A Quadrocopter Hovering Above a Person Wearing a Modified Cap

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Abstract

We here describe an application of a quadrocopter hovering stably above a person wearing a cap with 4 infrared LEDs. The application has originally been developed in the context of wearable computing. Our "wearable helicopter" hovers above the user. In further work, the system could send a bird's eye view of the area to the operator, while the robot follows him. The entire aerial robot works autonomously, all processing is done onboard. We use a miniature quadrocopter with an inertial measurement unit and a low-cost Wii remote camera, i.e., commodity consumer hardware. This proof of concept gives insight into flight control. The system is evaluated in a series of experiments.

1. Introduction

In this paper, we introduce the idea of using an autonomous quadrocopter, flying stably above the user's head. The user simply has to wear a modified cap.

The key idea of our approach is to track a pattern of infrared spots located at the cap. The camera looks downwards and is attached to the center of the quadrocopter frame. The pattern is designed to provide an efficient calculation of its position. In addition to the information given by the camera, we require data from the inertial measurement unit (IMU). By analyzing this information, we have four degrees of freedom (x, y, z, and yaw angle ψ) as inputs to the control loop to hover above the cap. The roll and pitch angles φ and θ are controlled internally by the control unit shipped with the quadrocopter, using only IMU data. φ and θ are adjusted in order to stay at an x and y position around 0. Our control loop is designed as a simple algorithm running on an onboard microcontroller at a high frequency.

Currently, existing quadrocopters are remotely controlled by an operator. Some models offer more comfortable commands like setting a specific GPS position or route. Nevertheless, the operator is busy handling the aerial vehicle. Our system would allow for hands-free operation, while the quadrocopter holds a constant relative pose over the user.

Our wearable helicopter prototype has been tested in a number of experiments. In this paper, we describe its design and our experimental results of hovering above the cap. This is a proof of concept. Criteria such as user safety, user acceptance and aesthetics have to be examined more closely later.

In our experiments, the aircraft hovers above the cap at a specified height between 30 cm and 1 m. The system is capable of hovering within a root mean square deviation below 3 cm at a height of 40 cm.

2. Related Work

Most flying vehicles which perform onboard vision-based tracking and navigation have a significant size and weight [1, 9, 10]: In that way, they are capable of carrying personal computers with modern gigahertz processors and accurate industrial stereo cameras. Smaller aircrafts have to cope with very limited payload capacity. To find a solution for flight control, some approaches transfer calculation to a ground station; this allows for complex flight control mechanisms [2, 5, 6], but limits autonomy. Controlling unmanned aerial vehicles without an onboard camera, but tracked by an external motion capture system, allows for accurate positioning at a high control frequency, as cameras of a high quality and fast computers can be used [3, 12]. However, the robots can only operate in a bounded laboratory environment. Mak et al. [7] describe a six degree-of-freedom visual tracking system for a miniature helicopter using only three onboard LEDs and a single on-ground camera. Roberts et al. [8] present a low-cost flight control system for a small outdoor helicopter where all processing is performed onboard. For a comparable solution on miniature flying robots as the Hummingbird quadrocopter, the system has to be even smaller and lighter. Hay et al. [4] explain how objects can be tracked optically using two Wiimotes and achieved accurate results with a minimum of hardware costs. These solutions deal with a minimum of hardware demands, but still depend on a permanent connection to the ground station to control a flying robot. Our approach is different from those described above, as we are using the IR camera from a Wiimote onboard. The approach only depends on four IR diodes as external landmarks, which can easily be integrated in a wearable cap, for instance.

Another project related to our approach is the topshot helmet constructed by Julius von Bismarck [11]. The helmet displays the user in a bird's eye view like it is known from some computer games. His first idea was to use a quadrocopter, but he did not have a proper tracking solution. The final configuration employs a balloon, connected to a helmet.

3. System Components

The construction of our system consists of a miniature quadrocopter, equipped with an infrared (IR) camera, and a cap provided with four infrared LEDs. We use an AscTec Hummingbird AutoPilot quadrotor helicopter. The camera is part of the Wii remote controller (informally known as the Wiimote), distributed by Nintendo. It is able to track infrared blobs at a frequency of 200 Hz and more. The integrated circuit supplies the pixel position of each tracked blob. This section describes the hardware of the quadrocopter, the infrared camera and the cap.

3.1. The Quadrocopter

The AscTec Hummingbird AutoPilot quadrocopter (Fig. 1) has a diameter of 53 cm and a weight of only 0.5 kg. With these properties it is able to fly indoor and outdoor with high agility. A 2,100 mAh lithium-polymer accumulator powers the electronic motors and the onboard electronics. A flight time of up to 23 minutes can be achieved, depending on additional payload and flight maneuvers.

The Hummingbird Autopilot platform provides a three-axis gyroscope, an accelerometer, a compass module, a GPS sensor and a pressure sensor. The sensors, the micro-controller and the flight control run at 1kHz such that a reliable stabilization of the quadrocopter is ensured. Hence, the Hummingbird already provides basic outdoor autonomy without any additional hardware. Abilities like hovering above a given position are realized with the GPS sensor. GPS-based flight is not feasible for our application, because GPS is not accurate enough, erroneous near buildings and restricted to outdoor usage.

As we also did experiments with other aircrafts, we decided to program a separate board, populated with an ATmega AVR 644P microcontroller clocked at 14 MHz. The entire control is processed on this board. Additionally, the microcontroller sends sensor information to the optional base station, which is solely used for monitoring purposes.

Figure 1. The AscTec X3D-BL Hummingbird quadrocopter.

The microcontroller framework is able to communicate with different control protocols such that our approach can be applied to various quadrocopters. The Hummingbird has proven to provide roll and pitch estimates of satisfactory quality, leading to accurate position estimates.

We attached the camera in the center of the quadrocopter frame. Thus, we do not need to calculate additional translations for position computations.

3.2. The Wii Remote Infrared Camera

When chosing a sensor for a miniature flying vehicle, we have to attach great importance to its size and weight. The Wiimote Infrared camera (Fig. 2) has a dimension of $8 \times 8 \times 5$ mm at a weight of 0.4 g. It is part of a Bluetooth compatible controller, designed for interfacing the Nintendo Wii game console. Beside the camera, the controller provides a three-axis accelerometer, 12 digital buttons and an expansion port to connect other input devices. The price is 40 €.

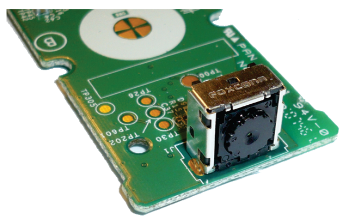


Figure 2. The sensor of the Wii remote.

Originally, the camera is used in conjunction with two infrared spots. In this way the system can determine the position and orientation of the controller to manipulate a cursor on the screen.

The camera system – a multi-object tracking engine (MOT sensor) – is manufactured by PixArt Imaging[1]. It is already capable of blob tracking of up to four IR sources. The actual resolution is internally increased eightfold to 1024×768 pixels by subpixel analysis. The camera sensitivity can be varied. Its horizontal field of view is approximately $45°$. The sensor provides information about the dot size, the intensity and the bounding box of an IR blob. We operate with a basic sensor mode, which conveys merely the pixel position at which the blob is located. Data are transferred via I^2C bus with a refresh rate of up to 250 Hz.

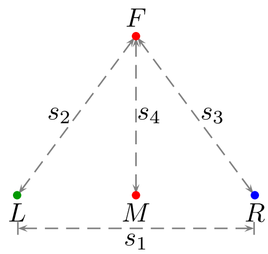
Just a few electronic components are required to integrate the sensor in a microcontroller circuit. The camera runs at 3.3 V and requires an external synchronisation of 24 MHz. As we know the I^2C bus address and the communication protocol, data can be obtained easily by an I^2C host via polling.

3.3. The Cap

The system requires a pattern of infrared lights which can be recognized by the camera. We constructed a cap with four infrared LEDs attached on top (Fig. 3(a)). This ensures precise positioning of the light sources and wearing comfort for the user. We chose a configuration with all LEDs lying in one horizontal plane.

The pattern is arranged as a T-shape (Fig. 3). It measures 90 mm from the left to the right IR spot (s_1), and 60 mm from the middle to the front IR spot (s_4). With their dimensions it fits easily on a standard cap. Each spot is represented by a single 940 nm wavelength infrared LED. This configuration has proven to be of good size for tracking, when the pattern must be recognized at a relatively close distance.

(a) The cap, modified for tracking.



(b) The pattern configuration.

Figure 3. A pattern of infrared LEDs, enabling the aircraft to recognize the user's position.

4. Pose Estimation

The quadrocopter is supposed to hover above the pattern which is integrated in a cap. To steer it has to know the position of the pattern relative to the quadrocopter. This section describes how the current position vector $\vec{p} = (x, y, z, \psi)^T$ is estimated. x, y and z are the Cartesian coordinates of the pattern center relative to the camera and ψ is the orientation in yaw. $\vec{p}$ can be estimated by using the Wiimote camera information. Roll and pitch are estimated by the IMU.

4.1. Pattern Analysis

In the first step the four elements of the pattern have to be identified. The size of the pattern has strong influence on tracking precision at different distances. Additionally, hovering close to the pattern is bounded by the field of view, while hovering at a large distance is limited by the intensity of the LEDs and the camera resolution.

By running the Wiimote camera in basic information mode, the positions of four points are transmitted to the microcontroller. To get unambiguous position information, the disordered points F (front), L (left), M (middle) and R (right) (Fig. 3(b)) first have to be identified. To sort the points, we choose an approach that focuses on fast processing on a microcontroller. Thus, we aim at an avoidance of floating point operations as well as trigonometric functions.

We determine a line defined by two of the four points, chosen at random. Then the distances of all remaining points to the line are calculated. This procedure is done for all twelve possible combinations. As M, L, R are lying in a line, a combination of M, L, R leads to the minimum point-to-line distance. The point not used in this combination can be indirectly identified as F.

M can be identified by finding the maximum distance between M, L and R. Let A and B be the remaining two points to recognize. By writing $A = (a_x, a_y)^T$, $M = (m_x, m_y)^T$ and $F = (f_x, f_y)^T$, the variable s is given by

$$s = \operatorname{sgn}[(a_x - m_x)(f_y - m_y) - (a_y - m_y)(f_x - m_x)] \quad (1)$$

1. http://www.pixart.com.tw/

A can be identified unambiguously as $A = L$ if $s > 0$, otherwise $A = R$. Now, we can proceed to determine the pattern position vector $\vec{p}$ relative to the quadrocopter. The yaw angle ψ and the distance z can be calculated directly from information given from the Wiimote. By contrast, the x and y position estimation depends additionally on accurate roll and pitch angle estimates as provided by the IMU.

4.2. Analysis of the Wiimote Camera Data

The following equations can efficiently be computed on a microcontroller and assume only a small displacement from the target position. The system has proven satisfactory accuracy and thus this simplified method can be used. For a bigger working area, where the quadrocopter can hover at positions other than zero, another method has been developed.

The yaw angle ψ is measured relative to the line defined by $\overline{MF}$ and can be easily calculated by

$$\psi = \operatorname{atan2}(m_x - f_x, m_y - f_y) \tag{2}$$

z-distance: The distance z from the camera to the pattern is computed by incorporate the view angle of the camera which is given as $\rho = 0.000761$ rad per pixel. Let s_i be the metric distance between two LEDs and d_i the pixel distance of the corresponding points. The distance z_i from the camera to the pattern can be estimated by:

$$z_i = \frac{s_i}{\tan(d_i \rho)} \tag{3}$$

We use this basic equation to estimate the distance, because the roll and pitch angles of the aircraft are usually only between $\pm 3\,^\circ$ during controlled flight assuming an stationary pattern. Thus, we can assume a nearly orthogonal view angle to the pattern. We used the following four distances in our experiments: $d_1 = |L-R|$, $d_2 = |L-F|$, $d_3 = |R-F|$, $d_4 = |M - F|$. Using only d_1 proved to give satisfactory results in distance measuring with a stationary camera. However, there might be disturbances during flight causing noise in subpixel analysis. This noise can be decreased by using the mean value:

$$z = \frac{1}{4}(z_1 + z_2 + z_3 + z_4) \tag{4}$$

After the identification of the points, the point order is kept. Using this additional information for sequential analysis, most information can be extracted with only two recognized dots. This is of great benefit, when occlusion or close distances prevent to capture all points.

4.3. Combining Wiimote Data With Information Given by the IMU

The x and y position of the pattern relative to the aircraft can only be estimated when the camera orientation is known. The camera orientation, which is identical to the quadrocopter orientation, is estimated by the onboard IMU (roll angle φ_{quad} and pitch angle θ_{quad}). Additionally, the position of the pattern in the camera image has to be calculated. The position of the pattern center is defined by M. Let $C = (c_x, c_y)^T = (384, 512)^T$ be the center of the image, defined by the camera resolution of 1024×768 pixels. Now, we can calculate the distance between M and C in x- and y-direction in pixels. As we know which view angle the camera provides per pixel, we can calculate the orientation of the pattern relative to the camera center (φ_{cam} and θ_{cam}).

$$\theta_{cam} = (m_x - c_x)\rho \tag{5}$$

$$\varphi_{cam} = (m_y - c_y)\rho \tag{6}$$

Potential inaccuracies in the camera arrangement are compensated with the calibration angles φ_c and θ_c. The calibration angles are constants, determined after attaching the camera by measuring the deviation with an adjusted robot. By combining the angles, the total displacement of the pattern can be estimated:

$$\varphi = \varphi_{\text{quad}} + \varphi_{\text{cam}} + \varphi_c \tag{7}$$

$$\theta = \theta_{\text{quad}} + \theta_{\text{cam}} + \theta_c \tag{8}$$

$$x = \tan(\varphi) z \tag{9}$$

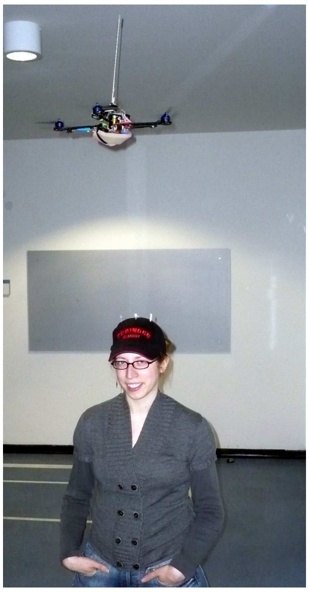
$$y = \tan(\theta) z \tag{10}$$

5. Flight Control

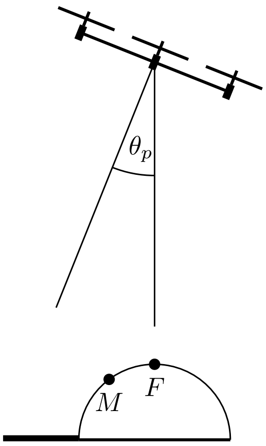
The idea of autonomously hovering above a person requires accurate flight controllers for the quadrocopter. With our system, even autonomous take off and landing is possible, which is described in [13]. However, in this paper we focus only on hovering, assuming the quadrocopter has already reached its stationary position above the cap with the IR markers.

By estimating the current position vector $\vec{p} = (x, y, z, \psi)^T$ of the pattern, a flight controller is able to navigate the aircraft to a desired position relative to $\vec{p}$. As the goal is to hover stationary above the pattern, x, y and ψ should stay zero and z was set to be 40 cm. Our control algorithms are similar to the independent, fast onboard controllers mentioned in [3], where four individual controllers are operating.

The control loop is currenty performed every 50 ms. Most of the time is needed to request the current pose estimation from the Hummingbird quadrocopter (30 ms). Additional 10 ms are required to send sensor information to the base station, where the current status is monitored and visualized. The remaining 10 ms are for retrieving camera sensor information and running the control algorithm. A considerably higher control frequency would be possible with an accelerated IMU request.



(a) The robot hovering



(b) Schematic lateral view of the configuration

Figure 4. The robot hovering autonomously in an angular attitude above the cap.

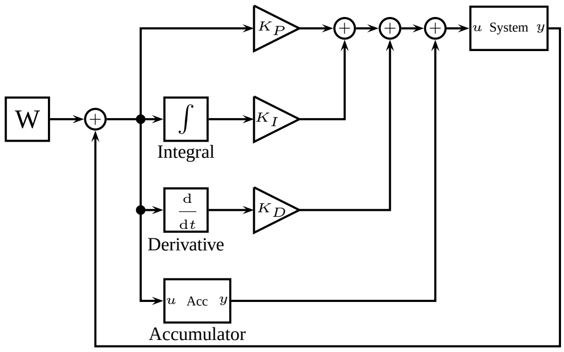


Figure 5. The thrust controller

5.1. Height Controller

The thrust control value, which has to be sent to the quadrocopter to hover at a desired height, varies while flying, as it depends on the actual payload and battery charge. This value can be determined by beginning with a default value and increasing it whenever the robot is below the desired height for some cycles, and decreasing it otherwise. We implemented a fast PID loop which controls the thrust value around the hover value. K_D is the major component. Fig. 5 shows the structure of the thrust controller.

5.2. Roll, Pitch and Yaw Controller

Our aircraft has a symmetric rotor configuration. Thus the x and y controllers are identical. Their control parameters are more difficult to derive than the height controller parameters, since the behavior response is not proportional to horizontal speed but to rotational velocities. To achieve a stable position hold, a predictive control, much like a human pilot would operate, is required. By designing a cascaded control loop, where speed and acceleration are highly weighted, the prognostic ability has been realized. Fig. 6 shows the structure of the x and y controller.

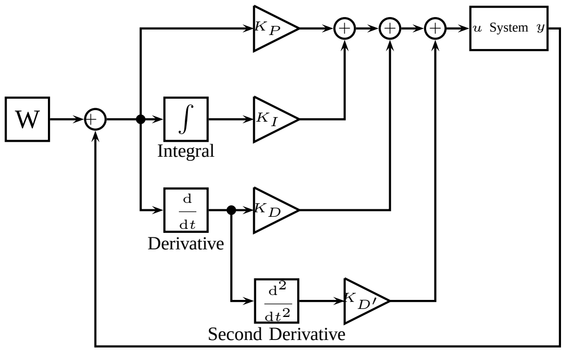


Figure 6. The x and y controller.

The integrated compass of the Hummingbird quadrocopter is used to control the coarse orientation. Our yaw controller is able to achieve accurate orientation to the pattern, even when it is rotated. Our yaw controller is implemented as a PID loop with a large K_P and a small K_I.

6. Experimental Results

Our aircraft provides basic autonomy for outdoor flights. However, GPS and air-pressure position hold are not safe and accurate enough for hovering precisely above a person. Therefore, the GPS-position controller and an air-pressure

Table 1. Controller characteristics of five minutes flight 40 cm above the cap

	$\Delta x/\mathrm{mm}$	$\Delta y/\mathrm{mm}$	$\Delta z/\mathrm{mm}$	$\Delta\psi/\circ$
Minimum	-43	-50	-122	-8.4
Maximum	40	40	136	3.7
Peak to peak	83	90	258	12.1
Mean	0.36	-0.07	-0.23	0.0
Standard deviation	13.2	13.47	27.18	0.2

sensor for height control have been disabled for our experiments. The yaw angle is controlled by the internal magnetic compass of the quadrocopter.

First experiments were done with a pattern constructed on a standard circuit board. Following a large number of flights and retrieval of working parameters, the system has shown accurate position hold capability. Details about hovering in a defined height above the pattern can be found in [14]. The system was capable of autonomous take off and landing as well [13]. For our wearable helicopter, the pattern is embedded on a cap and thus had to be slightly redesigned.

The quadrocopter produces a considerable amount of wind, leading to noticeable cooling. One problem is the loud noise, coming with the wind, and the lack of knowlege about the current behavior of the aircraft by reason that the wearer does not see it.

The position-hold results achieved in our experiments are comparable to those with the slightly larger pattern used in [13] and [14]. Table 1 shows the controller characteristics of the flight. A standard deviation below 3 cm in all three axes ensures proper hovering at 40 cm above the cap.

As mentioned in Section 4.3, the estimations of roll and pitch are essential for accurate x and y approximations. While the standard deviations of Δx and Δy are rather comparable, one can notice a larger standard deviation in Δz position control. The yaw angle is uncritical for our intention, but affected by all balancing maneuvers in flight and thus depends on the position changes in x-,y- and z-directions.

Figure 7 shows a detailed record of one minute of a flight 40 cm above the cap. The plot shows the smooth position estimation sent to the base station while flying. Outliers, caused by external influences, such as infrequent reflect lights can easily be filtered.

As sunlight contains a notable fraction of infrared light, reflections of sunlight can lead to wrong pattern interpretation. This could be reduced by stronger infrared sources and should be investigated in future work.

7. Conclusion and Future Work

Our wearable helicopter has proven that it is possible to hover autonomously above a person wearing a special cap. The deviation from the desired position, which we achieve

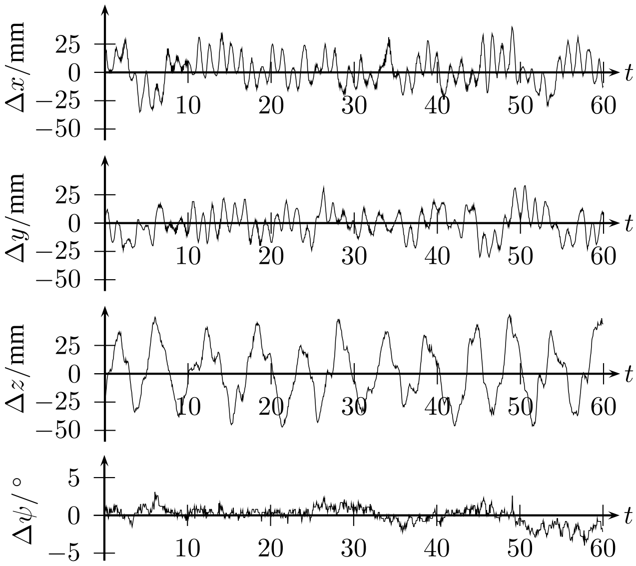


Figure 7. Position errors of five minutes hover flight 40 cm above the cap.

by means of our control algorithm, is small enough for quasi-stationary flight in an indoor environment.

The Wii remote camera is capable of accurate infrared (IR) blob tracking and provides the pixel position information of each source. A microcontroller is capable of estimating the position to the target and controlling a miniature flying robot in hovering flight without additional ground sensors and without a base station. However, in many countries regulations on the use of model airplanes require that a remote control must be present to take over control if needed. As the wearer does not see the aircraft while operating, a second person must be present, assuming this role. This rules out truly autonomous operation.

The distance to the target is limited by the dimension of the pattern and the IR light emission. By using multiple IR LEDs per point or stronger LEDs, the operating distance can be increased. However, an accurate roll and pitch estimation provided by the aircraft's IMU is essential for stable position hold.

The current frequency of 20 Hz is sufficient for robust hovering control. Nonetheless, when the user moves quickly, the camera loses sight of the pattern. An increased control frequency or a panning camera will advance the control accuracy and enable the wearable helicopter to track a moving person over time.

Indisputably, our approach can only be understood as a proof of concept, but reasonable tasks are also imaginable: A video camera attached to the helicopter could monitor a person or ground vehicle better than a human pilot could do it. This enables surveillance tasks of a novel category and enables the wearer to see himself from a new perspective.

The system could act as a digital periscope for observation from a concealed position. Inspection of places which are normally not reachable becomes possible. A similar system could be used in sport events, providing unusual camera shots. One could even envision a wearable helicopter flying above runners in running events or above the quarterback in football games to give a bird's eye view from their position, if the current short flying times of 15 minutes were longer and the wind from the rotors was ruled as acceptable or beneficial and not as giving unfair advantages or disadvantages. Also police workers could make use of such an aircraft for uncomplicated documentation of their assignment.

A stationary robot at a high altitude, not stringently directly above a person, could be used for enlarging mobile phone reception. So, a life-saving phone call might become possible in areas where connectivity is restricted.

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