Design of an embedded microcomputer based mini quadrotor UAV

Alexandros Soumelidis, Péter Gáspár, Péter Bauer, Béla Lantos, and Zoltán Prohászka

***Abstract*— This paper describes the design and realization of a mini quadrotor UAV (Unmanned Aerial Vehicle) that has been initiated in the Systems and Control Laboratory at the Computer and Automation Research institute of the Hungarian Academy of Science in collaboration with control departments of the Budapest University of Technology and Economics. The mini quadrotor UAV is intended to use in several areas such as camera-based air-surveillance, traffic control, environmental measurements, etc. The paper focuses upon the embedded microcomputer-based implementation of the mini UAV, describes the elements of the implementation, the tools realized for mathematical model building, as well as obtains a brief outline of the control design.**

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

I. INTRODUCTION

Constructing aerial vehicles that can move autonomously, without the interaction of any — either on-board or remote — human driver while executing tasks in highly intelligent way is an old desire of the mankind. In the not too far past these desires materialized only in the science fiction literature, whereas in our days they actually have become reality, and subject to science. Electronics, technology, information and computer sciences, and — last but not least — control science each has given its contribution in the development, hence research and development activities in the field of Unmanned Aerial Vehicles (UAVs) has by now gained great significance. Applying UAVs has become quite popular in several areas both in the military and civil sector, e.g. airborne reconing, surveillance, detection of natural disasters, realizing environmental measurements, etc.

Besides using the conventional aeroplane and helicopter arrangements in constructing UAVs, new types of air vehicles have also been proposed, and tested, based upon either new ideas, or reviving old ones. Such an old idea is the quadrotor helicopter, that was invented in 1920, however because of technological problems that could not been solved in the given level of development, it did not get in practical applications. The mainrotor–tailrotor, double–rotor or tandem arrangements proved to be realized more efficiently, hence these solutions became the basis of the generally used helicopters. However quadrotor arrangements possess some advantages over the conventional ones that 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. In the case of small size and weight electric drive motors can be used, hence due to the opportunities obtained by the contemporary electronics and computer techniques their coordinated control can efficiently be realized.

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 [1], [7], [2], [3], [4], [5]. Simultaneously some ideas for applications also emerged [9].

Systems and Control Laboratory at the Computer and Automation Research Institute of the Hungarian Academy of Sciences in collaboration with the Department of Control Engineering and Information Technology and the Department of Control and Transport Automation decided to design and build a mini quadrotor UAV that is intended to fulfil multiple goals. The original idea was to produce an UAV model that can serve as an agent in a cooperative air-vehicle control scheme operating in a small-size in-door test-field. The advantages of the quadrotor helicopter in this type of applications are obvious: simple structure (in comparison with the conventional types of helicopters), relatively slow movement, and maneuvering capabilities in small place (comparing to those of aeroplanes). However, in the course of planning other viewpoints have come into consideration:

- Modeling and control of the quadrotor helicopter poses several interesting problems falling in the field of nonlinear and hybrid systems, that conforms with the research profile of the participant institutions, hence it forms a new platform for testing the theoretical results.
- Quadrotor helicopter — due to its partially redundant structure — is an excellent object for applying fault detection, and isolation methods, as well as designing fault tolerant control schemes.
- Quadrotor helicopter — due to the complex measurement and control problem to be solved as it is correctly controlled — is an excellent example of applying embedded control systems that use microcontrollers, microcomputers of several complexity.
- Multiple quadrotor helicopters — interconnected by a digital communication network — forming a group controlled cooperatively is an excellent base of studying the characteristics of control–over–network strategies

A. Soumelidis and P. Gáspár are with Computer and Automation Research Institute of the Hungarian Academy of Sciences, Kende 13-17, H-1111 Budapest, Hungary `soumelidis@sztaki.hu`, `gaspar@sztaki.hu`

P. Bauer is with the Department of Control and Transport Automation, Budapest University of Technology and Economics, Bertalan Lajos 2, H-1111 Budapest, Hungary `bauer.peter@mail.bme.hu`

B. Lantos and Z. Prohászka are with the Department of Control Engineering and Information Technology, Budapest University of Technology and Economics, Magyar tudósok körútja 2, H-1117 Budapest, Hungary `lantos@iit.bme.hu`, `prohaszka@iit.bme.hu`

that is also a significant topic in the research activities of the participants.
- Developing an in-door quadrotor helicopter offers a good basis for the construction of an outdoor UAV that can execute several tasks (e.g. supervision, measurements) in the fields of protection of the environment, law-enforcement procedures, surface traffic control, etc.

Hence the design of a quadrotor UAV satisfying the following requirements has been decided:

- An UAV of size small enough to maneuver in an indoor site has been designed, however big enough to carry a camera or a measurement device besides its own electronics, power supply and drive compartments.
- 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.
- Let the UAV provide a high level of autonomy, i.e. let an on-board control — base upon on-board measurements — that can execute a series of predefined control action in autonomous manner.

Besides the control of a single UAV a significant objective become also the cooperative control of multiple vehicles, and as a future goal the coordinated solving of problems by groups of quadrotor UAVs.

The paper describes the embedded microcomputer-based implementation of the mini UAV by focusing mainly on the control structure, describes the elements of the implementation, the tools intended for use in the system modeling, as well as obtains a brief outline of the control design. In the following sections first an introduction will be given to the construction of a mini quadrotor UAV, than a measurement device is described the can be used in identification of the UAV drives, finally some ideas will be presented highlight the control design problems.

II. CONSTRUCTING A MINI QUADROTOR UAV

This section is devoted to the construction of a mini quadrotor UAV, that is suitable for both indoor and outdoor usage, can carry some payload that is enough to perform a camera/based surveillance, or several measurements, as well as is able to realize autonomous operation. The construction of the UAV is oriented mainly toward the control objectives that can be expressed in association with the functions to be performed.

The control objectives of the quadrotor UAV can be considered in several levels that shows some hierarchical structure:

- Realizing correct thrust, yaw, pitch, and roll control. This is conventionally implemented in the hobby-realizations of the quadrotor helicopter (see eg. Dragonfly or X-UFO), however — due to the simple instrumentation and processing — decoupling of control actions is usually realized in a moderate level requiring high skills of the operator to control.
- Realizing basic operation modes and maneuvers as hovering in a stable position, ascend / descend, forward / backward / lateral movement. This level of control is not implemented in the hobby-type realizations, these movements are to be realized by the operator on the basis of his/her skills and experience. 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, and this is the highest level that is intended to be realized within the current project. 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).
- A global control that includes also path planning falls out of the scope of this project, however it is subject of the research activities performed within the framework of cooperative control of air-vehicles. The cooperative control field can apply quadrotor UAVs as test vehicles either in an indoor or outdoor environment. Presentation of the results of these activities will be given elsewhere.

The first three options are intended to be realized within the framework of the current project, i.e. the highest level of control within the scope is as follow: a single action of control is an autonomous movement along a predefined path between two spatial points while fulfilling auxiliary conditions as predefined velocity, tracking error, etc. The control is realized upon on-board measurements that are performed by a system of sensors placed on the vehicle. The variety of sensors on the vehicles intended to use indoor or outdoor are different.

The on-board instrumentation intended to use in an in-door quadrotor UAV consist of the following items:

- Inertial sensors — MEMS-based accelerometers and angular rate sensors (giros)providing measurements is 6 degrees of freedom.
- Ultrasound or infrared sensor-based altitude measurement device.
- An indoor positioning system producing position, velocity and orientation measurements.

The instrumentation intended to use in an outdoor model is as follow:

- Inertial sensors — MEMS-based accelerometers and angular rate sensors (giros)providing measurements is 6 degrees of freedom.
- Barometric or laser sensor-based altitude measurement device.
- Magnetometer-based orientation measurement system (electronic compass).
- Global positioning system (GPS) for position and velocity measurements.

The elements of the sensor systems will be introduced in details later.

The actuator system of a quadrotor helicopter consists of four electric motors driving 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. A revolution or a torque control can be realized in the ensemble of a motor and the rotor mounted on it to ensure simple and efficient actuation, which can practically be realized within a local control loop.

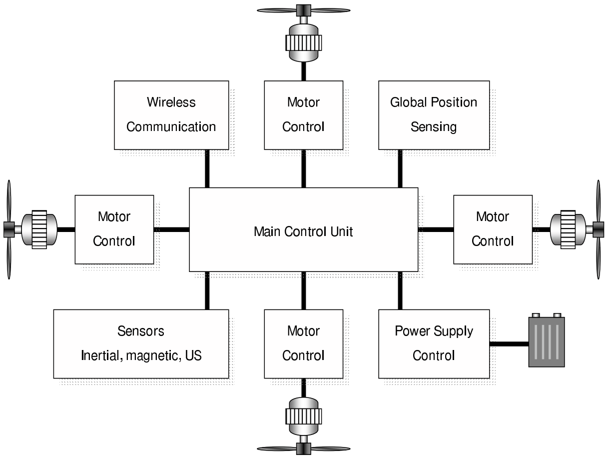


Fig. 1. Logical control structure

The main control of the quadrotor UAV is intended to be realized on an on-board embedded microcontroller. The planned operation scheme is the following: the initial data for control (the setpoint, the trajectory to be executed) are downloaded to the controller by applying wireless digital communication, and from this moment the execution of the control is performed autonomously. A global control of the UAV is performed by a sequence of these type of operations, and is realized centrally with the assistance of an ”earth” control agent. The control structure of the quadrotor UAV can be seen in Figure 1. An advantageous form of realizing the on-board control system is a distributed scheme based upon embedded microcontroller-based local control units (called ECU — Electronic Control Unit — in the vehicle terminology) interconnecting them in a network bus, as it can be seen in Figure 2. In the vehicle technology the CAN network is widely used for these purposes, however there exist new developments now to improve significant properties — e.g. reliability — of the communication, let us mention e.g. FlexRay.

The embedded control implementation offers numerous advantages in the realization of the UAV:

- The functions to be realized are divided into obvious, self-dependent subtasks that can simply be implemented by applying the means and methods that are specific in the corresponding field (e.g. motor control, or communication).
- Local realization of self-dependent sub-tasks allow the use of simple devices (e.g. microcontrollers), and as a consequence of the simplicity a more reliable solution is given.

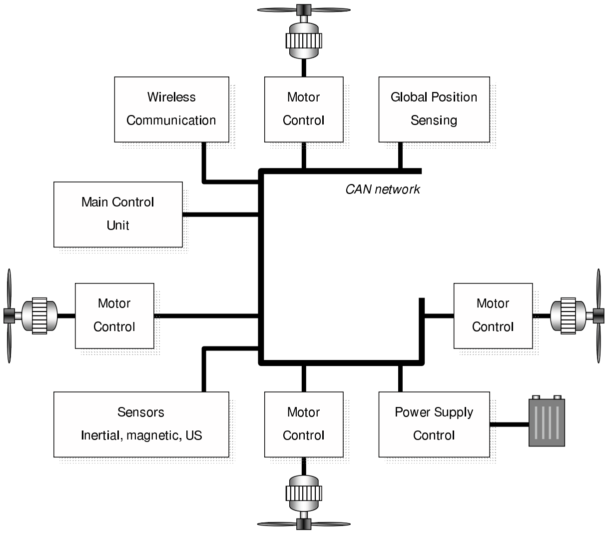


Fig. 2. Networked control structure

- The interfaces between the system parts are realized upon the basis of a network protocol that offers the opportunity of uniform design and analysis techniques. There exist numerous formal verification tools that can be applied in this field to improve the efficiency of the design process and ensure reliable realization.
- Numerous software tools are available for automatic generation of code from formal specification in several embedded microcomputer platforms. Using these type of tools significantly improves the efficiency of the design process.

An example of the software tools that can efficiently be used in this field is the Realtime Workshop and the Embedded Targets offered by Matlab and Simulink of Mathworks. This project intends to utilize the benefits of these tools by applying MPC555 of Freescale as the main control computer. Support for MPC555 is included in the Embedded Targets offered by Mathworks. The MPC555 microcomputer realizes PowerPC architecture with a 32-bit fixed- and floatingpoint arithmetics. It possesses numerous peripherals, among them 2-channel UART (for serial communication) as well as a 2-channel CAN controller. In the experimental realizations of the UAV the serial-line communication is used as interface to some standard peripherals, e.g. GPS or indoor positioning receiver, and a inertial measurement unit. In the ultimate configuration CAN (or in the future FlexRay) is intended to use as a universal interface.

The rotor drive motor control is realized as an 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. The more advantageous solution will be applied in the UAV. The motor control unit use CAN network to communicate with the main controller. There are multiple advantages of using BLDC motors: besides the high torque, and efficiency its flexible controllability is its most significant property, resulting the nonnecessity of any gearbox in generating the required rotation speed , as it can be controlled electronically.

An important sub-module of the UAV is the wireless digital communication module. The main function of the wireless communication is to send commands and download the initial conditions, setpoints, trajectories to the UAV; as well as reporting the state of the UAV in the reverse direction. No direct on-line control is intended to be realized by it, hence the amount of data to be transferred is relatively small. Two types of realizations — an IEEE802.11-based Wireless LAN (WiFi), as well as an IEEE.802.15.4-based PAN (Personal Area Network) — are considered mainly for short-range indoor purposes, both operating in the 2.4 GHz ISM band. Finding solutions for wide-range outdoor communication is considered to be a future task. WLAN possesses advantages in the realization, since it uses the well-known TCP/IP protocol, as well as realizes high data-flux that can be useful in some auxiliary functions, e.g. sending measurement data or even images originated from on-board sensors. IEEE802.15.4-based PAN realizes relatively slow data transfer, however it is optimized for very reliable communication. The IEEE802.15.4 standard is restricted only to the physical (PHY) and media access (MAC) level of the communication (according to the ISO/OSI nomenclature), the levels above 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. As a consequence: IEEE802.15.4-based PANs are advantageous solutions to realize control networks, hence they will be preferred in the field of indoor UAVs, while WLAN will be used in the prototyping phase.

Another important sub-unit of the UAV is the sensory system that — as it has been outlined above — can consist of global positioning, inertial, ultrasound distance measurement, and magnetic sensors.

Outdoor global positioning can be realized by applying a GPS receiver on-board. Various commercial products can be applied, those with acquisition-time 0.25 s, and accuracy of approx. 2.5 m form a good trade-off in the selection process. A more interesting thing is the realization of an indoor positioning system. Two principles has been selected to test as outlined as follow:

- A camera-based solution that applies image-processing methods to detect markers, and on the basis of them to derive position by using trilateration methods.
- A combined ultrasound and radiofrequency based solution: distance measurement is based upon ultrasound pulse transmission, while synchronization is performed by radiofrequency signals. By this method velocities can also be measured by applying the Doppler principle.

The indoor positioning system consists of an infrastructure installed in the test field, as well as on-board devices:

- The camera-based system is realized by using fixed cameras and on-board active markers, the position data is sent to the vehicles by communication.
- In the ultrasound solution the infrastructure consist of fixed ultrasound and RF transmitters, while there are ultrasound and RF receivers placed on-board. The computation for position data gained by trilateration are performed on an on-board microcomputer-based device that communicates with the main computer by CAN or serial line.

The indoor positioning systems described below are developed in the framework of student programs, and their results will be reported separately.

The inertial measurements are performed by MEMS-based acceleration and angular rate sensors realized in six orders of freedom, i.e. by measuring acceleration in X,Y,Z directions, as well as rotation around X,Y,Z axes. The inertial measurement unit is stand-alone device realized by a microcomputer, and communicating with the main computer by CAN or serial line.

An altitude sensor can be a useful complement of either the positioning or the inertial measurement system as it can supply more frequent data than the positioning system, and more accurate than the inertial one. For outdoor usage barometric pressure measurements can be used, while for indoor purposes ultrasound or infrared distance measurements are adequate. The measurement sensors are realized as stand-alone devices by using simple 8-bit microcontrollers, and communicating on CAN or serial line.

For experimental purposes in the prototyping phase a commercially available sensor unit is used that realizes most of the measurement tasks, and communicates with the main computer via serial line.

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.

III. AERODYNAMICAL DESIGN, IDENTIFICATION AND MODELING

Besides the electronic design a significant topic is the mechanical, aerodynamical design, that is based mainly on the skill and experience of colleagues belonging to the Control and Transport Automation Department of the Budapest University of Technology and Economics.

For supporting the mechanical and aerodynamical design, as well as obtaining a tool for modeling and identification of the aerodynamical properties of the drive–rotor mechanisms, a measurement device has been constructed. The schematic structure of the mechanical part of the device can be seen in Figure 3. The thrust, as well as the torque produced by the ensemble of the motor drive and the rotor is measured

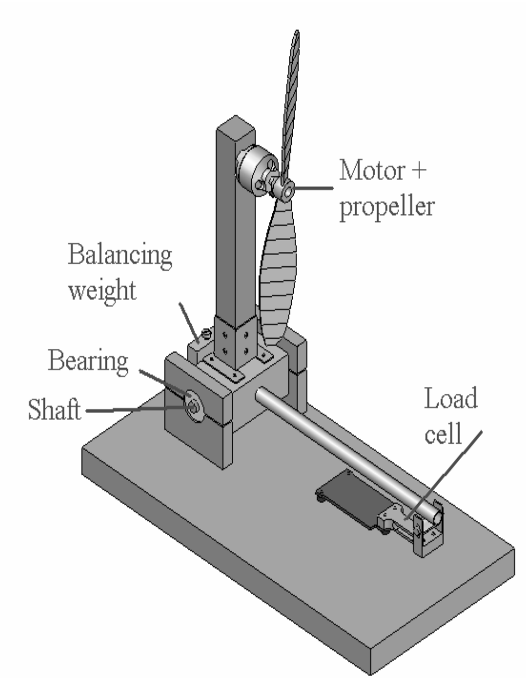


Fig. 3. The structure of the measurement device

by using a sensitive load cell. The signal of the load cell is amplified and processed by a microcomputer-based electronic device, that by connecting it to a personal computer produces single or multiple force measurements. Besides these measurements this microcomputer controls the motor, and performs rotation speed and motor current measurement, that are suitable for the complete monitoring of the motor.

A data acquisition application in the personal computer collects data and transforms them in forms that can be processed in evaluation and identification programs. In our praxis processing in Matlab is a feasible approach. The properties to be explored by these measurements are as follow:

- Deriving the static characteristics from the rotation speed to the thrust or torque resulting by the rotor.
- Deriving step- and impulse response, as well as transfer characteristics of the dynamical system consisting of motor-drive and rotor.
- Exploring the disturbing effects in the static and dynamic characteristics.

These examinations give significant contribution for the efforts aimed to produce accurate mathematical models belonging to the drive mechanism of the quadrotor UAV. On the basis of these models an accurate design of the rotor diameter and shape, the dominant rotation speeds, the necessary motor power, the allowable payload, and numerous other parameters can be designed.

Furthermore the results of these measurements are also for supporting control oriented modeling and control design.

IV. THE CONTROL OF A MINI QUADROTOR UAV

The modeling and control design of a mini four-rotor UAV is interesting for several reasons. It is interesting in 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. It is interesting in terms of possible practical applications, too. Moreover, it is interesting in education since this is a good tool for demonstrating control principles.

The purpose of the control design is to track a predefined trajectory with the smallest possible tracking error. There are several difficulties in performing such a design. The control inputs are nonlinear expressions of the individual trusts. Since they produce constraints on the input, constrained control design methods must be applied. The model is only an approximation of the plant to be controlled, thus the unmodelled dynamics and the parametric uncertainties should be taken into consideration. In practice the effects of disturbances and measurement noises should be also attenuated by the designed control.

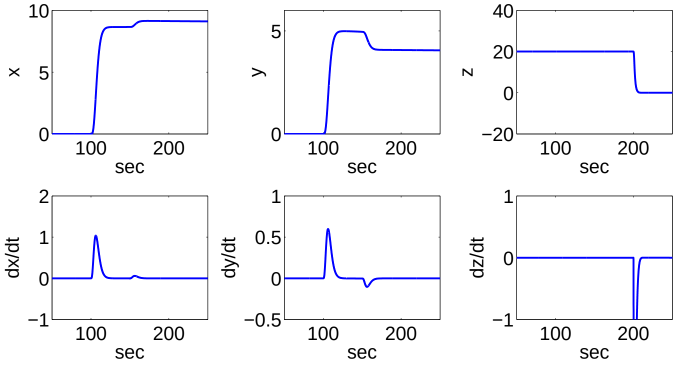
The following goals are set: the generation of feasible trajectories and the design of a robust controller. The papers concerned with quadrotor control usually focus on the first task, i.e., trajectory generation, see [4]. A complex trajectory is divided into sections in order to perform simple maneuvers, such as changing altitude, changing the lateral position, etc. As an illustration a complex maneuver is performed and the time responses of the UAV are presented in Figure 4.

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 are to be proposed, e.g. an approximate circle curve must be defined instead of an accurate circle motion in a horizontal plane.

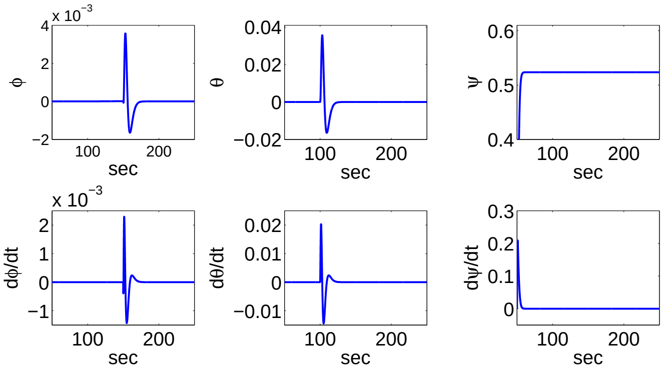
The other task is to design a controller to achieve the predefined trajectory with the smallest possibly error. This controller must be robust, i.e. it must attenuate the disturbance and noises and the model uncertainties must also be taken into consideration. This means that the controlled system should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

V. CONCLUSIONS

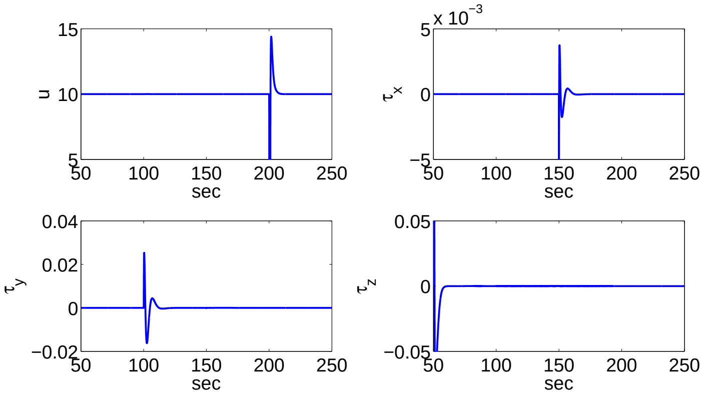
In this paper the design and realization of a mini quadrotor UAV using an embedded microcomputer-based implementation were presented. The UAV is developed in the Systems and Control Laboratory at the Computer and Automation Research institute of the Hungarian Academy of Science in collaboration with control departments of the Budapest University of Technology and Economics. The UAVs to be developed are intended to apply in air surveillance and environmental measurements.



(a) Displacement and velocities



(b) Angles and angular velocities



(c) Control force and torques

Fig. 4. Time responses in UAV maneuvers

VI. ACKNOWLEDGMENTS

This work was supported by the Hungarian National Office for Research and Technology through the project ”Advanced Vehicles and Vehicle Control Knowledge Center” (ref. number OMFB-01418/2004), which is gratefully acknowledged. The authors also gratefully acknowledge the contribution of Hungarian National Science Foundation (OTKA #K060767).

REFERENCES

[1] E. Altu, J.P. Ostrowski, and R. Mahony. Control of a quadrotor helicopter using visual feedback. *Proc. of the International Conference on Robotics and Automation, Washington*, pages 271–276, 2002.

[2] E. Altu, J.P. Ostrowski, and C.J. Taylor. Quadrotor control using dual camera visual feedback. *Proc. of the IEEE International Conference on Robotics and Automation, Taipei, Taiwan*, 2003.

[3] S. Bouabdallah, P. Murrieri, and R. Siegwart. Design and control of an indoor micro quadrotor. *Proc. of the IEEE Int. Conf. on Robotics and Automation, New Orleans*, 2004.

[4] P. Castillo, R. Lozano, and A.E. Dzul. Modelling and control of mini-flying machines. *Springer-Verlag, London*, 2005.

[5] P. Castillo, R. Lozano, and A.E. Dzul. Stabilization of a mini rotorcraft with four rotors. *IEEE Control Systems Magazine*, 2005.

[6] J. Escareno, S. Salazar-Cruz, and R. Lozano. Embedded control of a four-rotor uav. *Proc. of the American Control Conference, Minneapolis*, pages 3936–3941, 2006.

[7] T. Hamel, R. Mahony, R. Lozano, and J. Ostrowski. Dynamic modelling and configuration stabilization for an x4-flyer. *Proc. of the 15th Triennial World Congress, Barcelona, Spain*, 2002.

[8] J. Somló, B. Lantos, and P.H. Cat. Advanced robot control. *Akadémiai Kiadó, Budapest*, 1997.

[9] M. Valenti, B. Bethke, G. Fiore, J.P. How, and E. Feron. Indoor multi-vehicle flight testbed for fault detection, isolation, and recovery. *AIAA Guidance, Navigation, and Control Conference, Keystone*, 2006.