Pre-print version, published at MAV07 (EMAV2007)

Quadrotor Using Minimal Sensing For Autonomous Indoor Flight

James F. Roberts[*], Timothy S. Stirling[†], Jean-Christophe Zufferey[‡] and Dario Floreano[§]
Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, 1015, Switzerland

Abstract — This paper presents a Miniature Aerial Vehicle (MAV) capable of hands-off autonomous operation within indoor environments. Our prototype is a Quadrotor weighing approximately 600g, with a diameter of 550mm, which carries the necessary electronics for stability control, altitude control, collision avoidance and anti-drift control. This MAV is equipped with three rate gyroscopes, three accelerometers, one ultrasonic sensor, four infrared sensors, a high-speed motor controller and a flight computer. Autonomous flight tests have been carried out in a 7x6-m room.

I. Introduction

THERE are currently no Vertical Take-Off and Landing (VTOL) flying robots capable of hands-off autonomous operation within cluttered environments such as houses or offices. A robot with this capability could be useful for many applications including search and rescue, exploration in hazardous environments, surveillance, etc. However, there are many challenges that engineers must face before developing such a robot, including the strict limitations in sensing technologies, power consumption, platform size and embedded processing.

In order to safely manoeuvre within these environments it would be beneficial for such a robot to be able to hover. This alone introduces many difficult problems including stability control, altitude control, platform drift, collision avoidance and platform design, all being important for successful operation. The system must also be able to sense its environment, prevent collisions and manoeuvre accordingly.

Platform drift on hovering systems is an interesting and challenging problem for an indoor VTOL flying robot. Drift outdoors can be compensated[1] by using a Global Positioning System (GPS) however within indoor environments the task becomes much more difficult as GPS will not function due to the diminished reception. Recently there has been research done using visual tracking systems[2] to monitor and control a platform within a three dimensional flight space. These systems are extremely accurate and allow for complex control of trajectory however they place strict limitations on where the platform can fly due to the fact that they are confined to the space in which the tracking system is installed, consequently making them impractical.

Matsue and collaborators have presented a system using a toy helicopter that has shown the capability of autonomous hovering near walls[3]. This is achieved by using three infrared range sensors to measure the height above the ground and the distances to two perpendicular walls. The MAV has also shown the capability of autonomously following an infrared beacon as the beacon is moved along the ground beneath it[4]. The maximum range of the infrared sensors used on this system is 80cm, which means that the platform has to fly quite close to a corner, presented by two perpendicular walls, or the system will fail. Moreover, as there are only two sensors representing one quadrant of the 360º flight space the platform must also continue to face the correct direction, presenting a yaw rotational alignment problem. Furthermore, the helicopter is mechanically stabilised which greatly simplifies the task as there are simple requirements for inertial sensing or stability control. However we have observed that these mechanical stabilisation systems can limit the controllability of the platform and tend to introduce low frequency oscillations when trying to manoeuvre causing an undesirable and skewed trajectory.

---

[*] PhD Student, Laboratory of Intelligent Systems (LIS), ELE115, Station 11, Lausanne 1015.
[†] PhD Student, Laboratory of Intelligent Systems (LIS), ELE115, Station 11, Lausanne 1015.
[‡] 1st Assistant, Laboratory of Intelligent Systems (LIS), ELE138, Station 11, Lausanne 1015.
[§] Associate Professor, Laboratory of Intelligent Systems (LIS), ELE132, Station 11, Lausanne 1015.

Holland and collaborators have also been working with toy helicopters towards developing a swarm of hovering MAVs for implementation of a wireless cluster computer network[5-6]. The orientation and attitude of the helicopter is perceived by using a downward facing camera that looks at coloured circular patches placed on the ground. However, currently no autonomous flight results have yet been presented and the method places strict limitations on where the system can operate.

Green and collaborators have been working on an autonomous hovering fixed wing platform that is capable of following a wall and entering an open door way[7-9]. The system has an Inertial Measurements Unit (IMU) providing an attitude estimation for stability control, an ultrasonic sensor provides a stable altitude and an infrared sensor is used to detect the wall. The system has also shown collision avoidance capabilities[10]. However, these experiments have not shown that the platform is capable of hands-off automatic take-off, constant position control and automatic landing.

In this paper we present a Quadrotor weighing approximately 600g, with a diameter of 550mm, which includes three rate gyroscopes, three accelerometers, one ultrasonic sensor, four infrared triangulation-based sensors, a high speed motor controller and a flight computer. The prototype is capable of autonomous control indoors including: automatic take-off, constant altitude control, collision avoidance, anti-drift control and automatic landing. These capabilities have been demonstrated in an obstacle free 7x6-m room. To the best of our knowledge, our platform is the first Quadrotor capable of autonomous operation indoors, from take-off to landing, without the use of an external positioning system.

In the following section, we present the platform design, electronics and sensors. We then introduce the proposed control strategy, describe individual experiments and provide the results from the autonomous flight testing.

II. Platform

A. Platform Design and Propulsion System

The custom built platform in "Fig. 1" is based on a conventional Quadrotor design with some structural modifications. The entire body is fabricated from printed circuit board (PCB). The idea is to have a tight integration between the structure, electronics and sensors to reduce weight, minimise wiring, and improve manufacturability. The PCB body is extended out to support a carbon fibre ring that allows the MAV to survive small collisions with walls and other large objects including people. The system is designed so that additional control boards and/or sensors can be stacked in its centre with minimal effort. The propulsion system consists of two pairs of brushless out-runner motors, each pair fitted with 200mm contra-rotating plastic propellers which are powered by a single 2100mAH Lithium Polymer battery. This configuration provides approximately 350g of thrust for each motor, giving a total thrust of ~1400g. As the system is actively stabilised a thrust overhead of 100% is recommended for stable flight, thus allowing for a total take-off weight of ~700g. When fitted with the sensors and electronics the system could also carry an additional 100g payload however this would reduce the current endurance of 7 minutes to approximately 3 minutes. In the future we intend to drastically reduce the weight and optimise the structure of the platform to improve the flight time.

B. Sensors and Stability Control

The Quadrotor is naturally a highly non-linear and unstable platform which requires stability controllers to deal with its fast dynamics. If you are a skilled pilot it is possible to fly the Quadrotor with only rotational dampening control using three rate gyroscopes. However as this system is aimed at removing the pilot from the loop, a chip containing three accelerometers has been added to calculate and align with the gravity component of the earth, thus providing automatic levelling. In order to fuse this information together we implement a complementary filter that takes the integrated angular rate of the gyroscope and the measured Euler angle from the accelerometers[11]. The output of the filter is then fed into a proportional-integral-derivative controller. This is done for both pitch and roll stability control, yaw stability control is simply implemented using the rate gyroscope and a proportional controller. However even with automatic levelling the platform still has a tendency to drift due to the gyro run-away and external accelerations introduced by the motion of the platform. To correct for this drifting four perpendicular infrared distance sensors with a maximum range of 3m have been used "Fig. 2". These sensors can also provide a reference for manoeuvring in a two-dimensional space and allow for collision detection of large objects. The infrared sensors have been characterised as seen in "Fig. 4" to determine their transfer function by taking the 10-bit Analogue to Digital Converter (ADC) readings over a range from 0m to 4.5m in 100mm steps. The response of this sensor is comparable to a logarithmic function. The altitude of the platform is measured using an ultrasonic sensor "Fig. 3", this sensor has a minimum range of 152.4mm and a maximum range of 6477mm with a resolution of 25.4mm. This sensor has an onboard microcontroller that calculates the distance and converts it to an analogue voltage, PWM signal and USART.

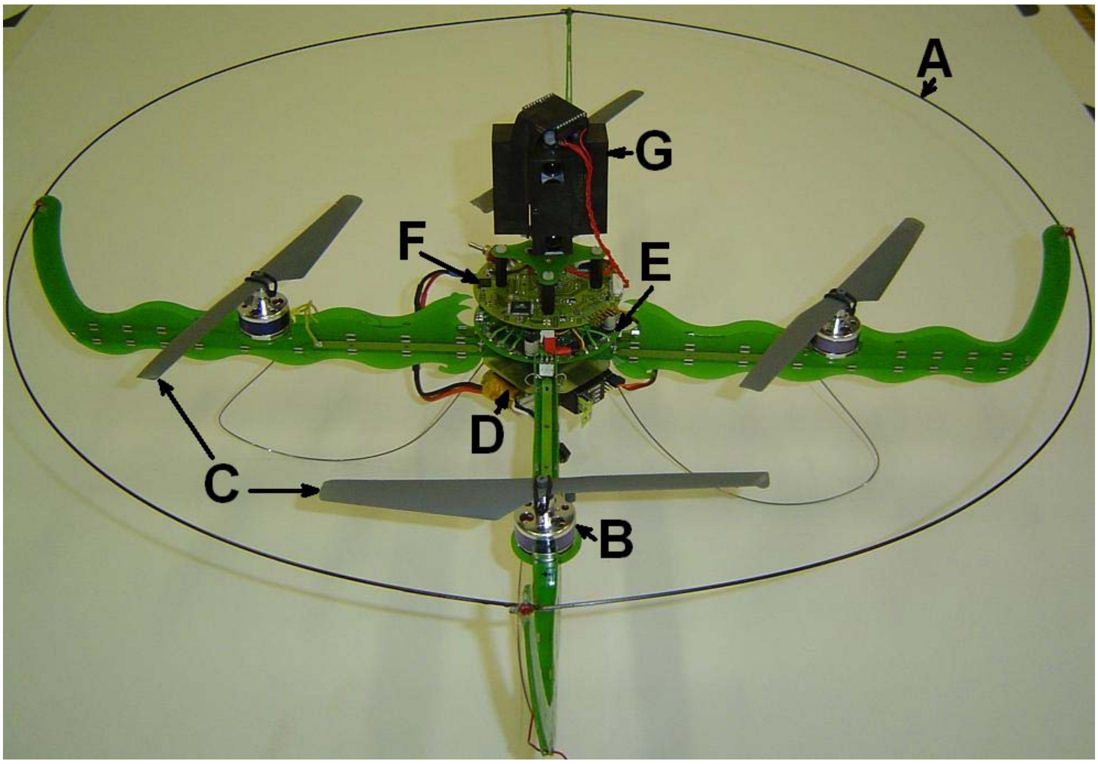

Figure 1. Custom Quadrotor platform: A.) protection ring, B.) brushless motor, C.) contra-rotating propellers, D.) LIPO battery, E.) high-speed motor controller, F.) flight computer, G.) infrared sensors

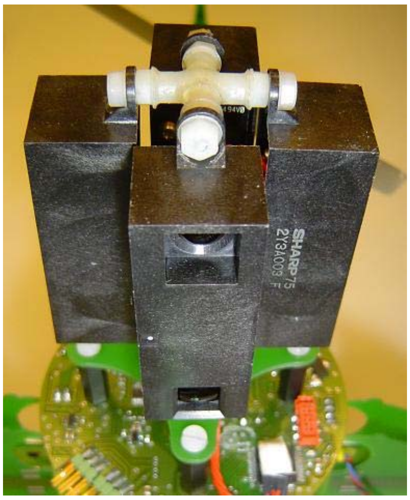

Figure 2. Infrared sensors

Figure 3. Ultrasonic sensor

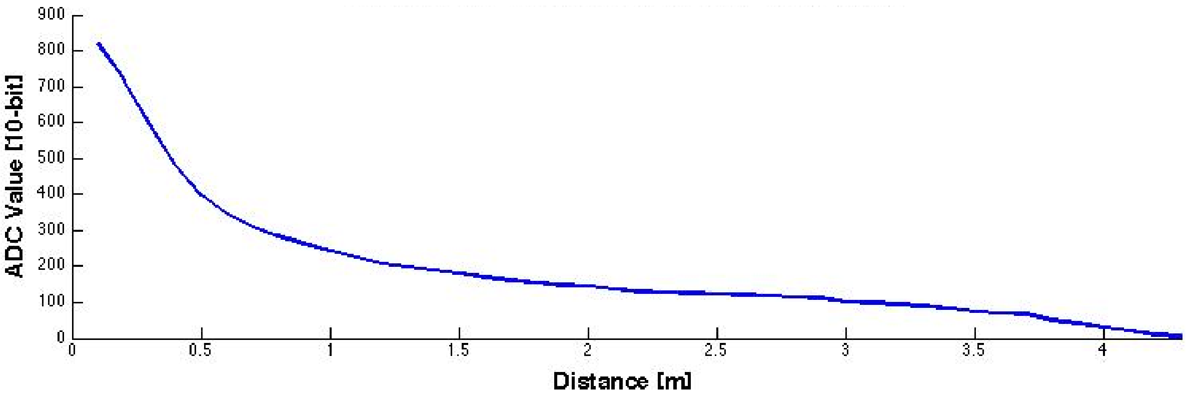

Figure 4. Infrared sensor transfer function

C. Embedded Electronics

The high-speed brushless motor controller board “Fig. 5” uses four, 8-bit ATMEL microcontrollers, one for each sensor-less out-runner motor. Schematics and PCB have been custom designed in-house however the source code has been provided by the Mikrokopter project[11]. Feedback for speed control is provided by the low pass filtered back EMF spikes produced when the motor is running. The three phase PWM signals run at 16 KHz to control the motor. Each motor can be updated at a rate of 500Hz, this allows for a high update rate of the entire stability control system, from sensor to actuator. By implementing an update rate an order of magnitude higher than the dynamics of the system a simple linear controller can be used to control the non-linear system. The four channel high speed motor controller communicates with the flight computer via I²C.

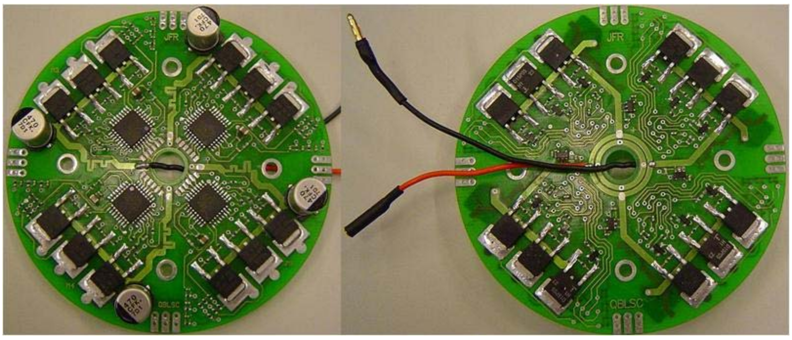

Figure 5. High speed brushless motor controller: left – top-view, right – bottom-view

The flight computer board “Fig. 6” consists of two microcontrollers, one 8-bit ATMEL allocated for low-level stability control (inspired by the Mikrokopter project[11]) and another faster 16-bit dsPIC for high-level autonomous control. This minimizes the risk of affecting the stability and manual controls when implementing new higher-level control strategies. The board houses the three gyroscopes and three accelerometers as well as an additional pressure sensor and two-axis magnetometer for altitude and heading control respectively. However, the later two sensors are not active in these experiments.

Figure 6. Flight computer

D. Connectivity

The ultrasonic sensor is connected via a UART interface and the four infrared sensors are connected directly to the dsPICs analogue inputs. A radio control receiver is connected through a PPM input to allow for manual flight control and switching between the autonomous and manual modes. The board also has extended connectivity for adding additional sensors and/or controllers via a serial interface. The serial interface can be configured for SPI or UART plus I²C, in this experiment a wireless, "XBeePro", downlink has been connected here for data analysis. Additionally the board has a 1MB EEPROM for storing experimental and/or configuration data.

III. Experiment Room

The room where the experiments were conducted is 6m wide, 7m long and 3m high "Fig. 7". A dome camera has been installed on the roof to track the platforms trajectory. This camera has a 180º field of view and is capable of seeing anywhere in the room below. To allow the platform to be seen clearly, the floor of the room was covered with white vinyl and all obstacles in the room were removed. A desk was left in one of the corners to hold a laptop computer, the computer is used to record the data from the camera and to allow quick re-programming of the control gains. When experiments are conducted a safety pilot sits along the centre of the bottom wall, the pilot has the ability to activate and deactivate the system to start/stop an experiment or in the case of a failure, control the platform manually. A script was written for MATLAB to extract the trajectory of the platform from a pre-recorded video. The initial position of the platform for each experiment is in the centre of the room.

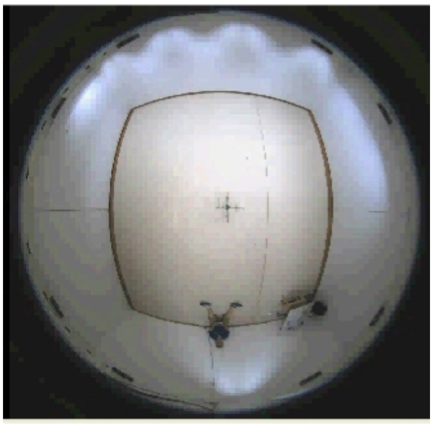

Figure 7. Camera view of experiment room

NOTE: The view from the camera is highly distorted. Because the platform flies closer to the camera the perceived position of the platform is worse than it actually is in reality. Due to this the following plots will include a dotted box defining the limits where the platform would collide with the wall at the pre-determined altitude.

IV. In-Flight Experiments

At this stage, the goal is to enable the Quadrotor to fly in the experiment room, with no obstacles, automatically take-off, fly at a constant altitude of one meter, achieve constant anti-drift control, and automatically land after one minute. This must be achieved without any human intervention.

We present three experiments that show the progression towards achieving this goal. The first experiment was designed to observe the altitude control capability. The aim was to achieve automatic take-off, altitude control and automatic landing with the pitch and roll controlled manually. The second experiment was designed to observe the hands-off capability by implementing the four infrared sensors. The aim was to use both altitude control and infrared collision avoidance to achieve a fully autonomous flight. The third experiment was designed to observe the hands-off capability by implementing the infrared anti-drift control. The aim was to achieve both altitude control and anti-drift control to have a fully autonomous stable hover in the centre of the room.

A. Altitude Control

In the first experiment, altitude control is achieved by means of a standard proportional-integral-derivative controller using the down-pointed ultrasonic sensor. To enable automatic take-off the set-point of the controller is slowly increased until the height is equal to one meter, this is done at a rate of approximately 150mm per second. Similarly, automatic landing is achieved by slowly decreasing the height set-point until the platform is on the ground. As shown in "Fig. 8", the altitude sensor data was logged during an autonomous take-off, hover and landing sequence. The platform takes-off slowly then proceeds to a stable hover at the set-point of one meter. After 30 seconds the system comes down slowly and lands. The response has been logged for ten independent flights to show the systems repeatability and robustness "Fig. 9". The mean altitude during stable hover was calculated to be 974.13mm, with a standard deviation of 30.46mm. The sensor resolution is 25.4mm therefore the deviation is well within two measurement steps. The 26mm offset is approximately equal to the sensor resolution. This suggests that the gravity component acting on the platform tends to push the altitude to the lower of the two sensor increments about the 1m setpoint.

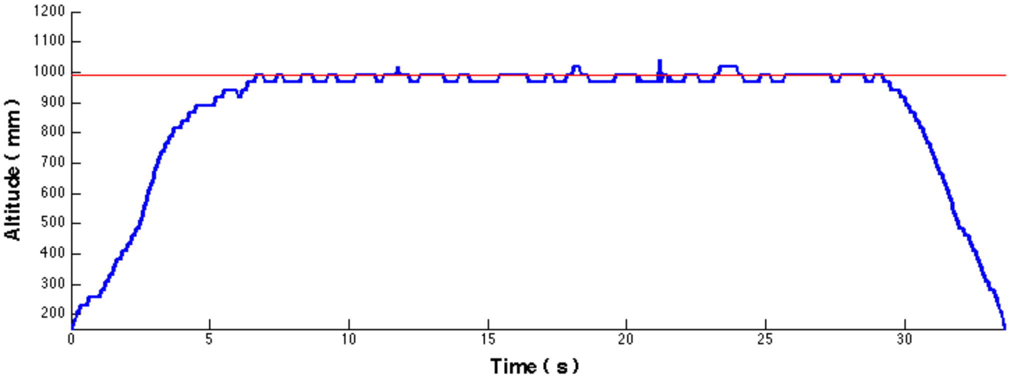

Figure 8. Altitude response during the first run - take-off, hover and landing

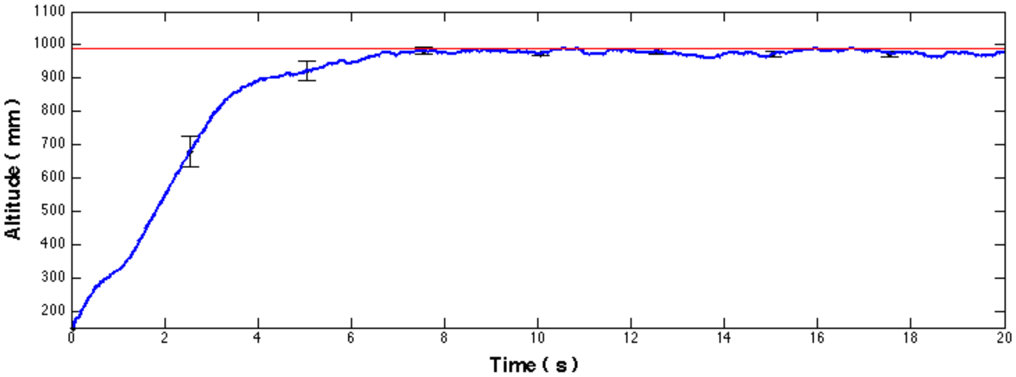

Figure 9. Mean altitude response of ten independent runs – take-off and hover

B. Collision Avoidance

In the second experiment, collision avoidance is achieved by means of a proportional-derivative controller and a distance balancing algorithm, one for pitch and one for roll. This algorithm simply calculates the difference in distance between the two opposing walls. The difference is then fed into the controller, the output then alters the attitude angle of the platform to turn away from the wall. The range of the infrared sensors has been limited to 1.5 meters by adding input limits on the ADC values within the acquisition code. As shown in "Fig. 10", the initial position of the platform is in the centre of the room. In the middle of the room, due to the limits placed on the sensor range, the sensors cannot detect a wall in any direction so the platform takes-off and flies in a random direction depending on its initial attitude. As it approaches the first wall the controllers act to prevent a collision and the platform flies off in another direction. This simple control approach allows the platform to fly safely avoiding the walls for as long as the battery permits.

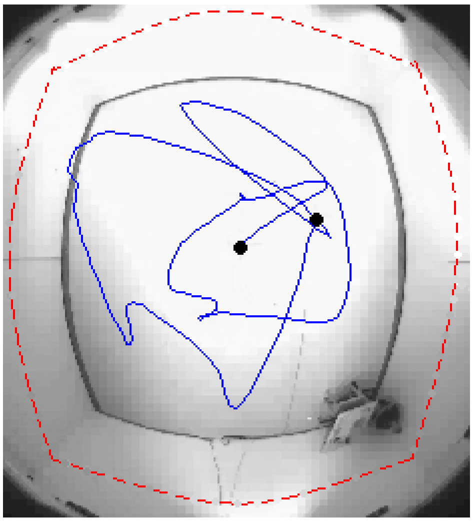

Figure 10. Collision avoidance trajectory plot – control gains: kp = 5 and kd = 200

C. Anti-Drift Control

In the third experiment, by keeping the same control strategy, reducing the controller gains and not limiting the range of the infrared sensors, a method to achieve anti-drifting has been demonstrated. As shown in "Fig. 11", the initial position of the platform is in the centre of the room. In the middle of the room the sensors can just detect the four walls however any reading below two meters is not accurate. The walls are between 3 and 9.2 meters away depending on the rotational orientation of the platform, so there is a 2x3-m rectangular boundary in the centre where the sensors cannot accurately detect the position of the platform. The drift during position hold is due to this uncertainty. When the platform takes-off it instantly begins to correct for drift and keep the platform in the centre of the room. This simple control approach allows the platform to hold its position safely close to the centre of the room for as long as the battery permits.

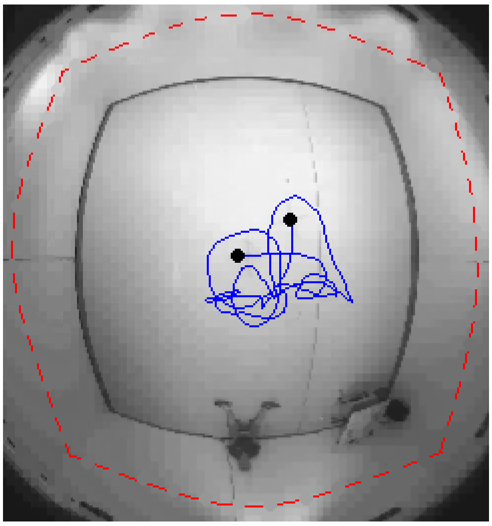

Figure 11. Anti-drift trajectory plot – control gains: kp = 2.2 and kd = 100

These experiments were carried out several times with the same control strategy and the platform demonstrated good robustness. As most rooms within houses or offices are less than 6-m in dimensions this sensing is considered adequate for such a system.

V. Conclusion and Outlook

This paper describes a Quadrotor system capable of autonomous operation within obstacle free indoor environments. The results show that the Quadrotor is capable of automatic take-off, constant altitude control, obstacle avoidance, anti-drift control and automatic landing. This has been achieved using simple sensing and control strategies. In the future, we plan to improve the sensing capabilities and perform more experiments with the current system, such as corridor following or autonomous flight in populated rooms.

VI. Acknowledgements

We would like to thank Guido de Croon for creating the MATLAB script for tracking the trajectory of the platform. This work is part of the Swarmanoid project funded by the Future and Emergent Technologies Division of the European Commission.

References

[1] Microdrones GmbH, “Microdrone MD4-200”, URL:
http://www.microdrones.com, Accessed July 2007.

[2] Gurdan, D., Stumpf, J., Achtelik, M., Doth, K-M., Hirzinger, G., Rus, D., “Energy-efficient Autonomous Four-rotor Flying Robot Controlled at 1 kHz”, 2007 IEEE International Conference on Robotics and Automation, Roma, Italy, April 2007.

[3] Matsue, A., Hirosue, W., Tokutake, H., Sundada, S., Ohkura, A., “Navigation of Small and Lightweight Helicopter”, Trans. Japan Society Aeronautical and Space Sciences. Vol.48, NO. 161, pp. 177-179, 2005.

[4] Ohkura, A., Tokutake, H., Sundada, S., “Autonomous Hovering of a Small Helicopter”, Trans. Japan Society Aeronautical and Space Sciences. Vol. 53, NO. 619, pp. 376-378, 2005.

[5] Holland, O., Woods, J., Nardi, R. D., Clark, A., “Beyond Swarm Intelligence: The Ultraswarm”, IEEE Swarm Intelligence Symposium 2005.

[6] Nardi, R. D., Holland, O., Woods, J., Clark, A., “SwarMAV: A swarm of Miniature Aerial Vehicles”, 21st Bristol UAV Systems Conference, April 2006

[7] Green, W.E., Oh, P.Y., “A Fixed-Wing Aircraft for Hovering in Caves, Tunnels, and Buildings,” IEEE American Control Conference, Minneapolis, MN, pp. 1092-1097, June 2006.

[8] Green, W.E., Oh, P.Y., “Autonomous Hovering of a Fixed-Wing Micro Air Vehicle,” IEEE International Conference on Robotics and Automation, Orlando, FL, pp. 2164-2169, May 2006.

[9] Green, W.E., Oh, P.Y., “A MAV That Flies Like an Airplane and Hovers Like a Helicopter,” IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Monterey, California, pp. 699-704, July 2005.

[10] Green, W.E., Oh, P.Y., “Optic Flow Based Collision Avoidance on a Hybrid MAV,” IEEE Robotics and Automation Magazine, (in press).

[11] Holger, B., Mikrokopter Open Source Quadrotor, “WIKI: MikroKopter.de”, URL:
http://www.mikrokopter.com, Accessed July 2007.