DEVELOPMENT OF AN AUTONOMOUS MICRO AERIAL VEHICLE (MAV)

Marco Buschmann, Stefan Winkler, Peter Vörsmann
Institute of Aerospace Systems, Technische Universität Braunschweig

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Abstract

This paper summarizes the recent work on Micro Aerial Vehicles (MAV) at the Institute of Aerospace Systems, comprising e.g. miniature Inertial Measurement Unit development and on-board computer design. The current prototype, "Carolo P50", is an autonomous MAV with a wingspan of 50 cm and a mass of 550 grams.

1 Introduction

Micro Aerial Vehicles (MAV) form a comparably new area of aeronautical research. This type of aircraft is defined by small mass and dimensions. Past and current MAV development mainly concentrates on aircraft miniaturization while setting autonomous operation aside [1,2]. 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. During the last three years, different concepts of aircraft were tested and investigated. 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).

Carolo P50 (figure 1) shows a classical configuration with a wingspan and length of approximately 50 cm. It has a mass of 550 g including a payload of 50 g. The electrical propulsion system is powered by a rechargeable Lithium-Ion battery. With endurance and range being a function of payload mass, the current configuration allows for an endurance of approximately 20 minutes and a range of 25 km at a cruising speed of 20 m/s. The payload consists of a miniature color video camera and a radio transmitter for delivering live video to ground control, which can consist of a TabletPC or a Personal Digital Assistant (PDA).

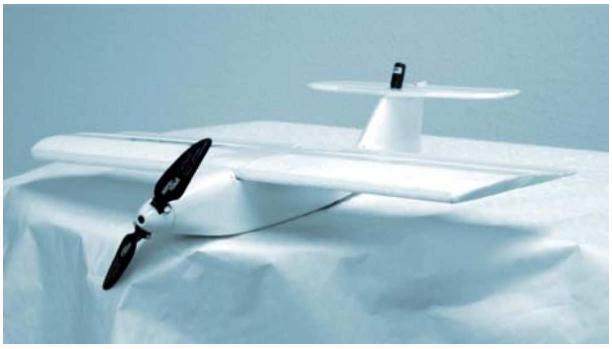

Fig. 1. Prototype "Carolo P50"

Besides this MAV, larger aircraft up to 2 m wingspan with one or two engines and masses up to 4 kg are used as test bed for subsystem development and as versatile sensor carrier for heavier payloads.

Possible applications for this family of aircraft are ground traffic surveillance, civil protection in case of natural disasters, measurements in the lower atmosphere for meteorological purposes or environmental protection.

2 Basics of MAV Research

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.

2.1 Flightmechanical Simulation

Special mathematical tools were developed to allow the simulation of the highly dynamic behaviour of a MAV. Basis is a non-linear flight-mechanical simulation tool [3] based on the commonly used Matlab/Simulink software, which considers especially MAV-relevant effects like motor torque or the 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 [4]. This turbulence probe is operated by the ILR for meteorological measurements and allows for wind vector determination with high spatial and temporal resolution.

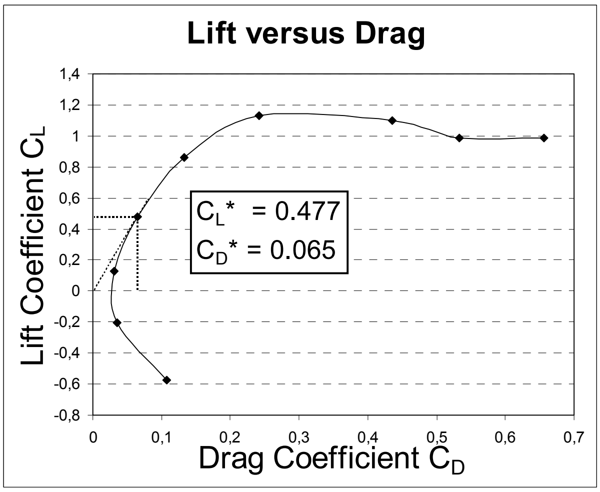

Fig. 2. Lift vs. Drag Diagram of Carolo P50

2.2 Wind Tunnel Tests

One base 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. 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:

$$C_L{}^* = 0.477$$
$$C_D{}^* = 0.065$$
$$\varepsilon^* \approx 7.8°$$
$$V^* \approx 15.5\frac{m}{s}$$

2.3 Controller Structure

Figure 3 shows the overall structure of the flight control system including the models of actuators, sensors and wind. The dynamic model of the aircraft provides a basis for the

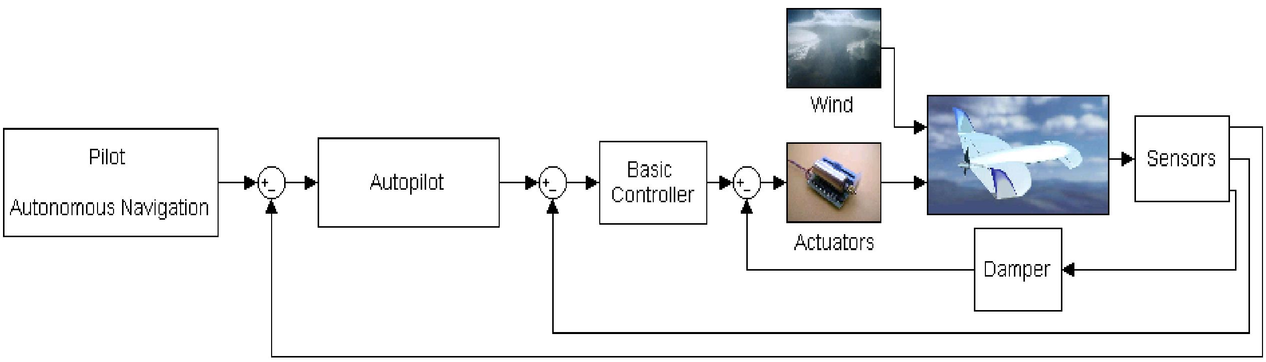

Fig. 3. Overall Controller System Structure

design of the flight control system (FCS) and the development of navigation filters using GPS and INS.

The flight controller has a conventional cascaded structure as shown in figure 2. The advantage is that the aircraft is still controllable on a lower level if a higher level malfunction occurs [5]. 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 fulfilment.

3 Enabling Autonomous MAV Flight

After the necessary theoretical work has been conducted, the necessary MAV subsystems were developed and built. As it can be seen in figure 4, the aircraft consists of several subsystems. In the following, some major concerns regarding the subsystem development are presented.

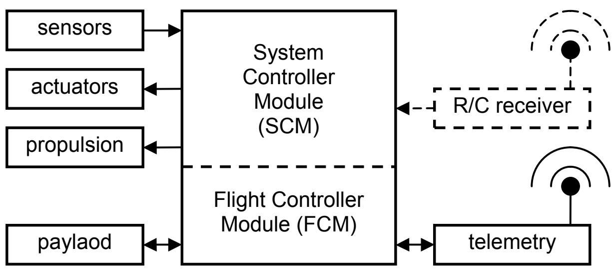

Fig. 4. Subsystems of Carolo P50

3.1 The Inertial Measurement Unit

An important component of the present aircraft state determination concept is an Inertial Measurement Unit (IMU) based on Micro-Electro-Mechanical Systems (MEMS). Two different 6-degree-of-freedom IMUs based on low-cost MEMS sensors were designed.

The first prototype uses three angular rate sensors with a measurement range of ±300 deg/s for attitude determination (roll, pitch and yaw). The linear accelerations are measured within a range of ±5 g for the load factor and ±2 g for the remaining two axes. In order to determine the temperature influence on the whole sensor package, a temperature sensor is used. The IMU has an analog interface, requiring separate analog-to-digital converters for interfacing to the on-board computer.

It was shown that proper calibration significantly increases accuracy [6]. For comparison, the IMU was mounted in the university's research aircraft, a DO-128, which was equipped with a Honeywell LaserNav inertial navigation system. Figure 5 shows an excerpt of the aircraft's measured attitude.

The solid line shows the attitude measured by the LaserNav, which was used to correct the IMU offsets at the beginning of the plots. The dashed line shows the non-calibrated and the dotted line shows the temperature-calibrated IMU data. As expected, the differences increase with time, but in case of the calibrated data set, the IMU error is greatly reduced.

One major problem in calibrating the IMU is the measurement of the sensor temperatures: Even at steady state, the temperature distribution within the IMU is not homogenous. By using only one temperature sensor, only rough temperature calibration is possible. For this reason, a second IMU prototype was developed and is now being tested. It uses different types of MEMS-based components with an integrated temperature sensor on each gyroscope, increasing calibration accuracy by considering local temperature variations within the IMU. Besides this, an A/D converter was integrated, simplifying the external interface while improving sensor signal integrity by avoiding long analog signal traces.

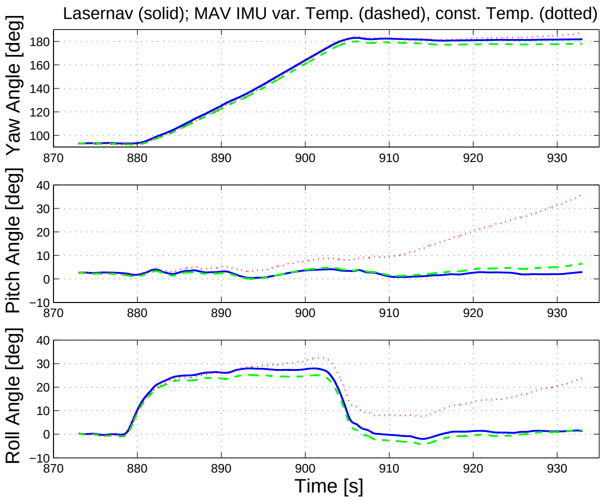

Fig. 5. Comparison of Attitude versus Time of LaserNav and Carolo IMU

3.2 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[1] 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 are 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 SCM 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.

3.3 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 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
- 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)

[1] RISC: Reduced Instruction Set Computer

4 Telemetry Concept and Ground Control

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[2] and a range exceeding 1000 meters. The high data rate allows for detailed sensor and controller state information for in-flight testing.

The payload data (life video) is transmitted via a dedicated analog video transmitter, since digital video data is not feasible for the on-board electronics at the moment.

4.1 Communication Structure

The communication between the MAV and Ground Control as well as within Ground Control is based on a server-client structure. As hardware platform, common Personal Computers are used. Ground Control software consists of different modules. A central server module hosts the data flow between different modules acting as clients. These modules provide e.g. data logging functionality or Graphical User Interfaces for visualizing sensor data or providing a digital map for waypoint editing. The entirety of server and all ground-based clients form Ground Control software, while the MAV itself is also seen as a client.

Communication between server and clients is based on the UDP[3] 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. 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.

[2] kbps: kilobit per second

[3] UDP: User Datagram Protocol (for IP-based networks)

4.2 Using Cellular Mobile Phone Network

For most everyday applications, a dedicated data link with a range of several kilometers is desired. The required data rate depends on the application, e.g. if payload data can be stored onboard or has to be transmitted in real time. Thus, the required data rate can be considerably low in case of meteorological measurements or environmental protection.

For this type of application, already existing communication infrastructure can be used [7]; in nearly every industrialized country, a cellular mobile telephone network is available. However, special care has to be taken since these networks are designed for data transmission to and from slowly moving terminal equipments on ground, but for slowly flying MAV at low altitudes, these problems seem feasible.

System	Data Rate [kbps]	Time per High Res. Image [s]	Time per Low Res. Image [s]
GSM	9.6	62.5	5.73
GPRS	28.8	20.8	1.90
UMTS	384.0	1.6	0.15

Tab. 1. Comparison of different Mobile Telecommunication Standards

Especially the General Packet Radio Service (GPRS), based on the Global System for Mobile communication (GSM) widely used e.g. in Europe, seems ideal for this purpose since it allows direct connection of the Flight Controller Module to the internet. Thus, mission control can be conducted from any computer connected to the internet.

For the purpose of ground traffic surveillance, current data rates are not satisfying to transmit life video data. However, new technologies like the Universal Mobile

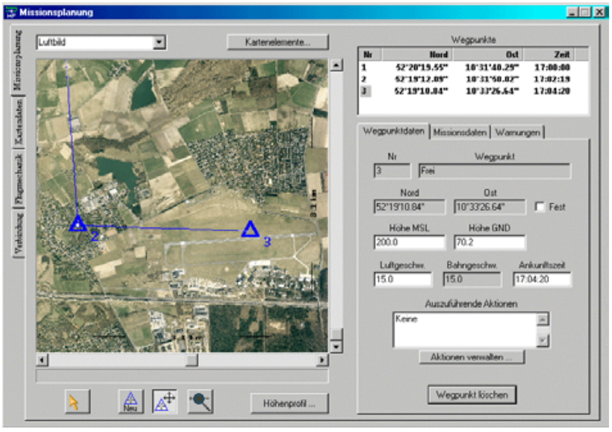

Fig. 6. Ground Control User Interface

Telecommunications System (UMTS) could offer an attractive alternative for video transmission in the future. Table 1 shows a comparison of different telecommunication standards and the time needed to transmit a compressed low resolution color image (320 x 240 pixel, approximately 5.5 kbyte) and a compressed high resolution color image (1024 x 768 pixel, approximately 60 kbytes), respectively. The listed data rates are optimistic values, since available data rate for GPRS and UMTS depends on network load, but it can be seen that UMTS would allow for digital live video transmission with low quality.

4.3 Ground Control User Interafce

Ground Control consists of the MAV server application and several clients for user interaction. The main client is the Mission Control software module, which provides the user with 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 6 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.

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