FLY BY WIRE FOR MODEL AIRPLANES

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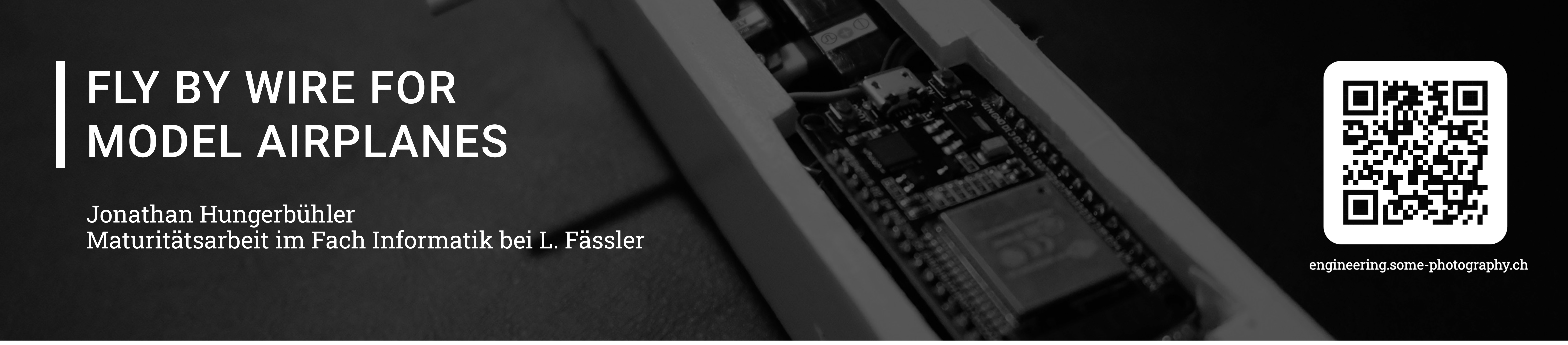


PROBLEM DESCRIPTION

A FBW-System forms an electronic link between the pilot and an aircraft’s components. This serves to increase controllability and safety of any given system.

The intention of this project was to create a functioning fly by wire system (FBW system) with a dedicated aircraft. To achieve this all relevant physical aspects regarding rigid body movement and fluid dynamics where considered. Said information was then used to construct a model of a fixed-wing aircraft. The resulting airframe was then fitted with the appropriate electrical systems to serve as a testing platform for the proposed flight controller and its associated algorithms. These form the main part of the project, ranging from telemetry handling, data acquisition and extended linear quadric state estimation to solution approaches for optimal control problems via closed loop policies. This allowed the implementation of a two axis attitude tracking servo as well as a yaw damping mechanism that fully manages the rudder during flight maneuvers. After the model aircraft was equipped with the FBW system, numerous flight tests were made to determine the tuning parameters. The most successful flight extended over about 200 meters.

FIXED WING AIRFRAME

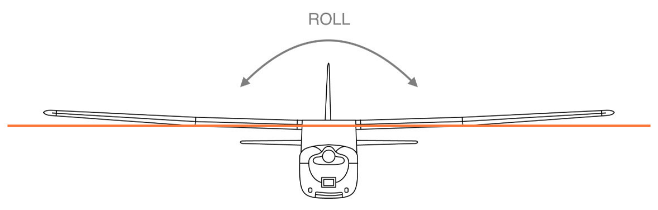
The mechanical design of the unmanned aerial vehicle (UAV) was centered around maximizing the vehicle’s efficiency to increase possible real-world applications. The airframe had to be modeled around a large payload carrying capacity and should offer good fuel efficiency. The set design criteria are best met by a fixed-wing design, which creates lift through immovable airfoils. This also comes with the added benefit of greater stability compared to rotary wings, further increasing system reliability.

WING CONFIGURATION

The wing configuration is a major aspect of fixed-wing airframe design, dictating most of the plane's roll dynamics. If the wings of an aircraft are located above the center of mass (on top of the fuselage) a roll stability is induced. Other benefits of this design decision are better ground clearance and easier access for equipment under the wings such as engines. On the contrary wings placed below the center of mass have an opposite effect, making the aircraft's roll axis more unstable but also more maneuverable. The dynamics of this can be compared to an inverted pendulum.

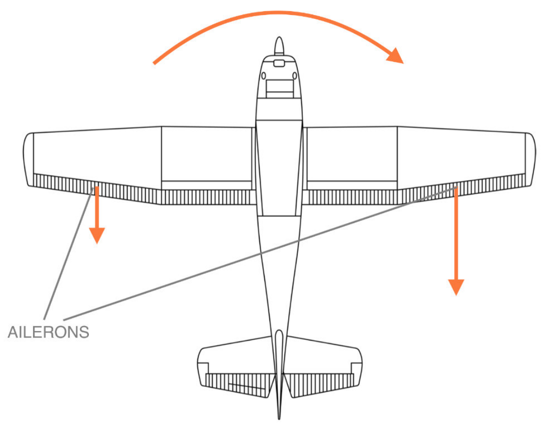
The angle between the wings and the horizontal reference line is referred to as dihedral (angled upwards) or anhedral (angled downwards). A positive dihedral angle has a stabilizing effect, as it creates a rolling torque that forces the airplane to level its wings horizontally.

The proposed design featured high-mounted wings and wing dihedral to form a stable testing platform. It should be kept in mind however, that this configuration decreases roll authority, making fast maneuvers difficult.



Wing Configuration

ADVERSE YAW



Adverse Yaw

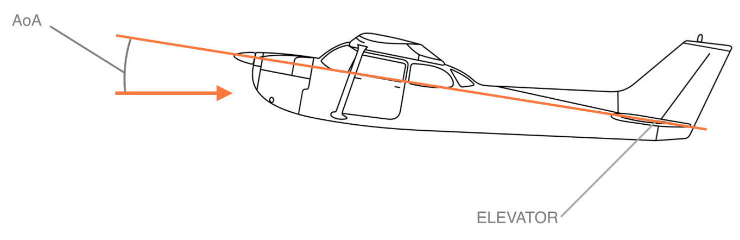
An aircraft controls its roll angle by deflecting the ailerons. This requires one to be deflected upwards while the other one is inverted, resulting in asymmetrical drag on the wingtips, as a rotational moment acts on the airframe, causing it to rotate around the yaw axis.

This behavior is undesired because it moves the plane's forward axis out of the airstream which has negative effects on aerodynamics and controllability. The angle between an aircraft's heading and the relative wind is referred to as sideslip.

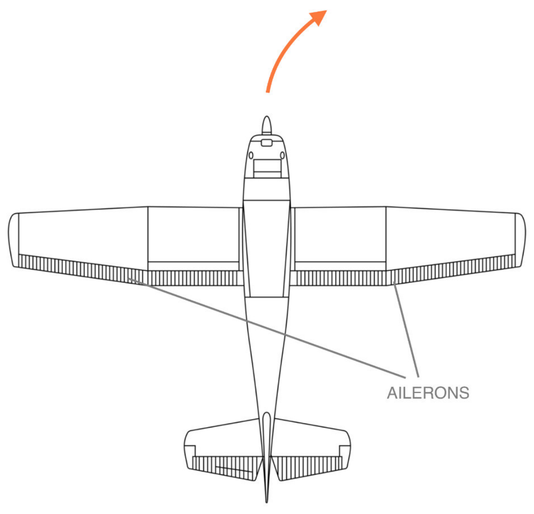
A method to overcome this would be to use the rudder for compensation. This approach was combined with the implementation of differential ailerons. These deflect further upward than downward, balancing the drag at each wingtip while still creating a rolling motion.

NAVIGATION

The navigation of a fixed-wing aircraft can be divided into longitudinal and lateral components. The first movement plane contains the aircraft's altitude. It is mainly a result of the lift generated by the wing and and gravity. The lift is dependent on the specific wing design, (relative) airspeed and the angle of the airstream to the wing, referred to as angle of attack (AoA). An aircraft's altitude is mostly controlled over changing the angle of attack by pitching the plane using the elevator or changing the airspeed by altering the engine power.
The lateral component involves the airplane's roll axis, which is essential for performing turns on the horizontal plane. The direction an aircraft is heading towards on said plane is referred to as its heading and is normally referenced to north. Rolling a plane causes the lift force, that always acts perpendicular to the wings, to point sideways, allowing to perform the turning maneuver. This however results in a smaller part of the lift acting against gravity which causes the aircraft to loose altitude. The most common way to counteract this effect is by increasing the lift again through use of the elevator. The radius of a turn maneuver is dependent on the current velocity and the roll angle. It should be noted that excessive roll angles create large G-Forces that pose a lot of stress on potential passengers and the airframe itself.



Longitudinal



Lateral

SENSORS

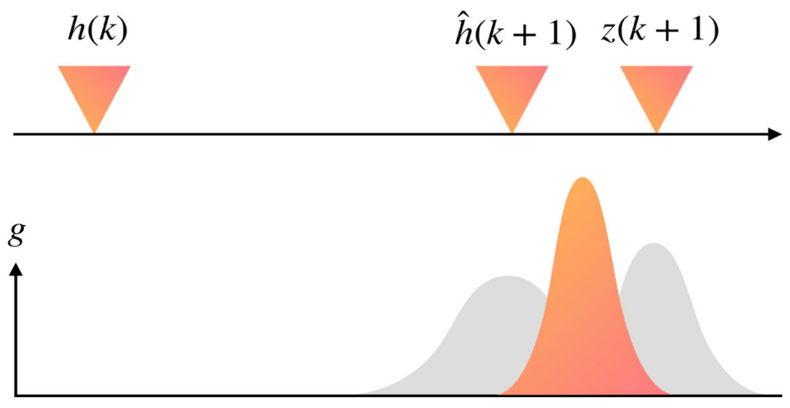
To collect flight information the system had to be fitted with numerous sensors. The most relevant parameters for basic in flight stabilization are altitude and attitude, which describes the aircraft's rotation angles. As space and payload capacity on the proposed model are limited only MEMS-sensors where chosen. To provide the necessary data the system was equipped with the following sensors:

MAGNETOMETER	BAROMETER	ACCELEROMETER	GYROSCOPE
Tracks magnetic north for navigation reference	Measures air pressure for altitude estimation	Measures linear acceleration of the aircraft and the gravity vector	Tracks angular velocity to estimate flight attitude

SYSTEM STATE ESTIMATION

Many MEMS-devices offer a high update rate in a physically small package, posing non-optimal conditions to perform the actual measurement. This introduces unwanted sensor noise into the system. The simplest way to deal with this noise is the implementation of an LPF (Low Pass Filter). These filters have a given cutoff frequency and suppress any parts of a signal that exceed said threshold. This however comes at a tradeoff for latency as stronger smoothing introduces a larger signal delay. This meant that LP-Filters could only be used to some extent.

A more advanced approach on signal processing is the implementation of a linear quadratic sate estimator, also known as Kalman Filter. These filters start with a known system state $h(k)$ at discrete timestep k. Given the dynamics of the observed system it is possible to make an estimate of the following system state $\hat{h}(k+1)$. This estimate is then combined with the actual measurement $z(k+1)$.



The estimate $\hat{h}(k+1)$ and the measurement $z(k+1)$ are both associated with an uncertainty. The first represents the filter's prediction error, caused by the utilization of the idealized system dynamics, while the other is a result of the before mentioned measurement error. The two states can then be merged, causing the uncertainty of the fused state to decrease.

FILTER EQUATIONS

Following are the equations of the classic Kalman Filter. Here x is a vector of the same dimension as the system's DOF and represents the state of the plant. P is the uncertainty associated with x in form of a covariance matrix. In the prediction step of the filter x and P are transformed using matrix A, which holds the linearized plant dynamics. Here the addition of Q represents the increased inaccuracy of the predicted result (i.e. the prediction error). The formed estimate $\bar{x}$, $\bar{P}$ is then fused with the measurement vector z. Here K' is the inverse of the Kalman gain, which performs the corrective step. It is computed from the covariance P *and* the measurement matrix H that maps a system state vector to the appropriate measurement vector z. The uncertainty introduced through measurement errors is incorporated by adding the measurement noise matrix R.

$$\hat{x}_k = Ax_{k-1}$$

$$\hat{P}_k = AP_{k-1}A^T + Q_k$$

Prediction Step

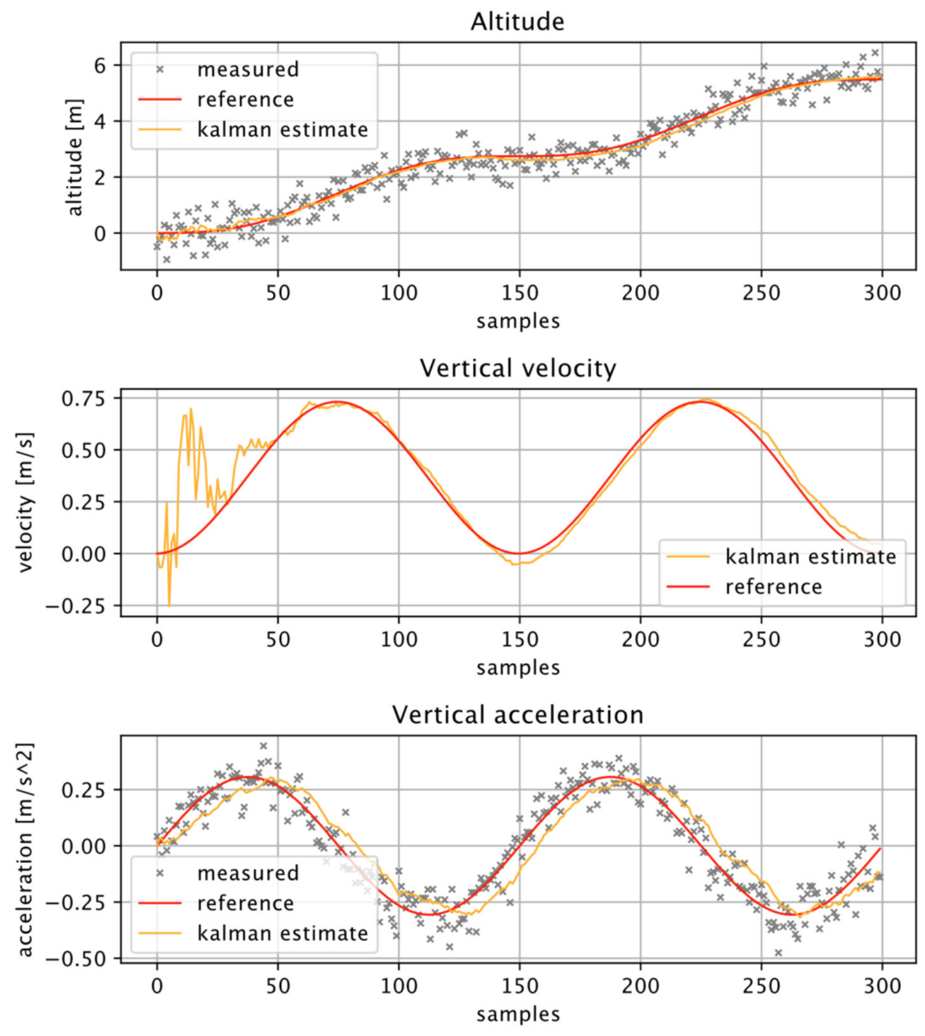
$$x_{k+1} = \hat{x}_k + K'(z_k - H_k\hat{x}_k)$$

$$P_{k+1} = P_k - K'H_kP_{k-1}$$

where

$$K' = P_kH_k^T(H_kP_kH_k^T + R_k)^{-1}$$

Update Step



RESULTS

To the left are results of the aircraft's altitude estimator. The measured variables where vertical acceleration from the accelerometer and the approximate height derived from the barometer using the international altitude formula. The grey markings show the actual measurements, red shows the ground truth reference and orange is the filter's output. The diagram shows that the system achieves a substantial noise reduction after the first initiation period.

CONCLUSION

This finalizes the project, resulting in a working model airplane that was used to develop a fly by wire system. The system consisted of an altimeter, accelerometer and AHRS system, forming a basic inertial navigation system. The implemented filters are flexible and easily adaptable to include more state variables and support redundant sensors. The controller is able to control the flight control surfaces, that have all been motorized, accepting either the desired attitude angles or turning rates for roll and pitch as an input. This forms a good foundation to implement a full autopilot in the future. The main requirement for this would be the addition of a GPS receiver giving the plane absolute positioning capability and also providing additional altitude data that could be fused into the altimeter. The main challenge of the project was its broad range of different topics. It was quite difficult to cover and document every subject in enough detail to get acceptable results, especially given the fact, that most of the fields involved are not covered in the school curriculum, requiring extensive research. Another challenge was posed through the extensive tuning required for the described sensor fusion and motion control algorithms. This problem however is already partially taken care of, as a new self-tuning algorithm is already nearing the first testing phase.