configured to operate with remote communication to the vehicle over Crossfire telemetry through the Mavlink protocol. Full calibration of on-chip instruments such as a barometer, compass, and accelerometer are indicative of chip ability to perform on a real plane. Controller connection is set up with servo mapping and range of 10km.

3 Related Work

Many previous implementations of tailsitter aircraft are more similar to multirotors than fixed wing planes. Well after the construction of helicopters and planes, the first implementation of an aircraft that was a cross between the two modes of flight began in the middle of the twentieth century, when the United States constructed the first tailsitter aircraft called the

Hummingbird. The Hummingbird had a single pilot and was powered by counter rotating propellers on its nose. Due to lack of maneuverability and poor performance, the project was scrapped. Later approaches only began once autonomous technology was prevalent.

Figure 2: Gas Tailsitter

Figure 1: Hummingbird

More recent studies that work with smaller autonomous vehicles typically use highly irregular wing shapes, in an attempt to maintain a manageable center of gravity, drag, and thrust when in horizontal and vertical flight modes (Hugh, Zhang, Li). Many also employ multiple motors for thrust differential. These projects work with control systems that are so different from the general design of typical aircraft that the control models can barely be applied to other aircraft without replicating an irregular wing shape. Other projects attempt to find solutions to control problems in laboratory scenarios, where aircraft can use information from external cameras and sensors to correct movements (Boyang). Both of these solutions to the problem of constructing tailsitter aircraft do not account for real-world factors, such as wind, GPS imprecision (not present in a lab), or the models applicability to traditional aircraft designs.

The approach taken in this experiment is to build a much simpler model based on a smaller amount of sensor input. Also, all in flight computations will be done in real time, on board the flying aircraft, which increases the range and response latency for the vehicle.

4 Technical Approach

The technical approach to this project is to create an autonomous flight model for an aircraft that already flies horizontally, and that uses only realistic data that could be used in the real world. In other words, the goal of this project is to turn an aerobatic single motor fixed wing plane into a tail-sitter, with hovering transition capabilities. The plane should be able to fly to, or hover at, waypoints and complete predetermined missions.

In order to test the feasibility of the project, initially the model was constructed in simulation, with a firmware package easily transferable to autonomous hardware chip. Using the Ardupilot Autonomous software package, emulating the hardware using a Software In The Loop (SITL) physics model it was possible to simulate an aircraft and its environment. Ardupilot is the most popular free autonomous flight package in the remote controlled (RC) vehicle hobby, with a large community development base and thousands of physical implementations (fixed wing, multicopter, and helicopter uses). Ardupilot has three different components in physical plane: first the flight controller, which runs the flight control model and handles all mission planning and execution, second the ground station (QGroundControl) where a user can send commands to the aircraft, and third a joystick where a person can pilot the aircraft in manual mode. In cases where the aircraft is connected while in the air, the ground station is used to plan and execute missions on the flight controller remotely. If the aircraft disconnects from the station, there are customizable presets for action, such as continue mission or return to land (RTL).

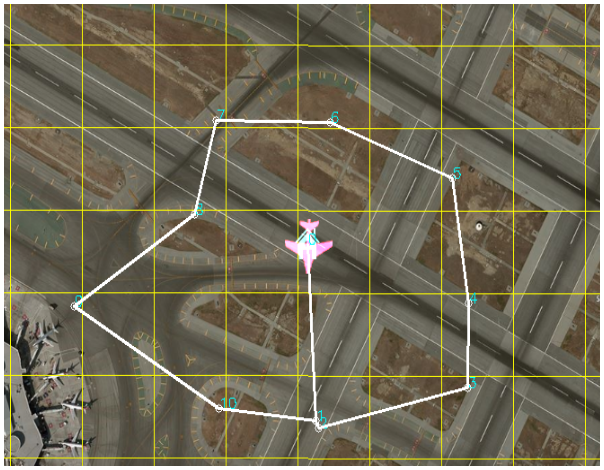


Figure 3: MavProxy Map View

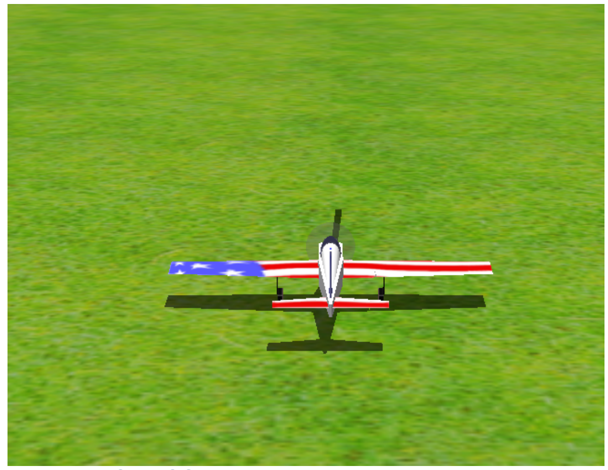


Figure 4: CRRCSim Aerobatic Plane Model

In a simulated model, there are more connected parts because the physics model must be computed virtually instead of just reading aircraft positions. In this case the Ardupilot SITL connects to a simulator (FlightGear) and the QGroundControl with the physics model JSBSim. Commands are entered in the SITL command window (known as MAVProxy) which control the state of the aircraft and its settings. Transitioning from horizontal flight more to vertical flight mode can be done with “mode QHOVER” where QHOVER identifies that the plane is hovering vertically. Transitioning back to normal flight is just as simple as changing the flight mode to ‘AUTO’ which returns to completing the mission.

The layout of the Hardware In The Loop (HITL) system was even more complicated. In the HITL system, the chip (flashed with ArduPlane 3.6.8 in Quadplane configuration) was connected to the RC transmitter through the Crossfire receiver and also to the computer running QGroundControl. Through QGroundControl, all of the sensors onboard the chip were simulated using data from FlightGear and the JSBSim flight dynamics model. In this way, it was possible to test the exact behavior of the chip to sensor data in simulation without building a physical plane, and to practice manual flight using a remote control.

5 Evaluation

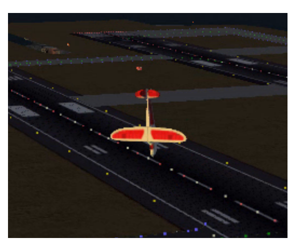
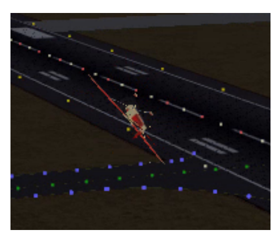
The goal of constructing a simulated model of the autonomous tailsitter aircraft is to develop working control models that can then be implemented in a physical plane.

Under the SITL implementation, a simulated plane with a working physics model can be piloted manually around a generated terrain (SFO in pictures below). Autonomous functionality with the SITL facilitates the creation of missions for the plane, as well as command line loading of parameter sets facilitates changes in the plane model and types mid flight. Ordering the plane to complete a mission is as simple as loading a mission, arming the throttle, and setting the mode to AUTO, which tells the plane to carry out the mission. At any point in flight, changing the flight mode can be done through the MAVProxy command line, and it is possible to have the plane in QHOVER mode for 10 seconds at a certain waypoint in a mission. In accordance with the goal of the project, having the aircraft QHOVER in a designated spot and altitude after completing a mission would allow for easy hand retrieval. All of this functionality is working, and transitions are fluid between different modes of flight.

Under the HITL implementation, a simulated plane can be flown in much of the same way that the SITL model operates, but all of the aircraft processing is done on the chip. This is much closer to the performance of the physical plane than the SITL model. Also, now the chip is connected over a rc signal to a controller which will be used in the final construction of the plane.

Problems with the parameters of the models of the flight simulator in both SITL and HITL configurations, however, inhibit the plane's ability to hover for a long duration (the aircraft stalls). In order to hover, an aircraft must have more thrust than its weight, and if it does not, it will immediately stall violently, since the center of drag is in front of the center of gravity. This is different from horizontal flight modes because in regular flight the thrust needed to keep the aircraft going forwards (and to climb) is much lower than the actual weight of the craft, this being the reason for horizontal flight efficiency. In other words, in order for an aircraft to be tailsitter capable, it must be overpowered for regular flight, and underpowered for hovering vertical movement. This is a small price to pay for the benefits of such unique flight capabilities. The current flight simulator does not accommodate for custom aircraft models, which could be more powerful and have more control authority, so the SITL and HITL are currently being tested with alternate simulators and flight models.

Given that testing is possible on an aircraft with enough power and enough control authority (most likely an aerobatic plane), full tailsitter capabilities should be possible with fluid transitions between flight models. Below are pictures of the current model implementation and the desired plane attributes:

Normal Mission Flight	QHOVER	Stall	Inability to recover in QHOVER mode (not enough control authority)
			

(Videos are available upon request)

All other desired capabilities are implemented such as mission planning, and remote autonomous control.

The current implementation the firmware on the flight controller chip has the potential to outperform many recent autonomous tailsitter implementations, many where there is an irregular wing shape or even a custom build control model. In addition to this, the firmware is compatible with any RC servos, any RC transmitter protocol, and a traditional ESC battery combination. Also, there are many more features that increase the complexity and possibility of vehicle behavior already built into the ArduPilot protocol, such as autonomous mission planning and failsafe RTL.

A physical aircraft with a configuration similar to the one shown in Figure 5 would be optimal for testing with this system. Light foam control surfaces with reinforced carbon structure would allow for maximum maneuverability and hovering ability while still supporting a flight controller and receiver connection. A high power to weight ratio would enable the craft to hover and the lack of aero foil wings would reduce the instability of vertical hovering.

Figure 5: A hovering foam aerobatic plane

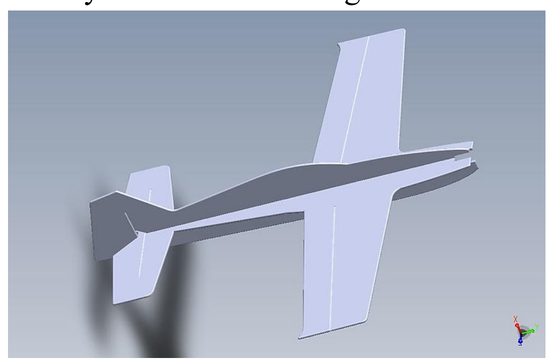


Figure 6: Design for foam "3D" plane

6 Conclusion

Fixed wing tail sitters allow for efficient flight over long distances but also give precise takeoff and recovery capabilities. Dual flight model systems that allow for the implementation of tail sitter aircraft eliminate many of the drawbacks of a single flight mode but are complex and require sophisticated software and hardware. In a simulated environment, a traditional winged aircraft that can fly horizontally was altered to also have vertical hovering capabilities. These software changes and remote piloting capabilities were constructed with the goal of transferring them to a physical aircraft, which will be able to complete missions autonomously with additional tail sitter capabilities.

While this project only includes the development of a tail sitter aircraft, the new capabilities of vertical flight alignment open up opportunities to complete even more intricate mission profiles. Examples of this include hand-launched, hand recovered personal surveillance planes, and systems for field deployment of reconnaissance vehicles. To enable these capabilities, it would be as easy as enabling features that already exist within the Ardupilot stack. Also, all of the aforementioned capabilities would be possible on a powerful, agile, single motor aircraft, which greatly increases the potential use cases for this software.

Other possible developments on autonomous tail sitter software is the robotic recovery of autonomous robots. It a robotic arm were to coordinate the recovery of a hovering fixed wing plane by communicating with the plane itself, this could change the way that aerial vehicles are recovered when runways are not available. Robotic recovery systems on ships, similar to the automatic docking mechanisms aboard the International Space Station could allow the concurrent deployment of multiple drones completely without human intervention, meanwhile maximizing the flight times of the autonomous vehicles by using a fixed-wing configuration.

Aside from autonomous vehicle interaction, future work with tailsitters could study the efficiency of wing shapes in different modes of flight. This is exemplified by the lift of aero foils in horizontal flight, but their increased drag off-axis lift in vertical hovering flight. Research into the relative benefits of how more aggressive aero foil shapes on tailsitter aircraft compromise different flight aspects in each mode of flight.

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