

Development of an Autonomous Flight Control System for a Distributed Electric Propulsion Flying Model

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Abstract. The scope of this work is the realization of a fully automated testing campaign, through the development of an autonomous Flight Control System (FCS), in order to support the model identification of a Distributed Electric Propulsion (DEP) scaled demonstrator. The autopilot has been used to follow a GPS trajectory, reach trim conditions, execute the required maneuvers, define and tune specific control actions and carry out automatic safety checks. The chosen software environment is PX4, an open-source professional autopilot, which has been extended and customized to carry out the flight operations needed for parametric identification, while fulfilling functional and safety-related requirements. In addition, a simulation environment has been set up for software testing and pre-flight configuration. The result is a fully automated platform for flight testing and advanced research within DEP models.

Introduction

In earlier works [1], a parametric model identification of a DEP flying model, the SwitchMaster, was carried out, leading to a numerical definition of its stability and control derivatives. Besides, it was observed how the blowing effect on the wings impacts several derivatives, which in particular can have an exponential growth as the blowing intensifies, due to the aero-propulsive coupling generated by the faster air flow on the wings with respect to that along the fuselage. The blowing can be quantified in terms of propellers advance ratio $J = \frac{V}{nD}$, where V is the true airspeed, n is the propellers rotational speed and D the propellers diameter. In fact low J values, that can be achieved at low airspeed and high propellers rotational speed, correspond to high blowing, and vice versa. The unblown case, defined as $J \rightarrow +\infty$, can be obtained by gliding. However, the main limitation of this work was the difficulty to have good trim conditions and a precise execution of the maneuvers, especially at high climb angles which are required to experiment high blowing, mainly due to the manual remote piloting. Hence, it was necessary to develop an autopilot to support the realization of a fully automated testing campaign and then improve the quality of the data collected to feed the model identification process, leading to a more realistic estimated DEP model.

System Requirements Analysis

Following a standard software engineering procedure, it was started defining the Goals of the System and the Domain Assumptions, which are hypotheses assumed to hold about the environment and the user's behavior. With this procedure, the System Requirements can be defined, being essentially conditions that the System must satisfy to reach the Goals, assuming true the Domain Assumptions. The main Goal can be expressed as follows:



The System must be able to reach trim conditions at any feasible combination of J and α , holding V_{TAS} and γ setpoints while following a GPS flight plan, then executing safely and autonomously all the needed maneuvers for parametric identification.

Hence, here are provided some examples of the Requirements that had to be satisfied, which led to significant changes and extensions of PX4:

1. The System must be able to execute climb and descent, following a climb angle γ setpoint defined by the User. The level flight should be treated as a particular case with $\gamma = 0$ deg.
2. Multiple circuits could be executed in automatic flight, following a GPS flight plan, and along each straight leg of the circuit one climb angle has to be scheduled.
3. After each climb or descent, the aircraft smoothly stabilizes at a given altitude, defined in the loaded flight plan. If that altitude cannot be reached within the given leg length, then it proceeds following the next waypoint, loitering to the final altitude if needed.
4. A Glide Mode has to be available, as a special case of descent, in which the aircraft keeps the motors at zero power and follows only a V_{TAS} setpoint, thus ignoring γ .
5. During each leg of the circuit, the System must be able to check whether trim conditions have been reached and maintained for a minimum time, then executes the scheduled maneuver automatically. During the whole maneuver duration, the autopilot must remain disengaged, as the control system should operate in open-loop. In addition, the control surfaces not involved in the excitation input at a certain time, must remain locked at a fixed computed trim value. However, the correction of the bank angle by the autopilot during longitudinal maneuvers could be tolerated in certain cases. When it is done, including the required free response time, the autopilot regains control and continues with the flight plan.
6. The System must provide a wide list of maneuvers, basically doublets and 3-2-1-1 involving all the control surfaces (elevator, ailerons and rudder), selectable from the ground station parameters menu. Each maneuver must be configurable at runtime, to comply with the parametric identification process and follow the flight campaign planning.
7. There must be automatic controls to abort an ongoing maneuver, or to prevent its beginning, whenever anomalous conditions are sensed in flight, like low airspeed and altitude, critical attitude and others. The maneuvers must also be interrupted when the aircraft is near to the altitude setpoint or to the next GPS waypoint. In addition, at any time the Test Pilot must be able to interrupt a maneuver and possibly regain manual control. The Glide Mode should be subjected to similar safety checks.

As a result of the requirements analysis, many functionalities have been progressively developed: Gamma Mode, Glide Mode, Trim conditions evaluation, Maneuver launch and execution, Maneuver aborting, Safety features, Control surfaces trim computation, Maneuver testing on the ground, TECS Stand-by Mode and Failure injection.

Control System Development

PX4 Autopilot consists of two main layers: the Flight Stack is an estimation and flight control system layer, while the Middleware is a general robotics layer that can support any type of autonomous robot, providing internal/external communication and hardware integration [2]. The Flight Stack is composed of many modules. The most important ones are Commander, Navigator, Position Control, Attitude Controller and Control Allocator, which are also shared by almost any airframe. For the fixed-wing configuration, there is also a Total Energy Control System (TECS), that is the core library of the PX4 Flight Stack.

In order to implement the above functionalities, three major PX4 modules were modified: Position Control, TECS and Control Allocator. The newly introduced Position Control sends to the TECS the altitude, climb rate and true airspeed setpoints, plus a message for Glide Mode triggering, along with many other flight data and information. The climb rate setpoint, when present, is derived from the scheduled γ_{sp} , by the simple relation: $\dot{h}_{sp} = V_{TAS}^{sp} \sin(\gamma_{sp})$.

The Position Control can also start and abort the maneuvers, when needed, using a dedicated message. The main output of the TECS is the couple thrust setpoint T_{sp} in percentage and pitch angle setpoint θ_{sp} , in radians. Then, the Attitude Controller, which has not been modified, transforms the Euler Angles setpoint into an angular acceleration setpoint vector, in body frame, while leaving the thrust setpoint as it is. A standard geometrical turn coordination algorithm is also exploited, to compute the optimal yaw rate setpoint from the roll and pitch angles. Finally, the Control Allocator takes in input the angular acceleration vector and thrust setpoints and applies the Allocation Algorithm, to compute the actuator input values normalized between -1 and 1 (0 and 1 for the motors). These, are then converted by a driver into PWM signals for the servos and UAVCAN values to be sent to the Electronic Speed Controllers.

For the development of the control system to be used in the testing campaign, it was decided not to completely replace the existing TECS [2], but to extend it and make it able to support the requirements and the introduced functionalities. This, mainly due to compatibility and integration with the existing software reasons, which lead to several advantages in terms of reliability and effectiveness of the new system. The general functioning of the Total Energy Control System is described in various other works [3], among which an earlier implementation in Simulink used for the definition of an automated testing campaign within the SwitchMaster project [4, 5]. The specific original PX4 implementation can be found in the related documentation [6]. In this work, it is described the development of an Extended TECS, realized by adding to the original multiple new inner states.

As described by the finite state automaton in Fig. 1, from Normal Mode the TECS can go to Glide Mode by reading a specific message, coming from the Position Control, as long as the climb rate setpoint does not exist. In this mode, the throttle setpoint is zero and the energy weights are set to give maximum priority to the Kinetic Energy Rate, while the Potential Energy Rate is ignored. This, because during a glide only the V_{TAS} setpoint should be followed, acting on the pitch output, whereas the vertical speed at trim conditions is dependent on the speed.

Climb and Sink Modes are activated when exists an altitude rate setpoint positive or negative, respectively, coming from Position Control. They are the two states supporting the Gamma Mode, with the level flight, namely $\gamma = 0^\circ$, included into the climb case. An altitude margin h_m is derived from the climb rate setpoint and a fixed time margin t_m , and corresponds to the Δh where the TECS starts reducing the climb rate to stabilize at the final altitude setpoint.

To achieve this, a gain k_h is computed as altitude error divided by altitude margin, then constrained between 0 and 1. Hence, when the distance in altitude to the setpoint goes below the margin (in climb coming from below the setpoint and vice versa), the gain starts decreasing from 1 to 0. Then, the nominal climb rate is reduced gradually, multiplying it by k_h , effectively stabilizing the aircraft near the altitude setpoint. The Stand-by Mode is an extra condition that can be activated in all the cases where a maneuver can be triggered, so in each of the previous modes but the Normal one, and allows to keep the TECS integrator states steady during the maneuvers, thus preventing saturation due to error increase caused by the disengaged control action.

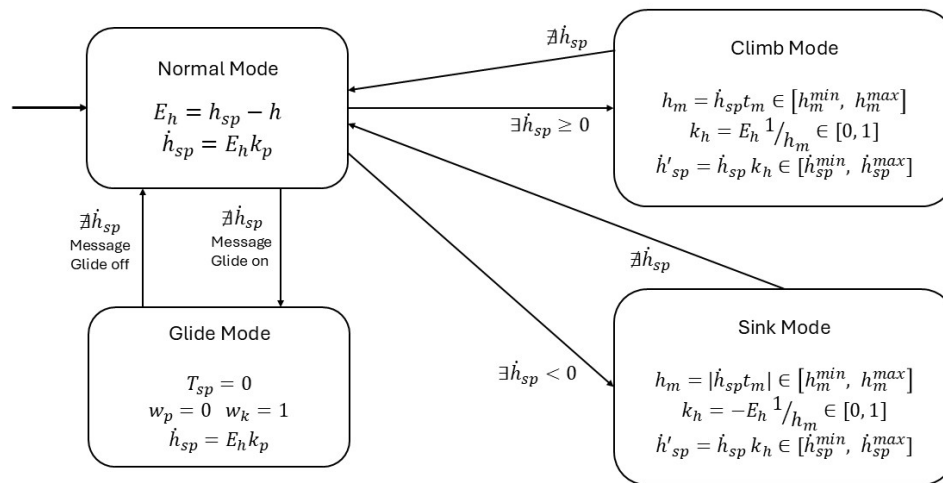


Figure 1: Simplified finite state automaton of the Extended TECS.

At each call of the main Position Control procedure, the system checks whether the distance between previous and next waypoint is greater or equal than a fixed minimum distance, defined as a parameter. Along with the distance, also the difference in altitude is evaluated: if the difference is positive, meaning that there is a climbing path between the waypoints, then it activates the Climb Mode, otherwise it goes towards the glide/sink branch, while the level path is included into the climb case. The Position Control scheduler then evaluates the current γ angle and computes the climb rate setpoint to be sent to the TECS. The case of $\gamma < 0$ (usually set to -1) is reserved for the triggering of the Glide Mode, whereas in each other case a positive angle is inserted as parameter in the system. In Normal Mode, the original PX4 algorithm is used, with altitude setpoints forming a linear trajectory between the aircraft and the next waypoint and the climb rate setpoint is computed by the TECS from the altitude error.

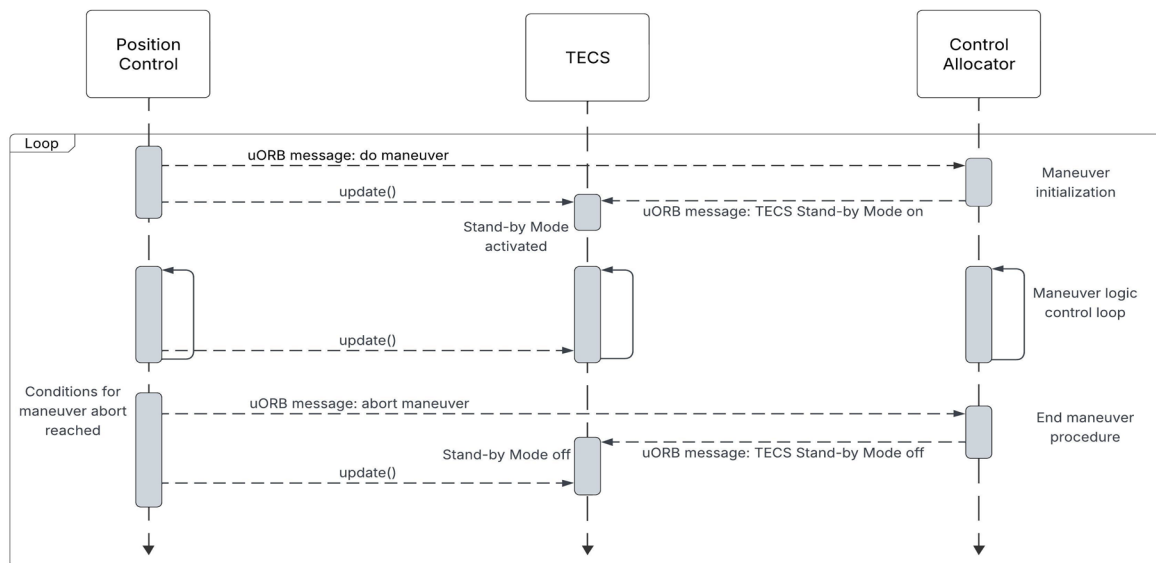


Figure 2: Sequence diagram describing the communication during a maneuver.

The other fundamental operations performed by the Position Control are trim conditions evaluation and safety checks. Regarding the trim evaluation, errors on γ and true airspeed with respect to the setpoint are continuously evaluated during the Climb and Sink modes, usually activated on the straight leg of the circuit [7], whereas in glide the only error considered is that on airspeed. Subsequently, as soon as the errors have been staying inside fixed thresholds for a

minimum user-defined time, the selected maneuver (such as an elevator doublet) is launched, by sending a specific message to the Control Allocator, as shown in Fig. 2. For what concerns the safety checks, they are similarly scheduled at each call of the Position Control procedure, as detailed in the next paragraph.

Finally, the modified procedures of the Control Allocator module are in charge of selecting and executing the commanded maneuver, configured by specific system parameters, through the manipulation of the actuator input values. In addition, a trim control value is computed for all the control surfaces and motors as a mean value of the sampled inputs immediately prior to the maneuver beginning and is used as a fixed offset to be maintained for the whole duration, including the final free response time. Hence, within this period of time the Control Allocator ignores all the inputs coming from the autopilot, realizing an open-loop behavior, plus initiates and ends the TECS Stand-by Mode, by sending a proper message. In this way, the maneuver execution is managed independently of the higher layer autopilot modules, which enables a responsibility decoupling and a safer logic. The sequence diagram in Fig. 2 describes the communication scheme among these modules throughout the maneuver execution.

Safety Features

Numerous automatic safety checks have been implemented and extended throughout the testing campaign, which in general do not require the pilot intervention and give control back to the autopilot, in case critical or upset conditions are sensed during the maneuvers or glide. The Position Control schedules these control procedures periodically, through the analysis of altitude, airspeed, sink rate, GPS position and attitude in real time. If a maneuver has to be aborted, the Position Control sends a message to the Control Allocator, which interrupts it in case it is still ongoing. The Control Allocator can also prevent the maneuver initiation in the case of out-of-bound ailerons or rudder trim computation. Lastly, the pilot can use two manual switches mapped on the remote control, one safety switch to override the maneuver logic and go back to automatic flight and a standard mode switch to activate the manual flight and immediately regain control, in which case the maneuvers and glide are always aborted.



Figure 3: The SwitchMaster demonstrator.

Conclusions and Future Developments

This work represents a remarkable advancement in the field of DEP advanced research and parametric model identification, since it has produced a complete platform for autonomous and safe flight testing of DEP demonstrators. The better quality of the trim conditions and executed maneuvers, made possible by the features implemented, allows an improved system identification process with respect to that performed with manual piloting [8]. The simulation and software testing subject, part of this project and as much important as the FCS development, will be dealt with in future publications, as it deserves a separate and exhaustive discussion.

In future developments, the whole FCS could be further extended with new functionalities and a more effective control action, starting from a better tuning of the TECS gains and the refinement of the control logic in glide, which in some cases showed poor performance.

In addition, a Total Heading Control System [9] is being evaluated to integrate the sideslip angle estimation into the yaw rate control logic of the Attitude Controller, in order to achieve a better turn coordination. Finally, the FCS should be generalized and adapted to models different from the DEP one, to obtain a portable platform which could support the automatic flight testing of other airframes, possibly also in general aviation. This could involve a change of the underlying software and hardware environment to become feasible.

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