IFSYS - A TU BERLIN UAV STUDENT PROJECT

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ABSTRACT

A student project for developing an automatic, unmanned aerial system (UAS) at the Institute of Aeronautics and Astronautics of the Technical University of Berlin is presented. Its objective is to improve aeronautical education especially in the area of flight physics and flight control. The project, called IFSys (Intelligent Flying System), offers students the opportunity to be involved in the complete life cycle of an aircraft from design, over production to operations and maintenance.

This paper explains how IFSys addresses this objective, describes how the design mission was selected, and outlines the general UAS concept with special emphasis on the automatic flight control system and the flight control law architecture.

1 INTRODUCTION

In spring 2006, TU Berlin launched the program “Offensive Wissen durch Lernen (OWL)”. Its goal is a sustained improvement of education and the support of the introduction of the two-cycle system (undergraduate / graduate) that is currently implemented at TU Berlin. As part of OWL, the student project IFSys (Intelligent Flying System) has the objective to offer students the opportunity to be involved in the complete aircraft life cycle from design, over production to operations and maintenance by developing an unmanned aerial system (UAS) on their own. The project lasts 3 years running from April 2006 until March 2009.

The multi- and interdisciplinary aspects of flight mechanics and flight control and the resulting requirements for education of undergraduate and graduate students is underlined in [10] and [11]. In [10] Schroeder and Field provide their personal view of how flight mechanics should be taught at universities in the US. In [11], Field summarises the results of the discussion on atmospheric flight mechanics education during a special AIAA panel session at the Atmospheric Flight Mechanics Conference in San Francisco in 2005.

Taking the importance of the interdisciplinary aspects into account, the IFSys project is an excellent platform to accomplish linkage between different disciplines like flight mechanics, aerodynamics, aircraft design, electronics, information technologies and project management. The IFSys project objective is to develop a deep understanding of the key aeronautical technologies and generate competences through the combination of theory and practice producing and operating the system.

So the interest lies not in building a specific unmanned aerial vehicle (UAV) that has special characteristics such as ultra-small, ultra-large, highly manoeuvrable or extended endurance. To succeed the students have to develop the system on their own applying the methods they have learned in lectures, and to demonstrate the capabilities of the self-developed model aircraft. Of course, more ambitious goals can be aimed for, if the first UAV and its payload is operating as planned.

1.1 Definitions

The term *unmanned aerial vehicle (UAV)* comprises the model aircraft with the automatic flight control system (AFCS), which includes the flight control computer (FCC), the flight control laws (FCL), the actuators, and the sensors, as well the remote control system that is integrated as a back-up during flight testing.

The term u*nmanned aerial system (UAS)* comprises all components needed for automatic unmanned flight operations. It includes the UAV, and in addition a ground station (GS) for mission planning and mission control, the payload, and the data links (DL) for payload and mission control.

1.2 Project plan

According to the project objectives, a tutor formed a group of approximately 10 students, which structured the work and defined the following work packages:

1. Project management,
2. Unmanned aerial system,
    - UAV development und manufacturing
    - Data link,
    - Ground station,
    - Simulation and test,
    - Payload (to be addressed later),
3. Flight testing and flight operations,
4. Public relations, marketing.

The tasks are shared between the students and are preferably processed in study and diploma theses. The target is an average of 5 theses per year. To guarantee the projects success one tutor is employed as project manager. Another tutor who shall operate the UAS in the third year will support him.

1.3 Milestones

Project success is measured by completion of the following milestones in due time:

M1 (07-2007): Mission and aircraft are defined, general UAS concept is available.

M2 (09-2007): Roll out of the UAV, 1st remotely controlled flight, AFCS concept defined,

M3 (06-2008): UAV is completed,

M4 (03-2009): UAS completed, 1st automatic flight, Final report delivered.

1.4 Sustainability

For sustainability, the UAV is developed as a modular system. This allows students exchanging certain modules by more sophisticated ones and to reuse the rest of the airplane. For example they may try to optimise aircraft performance by designing a new wing, or they may adapt the UAV to other missions with different types of payload, or they may investigate additional automatic functions by modifying the flight control laws. At a later stage, a lecture on UAS could be adopted as well.

2 MISSION AND AIRCRAFT CONCEPT

In the beginning of the project all student project members defined the mission, the fundamental UAS concept and the aircraft concept. These definitions and concepts are explained in the following sections.

The definition of the flight mission has to consider manifold restrictions regarding aircraft size and the air space, in which a UAV can operate. There are legal, financial, technical and operational constraints. The legal constraints are related to mass of the aircraft, airspace and operations. The most suited approach for a student project is a UAV in the class of model aircraft. If it is lighter than 25 kg, the UAV may operate on model airfields without special permission under supervision of a safety pilot [1]. The safety pilot does not need a licence, but he must have the airplane always in sight. That means the airplane flies in front of the pilot.

A safety concept shall guarantee that a safety pilot can take control whenever it becomes necessary. It should be possible for him to fly the UAV safely without exceptional piloting skills.

2.1 Design mission

The distance up to which the safety pilot can see the airplane limits the area in which the aircraft may fly. It is assumed that this is 1km. That is the range that manufacturers of remote control (RC) systems guarantee for their telemetry. To have a safety margin to trees and other obstacles, the UAV shall typically operate between 70m and 100m above ground. The aircrafts operations are limited by restrictions of airspace class G. The cruise speed is specified as V_A=20m/s. The minimum duration of a mission shall be 20 min.

FIG 1 shows the design mission. The task of the UAS is a generic one: it shall completely observe a given area with a camera. The weight of the camera can be up to 1.0kg as this is the maximum payload. Other payloads could be infrared sensors or probes, which measure chemical or biological particles in the air. Currently there is no intention to develop or to procure specific sensors. But this is an option for the future.

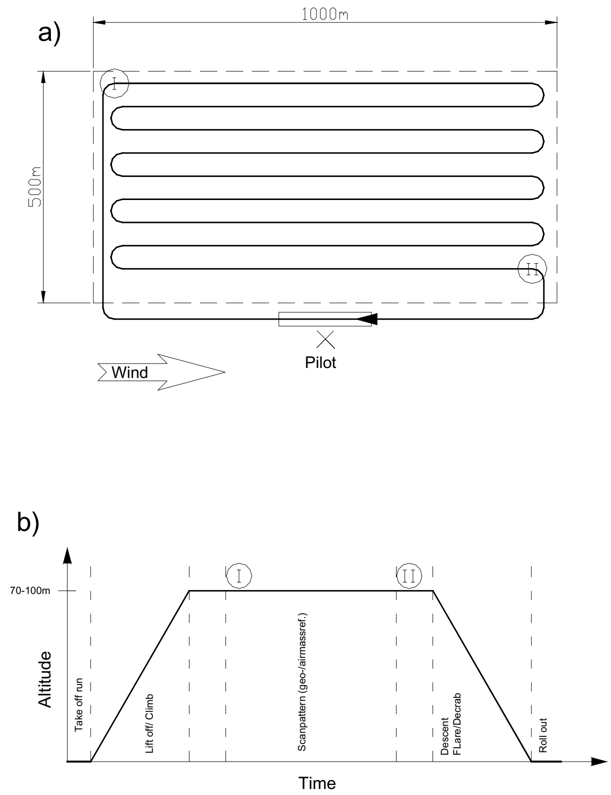

FIG 1: a) horizontal flight pattern, b) vertical profile

2.2 Aircraft concept

The students analysed the mission requirements and the mentioned constraints and derived the following aircraft concept.

The payload size and mass lead to an approximate aircraft weight of 9kg. An unswept wing with a large aspect ratio was selected to have minimum induced drag and a good lift to drag ratio. This yields maximum endurance for the observation mission.

The fuselage contains the payload, the engine, all computers sensors and data link components. It should also have some additional space for future additions and modifications. Therefore, a fuselage with a large volume is designed. This also has the advantage that less thermal problems and less electro magnetic interference problems have to be expected.

A pusher configuration was chosen to have enough unperturbed space in the aircraft's nose for the payload and to reduce the propeller slipstream impact on the wing aerodynamics. For the same reason the horizontal and vertical stabilizer have a negative V-shape. The rear fuselage is made of carbon fibres and arranged to protect the propeller and the engine against ground contact during rotation or landing. The aircraft's configuration is shown in FIG 2 and the characteristic data are given in TAB 1. An electrical motor was chosen to reduce emission and vibration. Electrical motors do not influence the location of the centre of gravity (cg) because no fuel is consumed. Their disadvantage is the low energy density.

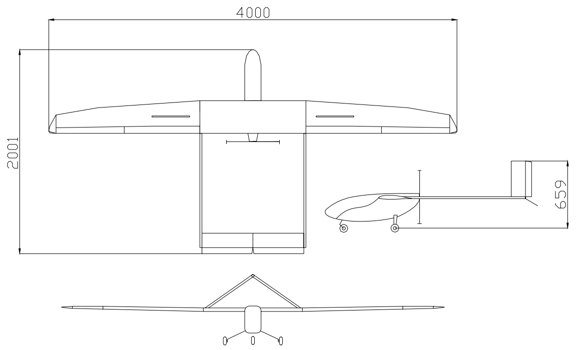

FIG 2: Aircraft concept

Mass	m	9 kg
Aspect ratio	Λ	11,2
Cruise speed	V_a	20 m/s
Payload	m_{pay}	1 kg
Motor performance	kW	1.5
Propeller diameter	d	20''

TAB 1: Characteristic data

3 UAS CONCEPT

The overall architecture of the UAS is divided into an airborne and a ground segment, as FIG 7 shows. The system is built from low-cost, off-the-shelf and self-developed equipment.

3.1 Data links

For communication between airborne and ground, three data links are provided. (i) The operator on ground communicates with the AFCS via a flight-critical data link that is realised by radio modems. Top-level commands like flight plan or mode changes are send to the UAV (uplink) and flight parameters for monitoring are transmitted via the downlink. (ii) A non standard RC receiver and a standard transmitter provide a back-up data link channel for the safety pilot. (iii) The data link for the payload (camera) is not defined yet.

The airborne components communicate via RS 232 data links among each other.

3.2 Automatic flight control system

The AFCS facilitates automatic flight. Its airborne segment consists of the following four subsystems plus the data link:

- the sensors to acquire the flight states,
- the Flight Control Computer (FCC), on which the flight control laws and the data fusion are implemented,
- the actuation for control surfaces and the engine, and
- the RC receiver, on which the safety concept relies.

3.2.1 Sensors

The sensor system, which is in FIG 9 on the left-hand side, consists of the following components:

- a self developed air data system,
- a commercial Differential GPS,
- a commercial magnetometer,
- a self developed Inertial Measurement Unit (IMU), and
- a height sensor.

The air data system is designed as a modular unit that determine $V_a, \alpha, \beta, q_{dyn}, H_{baro}$. The computation of those values requires total and differential pressure sensors and a temperature sensor. A microcontroller does the A/D signal conversion and the computation.

Position and attitude are measured via a Differential GPS and three axes magnetometer.

For sensing inertial accelerations and rates an IMU[1] is used and calibrated[2]. The information has to be A/D converted. For this purpose an A/D converter was developed.

The height will be measured either by an ultrasonic sensor or by miniature radar.

3.2.2 Flight Control Computer

The Flight Control Laws (FCLs) are computed on a single lane Flight Control Computer (FCC). For the FCC a PC 104 System is used, as it is small, light, has low power consumption and has sufficient computing performance. In combination with a standard operational system (Windows CE or Linux) there is no special programming knowledge necessary, as it would be the case for micro controller. The FCLs will be programmed in SIMULINK and compiled via the Real Time Workshop. The FCC has a 500 MHz AMD CPU, 512 MB Ram, a 2GB Flash disc and a variety of I/O modules, including 8 RS 232.

3.2.3 Actuators

FIG 3 shows the engine and the aerodynamic control

[1] The IMU is a loan by the Institute of Technical Computer Sciences, Real Time Systems & Robotics, TU Berlin.
[2] The calibration is part of a student thesis and uses takes place at the department of Space Technology of the Institute of Aeronautics and Astronautics, TU Berlin

surfaces, each actuated by an electrical servomotor, which are used for automatic control. There are:

1) two ailerons,
2) rudder functionality (asymmetric deflection of the V-shape empennage),
3) elevator functionality (symmetric deflection of the V-shape empennage),
4) two airbrakes,
5) two flaps (useable for direct lift control, DLC), and
6) a 1.5 KW engine with a fix 2 blade propeller.

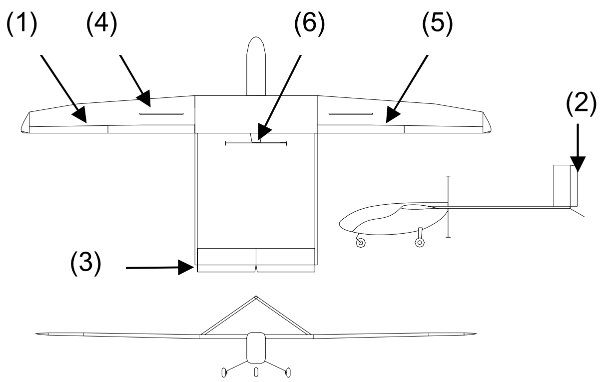

FIG 3: Actuation overview

3.2.4 Safety concept

For the safety concept, the safety pilot has always the chance to overrule the controller via the ACT Diversity Receiver. This concept is similar to the teacher/student mode in modern remote control systems. In this case the AFCS is the student.

3.2.5 Sensor system

FIG 9 gives an overview of the sensor system that consists of multiple sensors and the data fusion software that is computed in the FCC together with the flight control laws.

An Integrated Navigation System (INS), shown in FIG 8, is developed to measure inertial data and compute navigation information. The low-cost INS provides good short-term accuracy but needs aid from an external source that has good long-term accuracy. Here, a DGPS is used. A number of INS-GPS integration schemes exist: (i) uncoupled, (ii) loosely coupled, (iii) tightly coupled, and (iv) deeply coupled systems. The closer the coupling is the higher is the precision that can be yielded. However, the computation effort increases with closer coupling. As a good compromise a tightly coupled approach is projected. The significant advantage compared to loosely coupled systems is that even with less than four satellites the INS can be aided by DGPS and hence the navigation errors in such phases can be decreased. A disadvantage is the higher integration effort [2].

FIG 4 shows the micro controller and the sensors for the air data system. A student from the Faculty of Electrical Engineering and Computer Science designed the system hardware. This example shows that the student project team is capable to find group members with required expert knowledge not only in the Institute of Aeronautics and Astronautics and in the faculty of Mechanical Engineering and Transport Systems but also in other faculties.

To increase the signal quality over a wider frequency range a complementary filter as shown in FIG 10 is under construction. The filter will combine the measured angle of attack α and the kinematical angle of attack α_K as well as the sideslip angle β and the kinematical sideslip angle β_k.

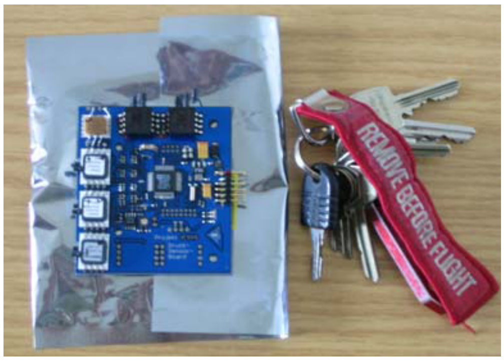

FIG 4: micro controller and the sensors for the air data system

As the measurements of α and β contain high-frequency noise, they both are low-pass filtered. The kinematical sideslip angle that is calculated by integration of the non-linear side force equation, eq. (1). β_k is accurate in the higher frequency band but contains a bias that is eliminated by a high-pass filter.

$$(1) \quad \dot{\beta}_k = \frac{n_y g + g \sin\Phi \cos\Theta}{V_k} - r_k + p\alpha_k$$

$$\beta_k \approx 0, \cos\alpha_k \approx 1$$

High-pass filtering is necessary as well for α_K which is calculated by eq. (2), see [3].

$$(2) \quad \alpha_k = \frac{\Theta - \gamma}{\cos\Phi}$$

3.2.6 Flight control law concept

The task of the AFCS is a 4D (3D plus time) navigation of geo-referenced trajectories or air mass referenced navigation. The geo-referenced mode is used for scan pattern. The air mass referenced mode is used to investigate the air. For a complete mission the following modes have to be implemented:

- Take off run and lift off,
- Air mass referenced navigation ($V_{A\,com}, H_{baro\,com}$),
- 4D navigation ($North_{com}, East_{com}, H_{com}, V_{k\,com}$),
- Flare and decrab,
- Touch down and roll out,
- Go around.

The control system has three hierarchical levels, each with a dedicated control loop, as FIG 13 shows. The control loops are:

- Navigation control,
- Outer loops,
- Inner loops.

Trajectories are generated on ground as part of the mission planning and the resulting navigation commands are transmitted via radio modem to the AFCS.

This paper focuses on the fundamental concepts of the inner and outer control loop. The flight control law concept was developed and realised by an aerospace student in a diploma thesis [4]. It uses the model following concept for the inner loops and the ideas of the total energy control system for the outer loop.

Inner loop control

The inner loops use a model following approach, as shown in FIG 5. The Matrix $\underline{\underline{H}}$ generates a pre-command to achieve a satisfactory initial and steady state response. The error between model states ($\underline{x}_M$) and process states ($\underline{x}$) is determined and minimised by error feedback through the error matrix $\underline{\underline{M}}$. In this way, it is achieved that the dynamic behaviour of the process equals the ideal model behaviour. The feedback matrix $\underline{\underline{K}}_M$ allows modifying the dynamics of the process independently.

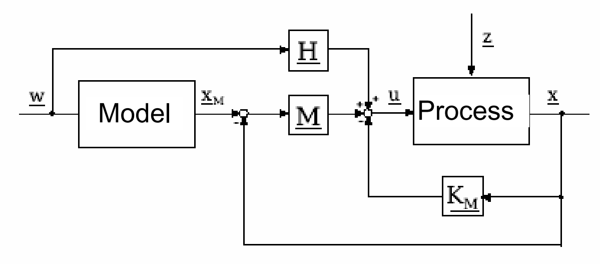

FIG 5: Model following approach (parallel structure) [4]

In this parallel structure, the dynamics of the controlled process depend on the matrices $\underline{\underline{M}}$ and $\underline{\underline{K}}_M$. The process and the model blocks are coupled only via $\underline{\underline{M}}$ and the process states are not fed back into the model.

With the introduction of $\underline{\underline{K}} = \underline{\underline{K}}_M + \underline{\underline{M}}$, the structure can be transformed into an equivalent serial structure ([4], [5]).

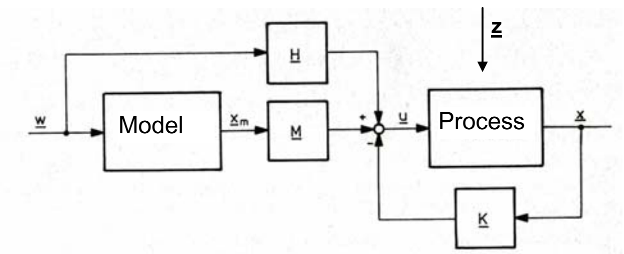

FIG 6: Model following approach (serial structure) [5]

Therefore, the disturbance dynamics of the process are dependent on $\underline{\underline{K}}$ and the model dynamics are dependent on $\underline{\underline{K}}_M$. The process and the model dynamics are still coupled via $\underline{\underline{M}}$. The structure's advantage is the possibility to design the reference reaction independently from the disturbance reaction as eq. (3) shows.

$$
\begin{bmatrix} \dot{\underline{x}} \\ \dot{\underline{x}}_M \end{bmatrix} = \begin{bmatrix} (\underline{\underline{A}} - \underline{\underline{BM}}) & \underline{\underline{BM}} \\ \underline{\underline{0}} & (\underline{\underline{A}}_M - \underline{\underline{B}}_M \underline{\underline{K}}_M) \end{bmatrix} \begin{bmatrix} \underline{x} \\ \underline{x}_M \end{bmatrix} + \dots \\
\cdot \begin{bmatrix} \underline{\underline{BH}} \\ \underline{\underline{B}}_M \underline{\underline{H}} \end{bmatrix} \underline{w} + \begin{bmatrix} \underline{\underline{E}} \\ \underline{\underline{0}} \end{bmatrix} \underline{z} \tag{3}
$$

In all three axes, second order models are used: an approximated short period model represents pitch dynamics, a Dutch roll model characterises yaw dynamics and a roll model for the bank angle represents roll dynamics.

Total Energy Control System

In [6], [7] and [8] the "Total Energy Control System" (TECS) is introduced as a concept to control the aircraft by energy principals. It is a multi-input, multi-output approach. TECS can be divided into two parts: the TECS core (see FIG 11) and the part that describes the TECS architecture and the mode hierarchy. For the IFSys flight control system the architecture and mode hierarchy are modified compared to the original one in [6] and [7]. The modified hierarchy is shown in FIG 12.

TECS core

Considering the aircraft as a point mass, its total energy is given by the sum of potential and kinetic energy:

$$
\begin{aligned} E_{total} &= E_{pot} + E_{kin} \\ E_{total} &= mgH + \frac{m}{2} V_k^2 \end{aligned} \tag{4}
$$

Differentiation of the total energy yields the energy rate:

$$
\frac{dE_{total}}{dt} = mg(\dot{H} + \frac{V_k}{g} \dot{V}_k) \tag{5}
$$

which can be made to the dimensionless energy rate, if it is divided by weight and flight path velocity:

$$
\dot{E}_{spez} = \frac{\dot{E}_{total}}{mgV_k} = \frac{\dot{H}}{V_k} + \frac{\dot{V}_k}{g} = \gamma + \frac{\dot{V}_k}{g} \tag{6}
$$

The thrust is the main energy source of an aircraft. Therefore, the thrust is the preferable control variable for the energy rate.

For redistribution of potential and kinetic energy that is for example necessary if the aircraft is too high and too slow, the energy distribution rate parameter $\dot{L}_{spez}$ is introduced:

(7) $\dot{L}_{spez} = \gamma - \frac{\dot{V}_k}{g}$

The elevator deflection is the preferable control variable for $\dot{L}_{spez}$.

Proportional feedback of $\dot{E}_{spez}$ to thrust and $\dot{L}_{spez}$ to the elevator replaces feedback of γ and $\dot{V}_k/g$.

For steady state commands γ_{com} and $\left(\dot{V}_k/g\right)_{com}$, integral control terms need to be used. The extra zero of a PI-controller, which tends to cause an overshoot in the transient command response, can be avoided by using the error signals only in the integrated control path, while the proportional control paths use the feedbacks of γ and $\dot{V}_k/g$. This leads to the following control laws that are implemented in the TECS core shown in FIG 11:

(8)
$$F_{com} = \left[\left\{\left(\gamma_{com} - \gamma\right) + \frac{\dot{V}_{k\,com} - \dot{V}_k}{g}\right\}\frac{K_{TI}}{s} - \left(\gamma + \frac{\dot{V}_k}{g}\right)K_{TP}\right]$$
$$\eta_{com} = \left[\left\{-\left(\gamma_{com} - \gamma\right) + \frac{\dot{V}_{k\,com} - \dot{V}_k}{g}\right\}\frac{K_{EI}}{s} + \left(\gamma - \frac{\dot{V}_k}{g}\right)K_{EP}\right]\ldots$$
$$\ldots + \text{inner loops}$$

TECS architecture and mode hierarchy

The TECS concept provides an easy implementation of numerous modes and protections. For the AFCS the essential modes are:

- Air mass referenced navigation ($V_{A\,com}, H_{baro\,com}$), and
- 4D navigation ($Lat_{com}, Long_{com}, H_{com}, V_{k\,com}$).

Important protections are:

- maximum load factor $n_{Z\,max}$,
- maximum and minimum (stall) speed V_{max}/V_{min}.

The load factor protection is implemented by a $\dot{\gamma}$ limitation, as shown in FIG 12.

Due to the two navigation modes the measured height has to be switched from barometric height (H_{baro}) to geo-referenced height (H_{corr}). If the UAV flies below a certain height, the height information will be linearly blended to height above ground (H_{RA}).

The control law for the TECS core commands are generated via eq. (9).

(9)
$$\gamma_{com} = \frac{(H_{com} - H)K_H}{V}$$
$$\frac{\dot{V}_{k\,com}}{g} = \frac{\left(V_{k\,com} - V_k\right)K_V}{g}$$

This concept shows good performance with regard to 4D navigation and disturbance rejection [4].

4 CURRENT PROJECT STATUS

The IFSys project is well on track. Milestone M1 is completed, as presented. Milestone M2 is completed as well. The target of 5 study/diploma theses per year is reached for the first year. The development of a flight simulation program is in progress [9] as well as the control law design for the AFCS and the development of the air data system and the inertial navigation system.

Details on the progress can be found at the projects homepage:

http://www.ilr.tu-berlin.de/htdocs.ILR/ILR/index.html .

5 CONCLUSION

The student project IFSys has started promisingly. It seems that its objective to train students in developing a deep understanding of the key aeronautical technologies and to generate competences through the combination of theory and practice by producing and operating the system, will be achieved.

6 ACKNOWLEDGEMENTS

The work reported on herein was financed by the TU Berlin program “Offensive Wissen durch Lernen”. Furthermore, we want to thank Prof. Dr.-Ing Gernot Hoffmann, Emden, for providing extensive material on the UAS that he had developed and the Institute of Technical Computer Sciences, Real Time Systems & Robotics, TU Berlin, for the loan of the IMU.

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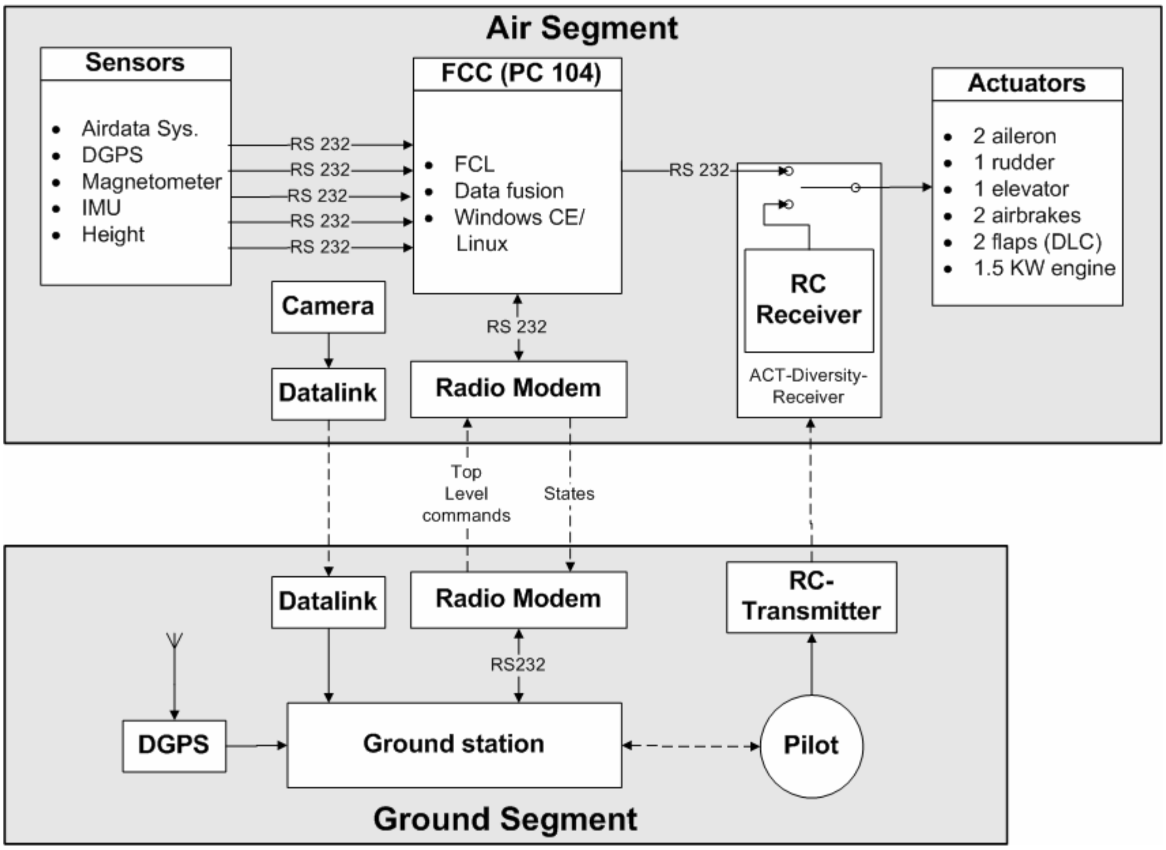

FIG 7: System architecture

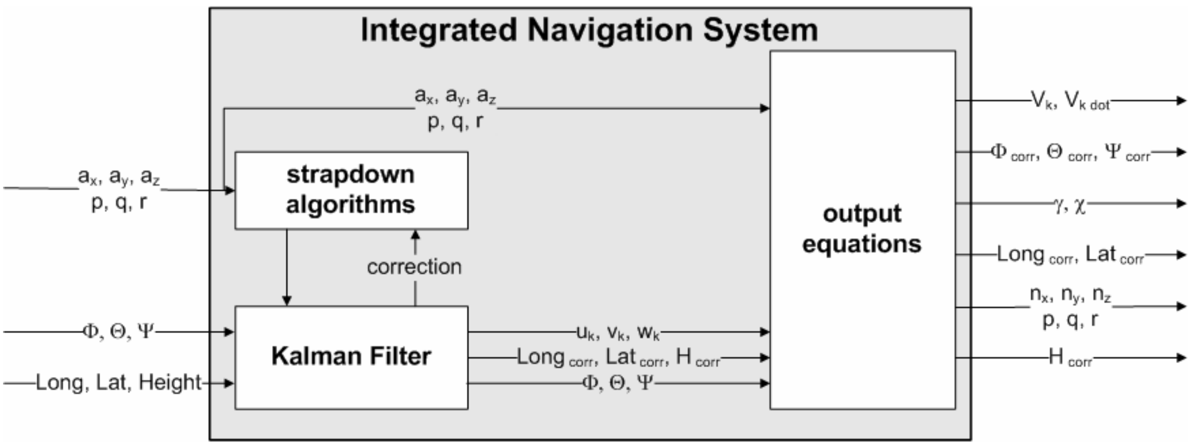

FIG 8: Integrated Navigation System (INS)

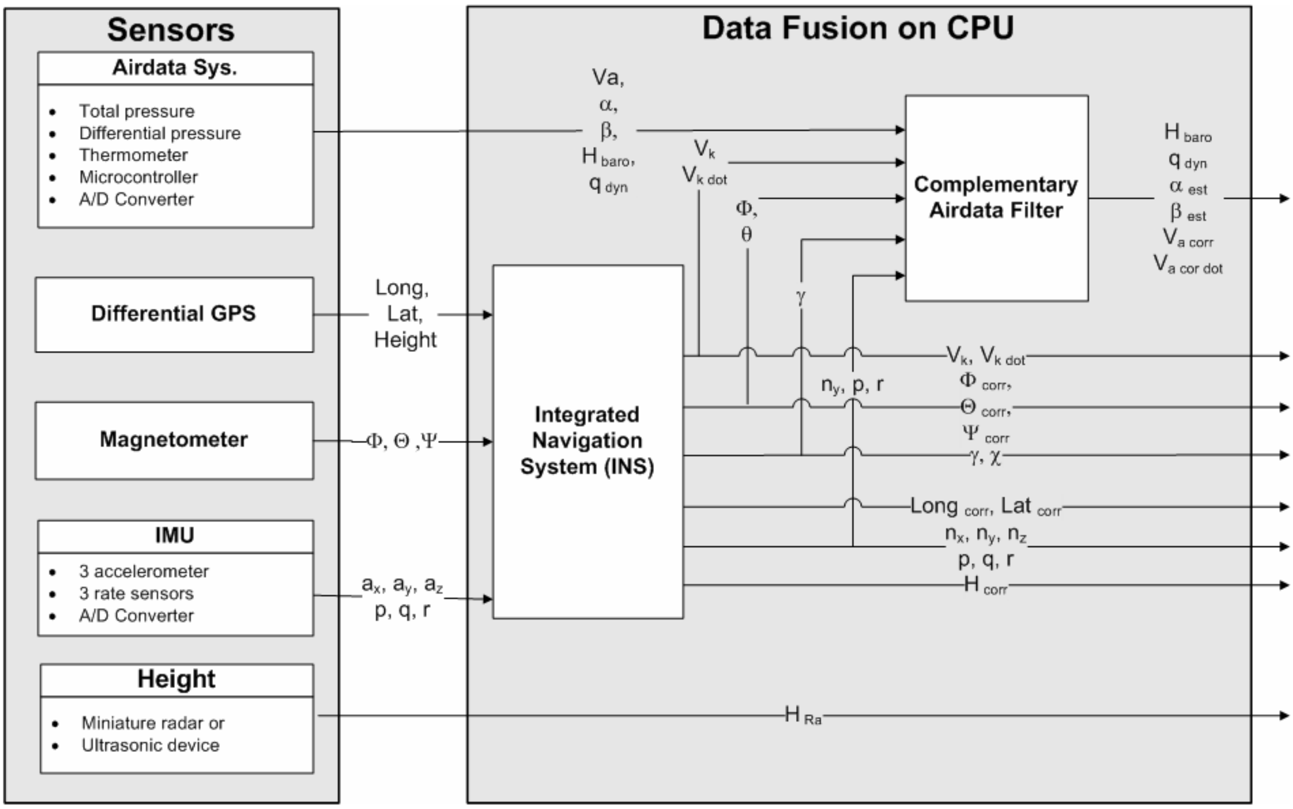

FIG 9: Sensor and Data Fusion overview

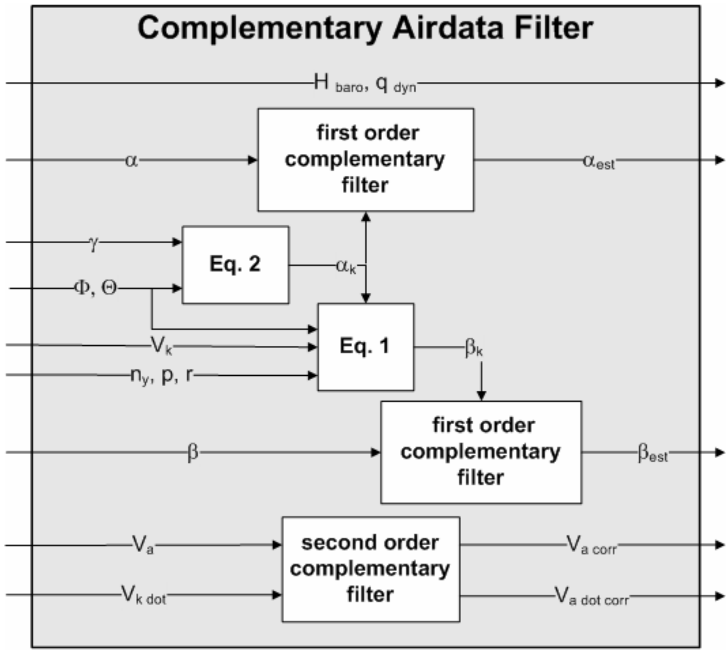

FIG 10: Complementary air data filter

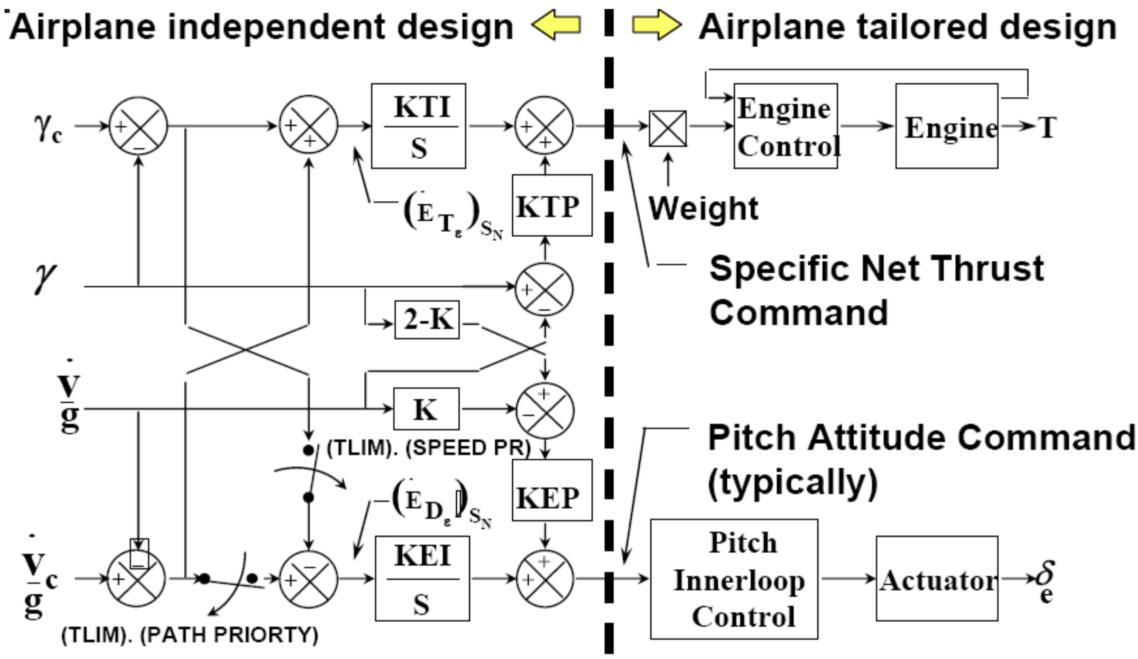

FIG 11: TECS core [8]

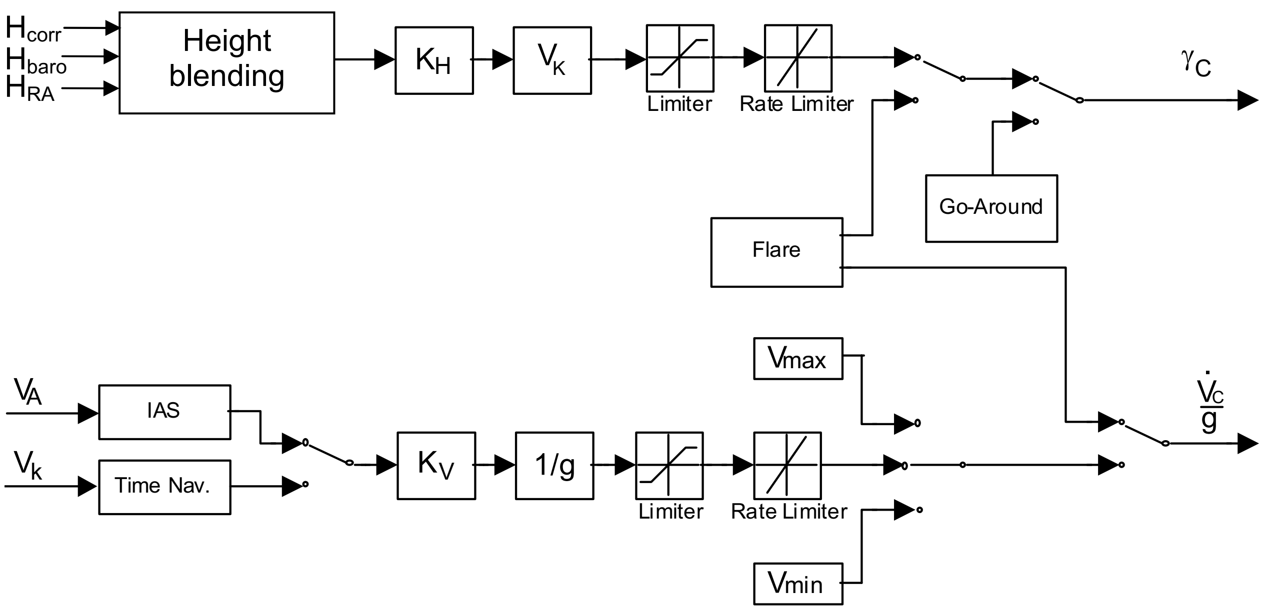

FIG 12: Modified TECS architecture

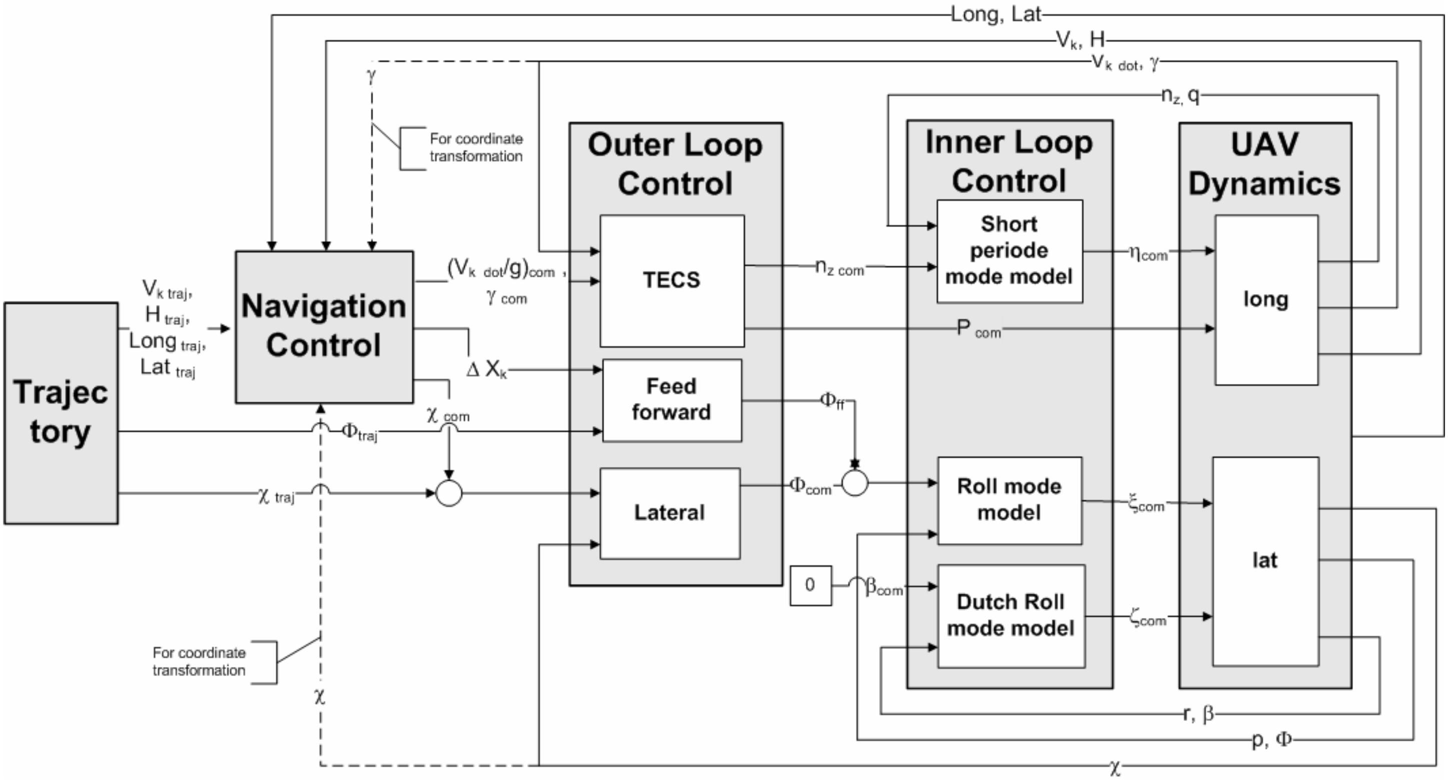

FIG 13: Flight control law overview