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MMAV - A MINIATURE UNMANNED AERIAL VEHICLE (MINI-UAV) FOR METEOROLOGICAL PURPOSES

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1 INTRODUCTION

Micro Aerial Vehicles (MAV) form a comparably new area of aeronautical research. This type of aircraft is defined by take-off weights typically less than 500 g and very small dimensions, e.g. wingspans under 50 cm. Intense research is conducted worldwide to further reduce MAV mass and size (e.g. Grasmeyer, 2001; Wu, 2004).

Within this paper, this term is expanded to also include so-called miniature unmanned aerial vehicles (Mini-UAV), which comprise typically of aircraft with a wingspan of a few meters and several kg of take-off mass.

Most current MAV projects concentrate on size and mass but neglect autonomous operation which means a pilot on the ground has to control the aircraft manually. The main research activity at the Institute of Aerospace Systems (ILR) of the Technische Universität Braunschweig, Germany, is the development of a fully autonomous MAV, operating without any intervention from ground.

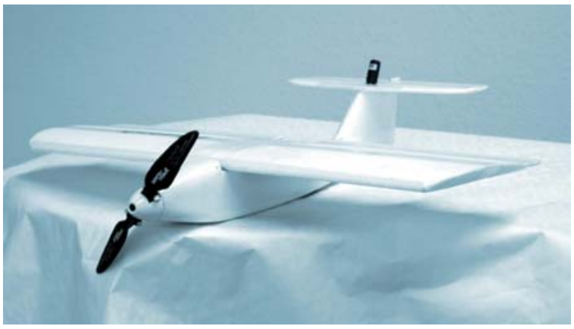

Fig. 1: Carolo P50

During the last three years, different concepts of aircraft were investigated and the necessary subsystems were developed. This resulted in the “Carolo” family of autonomous aircraft with small dimensions and masses with “Carolo P50” being the smallest and lightest autonomous Micro Aerial Vehicle (MAV) with a wingspan of *50 cm* and a mass of *550 g*, as shown in figure 1. This paper gives an overview about the project and suggests the use of an autonomous MAV for meteorological purposes.

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2 TOWARDS AUTONOMOUS MAV FLIGHT

Several steps had to be taken to develop an autonomous MAV: The development of a simulation environment, the experimental derivation of an aerodynamic data set of the aircraft and the design of an appropriate controller structure. The following subsections describe these steps briefly for the work on the smallest prototype Carolo P50 to show the functional principles.

2.1 Flightmechanical Simulation

Special mathematical tools were developed to allow the simulation of the highly dynamic behavior of a MAV. Basis is a non-linear flight-mechanical simulation tool as presented by Kordes et al. (2003). It is based on the commonly used Matlab/Simulink software and considers especially MAV-relevant effects like the motor gyro effect.

Besides this, the dynamic behavior of sensors and actuators were modeled to allow for realistic simulation of aircraft behavior. In addition to several mathematical wind models, real wind field data can be used, which were measured by the helicopter-borne turbulence probe “Helipod”. This measurement system is further described e.g. by Bange and Roth (1999) and Muschinski et al. (2000). This turbulence probe is operated by the ILR for meteorological measurements and allows for wind vector determination with high spatial and temporal resolution.

2.2 Wind Tunnel Tests

One foundation for MAV simulation is the determination of the aircraft’s aerodynamic properties. For this reason, wind tunnel tests were conducted at the Institute of Fluid Mechanics (ISM) of the Technsiche Universität Braunschweig. By varying the angle of attack, sideslip, elevator, ailerons and flaps, a 5-

dimensional parameter field was derived which formed the basis for realistic flightmechanical simulation. Table 1 shows the variation of these parameters. Especially the sideslip variation towards comparably high angles is necessary, since MAV operate at flight speeds which can have the same magnitude as gusts.

Parameter	Range
Angle of Attack	-10 < α < +10
Sideslip	-32° < β< +32°
Elevator	-15° < η +15°
Aileron	-15° < ξ < +15°
Flaps	-8° < κ < +12°

Tab. 1: Parameters for 5-dimensional aerodynamic Parameter Field

Figure 2 shows the lift versus drag diagram of Carolo P50. From this diagram, the dimensionless coefficients for the ideal ratio of lift C_L* to drag C_D* and the minimum glide angle ε* can be derived. These parameters as well as the corresponding speed *V** are:

$$
\begin{aligned}
C_L * &= 0.477 \\
C_D * &= 0.065 \\
\varepsilon * &\approx 7.8° \\
V * &\approx 15.5 ms^{-1}
\end{aligned}
$$

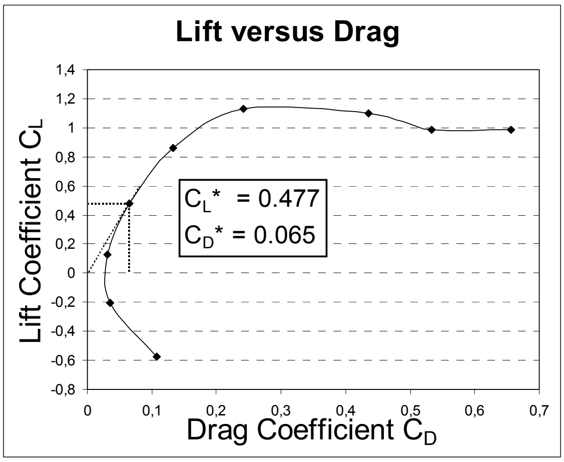

Fig. 2: Lift vs. Drag of Carolo P50

2.3 Controller Structure

Figure 3 shows the overall controller system structure including the models of actuators, sensors and wind. The dynamic model of the aircraft provides a basis for the design of the flight control system (FCS) and the development of navigation filters using GPS and INS as stated e.g. by Winkler et al. (2003). The flight controller has a conventional cascaded structure (figure 3). The advantage is that the aircraft is still controllable on a lower level if a higher level malfunction occurs. The flight controller consists of a damping system, a basic controller to stabilize the aircraft's attitude and an autopilot for track, altitude and airspeed control. The highest level is the navigation unit, responsible for waypoint navigation and mission fulfillment. Since the controller was designed for highly agile aircraft, it is comparably simple to adjust the controller parameters for larger aircraft with larger inertia.

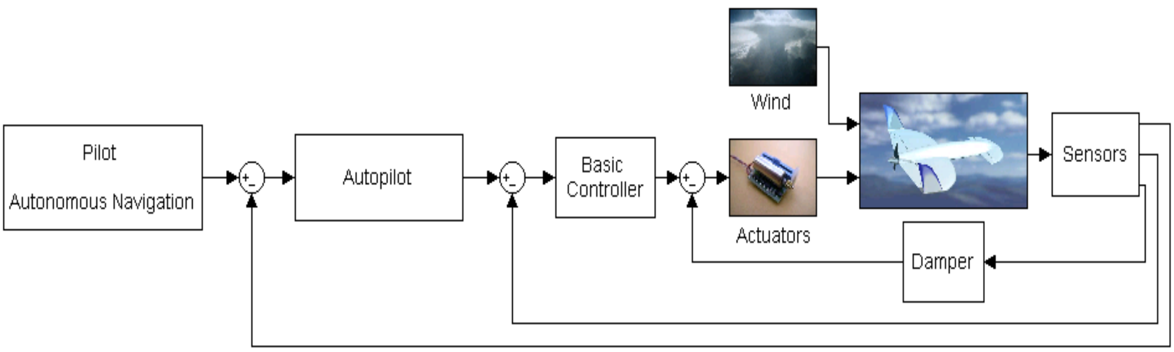

Fig. 3. Overall Controller System Structure

3 THE MAV FAMILY "CAROLO"

The goal of the "Carolo" project is the development of the smallest autonomous MAV possible. The smallest prototype has a payload of just 50 g which is not suitable for most research applications. During development of the Carolo P50, several larger aircraft were developed to serve as test bed for controller development and subsystem integration. All Carolo aircraft share the same hardware which consists of sensors for attitude and position determination, model plane actuators for driving the rudders, and an electrical propulsion system. Figure 4 shows the different subsystems and their interconnection. Central element is an on-board computer, which is small and lightweight, yet powerful enough to host the sophisticated control algorithms.

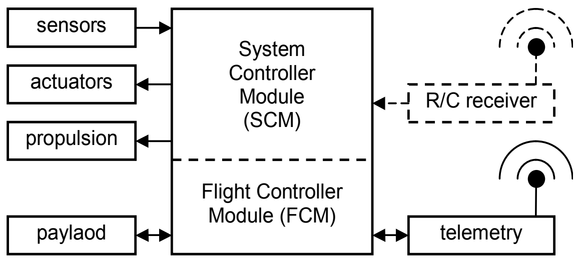

Fig. 4: Subsystems of a Carolo aircraft

3.1 On-Board Computer Structure

The demands on the on-board computer are very versatile: On one hand, different types of electrical interfaces are needed for communication with the other subsystems. On the other hand, sufficient calculating power has to be provided to host the flight control and navigation algorithms. In addition, strong constraints regarding size, mass, and power consumption apply for the use within a MAV.

For this reason, the on-board computer is split into two modules: The System Controller Module (SCM), which consists of a microcontroller with versatile analog and digital interfaces for the aircraft's subsystems, and the Flight Controller Module (FCM), a powerful 32 bit RISC microprocessor with 64 MB of RAM to host even demanding flight control algorithms.

Communication between subsystems and data processing is organized in time slices with a frequency of 100 Hertz. The sensors are connected to the SCM. The sensor data is sent from the SCM to the FCM via a high speed serial link. The FCM solves the control and navigation algorithms (state determination, flight control etc.) and the computation results are then routed via the MSC to the actuators and propulsion system.

Compared to a single module solution, this split computer design results in an increased latency of one time slice for the data flow from the sensor to the actuators. But hardware development and maintenance as well as software development and debugging is greatly simplified. In addition, a modified receiver for a model plane remote control can be connected to the SCM, allowing to directly remote control the aircraft. This is an important safety feature during flight tests when new control algorithms within the FCM software are to be tested: Even in the worst case, a malfunction of the FCM cannot block the remote control signals from the safety pilot on ground and the aircraft can be landed manually without danger for man or material.

While the on-board computer was designed to process the basic flight data needed for attitude and position determination, it offers free capacities for integrating additional sensors, e.g. for meteorological measurements.

3.2 The Autopilot

The main Sensors and the on-board computer were integrated into a single block serving as autopilot. Since it was designed for minimum weight and size and to control highly agile aircraft, it is comparably easy to adapt it for the use in larger aircraft. The current autopilot prototype consists of two printed circuit boards and has the following characteristics:

- 6 degree-of-freedom IMU
- static and dynamic pressure sensor
- 16 channel GPS receiver
- 32 bit computer with 64 MB RAM for flight control algorithms
- control of up to 6 servo actuators
- input for remote control receiver as backup for flight tests
- capabilities of interfacing to additional data sources (sensors)
- power consumption: < 1.5 W
- overall mass: 85 grams
- overall size: 40 x 40 x 80 mm³

- 50% reduction in weight and size expected by higher integration (prototype scheduled for 09/2004)

3.3 Telemetry Link and Data Storage

Principally, a telemetry link is not needed for an autonomous aircraft. But of course, for mission control and adjustment and for receiving payload data, a telemetry link between the aircraft and Ground Control is necessary.

As can be seen in figure 4, the telemetry module is connected directly to the Flight Control Module. This is done by means of a standard asynchronous serial interface, which allows for easy exchange of the telemetry module itself according to mission demands. The current prototype incorporates a frequency hopping spread spectrum radio modem with an effective data rate of approximately 20 kbps and a range exceeding 1,000 meters. The high data rate allows for detailed sensor and controller state information for in-flight testing, but for practical applications, high range is probably much more important than high data range.

As alternative for real-time transmission, data can be stored on-board on a Multi Media Card (MMC), a small solid state storage card which originates from electronic appliances like digital cameras or Personal Digital Assistants (PDA). This type of storage card is available with capacities up to 512 Mbytes and can store flight data for several hours of flight. After landing, the card is removed and the data is read by a common personal computer by means of a small, dedicated card reader hardware.

3.4 Ground Control

Ground Control consists of a common personal computer and a specially developed software package. The Ground Control software is based on a server-client structure:

A central server module hosts the data flow between different client modules. These modules provide e.g. data logging functionality or Graphical User Interfaces for visualizing sensor data or providing a digital map for waypoint editing. For the server, the aircraft itself is seen as a client module.

Communication between server and clients is based on the UDP network protocol, allowing the ground control modules to run on a single PC or on different computers connected by local network or the internet. For connecting to the MAV, special telemetry hardware is used, as previously described. The choice of using a rather sophisticated data protocol increases the workload of the Flight Controller Module on board, but greatly increases flexibility. It is also the basis for controlling multiple MAV from one Ground Control in the future. This allows for controlling whole swarms of MAV.

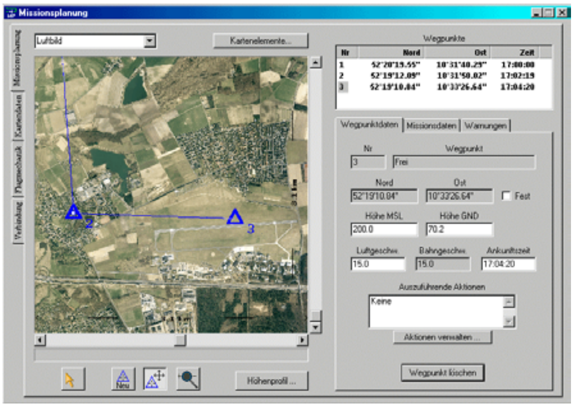

Fig. 5: Mission Control Module

The main client module for the user is the Mission Control software module, which provides a digital map of the operational area. This map can consist of a digitized topographic or city map, combined with elevation information, or digital landscape models. Figure 5 shows a screenshot of the current software version. In this case, a digitized air photograph combined with a digital elevation model was used. The user can set waypoints on the map, thus determining the MAV's flight path. With each point, special actions can be associated, e.g. “circling in constant height for 60 seconds'”.

The mission is planned before take-off and transmitted to the MAV via the server and the telemetry module. During mission, the actual position of the MAV is displayed within the digital map, allowing supervision of the MAV's route. The flight path can be adapted manually at any time by editing the flight path on the map and sending a waypoint update to the MAV.

4 THE METEOROLOGICAL MAV (M^2AV)

Since the ILR has several years of experience in the field of airborne turbulence measurement with the helicopter-borne turbulence probe Helipod, it stands to reason to use the present knowledge in the field of real-time meteorological measurement technology to develop an autonomous meteorological micro aerial vehicle, shortly called M^2AV.

Fig. 6: Carolo T140

As mentioned before, a conventional model plane is used as test bed for hard- and software development and testing (figure 6). This aircraft is a twin engine design with a wingspan of 140 cm (hence the name T140) and a maximum take-off weight of 2 kg, including 300 g of payload. It is hand-launched which makes handling and operating the aircraft very easy. With an endurance of approximately 30 minutes, the range accounts for 27 km at a cruising speed of 15 m/s. To restore operational readiness after landing, the batteries simply have to be recharged or replaced by a fresh battery pack.

4.1 Possible M²AV Missions

The described properties of the Carolo T140 makes it an ideal test platform for a M²AV to measure the basic atmospheric parameters temperature, humidity and wind vector.

The operating altitude is between 10 m (appropriate elevation model to avoid obstacles provided) and 1 km above ground, making it especially suitable for boundary-layer research. Higher altitudes are possible at the expense of endurance. By using special lifting aids like balloons, the M²AV could act as an auto-homing radio probe which returns automatically after releasing the balloon at a specified altitude. However, constraints like icing in the upper troposphere have to be considered carefully.

By using multiple M²AV simultaneously, the area coverage can be drastically increased compared to existing meteorological systems.

4.2 Measuring Temperature and Humidity

The basic constraint for developing MMAV sensors is the limitation of payload mass. For temperature, a split sensor concept as applied in the Helipod seems advisable: Two temperature sensors with different characteristics will be used: One sealed Pt100 element with high accuracy but slow response time in the magnitude of 10 s and one open element with a fragile mechanical design and rather poor long-term stability but very fast response time in the range of 10 ms. By complementary filtering, the characteristics of both sensors can be combined: Long-term stability with high accuracy and fast response time. The possible accuracy depends strongly on the data acquisition system, and here mainly the analog sensor supply electronics and the analog-to-digital conversion. Fortunately, very precise and compact components are available today which allow a data sampling precision of 16 bit and better, resulting in a achievable resolution of several Millikelvin for a measurement range from –40 to +60 °C.

For measuring humidity, few sensors are offered which fulfill the requirements regarding size and mass. This limits the possibilities to rather slow sensors with response times in the magnitude of 10 s and accuracies about 2%.

Depending on the required precision, the integration of temperature and humidity sensors in the Carolo P50 and T140 type of aircraft seems feasible, with using a simplified, one-sensor temperature measurement scheme in the P50. First tests with the T140 are scheduled for this year (2004).

4.3 Measuring the Wind Vector

Since one focus of meteorological research at the ILR is the investigation of turbulent fluxes in the boundary layer, a M²AV will be equipped with a miniature 5-hole probe. This probe was developed and manufactured by the Institute of Fluid Mechanics (ISM). Figure 7 shows the complete probe and figure 8 shows the probe’s tip in comparison with a 1-euro-cent coin and.

Fig. 7: Miniature 5-hole Probe

Fig. 8: Tip of Miniature 5-Hole Probe

The 5-hole probe has a mass of 22 g and a diameter of 6 mm. It is intended for the measurement of angles of attack and sideslip in the range of –45° to +45° each.

For deriving the angle of attack and the sideslip, the relative pressures between the 5 holes will be measured. For a first test of pressure transducers and analog front-end, a small electronic board which incorporates altogether 6 pressure transducers was developed (figure 9). Table 2 shows its characteristics.

Wind tunnel tests with different configurations are scheduled for this year, with integration into the Carolo T140 taking place in 2005.

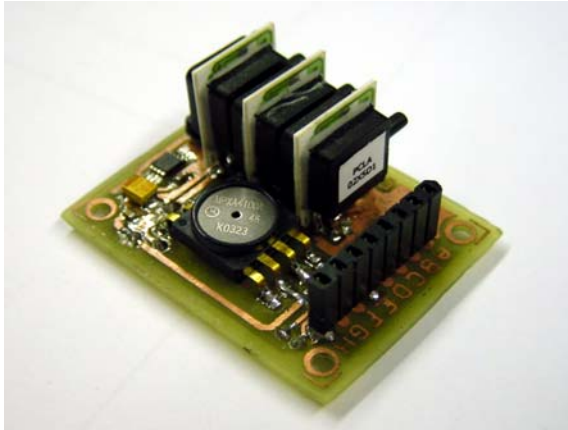

Fig. 9: Pressure Transducer Test Board

#	Sensor	Range
1	dynamic pressure	0..+1250 Pa
4	relativ epressure	-250 ..+250 Pa
1	static pressure	20 kPa..105 kPa

Tab. 2: Pressure Transducer Electronics

4.4 Data Acquisition and Processing

The implemented autopilot hardware as described before offers some free capacities for data acquisition. The autopilot sensors for attitude determination (accelerometers and gyros) are sampled in time slices with a frequency of 100 Hz.

Additional sensors can be connected by means of a synchronous serial interface. The autopilot also includes sensors for deriving the altitude from the static pressure and the velocity from the dynamic pressure, but the quality of these data is not sufficient for meteorological purposes. Thus, external sensors have to be connected for every meteorological measurand of interest.

A variety of small analog-to-digital converters with power consumption in the magnitude of several 10 mW are available. Depending of the converter’s topology, resolutions of 16 bit and more are possible with data rates in excess of 100 Hz. These electronic components can be interfaced directly to the synchronous serial interface of the on-board computer. External sensor data rate is limited to approximately 40 bytes per timeslice. This is sufficient for e.g.

8 sensor channels with a resolution of 16 bits for temperature, humidity and the differential pressures delivered by the 5-hole probe, and one sensor channel with higher resolution for measuring the static pressure.

5 CONCLUSION AND OUTLOOK

At the Institute of Aerospace Systems, a family of autonomous Micro Aerial Vehicles (MAV) was developed. The aircraft are controlled by setting waypoints on a digital map by means of a special software running on a common laptop or TabletPC. Telemetry link from Ground Control to the aircraft is currently done with a dedicated radio modem with short range (1000 m), but due to the modular design, replacement by other telemetry hardware with much higher range is comparably easy. Since the aircraft operate autonomously, telemetry link is only necessary for supervision and mission updates and is not vital for aircraft operation itself. Payload data can be stored on solid state memory cards, allowing high volumes of data storage and easy handling of data after landing.

Two MAV prototypes, Carolo P50 and Carolo T140, are available for meteorological payload integration: The Carolo P50 has a payload of 50 g and is suitable for rough meteorological measurements of temperature and humidity. It could act as a flexible tool for delivering rough meteorological key data during field experiments.

The second prototype, Carolo T140, allows for payloads up to 300 g and will be equipped with high precision measurement of temperature, humidity and wind vector. This meteorological micro aerial vehicle (M²AV) can be used to explore the lower atmosphere, especially the boundary layer. Its main advantage compared to existing systems is the easy handling and the possibility to cover big areas simultaneously by using multiple MAV.

The Carolo T140 has an endurance of approximately 30 minutes which results in a range of 27 km. A new aircraft “Carolo P200” is under development with a wingspan of 200 cm and a maximum take-off weight of 4 kg. This sensor carrier will expand the possibilities of the Carolo family especially for missions which demand for higher operational altitudes or longer endurance.

6 ACKNOWLEDGEMENTS

The authors wish to thank the European Union for partially financing the project and the Institute of Fluid Mechanics (ISM) of the Technische Universität Braunschweig, Germany, for providing the miniature 5-hole probe.

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