Teleoperation Assistance for an Indoor Quadrotor Helicopter

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Abstract. This paper presents design details of a teleoperated miniature aerial vehicle for indoor scenarios. A 600 MHz board computer has been interfaced with a digital camera, a miniature 2D laser range finder and a commercially available quadrotor helicopter. An ad-hoc wireless local area network (LAN) link between the board computer and a notebook is established to feed back sensor data of the helicopter to a teleoperation user interface. The platform has been built to compete in the EMAV 2008 indoor flight competition in Braunschweig, Germany [1]. The corresponding indoor mission which requires 3D navigation capabilities is described in detail. Altitude and position control have been implemented and tested on our vehicle to assist piloting. Significantly improved operability compared to non-assisted teleoperation has been achieved.

Keywords: miniature aerial vehicle, quadrotor, assisted teleoperation

1 Introduction

Due to possible applications such as reconnaissance missions or inspections of industrial and civil structures, unmanned rotorcrafts have attracted a lot of interest in the research community in recent times [2], [3], [4], [5]. Using flight as a locomotion principle can provide several distinct advantages over surface-bound locomotion for these applications. A rotorcraft might just fly over obstacles which may prove difficult to overcome for legged or wheeled vehicles. Furthermore, situations might be assessed faster from a bird's eye perspective than from a surface-bound viewpoint.

In order to create practical unmanned rotorcrafts which may be employed in real-world scenarios, emphasis should be laid on vehicle robustness and ease of operation. This is especially true for indoor scenarios where collisions with obstacles are always imminent.

Flying within confined and cluttered indoor environments imposes strong constraints on the practical size of indoor rotorcrafts and thereby also limits vehicle payload capabilities and flight endurance. Furthermore, only a very small selection of sensors and computing systems can be employed under the given limitations. This combined

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with the absence of an easily accessible position estimate, as from a GPS-signal, makes indoor navigation and control of miniature aerial vehicles (MAVs) difficult. Safely navigating unmanned rotorcrafts within indoor environments – using teleoperation or an autonomous control system – is therefore still an unsolved problem.

The EMAV indoor competition 2008 in Braunschweig, Germany proposed an indoor scenario to push and compare research for autonomous indoor navigation and control of MAVs. Figure 1 explains the single mission points which had to be completed. Three operation modes were accepted for the competition with increasing scores for higher levels of autonomy: remote control with direct visual contact, remote control with no direct visual contact (teleoperation) and fully automated control. All sub-missions had to be completed in the same mode of operation. Full, three-dimensional navigation is required to complete this mission as obstacle passing has to be accomplished not only while moving in a horizontal 2D plane but also in the vertical direction when flying through the chimney. This leads to particular requirements which have implication on the entire system, especially on the choice of sensors and their placement.

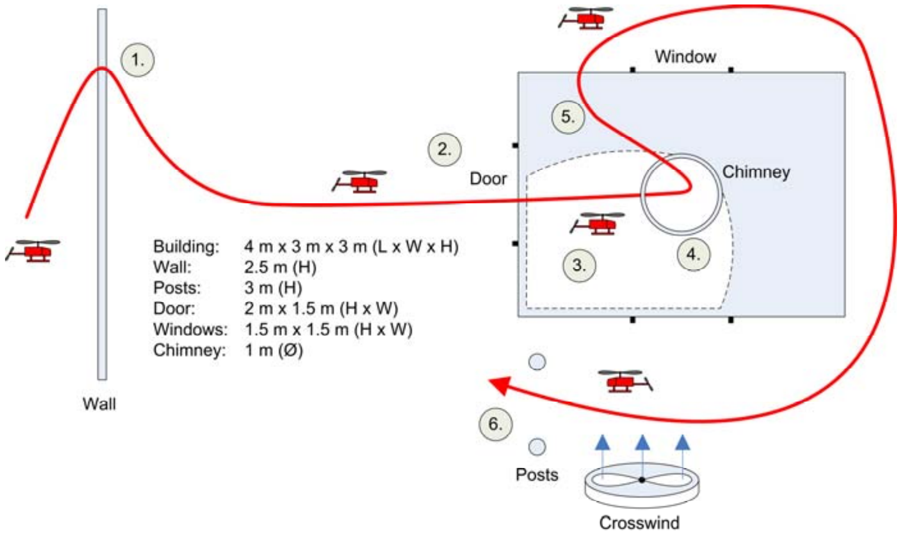

Figure 1 Mission for the EMAV indoor competition 2008. 1. Fly over wall. 2. Enter cottage through door. 3. Identify a target on the floor and on the wall. 4. Exit cottage through the chimney. 5. Hover above cottage for 10 seconds, then land on the roof. 6. Take off from roof, fly through posts and past crosswind of 5 m/s.

In order to devise a system which can reliably operate in an environment similar to the depicted one, directly aiming at full autonomy may lead to very problem specific solutions. Therefore, an alternate research route is proposed starting with a simple teleoperation scheme. Over the course of progressing research efforts, more and more sophisticated pilot assistance modes can then be added to ease system operation and to increase the overall level of system autonomy. This bottom-up approach might lead

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to solutions with a more general applicability in real-life indoor scenarios. The first steps on this research route are described in this paper.
In the following chapter we describe our platform and teleoperation system, motivate the choice of its components and present the employed software framework. Thereafter, performance tests of two assistance modes and their applicability for the indoor competition scenario of EMAV 2008 are presented.

2 System Description

In order to create a flexible research rotorcraft a modular approach has been chosen. Commercially available hardware components have been combined, resulting in a maintainable and easily extendable system with range finding and onboard image processing capabilities.

2.1 Hardware Design

The presented research platform (Figure 2) is based on the commercially available "Hummingbird" quadrotor helicopter [6]. Attitude stabilization running at 1 kHz is already implemented on the vehicle and a serial interface is provided in order to connect the quadrotor to a higher level processing unit. This helicopter is capable of lifting high payloads, still offering reasonably long flight times (~10 minutes @ 200 g payload) and owns a crashworthy carbon fiber structure.
A small 600 MHz computer (gumstix verdex XL6P) [7] is connected to the serial interface of the quadrotor helicopter via an expansion board (gumstix console-vx). This computer runs a μLinux operating system and is capable of using cross-compiled versions of open-source libraries well known to the robotics community (Player [8], CMU-IPC [9], OpenCV [10] and others). Custom software can easily be developed and tested on a standard Linux system and installed on the μLinux computer in a later state. Three RS-232 ports, one USB port, an I^2C interface and GPIO lines are made available over the console-vx expansion board.
Using one of the RS-232 connections, pitch, roll, yaw and thrust commands can be sent to the helicopter's flight computer and inertial measurement unit (IMU) data can be gathered to implement and test higher level controllers on the processor of the verdex motherboard.
A wireless-LAN module (gumstix netwifimicroSD EU) is connected to the verdex computer in order to establish a robust communication link between a notebook running a standard Linux kernel and the helicopter.
The digital camera (Logitech Quickcam Communicate STX Plus) connected to the μLinux computer using USB, captures images which are fed back via the wifi-link to the base station. For indoor environments this digital image transmission provides significant advantages over an analog solution due to reduced transmission noise. Image processing may be executed on and off board without having to cope with image artifacts often observed in analog camera systems.

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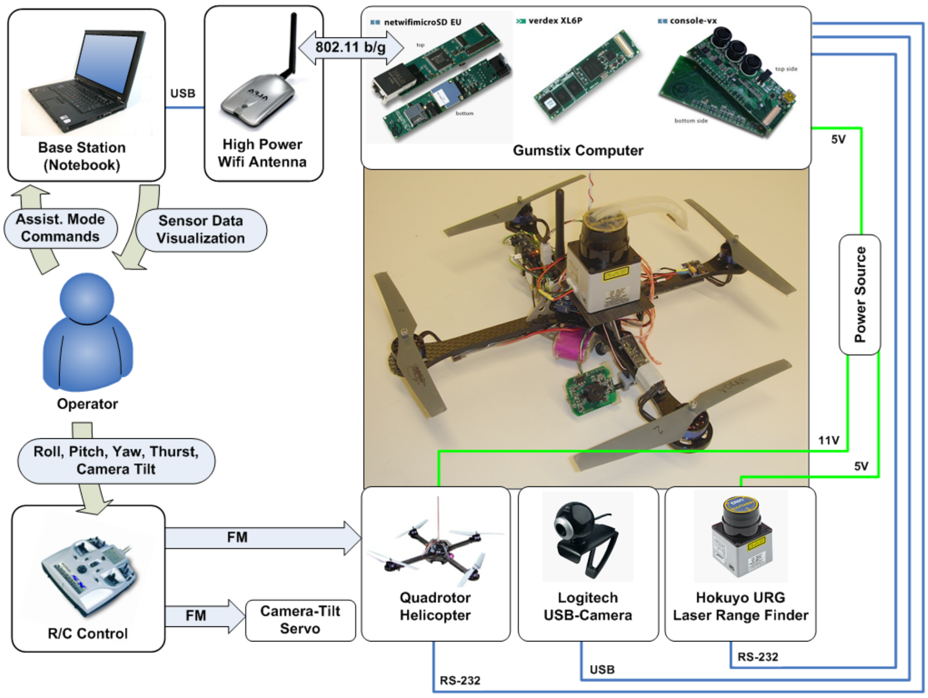

Figure 2 System diagram of the research platform.

The 180°-camera-tilt mechanism allows identification of floor-targets and helps in passing the chimney during the EMAV mission. The 6-channel remote control is used to change the servo motor position and thereby the tilt-angle of the camera.
A "lightweight" laser range finder [11], connected to the verdex computer, completes the system. Horizontal range data between 0.06 and 4.0 meters is collected in a 240°-sector at 10 Hz. A mirror at the side of the range finder deflects part of its beams to the floor allowing altitude measurements. This results in a multipurpose sensor which may be employed for localization, collision avoidance and altitude control.
The complete system has a total weight of 710 g, a flight endurance of 8 minutes and – including a safety bumper made from carbon rods – a diameter of 0.6 meters.

2.2 Software Design

The software architecture depicted in Figure 3 has been implemented using object oriented programming in C++. Communication via TCP/IP has been realized using the Inter-Process Communication Package (IPC) from Carnegie Mellon University.

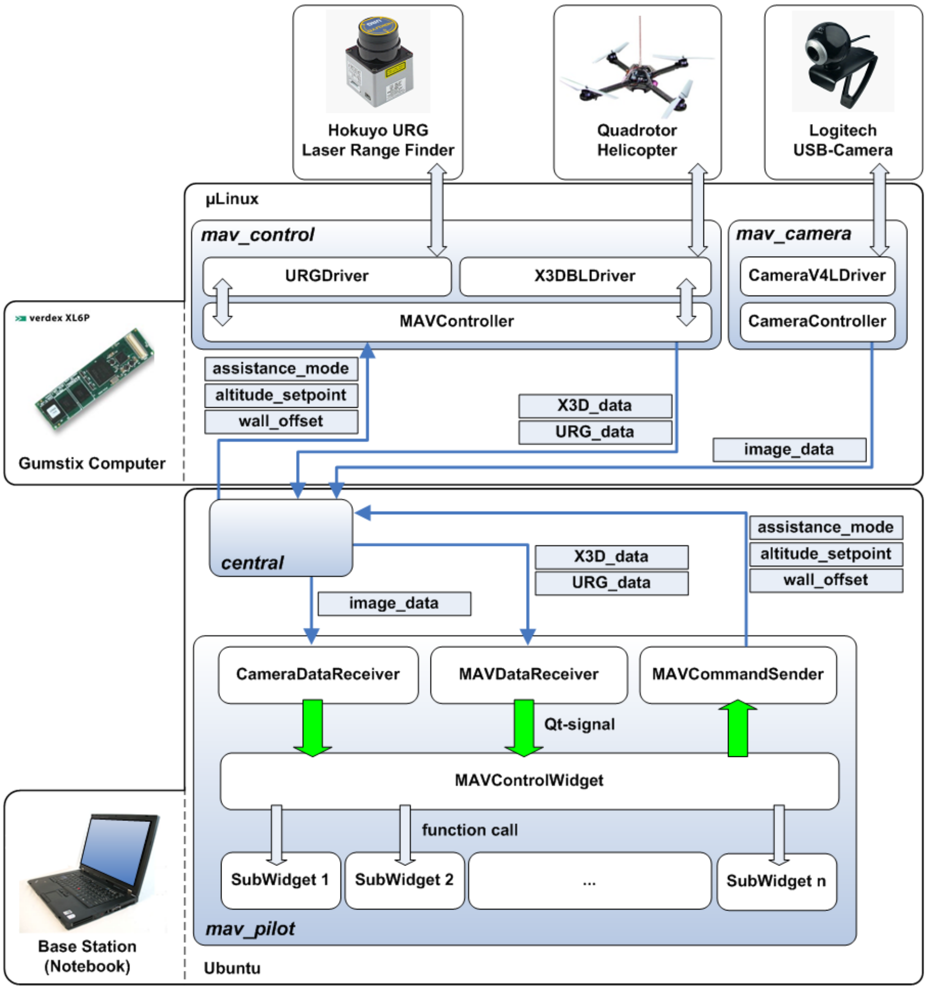

Figure 3 The software architecture for the teleoperation user interface on the base station and the assistance control loops on the onboard computer.

The IPC C-library provides a program called *central* which functions as a message dispatcher. Multiple user programs (modules) running on the same or several interconnected computers can communicate with each others via this program. C++ wrappers have been implemented which allow exchange of information between the base station and the helicopter's onboard computer using specific message packages. User space drivers have been written to access the helicopter, the laser range finder and the USB-camera. On top of these drivers, controller classes have been implemented which are regularly called by IPC-callbacks to collect data or execute control operations.

Two programs – *mav_control* and *mav_camera* – are running on the helicopter's onboard computer in parallel. The *mav_control* module gathers data from the helicopter and the laser range finder, runs the assistance control loops and publishes the collected data to the base station via the *central*. In order to allow acceptable frame rates on the teleoperation user interface, frame grabbing has been moved to a separate process (*mav_camera).* It collects JPEG-compressed images employing a video4linux based camera driver and publishes them to the base station at 20 Hz.

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The user interface application (*mav_pilot*) has been implemented based on Qt [12] and OpenSG [13]. Visualizations of range finding data, camera images, assistance mode information and the helicopter's IMU-data and voltage level are displayed. A communication layer consisting of several data receiving and command sending classes relays incoming or outgoing messages to or from the main widget (*MAVControlWidget*). Several sub-widgets are embedded within this main widget displaying the different types of information. Both, the visualization and the communication layer can be easily extended and modified.

3 Teleoperation Assistance

Quadrotor helicopters are highly dynamic and inherently unstable systems. Despite the high frequency attitude control which is already implemented on our vehicle, position drift still occurs. Tests with an experienced model helicopter pilot showed that the utilized quadrotor is difficult to control during teleoperation based on visual feedback only. The degree of immersion and depth perception provided by the camera images and the visualization of the range finder data are not enough to precisely control the helicopter's position. Piloting the vehicle inside the narrow cottage was particularly demanding due to the unnatural field of view of the camera. Simple maneuvers such as keeping the vehicle in a stable hover at a constant altitude already proved challenging. Therefore, altitude control has been realized as a first assistance mode to remove this burden from the pilot. A proportional derivative (PD) controller has been implemented on the board computer collecting altitude measurements form the laser range finder and adjusting the helicopter's thrust to keep a predefined height above the ground.

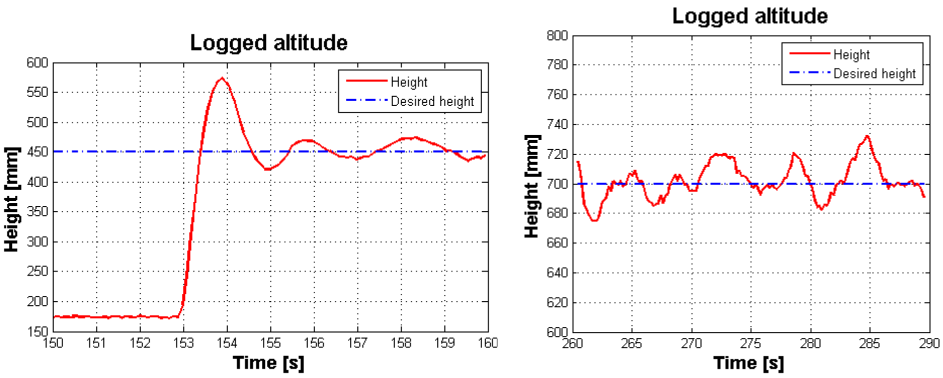

Figure 4 Step response of the system during an autonomous take off to an altitude of 0.45 meters and logged altitude during flight at 0.7 meters ($K_P = 30.0$, $K_D = 15.0$).

Figure 4 shows experimental results from an autonomous take off maneuver and the altitude control during level flight. The desired height of 0.45 meters during the autonomous take off is reached in 1.5 seconds with an overshoot of 0.17 meters. A smoother take off maneuver could be achieved by further adjusting control gains and

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by sequentially increasing the controller setpoint until the desired height is reached. During level flight the altitude is stabilized at a desired value within ± 0.04 meters. This assistance mode has been extensively used during the EMAV mission.
The most challenging maneuver in the EMAV competition is the chimney passing. Keeping the helicopter well aligned with the axis of the chimney while entering and passing through it could not be accomplished by our pilot relying on the upward tilted camera only. Therefore, a position controller using the range finder is required which centers the vehicle in the middle of the room and thereby automatically aligns it with the axis of the chimney. The same position controller can also be used to safely fly through the chimney. Two PD controllers have been implemented adjusting pitch and roll to keep a constant offset to a wall on the right and in front of the helicopter.

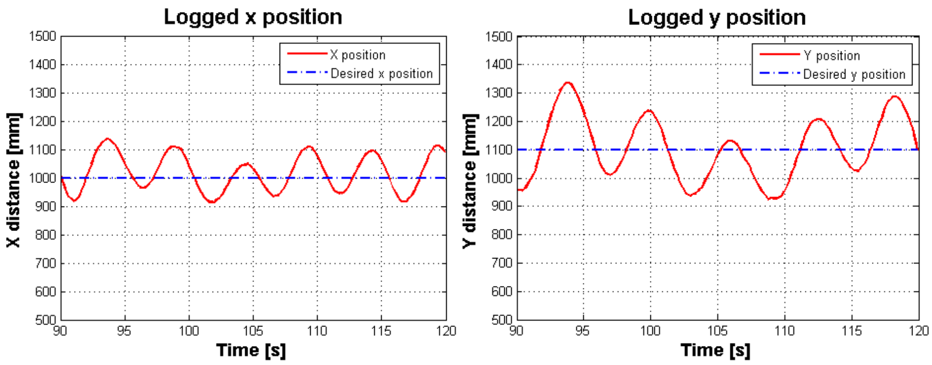

Figure 5 The wall offsets from two perpendicular walls to the front and to the right of the helicopter have been recorded during a position control flight experiment. The front offset (X) is stabilized at 1.0 meters using a PD controller ($K_P = 25.0$, $K_D = 35.0$) adjusting the helicopter's pitch angle. The offset to the right wall (Y) is stabilized at 1.1 meters using another PD controller ($K_P = 15.0$, $K_D = 25.0$) adjusting the helicopter's roll angle.

Figure 5 shows the recorded distances to the front and to the right of the helicopter during a position controlled flight in a test environment. Position stabilization with a deviation of ± 0.15 meters to the front wall and ± 0.25 meters to the right wall has been achieved. The discrepancy in the position oscillations in x- and y-direction results from the difference of the vehicles second mass moments of inertia around its pitch and roll axes.
Due to the vehicle diameter of 0.6 meters, only a 0.2 meter margin remains between the chimney and the helicopter when passing through it. Safely entering and passing the chimney could therefore not be demonstrated using the current controllers. This might yet be optimized by better tuning of the control parameters. Further improvements may be achieved, also using the acceleration measurements of the helicopter's IMU instead of relying on the range measurements only. This would allow pushing the position control frequency beyond the 10 Hz limitation of the range finder to cope with the system's fast dynamics.

4 Conclusion and Future Work

This paper presented a teleoperated quadrotor helicopter with altitude and position control to assist piloting within indoor environments. Design details of the hardware and software implementation and test results of the pilot assistance controllers have been described. The adopted design approach not only aimed at a system which works for the proposed EMAV indoor scenario but is flexible enough to allow rapid modification and enhancement for further research.
Future work shall also employ vision as an additional sensor, fuse operator and assistance controller commands and optimize the entire system. This shall be achieved through further experimentation and better embedding of validated system components.

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