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TAI ROTARY WING UAV MODELING AND FLIGHT CONTROL SYSTEM DEVELOPMENT

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ABSTRACT

An existing Mosquito XE single seat helicopter has been converted to a fully autonomous UAV system. A first principles math model based on adaptation of Sikorsky GENHEL rotorcraft simulation framework on Mosquito platform has been developed. The generated non-linear mathematical model has been used to develop the automatic flight control system (AFCS) and to support Systems Integration Laboratory (SIL) work. The AFCS includes a Stability Augmentation System (SAS) to support external safety pilot during remotely controlled (RC) flights, an autopilot to control angular rates and the position of the helicopter, a navigation algorithm to perform way-point navigation with an emergency mode to return air vehicle to a prescribed point, and an Automatic Take-off and Landing System (ATOLS). The air vehicle has been structurally modified to support the avionics and the electrical system installations. The converted unmanned air vehicle has initially been flown for external safety pilot familiarization and SAS gain tuning after extensive pilot training in the SIL. Real time calibration tests for all AFCS modes have been carried out until satisfactory performance is observed to perform a ground generated mission plan, which may be modified during flight, composed of autotakeoff, way-point navigation and autoland.

INTRODUCTION

The main objective of this paper is to put forward the applied automatic flight control system development and test phases for a rotary wing UAV, flight test results, and some lessons learnt.

At the beginning of the development phase of AFCS algorithms of a Mosquito XE rotary wing platform, which has been made unmanned by Turkish Aerospace Industries, Inc. (TAI), a pilot project with a much more smaller MaxiJoker platform that weighs about 1/25 times the Mosquito platform had been initiated. The purpose was to validate the structure of the controller algorithms firsthand in order to stay on the safe side. The flight test results that are presented in this paper belong to this smaller platform having the same AFCS structure as the bigger one.

Each platform has been mathematically modeled in Matlab/Simulink environment. The inner and outer loop controller algorithms have been developed in the same environment utilizing the corresponding mathematical model. As the next phase, detailed tests in real-time SIL environment have been carried out before flight tests. Throughout the flight tests of the smaller platform, AFCS gains were calibrated and some structural and logical enhancement needs for AFCS algorithms have been determined in order to update the algorithm version of each platform in parallel.

As the maturity of the inner-outer controller structure, mode management and flight management logics was achieved with MaxiJoker platform, with the ground tests, tethered tests and free flight tests respectively in time, calibration process for Mosquito platform has been started.

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MATHEMATICAL MODELING

The non-linear mathematical model is an analytical representation of total forces experienced by the entire helicopter in six rigid body degrees of freedom. Additionally, modular structure with large angle consideration ensures high fidelity in both steady and maneuvering flight conditions [Howlett, 1981]. Computations for the main rotor aerodynamics are based on blade element theory. Each blade segment is subjected to helicopter motion together with the rotor speed and blade motion itself. After the calculation of velocity components of each blade segment, angle of attack and dynamic pressures are determined. For a wide range of angle of attack and Mach numbers, CFD results of the blade geometry are used to find corresponding aerodynamic load for each blade segment. Blade flapping motion is included in the calculation of resulting aerodynamic loads for each blade. This summation includes carrying loads from blade span axes and rotating shaft axes to the fixed shaft axes, and finalizing at the body axes of the helicopter. The fuselage aerodynamic loads are provided by CFD analyses for a wide range of angle of attack and sideslip angles. Airflow at the tail rotor is derived from the free stream velocity under the effect of main rotor and airframe wash. Bailey theory is used in order to compromise tail rotor motion in a linearized closed form [Ballin, 1987]. At the end, aircraft motion module gives the solution of states as the inputs of the next time step.

AUTOMATIC FLIGHT CONTROL SYSTEM DEVELOPMENT

The automatic flight control system (AFCS) is a modular architecture that is governed by a mode-management unit. AFCS is composed of 7 modes: RC and SAS, AP_Inner, AP_Outer, AutoLand, AutoTakeOff, Navigation and Emergency. Each mode is manually selectable by the operator whenever needed. RC mode is used for piloting and safety purposes, AP_Inner and AP_Outer modes are utilized for system calibrations and the remaining modes are used for automatic navigations. All of these modes can be activated at any instant of the flight. In the Figure 1, the overall logic for the control system with the mode management unit is shown.

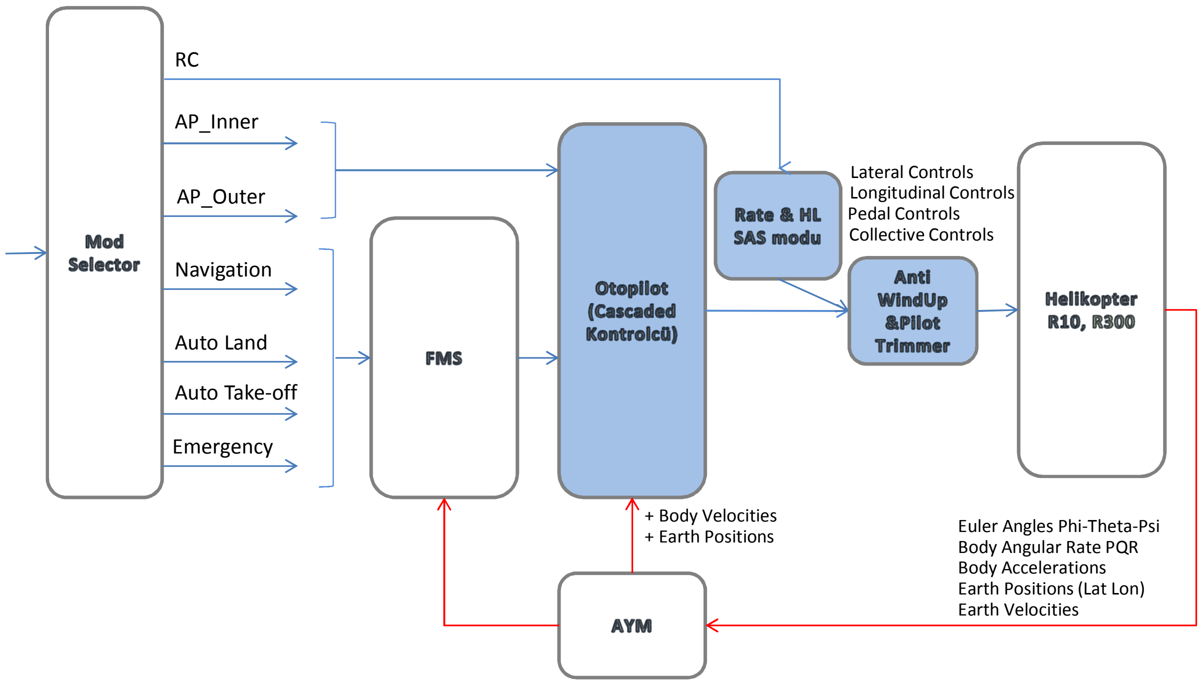

Figure 1: *Mode-management unit and the overall control system*

Stability Augmentation System (SAS), Attitude and Position Hold Controllers

The flight references are directly provided to the servos by the pilot in the RC mode (except pedal axis, during headlock-SAS is operational). In the AP_Inner mode, the reference signals are roll, pitch and yaw angles. The corresponding sensory Euler angular feedbacks are provided to the controller with rotational speed signals for PID controls. In the AP_Outer mode, the reference signals are earth-axis positions. The corresponding sensory earth-axis positions are provided to the controller with velocities. The AP_Outer controller outputs are converted to the inner mode angular references by a transformation module. Therefore the structure is a cascaded controller composed of inner and outer loops when the AP_Inner is not used alone. The details of the controller structure can be found in [Johnson and Kannan, 2002]. The remaining modes generate a reference trajectory to the cascaded control system based on desired ground speed.

Cascaded control module is linked to the embedded inverse linear model (LMI) which is derived from the nonlinear model of the helicopter. LMI produces the lateral, longitudinal and pedal controls to the servo actuators. The collective channel is derived by a PD and PI cascaded controllers. The feedback loops with reference signals are shown in the Figure 2.

In RC mode, the pilot is supported by headlock and rate type SAS modules depending on the selection. Headlock SAS holds the yaw angle at the specified angle whereas the rate-SAS aims only to damp the angular rates.

Transitions to all modes are stable. The mode management system organizes the timings for the control modules to have the appropriate above ground level (AGL)-above sea level (ASL) altitude feedback initializations, integral-resets and mode activation-deactivation instants.

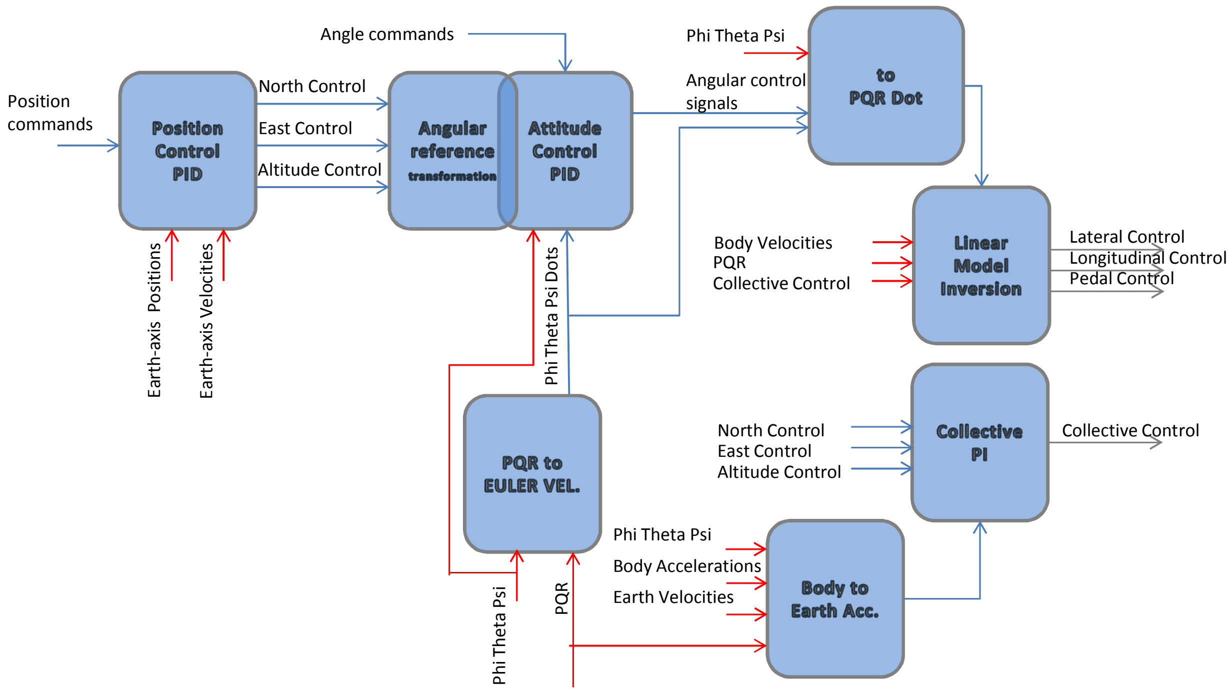

Figure 2: *Cascaded control loops with the feedback signals*

In Figure 3, overall control system performance during a real time flight is shown. The system takes off autonomously and then navigation mode is applied. After mission is successfully completed, the UAV lands autonomously. The internal loop control performance with roll-pitch angular controls are successfully carried out. The position controls in N-E axis is robust in following the desired speed and positions.

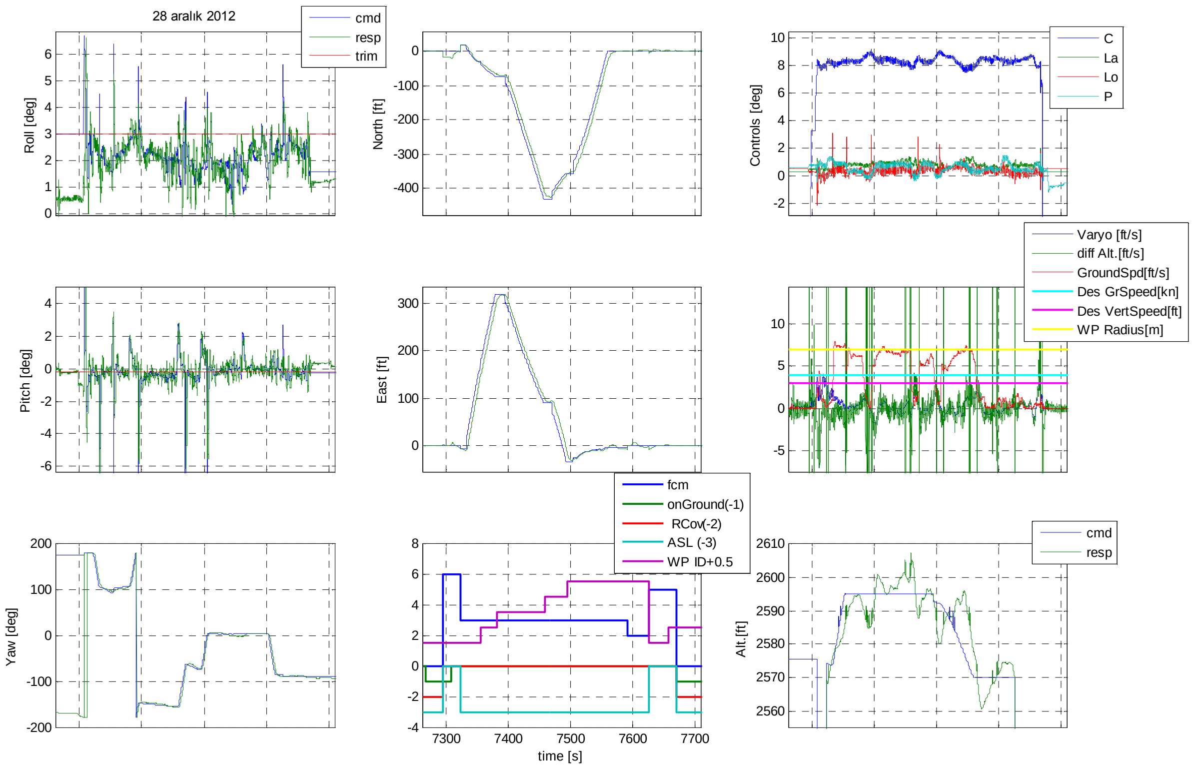

Figure 3: *Cascaded control system performances in terms of NED positions and Euler angles*

Flight Management System (FMS): Way-point (WP) Navigation

The navigation block expects mission plan coordinates, desired ground and vertical speed as inputs. It generates north, east, altitude and heading commands to the inner loop.

In lateral navigation, position and heading commands are determined based on the active WP position and bearing w.r.t. the helicopter. A maneuver logic was written based on the flight tests. Position and heading commands are limited by checking position and attitude in real time. WP is updated after position and speed requirements are satisfied.

Linear trajectory following is commanded in vertical navigation. The altitude command is based on the desired speeds and alongtrack calculation.

Hover can be forced at the way-points. The heading of the hover maneuver is defined in the mission plan.

Figure 4 shows trajectory of an FMS demonstration with a desired ground speed of 6 knots. The turn is in counter clockwise direction. In Figure 5, position commands and responses are shown. The lateral positions are fixed when the helicopter is close to the WP. Speed is reduced for turn. Desired speed is commanded after way-point is updated and heading is suitable for the maneuver. Altitude command is held with a 20 ft maximum error.

High speed FMS trials are shown in Figure 6 and Figure 7. Desired ground speed of 24 knots is commanded. Flights from South to North are achieved with less crosstrack. The heading reading error at South is estimated to be greater than it is at North. Magnetometer is calibrated and heading error is reduced to ±7 degrees with ground tests. The sensor is placed as far as possible from the power lines. However, change in electrical currents can still create hard iron errors. A ground speed of 20 knots is reached towards South. Helicopter flying with sideslip due to heading error experiences more drag. This affects the velocity performance of the FMS. Altitude is held within ±30 ft. The maximum deviations are observed in the acceleration- deceleration phases of the flight.

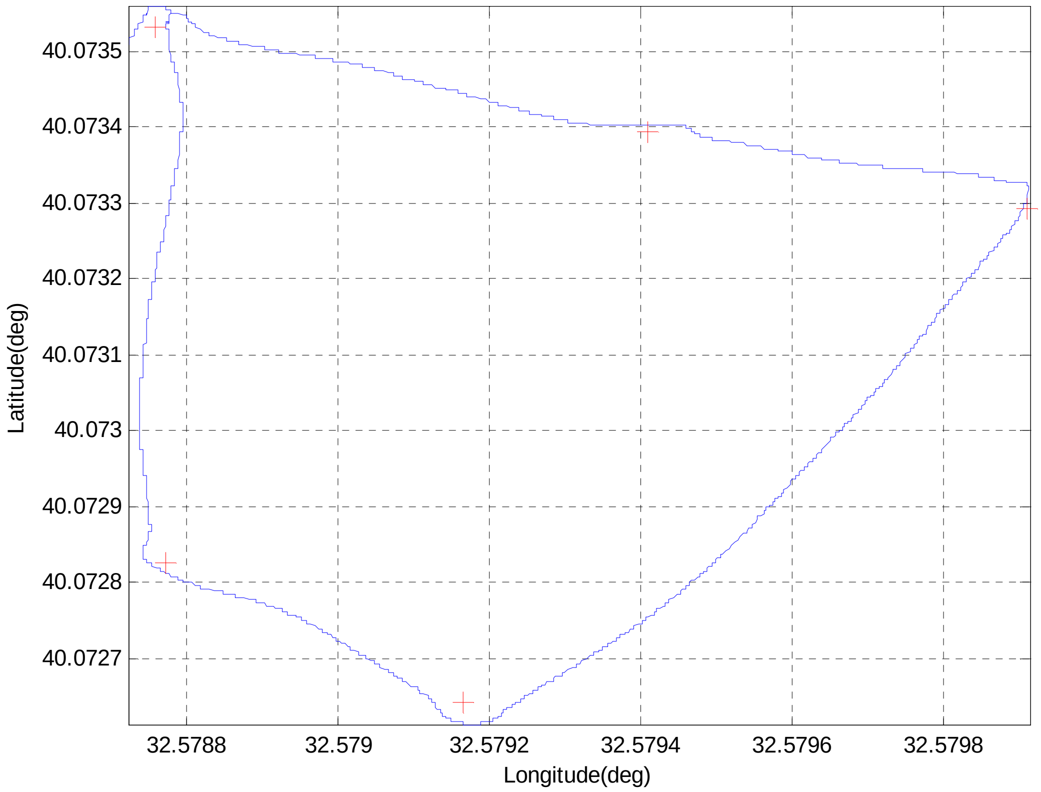

Figure 4: *FMS flight with 6 knots*

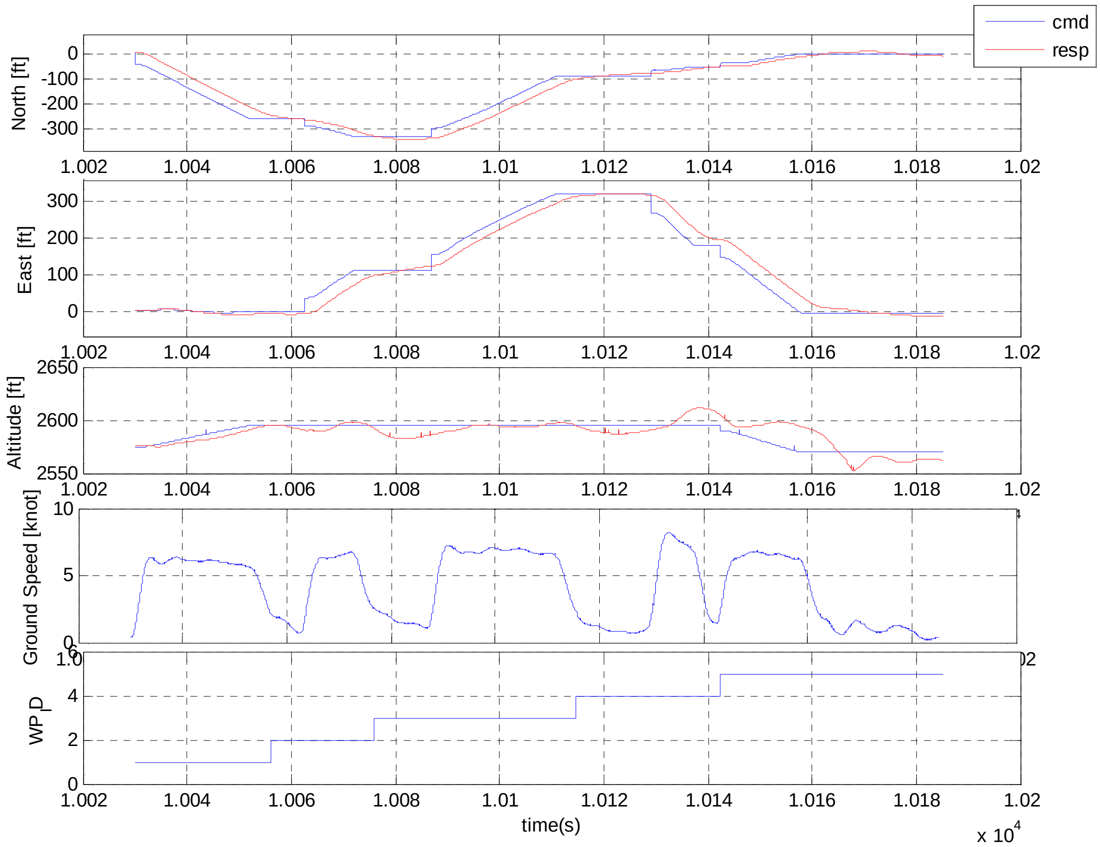

Figure 5: *FMS flight with 6 knots*

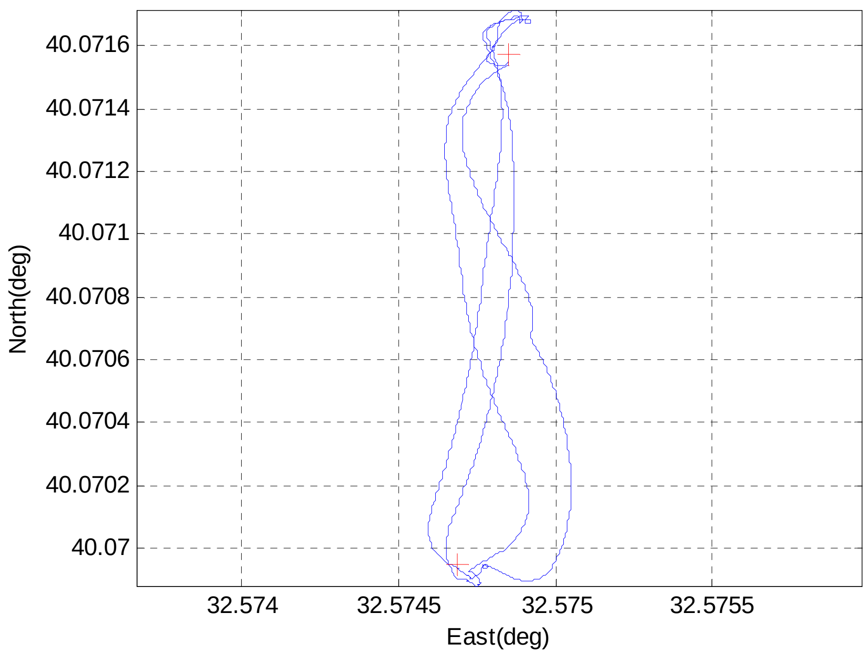

Figure 6: *FMS flight with 24 knots*

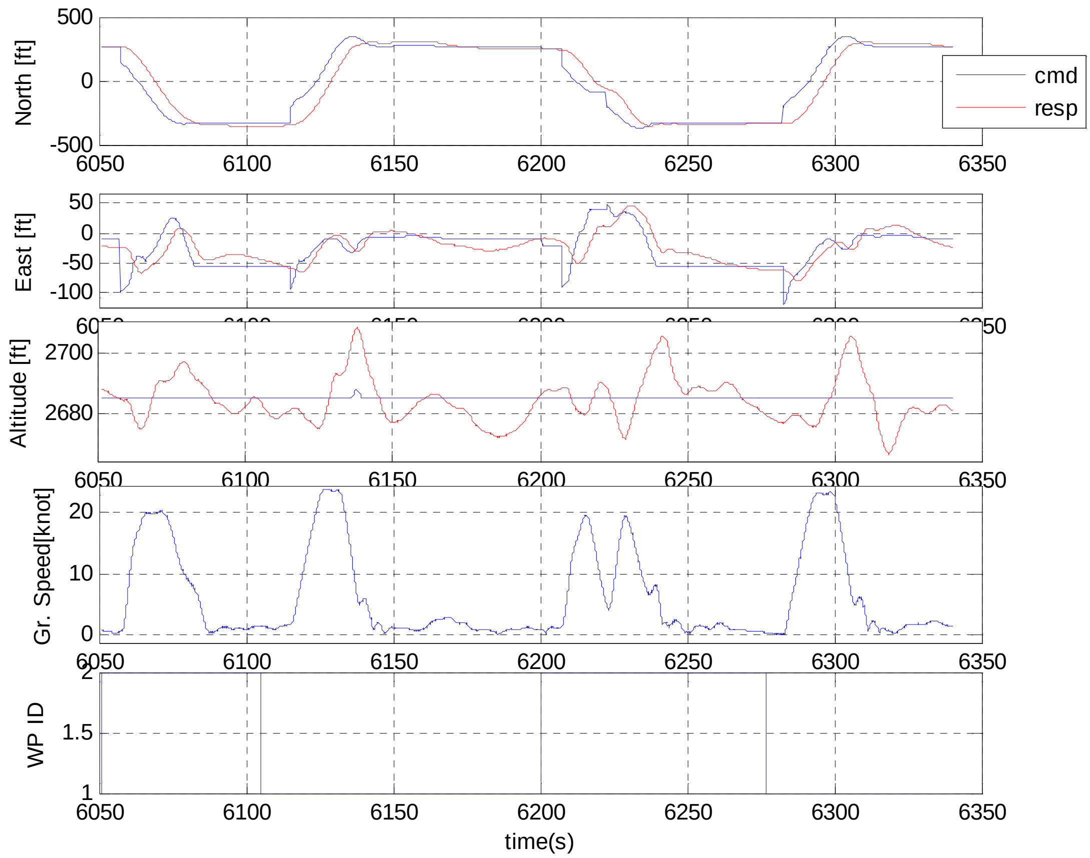

Figure 7: *FMS flight with 24 knots*

Automatic Take-off and Landing System (ATOLS)
Automatic take-off and landing is achieved using relative position data w.r.t. the take-off/landing point. It can be obtained from ultrasonic altimeter and camera. The computations are merged with GPS/barometric altitude data in case of failure of sources. Camera and ultrasonic data is fused with IMU data for better accuracy. In Air/On Ground logic is created for mode switching. The algorithms check consolidated AGL and acceleration signal. ATOLS navigation algorithm is similar to FMS.

Take-off begins with preset commands and SAS. Enough collective is commanded for mild climb and In Air transition. After the transition, a position above ground is commanded.
Figure 8 shows an automatic take off. The preset control commands and SAS are active until 7308-s. At 7303-s, a jump in altitude is observed. This is due to ultrasonic altimeter correction to the altitude data. The controller takes over the system with 15 ft North error and successfully compensates in 5 seconds. The slip towards east is stopped with 8 ft error. Altitude command, which is 20 ft, is held with 3 ft error.
A suitable position above touchdown point is commanded at landing. Algorithms check time, position and velocity for enabling descent. The descent velocity should be high enough to prevent lateral dispersion close to ground and low enough to prevent structural damage. An altitude below surface is commanded to guarantee touchdown. After On Ground transition, pre-defined commands and SAS are activated.
Figure 9 shows an automatic landing example. After the initiation of landing, system controls distance to commanded positions, altitude and speed to determine descent. At 5353-s, a command below ground is generated. Helicopter approaches with a descent rate just above 2 ft/s. Descent rate is reduced just below 2 ft/s before touchdown. Collective reduction because of ground effect can be observed between 5361-s. and 5363-s. A deviation of 7 ft is observed in north direction. This is due to drag change close to the ground.

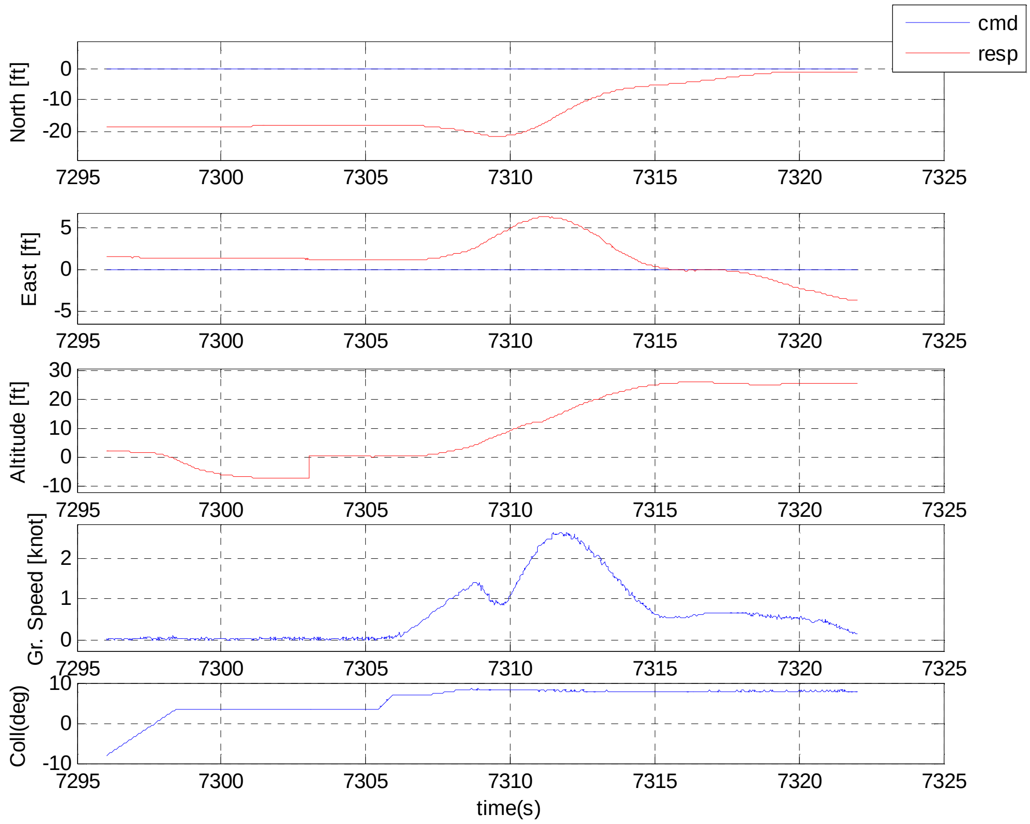

Figure 8: *Automatic Take off*

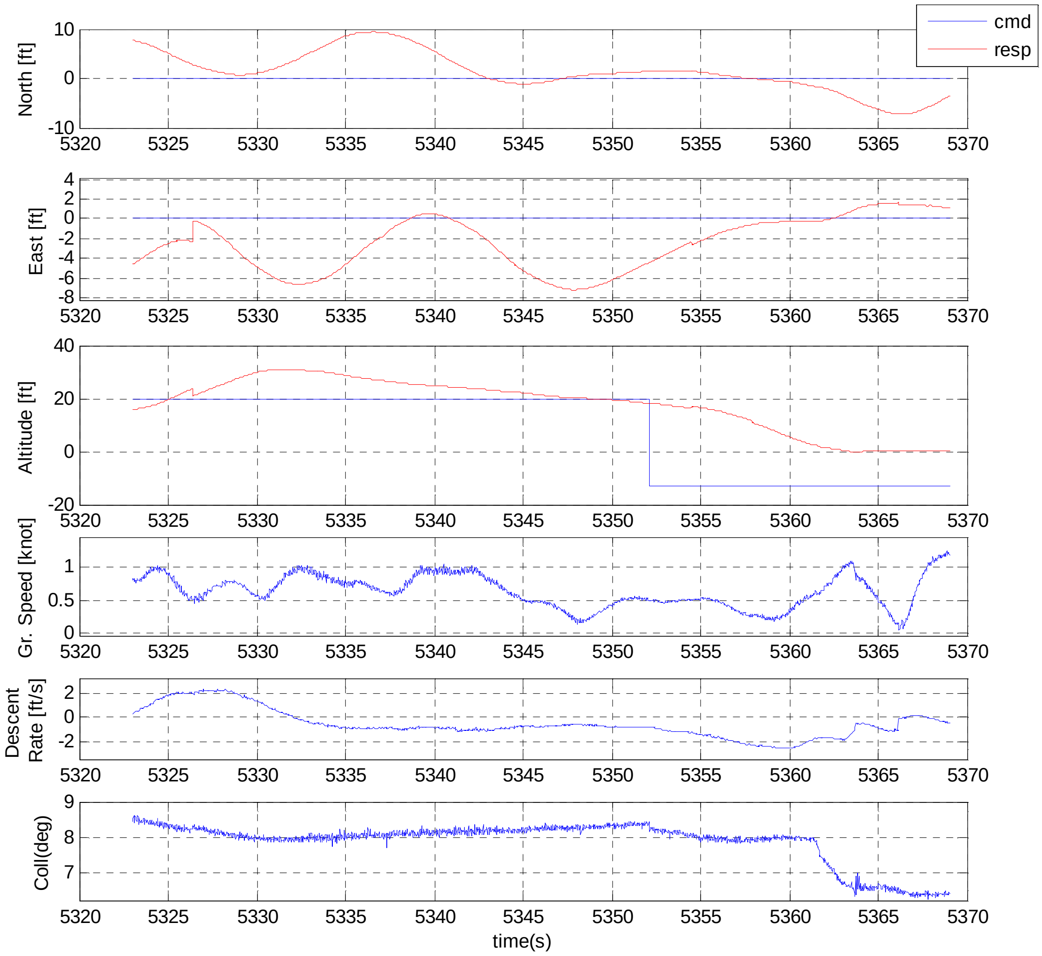

Figure 9: *Automatic Landing*

CONCLUSION

The methodology that includes developing AFCS algorithms for a smaller rotary wing platform and flight testing it accordingly before transition to the bigger platform helped cleaning the AFCS design bugs in a practical way initially since it is easier for the pilot to take over in any case during flights. It is concluded that for this kind of AFCS development methodology that starts with model based design but also relies on flight tests for fine tuning, a backup RC mode together with a calibrated SAS is essential.

During the development phase of the helicopter AFCS algorithms, flight tests for gain and preset command calibrations took a considerable amount of time in addition to necessities that arose for algorithm version updates and SIL tests which were repeated after each update. It is obvious that this period is unavoidable but with a more representing mathematical model of the helicopter, it could be shortened.

Mathematical model of helicopter dynamics will be improved by adding rotor transient wake distortion effect on inflow model [Zhao, 2005]. This expectance is supported by vortex tube analysis which will model the aerodynamic interaction among helicopter components with main rotor during maneuvers. Additionally, flight tests are planned in order to realize system identification of helicopter dynamic model and so the lacking sides of the model will be completed.

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