Control of an experimental mini quad-rotor UAV

Alexandros Soumelidis, Péter Gáspár, Gergely Regula, Béla Lantos

Abstract— **The design and the initial realization of control on an experimental in-door unmanned autonomous quadrotor helicopter is presented. This is a hierarchical embedded model-based control scheme that is built upon the concept of back-stepping, and is applied on an electric motor-driven quadrotor UAV hardware that is equipped with an embedded on-board computer, inertial sensor unit, as well as facilities that make it suitable to be involved in an in-door positioning system, and wireless digital communication network. This realization forms an important step in the development process of a more advanced realization of an UAV suitable for practical applications; it aims clarification of the control principles, acquiring experience in solving control tasks, and getting skills for the development of further realizations.**

Index Terms— **unmanned aerial vehicles, quadrotor helicopter, vehicles control, embedded control.**

I. INTRODUCTION

Presently unmanned aerial vehicles — UAVs — increasingly attracts the attention of the people including laymen, potential appliers, vehicle professionals, and researchers. UAV field seems to step out of the exclusivity of the military applications, and a lot of potential civil applications have emerged, and research and development in this field has gained increasing significance. The research teams affiliated with the authors are interested in many respects in this field, many efforts are spent in several research areas in connection with the individual and cooperative control of aerial and land vehicles including the unmanned ones. Developing an unmanned mini quadrotor helicopter that is able to execute autonomously a mission, e.g. performing a series of measurements in predefined positions, or completing a surveillance task above a given territory is one of the goals formulated for the near future. An introduction into the goals, the realization alternatives, as well as an outline of the development process can be found in [1].

The idea of constructing a quadrotor helicopter is not new, the first attempt to realize one is dated to 1907, that was the Gyroplane No. 1 of Louis and Jacques Bréguet (France); it precedes the construction of the nowadays used conventional helicopter types. Further attempts to realize quadrotor are e.g. the models of George de Bothezat (Dayton, Ohio) in 1922, that of Etienne Oemichen (Peugeot, France) in 1923, and the most recent is Convertawings Model "A" Quadrotor (Amityville, USA) in 1956. For details on the history of helicopters see e.g. [2]). However these realizations — because of technological problems that could not been solved in the given level of development — did not get into practical applications. A sustained stable flight required accurately synchronized rotation of the four rotors that was quite difficult to be realized with combustion engines, furthermore either control theory and technology in those ages could not cope with the problems arisen. The mainrotor–tailrotor, double–rotor or tandem arrangements proved to be realized more efficiently, hence these solutions became the basis of the nowadays used helicopters. However quadrotor arrangements possess some advantages over the conventional ones that — on the level of development in the control field today — can be utilized in the field of small-form UAVs: by using four rotors that can rotate with individually controllable speeds make unnecessary the alteration of the rotor blade's incidence angle, hence the mechanical structure of the helicopter becomes quite simple. Using electric motors with delicate control electronics to drive the rotors, electronic sensors to measure the position and the movement of the vehicle, as well as digital controllers realizing advanced control algorithms can result in efficient quadrotor realizations with stable, reliable operation.

Recently numerous control laboratories — usually belonging to universities — initiated projects with the purpose to construct small-form quadrotor UAVs, as well as to solve the control problems raised in association with them, see for example [3], [4], [5], [6], [7], [8].

This paper describes the design and the initial realization of control on an experimental setup of a mini quadrotor UAV intended for in-door control use. This realization is an important step in the development process of a more advanced realization being suitable for applications; it aims clarification of the control principles, acquiring experience in solving control tasks, and getting skills for the development of further realizations. In the following chapters first the construction of the experimental quadrotor UAV is outlined, then the structure and the basic principles of control are described, finally some implementation issues and a simulation example are given.

II. BUILDING A MINI QUADROTOR UAV

The experimental quadrotor UAV satisfies a simplified specification compared to the original concept, however it contains all the parts that are required to realize all the individual and cooperative control tasks — in a smaller scale in an in-door environment — that have been specified for the future models intended for applications. The requirements

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of primary significance for the design of an experimental quadrotor UAV are as follow:

- The size of the UAV is small enough to maneuver in an in-door environment, however it is big enough to carry the high complexity on-board electronics that is suitable for realizing the control algorithms without any compromise.
- The power of the UAV is high enough to carry the above mentioned parts, while its power supply system can provide enough energy to obtain relatively long flight time.
- The UAV possesses all the means that are required to participate in an in-door positioning system, and to be able to acquire its position data.
- The UAV is able to communicate with a ground station, at least in the respect of accepting commands and reporting data.

According to future plans multiple UAVs are intended to build and control them in several cooperative schemes, hence the communication is worth to be realized in such a way that a network with suitable topology could be formed.

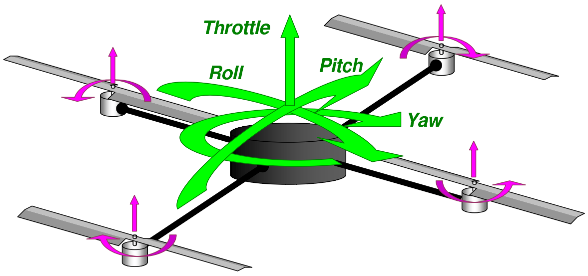


Fig. 1. The quadrotor concept

The concept of the quadrotor helicopter is illustrated in Figure 1. The actuator system consists of four rotors placed in the four corners of a planar square, those ones placed oppositely rotate in the same direction, while the perpendicular ones rotate reversely. The attitude and the movement of the quadrotor can be controlled by suitable changing the revolution of the rotors that results in different thrust and torsion. The rotors are driven by electric motors; its revolution can efficiently be controlled by local electronic motor controllers.

The rotor drive motor control has been realized as independent module that is implemented in four instances on every vehicle. Sensorless BLDC (Brushless DC) motor is used controlled by a simple 8-bit microcontroller. Revolution or torque control is realized on the basis of several control methods, from the conventional PID control until optimal and robust state-space realizations. There are many advantages of using BLDC motors: besides the high torque and efficiency their ability to operate — by using adequate electronic control — in a wide range of rotation speed, without the need of additional mechanical elements (e.g. gear-boxes).

The control of a quadrotor helicopter can be realized on the basis of on-board measurements that are performed by sensors placed on the vehicle. An efficient, accurate enough, and besides these inexpensive solution for measuring the state of the helicopter can be based upon MEMS-based inertial sensors including accelerometers and angular rate sensors (gyros). However measuring accelerations and angular rates even in six degrees of freedom is not sufficient to derive the exact spatial position and attitude of the vehicle; to be provided with absolute position measurements a positioning system is needed. In outdoor environments the GPS system is a suitable means to determine absolute position — usually by combining them with the inertial measurements to avoid problems arisen from the sparse time-scale and availability of GPS; and magnetometers can be used for getting attitude measurements. However in an indoor test environment neither GPS nor magnetometers can effectively be applied. Position and attitude measurements can be achieved by the usage of an indoor positioning system. In connection with the experimental quadrotor UAV a vision-based positioning system has been designed. Color-coded illuminated markers are placed on the vehicle in planar arrangement that are detected by an external multicamera vision system. The vision system periodically determines the position and attitude data, that are transferred to the vehicle via wireless communication.

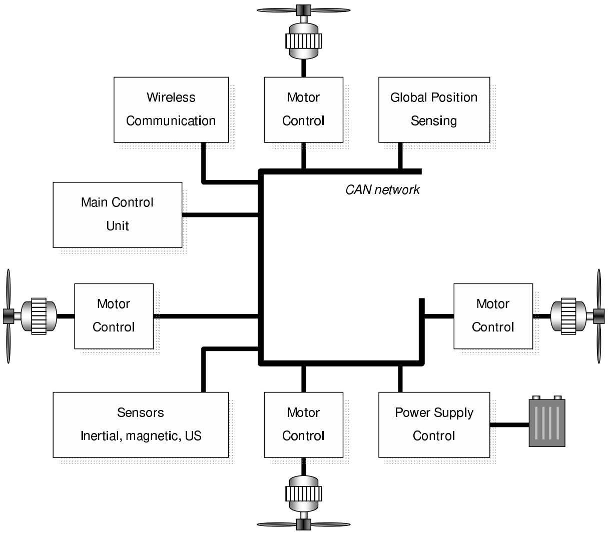


Fig. 2. Control structure of the UAV

The basic operation of the quadrotor UAV consist of a measurement–control–actuation loop. The control actions are realized by an electronic control unit (ECU). For this purpose a Freescale MPC555 microcomputer is used. It is advantageous if the on-board control is hierarchically distributed, the local control and regulation tasks are realized by local microcontrollers of the appropriate size and computing power that are interconnected by a digital network. The local tasks that can be realized are as follow:

- Main control: realizing the measurement–control–actuation loop.
- Actuator control: rotation speed regulation of the four

motors driving the rotors.
- Sensor control: set up and execution of the inertial measurements, as well as preprocessing of data.
- Power supply control: power supply supervision and emergency handling.
- Communication control: joining into the wireless communication network and performing data exchange.

The structure of a networked realization scheme of this distributed control system can be seen in Figure 2. A simple, however efficient and reliable enough network that can easily implemented is CAN. It is well known and widely used in the vehicle industry; as well as it is supported by the microcomputer selected for main control.

The MPC555 microcomputer realizes a 32-bit PowerPC architecture supporting 32-bit fixed and 64-bit floating point arithmetic. It contains numerous peripherals, among them a 2-channel CAN controller. An incomparable advantage offered by the MPC555 microcomputer platform arises from the software tools that are available. The Realtime Workshop and the Embedded Target for MPC555 offered by Matlab and Simulink of Mathworks results in a convenient and easy to use means for control software prototyping. The MPC555 microcomputer is also well supported by the open source community, e.g. the free and open source eCos real-time operational system has been implemented on this platform.

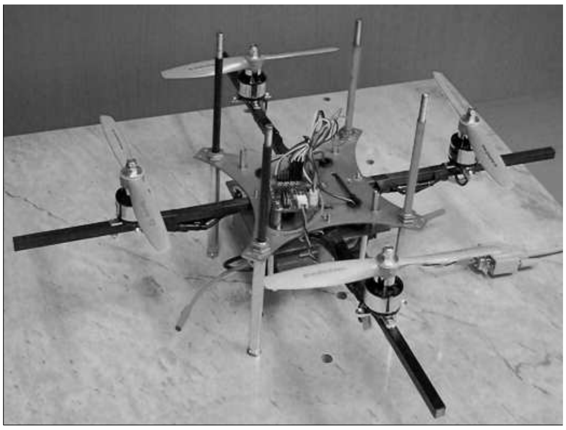


Fig. 3. The experimental quadrotor UAV

A significant component of the UAV is the wireless digital communication unit. Via wireless communication the UAV can maintain a command–data link with a ground control unit, as well as the measurements of the indoor positioning system are transferred to the UAV by this way. In the future case when multiple UAVs will be run in a common test field an ad-hoc digital communication network should be realized. The cooperative control of multiple UAVs, besides the star topology with the ground control unit in the center that simply can be realized, can require more advanced topologies like mesh. The Personal Area Network (PAN) defined by the standard IEEE802.15.4. operating in the 2.4 GHz ISM band seems to be a suitable platform for our requirements. It realizes relatively slow data transfer (comparing e.g. to IEEE802.11b-g WLAN) however it is optimized for high reliability communication [9]. The IEEE802.15.4 standard is restricted only to the physical (PHY) and media access (MAC) level of the communication, the levels above these layers should be realized by the user. However the structure of these networks is simple, obvious, and well documented, as well as there are numerous MAC-layer implementations available for several microcomputer platforms that can be used. Further advantage of the IEEE802.15.4 solution is that it can be configured so that real-time communication is realized with guaranteed timing. Several network topologies can be realized including star and mash topologies.

An important part of the UAV is the power supply system. Its basic element is the battery, that should be of high capacity while it can represent light weight; Lithium Polymer (LiPOL) batteries are used to fulfil the requirements. The power-supply sub-system produces the necessary supply voltages to the other units, furthermore monitors the battery charge, and produces alarms in the case of shortage or faults, that are sent to the main computer via CAN communication.

The experimental quadrotor UAV that has been built can be seen in Figure 3. Some details of the implementation are as follows:

- Four small size BLDC motors of outrunner type — with diameter 28 mm, rotation speed 1469rpm/V, maximal current 6A, and efficiency 80% — have been used.
- The main power supply consist of a 3-cell LiPOL battery of capacity 4100 mAh and weight 160 g. An additional smaller battery serves as a power source for the on-board electronics.
- Two normal and two reverse pitch propellers of diameter 18 cm are used as rotors.
- A uniquely constructed chassis of dimensions 380 mm x 380 mm built up of light carbon and epoxy materials has been realized.
- A microcomputer board consisting of an MPC555 processor, 4 MB RAM and 4 MB flash memory is used, product of Phytec (Germany).
- An inertial measurement unit (IMU) of type MNAV100, product of Crossbow (USA) has been applied for on-board measurements.
- ATCAN128 8-bit microcontrollers of Atmel (USA) have been applied for the purpose of motor control and communication.
- A vision-based indoor positioning system consisting of four analog cameras, with individual image digitalization and image processing subsystems connecting by Ethernet to the ground control unit is under development. The on-board components of the system are color markers in the form of spheres of diameter cc. 25 mm, illuminating by RGC LEDs.
- A wireless communication system based upon the IEEE802.15.4 protocol consisting of standard as well as uniquely designed communication elements has been set up and is developed continuously.
- A high-performance Linux-based graphic workstation serves as a ground control station.

The on-board control application development is achieved by using the Real Time Toolbox and the Embedded Target for MPC555 in Simulink and Matlab of Mathworks in the current phase of the realization.

III. THE CONTROL HIERARCHY

The control objectives of the quadrotor UAV can be classified in different levels that show some hierarchical structure:

- Realizing correct thrust, yaw, pitch, and roll control by providing efficient decoupling and stability of control actions — these are basic requirements in the manual control of the quadrotor helicopter.
- Realizing basic operation modes and maneuvers as hovering in a stable position, ascend / descend, forward / backward / lateral movement. An efficient autonomous realization of these actions can be obtained by the result of a control design procedure that is based upon the mathematical model and uses accurate expression of auxiliary conditions, quality requirements, as well as constrains.
- Realizing the movement on a predefined trajectory is a higher level of control that can be realized on the quadrotor UAV. The control strategy that is designed should satisfy auxiliary conditions (e.g. velocity along the path), requirements (e.g. accuracy of following the path), as well as constrains (e.g. power limitations).
- Global control of a quadrotor UAV including path and mission planning.
- Global cooperative control of a group of quadrotor UAVs consisting of path and mission planning.

The first three options are intended to be realized within the framework of the activities covered by the current paper. Path planning of the experimental UAV is performed off-line. The predefined paths — belonging to a specific navigation example — are stored in the ground control unit, and they are sent to the UAV as needed through wireless communication governed by a global control interface application.

A comprehensive path and mission planning both in individual UAVs and groups formed by them falls out of the scope of this project, however it is the subject of other current and future research activities.

IV. CONTROL OF A MINI QUADROTOR UAV

This section is devoted to the control design of the experimental quadrotor UAV. The purpose of this experiment is to design a controller for the UAV that is able to perform simple movements up to realizing complex navigation tasks on the basis of a feasible mathematical model of the helicopter. Besides the practical usefulness — in the respect of potential applications — of this proposition, it is also challenging in the terms of control theory since the control design is based on a significantly nonlinear model, in which various performance specifications must be met and several constraints and uncertainties should be taken into consideration.

A model of the full quadrotor helicopter dynamics is obtained from the Euler-Lagrange equations with external generalized forces, see [6], [4]. Several papers are concerned with the control design methods from backstepping to sliding-mode control based on the nonlinear model, see e.g. [3], [10], [11]. In these papers full state feedback is proposed and the state signals are assumed to be measured. Several papers focus on the navigation task in which visual information from a camera is used, see e.g. [5]. A possible method to the generation of a complex trajectory is presented in [7].

The control design proposed in this paper is based on a backstepping method. Since not all the state signals used in the controller are measured a state reconstruction algorithm is also applied by using an extended Kalman filter. A complex navigation task consisting of simple maneuvers is also proposed. The controller is tested by a hardware-in-the-loop procedure. In the first part of this section the control design based on a backstepping method is presented. The state estimation is based on an extended Kalman filter. Then the implementation of the distributed control is presented and some important details are highlighted. In the last part the operation of the controller is illustrated through a navigation example.

A. *Model-based control design based on backstepping*

The helicopter is an under-actuated system because it has six degrees of freedom while it has only four inputs, i.e. four rotors. The system has been divided into two subsystems: a translation and a rotation subsystem corresponding to the helicopter model:

$$\dot{x} = f(x)x + g(x)u$$

where $x = \begin{bmatrix}\xi & \dot{\xi} & \eta & \dot{\eta}\end{bmatrix}^T$ with $\xi = \begin{bmatrix}x & y & z\end{bmatrix}$, $\eta = \begin{bmatrix}\phi & \theta & \psi\end{bmatrix}$. Here x, y, z are the position coordinates, ϕ, θ, ψ are the angles around the axes. The control inputs are the throttle input: $u = \begin{bmatrix}u_0 & \tau_{Bx} & \tau_{By} & \tau_{Bz}\end{bmatrix}^T$. The throttle input is the sum of the thrusts of each motor.

Two controllers that are related to each other logically are designed based on a backstepping method. First, the control of the position subsystem gives an estimation for the orientation angles and the control u_0 by using the actual ξ_m and the target (defined) ξ_d. Second, the control of the rotation subsystem calculates the control torques $\tau_{Bi}, i \in \{x, y, z\}$ needed for the access of the orientation angles η. In the third step, the angular velocities of the rotors $\Omega_j, j \in \{1, \ldots, 4\}$ are calculated based on the required control inputs. The control structure is illustrated in Figure 4.

The basic purpose of the control design is to guarantee stability and predefined performance specifications concerned with time setting, overshoots, tracking error, etc. The control design for the nonlinear models is based on a backstepping method, in which the state signals are assumed to be available, e.g. [12]. The autonomous operation of the helicopter uses an on-board inertial sensor (IMS) measuring 3D angular velocities $(\dot{\phi}, \dot{\theta}, \dot{\psi})$ and linear accelerations $(\ddot{x}, \ddot{y}, \ddot{z})$ using MEMS. The positions in the earth coordinates are measured by using the indoor positioning system data.

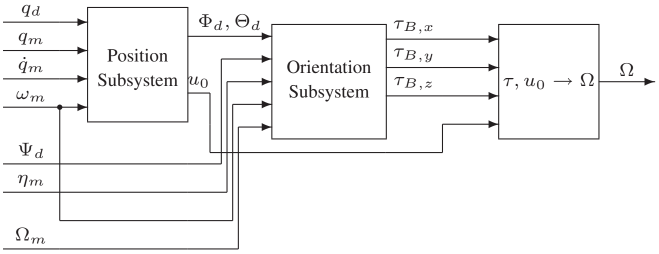


Fig. 4. Control structure based on a backstepping method

Since some of the state signals used in the controller are not measured, a state reconstruction procedure is also built in the controller. The two sources of the signals are the IMS and the positioning system. A method applied to obtain the unknown state signals is to construct an observer for the extended system, called an Extended Kalman Filter (EKF). Taking into consideration the different selection of sampling intervals of the IMS and of the positioning system two extended Kalman filters are designed. The Kalman filters co-operate with each other. The first EKF (EKF_1) estimates the orientation of the helicopter, e.g. the angles and their first and second derivatives, while the second EKF (EKF_2) estimates the position and the velocities. The structure of the estimators is illustrated in Figure 5.

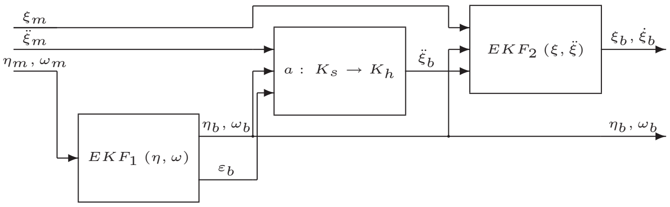


Fig. 5. The structure of the state estimation

The purpose of the control design is to track a predefined trajectory with the smallest possible tracking error. In practice a navigation point must be approximated with a predefined accuracy considering the positions and orientations. Meanwhile the moving of the helicopter must be carried out with a constant speed or a predefined speed, i.e. reducing the velocity is undesirable. There are several difficulties in performing such a design. The model is only an approximation of the plant to be controlled, thus the unmodeled dynamics and the parametric uncertainties should be taken into consideration. In practice the effects of disturbances and measurement noises should also be attenuated by the designed control.

In our approach a complex trajectory is divided into sections in order to perform simple maneuvers, such as changing altitude, the lateral position, etc. In practical applications the design of a feasible trajectory is important, e.g. moving with a constant speed, moving between two points. However, the infeasible trajectories must be omitted or alternative trajectories must be proposed, e.g. an approximate circle curve must be defined instead of an accurate circular motion in a horizontal plane.

As an example the quadrotor may advance towards the next navigation point in the algorithm if the following conditions are satisfied:

$$\sum_{j=1}^{3}(\xi_j - p_{i+1,j})^2 < \lambda \sum_{j=1}^{3}(p_{i,j} - p_{i+1,j})^2$$

$$|\Psi - \Psi_{i+1}| < \Delta\Psi_0 = const.$$

where ξ is the current position, p_i, p_{i+1} are consecutive navigation points of the predefined trajectory. The parameter λ should be chosen to keep the helicopter in continuous motion, e.g. $\lambda = \frac{1}{16}$ is suitable in our case. Abrupt changes may occur between two navigation points during the manoeuver. In order to guarantee the smooth motion the predefined path must be refined by using a filtering procedure in order to avoid the risk of a numerical instability. A block with the following weighting function is able to perform this task: $W(s) = \frac{p_s^n}{(s+p_s)^n}$ with $p_s > 0$. By setting $n = 3$ the second derivatives of the signals will remain smooth.

The other task is to design a controller to achieve the predefined trajectory with the smallest possible error. This controller must be robust, i.e. it must attenuate the disturbance and noises and the model uncertainties must also be taken into consideration. This means that the controlled system should be robustly stable around the desired flight envelope (path). This requirement defines a selection criterion for the definition of a ”feasible” trajectory as well.

B. Implementation issues

In the implementation of the designed control procedure on the quadrotor UAV the real-time operation must be guaranteed. An embedded realization based upon the MPC555 microcontroller by using the Real-Time Workshop and Embedded Target for MPC555 can satisfy this requirement. To verify this a hardware-in-the-loop testing procedure of the controller has been carried out, in which the system is emulated by dSPACE components. The structure of the distributed control is illustrated in Figure 6.

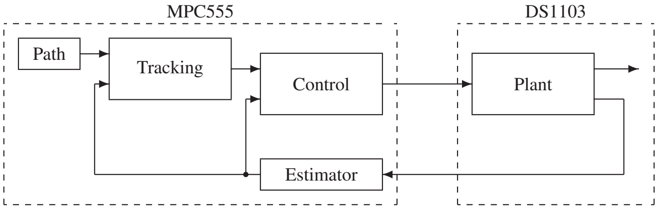
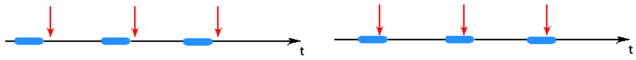


Fig. 6. The scheme of the distributed control

The behaviour of the quadrotor is emulated on the dSPACE component and so are the IMS and the positioning system’s results. Because of its flexibility and high level of security, communication between the two units is carried out via CAN interface. Moreover, communication via CAN is supported by Simulink library blocks, which makes the prototyping easier.

Testing a control algorithm in a distributed environment brings up several issues like synchronization and data integrity. A special starting mechanism is needed to avoid undesired functioning of the control loop since dynamical components are implemented on both processors (e.g. the model of the quadrotor and the EKFs).

It is also crucial to maintain data integrity during the flight since starting the calculation of the control inputs before receiving all measurement data may make the control loop unstable. Therefore, all data sent by the dSPACE unit are timestamped, which causes slight loss of precision due to the limited size of a CAN message packet. Data acquisition on the MPC555 is performed at a higher frequency compared to that of the control algorithm in order to reduce delays in the loop. Figure 7 illustrates the importance of the data integrity (arrows: starting of the calculation cycle, bars: duration of the data acquisition).



(a) Normal operation (b) Faulty operation

Fig. 7. Data integrity in the algorithm

C. A simulation example

Various simulations are performed and several experiments are implemented on the test bench in order to validate the designed controller. As an illustration a complex maneuver is performed and the time responses of the quadrotor helicopter are presented. In the first example the helicopter must follow a predefined regular pentagon. The 3D plot of the movement together with the position and orientation signals are illustrated in Figure 8.

V. CONCLUSIONS

In this paper the design and the initial realization of control on an experimental in-door unmanned autonomous quadrotor helicopter has been presented. This realization forms an important step in the development process of a more advanced realization of an UAV suitable for practical applications; it aims clarification of the control principles, acquiring experience in solving control tasks, and getting skills for the development of further realizations. The paper describes a hierarchical embedded model-based control scheme that is built upon the concept of back-stepping, and is applied on an electric motor-driven quadrotor UAV hardware that is equipped with an embedded on-board computer, inertial sensor unit, as well as facilities that make it suitable to be involved in an in-door positioning system, and wireless digital communication network.

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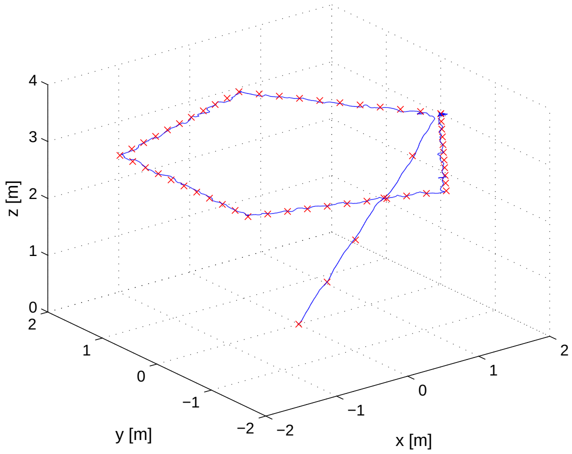
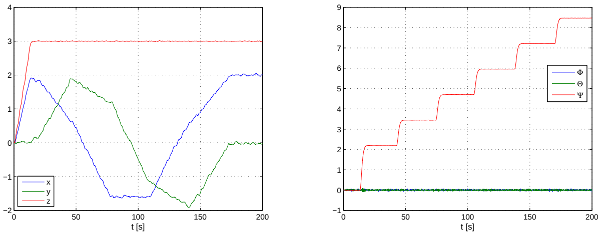


(a) Trajectory in 3D



(b) Positions (c) Angles

Fig. 8. Track a predefined trajectory

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