Micro Unmanned Aerial Vehicle Visual Servoing for Cooperative Indoor Exploration

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Abstract—Recent advances in the field of Micro Unmanned Aerial Vehicles (MAVs) make flying robots of small dimensions suitable platforms for performing advanced indoor missions. In order to achieve autonomous indoor flight a pose estimation technique is necessary. This paper presents a complete system which incorporates a vision-based pose estimation method to allow a MAV to navigate in indoor environments in cooperation with a ground robot. The pose estimation technique uses a lightweight Light Emitting Diode (LED) cube structure as a pattern attached to a MAV. The pattern is observed by a ground robot's camera which provides the flying robot with the estimate of its pose. The system is not confined to a single location and allows for cooperative exploration of unknown environments. It is suitable for performing missions of a search and rescue nature where a MAV extends the range of sensors of the ground robot. The performance of the pose estimation technique and the complete system is presented and experimental flights of a Vertical Take-off and Landing (VTOL) MAV are described.

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1. INTRODUCTION AND RELATED WORK

Unmanned Aerial Vehicles, or UAVs, are now performing missions with increasing levels of complexity. Flying robots carry out tasks which can be considered dull, dirty or dangerous, successfully replacing human pilots. Outdoor flying unmanned vehicles have received a considerable amount of research and industrial attention over the years. Complete systems are available for military and civilian applications. There exist many examples of advanced tasks which can be solved by UAVs fully autonomously [1]. Those systems take advantage of methods from many interdisciplinary fields, such as airframe design, control and artificial intelligence and require robust integration of various technologies.

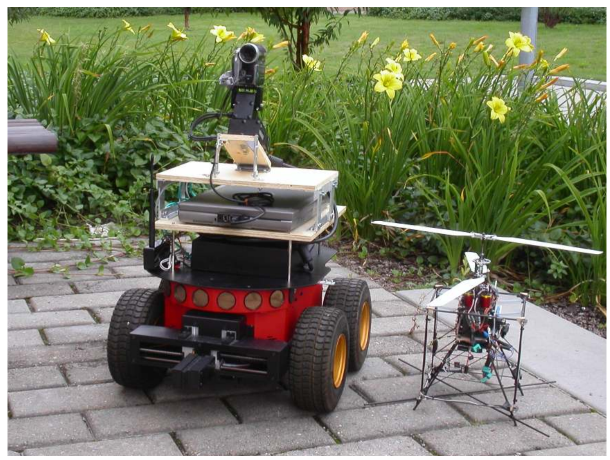

Figure 1. Main elements of the experimental system: The LinkMAV and the ground robot.

Outdoor flying UAVs have become more sophisticated and use a wide variety of sensors. They also come in various configurations making them applicable in many different types of scenarios. For example, fixed-wing UAVs can be used to patrol borders or monitor forests in search of fires. On the other hand, rotary wing UAVs are suitable for performing missions in urban environments often cluttered with obstacles. The sensors they carry allow, for example, for safe low altitude, high velocity flight in such environments [2]. An open problem in the development of UAVs is to navigate in confined spaces, such as inside buildings. A solution to this problem would open a new set of exciting applications.

The level of maturity of indoor flying UAVs is not as impressive, partially due to technological restrictions stemming from the required miniaturization of platforms and sensors. Although progress in this field has been made, MAVs flying indoors suffer from an obvious disadvantage over their outdoor counterparts. The most commonly used positioning system, GPS, is not reliable indoors. Several solutions have been proposed which allow operation of UAVs in indoor environments. Most of them use computer vision techniques in different forms and configurations.

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In a recent approach, the Vicon MX camera system [3], usually used for motion capturing applications, has been used to enable indoor navigation of MAVs. It incorporates a set of cameras which also illuminate the environment with highly efficient and powerful LED light. The system can be used to deliver a MAV's position and attitude information in real-time at a rate of up to 120 Hz. The system delivers a 6 Degrees of Freedom (6DOF) solution thanks to lightweight reflective balls attached to a vehicle's structure. A six camera configuration of the Vicon system allows, for example, for simultaneous tracking of four quadrotor MAVs and multiple ground vehicles in a 5x5x2 meter flight volume [4]. A disadvantage of this technique is the static nature of the environment setup where motion capturing or pose estimation takes place. Once cameras are set up they remain stationary. Exploration of an unknown environment cannot be performed using this method, thus restricting possible applications.

A different approach has been suggested in [5]. The solution consists of two cameras, one mounted on a pan-tilt unit on the ground and one onboard a quadrotor MAV. The two cameras track colored blobs attached both to the UAV and to the ground camera. The disadvantage of the solution is a rather limited flight volume accessible to the MAV. This method allows for indoor flight but preferably above the ground camera, considerably limiting the flight envelope. Even if the camera is placed on a moving platform, the UAV cannot move far away from it.

Pose information can also be obtained from a target which takes advantage of a moiré pattern [6]. The pose of a camera is calculated relative to a novel pattern which requires backlighting. The flight test results presented show the applicability of the method for controlling a quadrotor platform by calculating its position (X Y Z) and the yaw angle of the UAV. The disadvantage of the system is again the requirement that a MAV stays above the pattern, which limits the usefulness of the indoor flying vehicle.

Other approaches to indoor MAV navigation include using artificial markers commonly used in augmented reality applications [7], or fusing vision information (obtained from light diodes attached to a MAV) and inertial data for a real-time attitude estimation of a quadrotor platform [8]. Alternative solutions take advantage of an artificial beacon on a blimp MAV [9] or use custom low power FPGA (Field-Programmable Gate Arrays) boards for vision aided attitude stabilization for a quadrotor MAV [10]. None of them, however, present a complete system which displays attitude and position estimation and navigation functionality for an untethered micro-scale UAV platform in a convincing way in realistic indoor environments.

Our approach allows for a 6DOF indoor pose estimation and navigation with a larger flight envelope and is not bound to a specific location. The system consists of a UAV and a ground robot and allows for navigation wherever a ground robot is able to drive. The fact that the UAV can fly away from the ground robot makes the flying vehicle behave as an "external sensor" which provides sensor data normally not accessible from the point of view of a ground robot alone. We chose to include an Unmanned Ground Vehicle (UGV) in our system because commercially available flight control boards do not have sufficient computational power, low weight and low power consumption to allow onboard micro UAV image processing and control enabling self-contained navigation. A video camera which is connected to a computer performing the image processing is placed on the ground vehicle. This avoids the need for a wireless transmission of the video stream and allows for obtaining interference free images as well as avoids the problem of camera vibration onboard a UAV. Such a solution greatly improves the robustness of the vision system.

Additionally, the video camera is placed on a pan-tilt unit which allows for navigation of a MAV even if the ground vehicle is stationary. This also makes the system able to maintain control over the MAV in case of flight disturbances, which often occur in indoor environments when passing by a fan or an open door. A camera placed on a pan-tilt unit tracks the flying vehicle and constantly delivers its pose allowing a controlled flight.

The remainder of the paper is structured as follows. We start with a general description of the system in Section 2. Section 3 presents details of the custom LED pattern design, image processing and the pose estimation technique used. Section 4 describes the control of the UAV based on the computed pose. The experimental setup and flight tests are presented in sections 5 and 6 respectively. Finally, we conclude and present future work.

2. System overview

The following section describes the system which has been used as a prototype for the validation of the method presented. The two main elements, the UAV and the ground robot system, are presented in Figure 1. All functional subcomponents and interconnections between them are presented in Figure 2.

The ground robot system using its video camera and the algorithm presented in section 3 estimates the UAV position and the attitude. The estimate is used to provide the UAV with the outer control loop signals keeping it in a target position, altitude, and heading relative to the UGV's body. The UAV control signals generated by the ground robot are passed through the backup pilot's system. The ground station (GS) provides a graphical user interface for the ground robot operator as well as for setting up the UAV's target position, altitude, and heading. A detailed description of each system is provided in the following subsections.

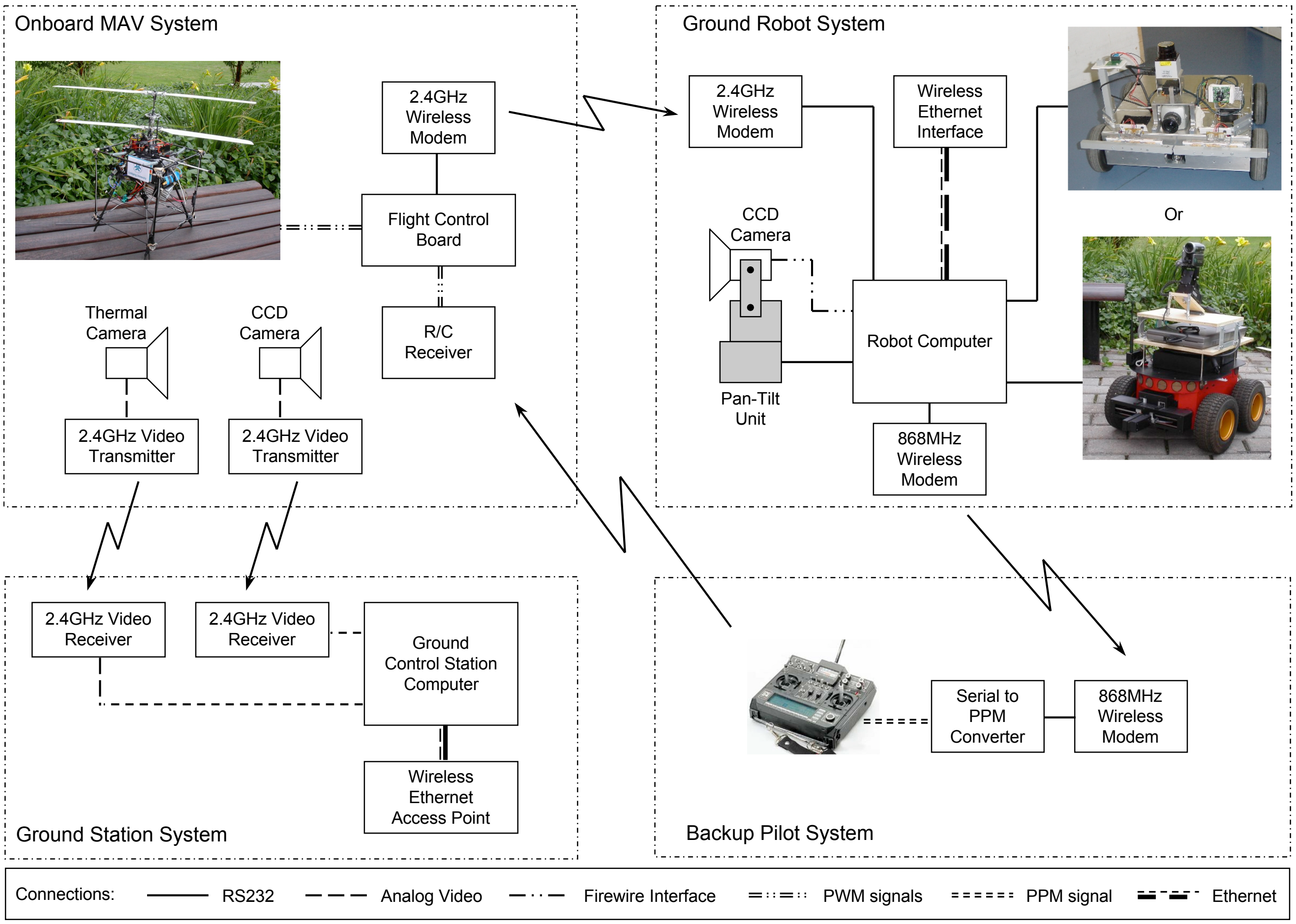

Figure 2. The experimental system subcomponents and interconnections between them.

LinkMAV System

The UAV used in the experiments is the LinkMAV [11] - an in-house developed, double-rotor coaxial helicopter platform. It weights around 500 grams without payload, is smaller than 500 millimeters (largest dimension), and can stay up in the air for up to 20 minutes. In 2005 and 2007 the platform took part in the US-European Micro Air Vehicle Competition winning the best rotorcraft award and scoring 3rd place in the indoor competition, respectively.

The LinkMAV is equipped with two lightweight cameras: a thermal camera and a color CCD. The thermal camera is a Thermal-Eye 3600AS from L-3 Communications [12] which delivers a PAL resolution video stream. The CCD camera is a miniature high resolution Panasonic KX141 from Black Widow A/V [13]. Both video signals are sent to the ground station using 2.4GHz transmitters and receivers from Black Widow A/V [13] for the ground operator view or on-ground image processing purposes.

During the experiments, the LinkMAV used a MicroPilot 2028g flight control board [14] for attitude stabilization. All control inputs (i.e. roll, pitch, yaw, and altitude) to the MicroPilot board are in the form of PWM (Pulse Width Modulation) signals provided by the onboard R/C receiver.

The onboard autopilot is connected through the 2.4GHz wireless modem to the ground robot system in order to provide input control signals used in manual mode. They are required to initialize the LinkMAV outer control loop calculated by the ground robot in order to avoid sudden jumps in position, altitude, and heading when switching between manual and autonomous flight modes.

Backup Pilot System

The backup pilot's remote control system includes a standard R/C transmitter (MC-24 from Graupner) which is used to send control commands to the LinkMAV during the flight. The backup pilot can always cut off the automatic control by taking over direct control over the UAV in a flight. This implements the safety mechanism needed during flight testing and development.

Control signals for automatic mode are sent by the ground robot through a 868MHz wireless modem from Aerocomm [15]. These commands are then transformed by a microcontroller based converter into PPM (Pulse-Position-Modulation) signal which is sent through the MC24 transmit-

Figure 3. A. A schematic view of the LED cube with the actual color diode placement B. LinkMAV with the LED cube C. Video frame from a camera with a very fast shutter speed.

ter directly to the onboard R/C receiver. The transmission is carried out using a 35MHz frequency band and is optimized for safety and robustness. The use of the backup pilot's remote control system for automatic mode introduces delays in the outer control loop but can be avoided in the future by using a more flexible flight control board that is capable of receiving servo control signals by a RS232 interface directly.

Ground Robot System

Two ground vehicles were used for experimentation: a Pioneer 3 AT outdoor robot from MobileRobots Inc. [16] and a Zerg platform developed at Freiburg University [17]. A 1.6GHz Pentium Mobile laptop was used to control the robot including the pan-tilt unit (DirectedPercpetion 46-17.5W [18]) and to host image processing algorithms. A Sony DCR-HC90E video camera is connected to the laptop through a Firewire interface. A full resolution video stream was used (i.e. PAL 720 by 576 pixels) to compute the UAV's pose.

Ground Station System

The ground station subsystem receives both thermal and color CCD analog video signals which can be used by the GS computer for image processing purposes or ground operator view. The graphical user interface (GUI) provides a means for the control of the UGV and the LinkMAV through a wireless Ethernet connection.

3. Pose Estimation Method

In order to calculate the 6DOF pose of the flying vehicle, a vision system has been designed. It includes a custom designed LED cube shaped structure, a video camera mounted on a pan-tilt unit and a computer vision technique which detects colored diodes in the received video stream. A detailed description of all the components is provided in the following subsections.

Pattern design

The pose estimation method relies on a specially designed cube-shaped structure mounted on a UAV (Fig. 3A,B). Only one of its faces is required to be visible to the camera for the pose estimation algorithm to deliver a solution. The UAV can perform a full 360 degree yawing motion in order to point its onboard sensors in a desired direction. The fact that side faces of the cube are used for determining the pose of the MAV frees the UAV from the requirement of staying atop the video camera. This makes the flight envelope considerably larger as the UAV can fly away from the ground robot within a certain range. The top and bottom faces of the cube are not considered because they are obscured by the rotor and the landing gear respectively. Including the bottom face would not pose a problem, except for the requirement of additional diodes, but would not extend the allowed flight volume in a substantial way.

There are two high-intensity LEDs (SuperFlux from LumiLeds) in each corner of the cube mounted at 90 degree angles to increase the usable viewing angle to 90 degrees. Colored diodes are used to uniquely code each of the 4 faces. Only red, green and blue colors are used to minimize the possibility of color misclassification in the case of large distance between a diode and a camera. Other colors (i.e. magenta and orange) were tested but produced misclassifications, especially at larger distances or steep viewing angles.

The size of the cube was determined based mainly on the properties of the MAV at hand, specifically its size and the take-off weight. The cube used in the experiments measured 187x198 mm and was made out of carbon fiber rods. The structure was attached to the MAV frame by a system of springs to cancel the influence of high frequency vibrations generated by the spinning rotors. Its total weight (carbon fiber rods, balsa wood, diodes, resistors and a connector) is approximately 60 grams. It uses a small battery which is matched to the flight endurance of the UAV.

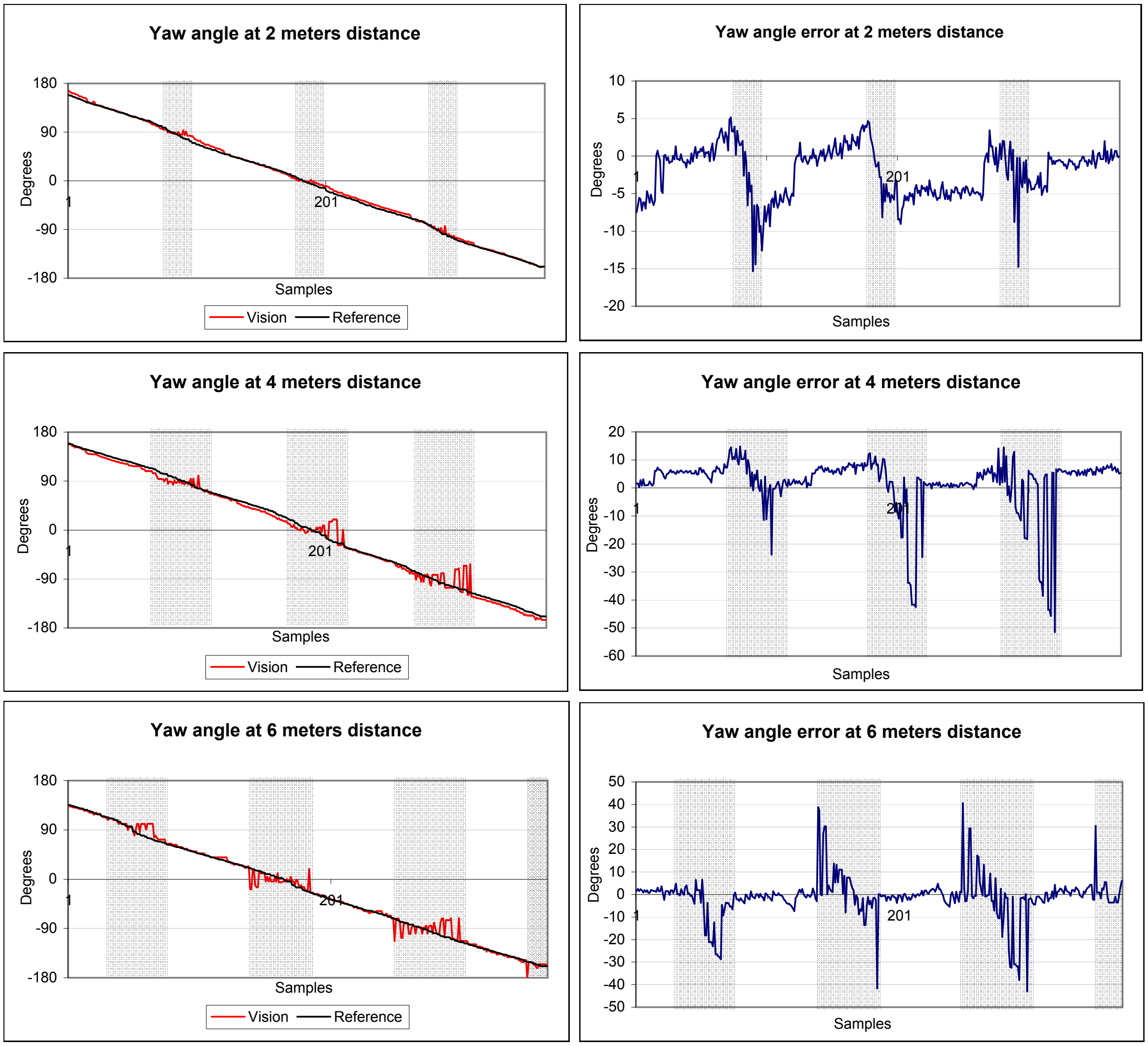

Figure 4. Measured values of angles and error for the yaw axis.

Image processing

In order to filter out as many potential false positive classifications as possible, the camera operates with a very fast shutter speed (Fig. 3C). This makes the process of finding cube corners easier and more robust since most of the background becomes black. To cope with false diode classifications, which often occur in case of direct sunlight illuminating the background, an additional check has to be performed. It includes examining all possible combinations of detected diodes in order to find those which belong to a valid configuration. This requires finding configurations of four LEDs with properly ordered colors yielding minimal size and holding appropriate angle relationships between corners of a pattern.

In case two faces are visible to the camera (around multiples of 45 degrees yaw angle) and six diodes are identified, only one face is chosen based on the distance between corners. The face with maximal distance is preferred in order to minimize the influence of the camera resolution on the final result. The more pixels describing distance between classified diodes, the more accurate the result.

Image coordinates of four identified diodes of one face are processed by the Robust Pose Estimation from a Planar Target [4] algorithm to extract the pose of a face. Knowing which face is visible and the angles of the pan-tilt unit on which the camera is mounted, the complete pose of the UAV relative to the ground robot is calculated.

Pose estimation accuracy

The accuracy of the pose estimation method has been measured in a series of experiments. They were performed as static measurements due to the impossibility of measuring ground truth values during flight. Both attitude and position precision were assessed. The LED cube pattern was mounted on a pan-tilt unit (DirectedPercpetion 46-17.5W) on a test bench. Distances were measured using a measuring tape. The angles were recorded from the pan-tilt unit which was commanded to perform movements in both axes. To measure the yaw error of the vision system, a scan of range from 159 to -159 degrees (i.e. the standard maximum range of the particular unit) was performed in the pan axis. Figure 6 shows example plots of vision-measured and pan-tilt unit reference angle values for this experiment at 2 meters distance.

Experiments were performed at distances from 2 to 6 meters to determine the maximum range at which the result would allow controlled flight of the UAV. The minimum range of 2 meters stems from the size of the cube pattern and the camera's optical properties. Closer distances would require a smaller pattern in order for it to stay within a usable field of view of the camera. In case of flight disturbances caused, for example by a fan, an open door, or a close proximity to an obstacle, a certain margin has to be reserved for the MAV to stay within the camera view.

Figure 4 presents angle measurements and errors at 2, 4, and 6 meter distances within range from 159 to 0 degrees. As expected, the vision system experiences difficulty resolving a pose when a face of the cube pattern is parallel to the camera image plane. Angle values for 2, 4, and 6 meter distances of 13, 20, 25 degrees (greyed areas in plots), respectively, introduce pose estimation inaccuracies which mainly contribute to the measurement error. Outside those ranges of angles, the accuracy of the measurement is very good. The values limit the usable range of allowed yaw angles and were avoided in real flight experiments. For the same reason the flight envelope was limited in distance to approximately 4 meters.

The remaining error of approximately 4, 7, and 9 degrees for 2, 4, and, 6 meters respectively, can be attributed to the camera resolution and inaccuracies in the cube pattern structure construction itself.

The pitch angle accuracy is approximately the same (small difference in width and height of a face) as for yaw because of the symmetry of those two axes (X and Y axes of the image plane).

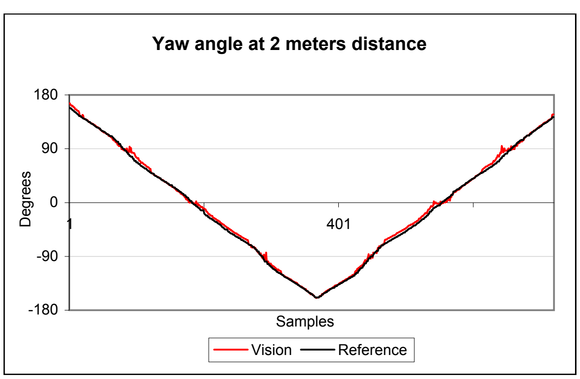

Figure 6. Measured values of angles for yaw axis.

The accuracy of the roll angle was measured in the same fashion as in the case of the yaw axis. The pan-tilt unit was commanded to sweep from 39 to -31 degrees in the tilt axis and the measurements were performed at distances from 2 to 6 meters.

Figure 5 presents angle measurements and errors at 2 and 4 meter distances. The error grows slightly with distance. Standard deviations for measured distances increase but are approximately the same (1.3 degree). This stems from the fact that this axis can be resolved from vision without ambiguities. The roll angle is measured with sufficient accuracy for this application.

The distance measurement was performed at distances from 2 to 5 meters. For distances up to 3 meters, the error was smaller than the accuracy of the ground truth measurement (e.g. the exact placement of the CCD element of the camera is unknown). For distances of 4 and 5 meters the absolute error was approximately 13 and 45 centimeters, respectively. The absolute error and its standard deviation grows with distance because of the growing penalty of the camera resolution (the ratio between physical distance between diodes to number of pixels increases). Figure 7 presents distance error standard deviations for distances from 2 to 5 meters. This includes yaw angles when a pattern is close to parallel to the image plane.

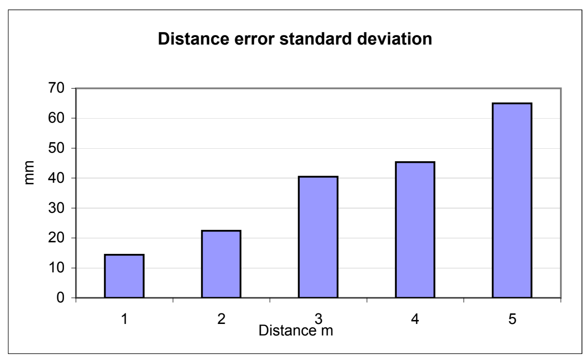

Figure 7. Standard deviation of distance error for several distances.

During a real flight, measurements are expected to be worse due to vibration of the platform and the LED pattern cube. For the flight tests performed, however, it did not pose a noticeable problem. The final vision-only flight envelope is limited to approximately 4 meters distance and by poses where a cube pattern face is parallel to the camera plane as described above. Those poses are avoided during the flight.

4. Control

The control system signal flow is depicted in Figure 8. The inner control loop used for the attitude stabilization is closed onboard the LinkMAV by means of the MicroPilot autopilot. The board utilizes a 3 axis accelerometer and a MEMS (Micro-Electro-Mechanical Systems) gyroscope to provide

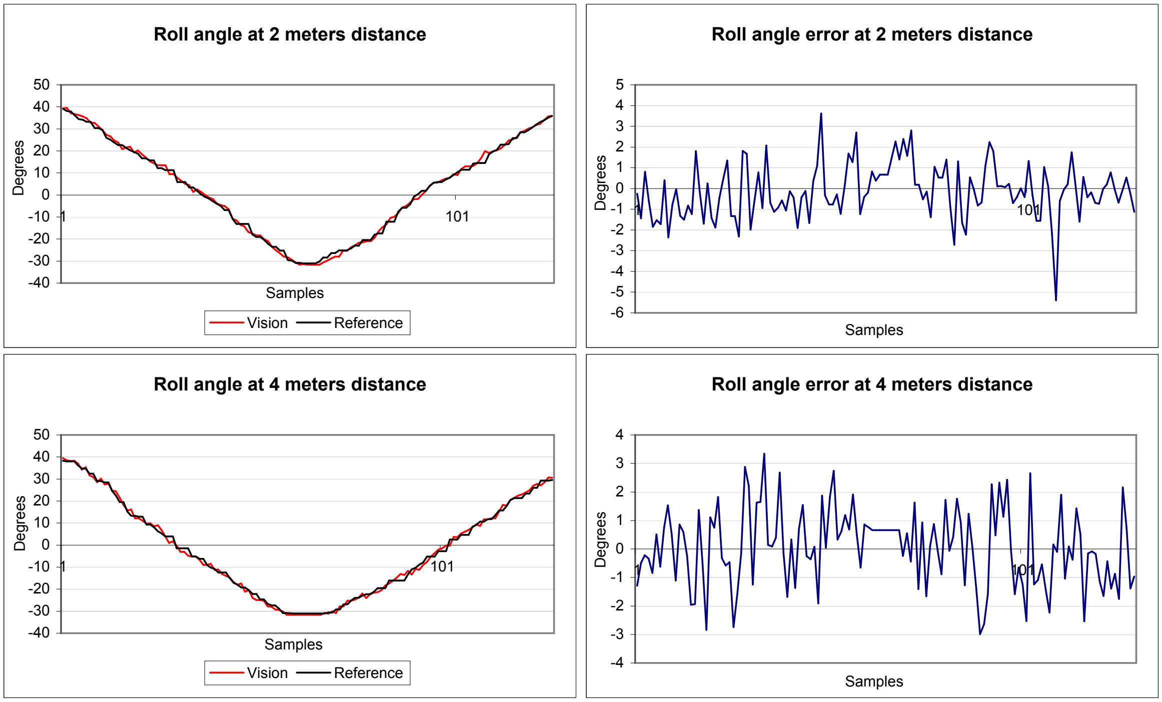

Figure 5. Measured values of angles and errors for roll axis.

attitude angle estimation for the inner PID stabilization control loop. The autopilot accepts control inputs in form of PWM signals, which correspond to:

- angle in case of roll and pitch channels,
- angular velocity in case of the yaw channel,
- mixed collective pitch and rotors' rotation speed in case of the altitude channel.

A PID controller was developed for the outer control loop. The loop closure is depicted by the grayed arrow in Figure 8. The image processing pose estimation output (X, Y, Z relative position, and the yaw angle) was processed by means of first order low-pass filters. This solution produced accurate state estimation results for the LinkMAV control.

Special care was taken during tuning of PID controller loops due to a high latency in the system. It was mainly caused by low-pass filters and the need to include the backup pilot's system in the control chain. This can be avoided in the future by using Kalman filtering or other optimal estimation methods. It can be additionally improved by introducing a different autopilot onboard the UAV, thus making the response of the control system faster.

The control mode was used in two operational modes. One allowing the ground operator to change the target position, heading, and altitude of the UAV relative to the ground robot's pose. The other mode allows for driving the robot and keeping the target pose between the robots constant. A combination of the two is also possible.

The design of the control system presented in this section proved to be sufficient for the position control of the UAV, although some improvements, as mentioned before, could be made. The UAV was able to navigate in indoor environments in the flight envelope constrained by the image processing method described in Section 3.

5. EXPERIMENTAL SETUP

Several hours of flight tests were performed with the system described. Two kinds of experiments are presented here to demonstrate the suitability of the system for realistic indoor missions. Test flights were performed with all parts of the system fully operational, no tethers or external power supplies were used. The system was operated by a single ground operator who was commanding the ground robot to drive to a certain location and placing the MAV in a proper relation to the UGV. Autonomous take-off and landing was not implemented and a backup pilot performed those parts of the mission manually. After the MAV entered into the view of the camera and the system was initialized, the control was handed over to the system.

Exploration

The basic exploration mode is necessary to drive the UGV to a desired location and does not require any direct control over the MAV. The ground operator only commanded the UAV to place itself in a certain pose in 3D space defined as lateral displacement (X, Y), altitude, and yaw angle relative to the ground robot.

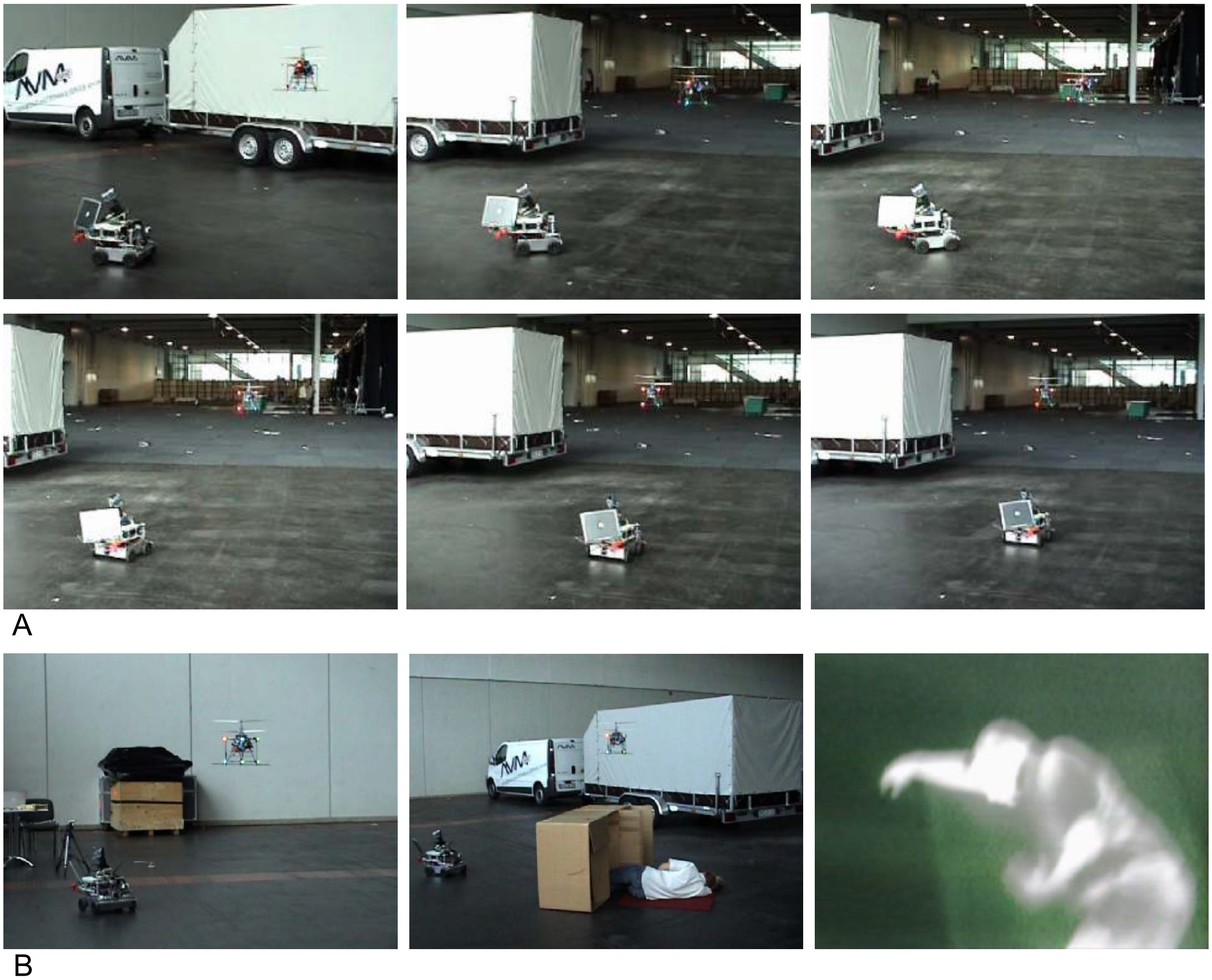

Figure 9. Top 6: Frames of video of the system during exploration task. Bottom 3: Frames of video of the system reaching behind an obstacle.

"Eye-in-the-sky"

The second flight presented here, demonstrates an application of the system as an extended camera which provides video footage from a position not accessible from a ground robot's point of view. A cardboard box was placed on the path of the UGV simulating an obstacle. A person was lying behind the box and the task was to provide footage from behind the obstacle. The box was approximately one meter high and anything behind it was out of reach for the ground robot's video camera.

6. EXPERIMENTAL RESULTS

The system presented could be of great aid in the exploration of unknown environments. Figure 9A shows six sample frames of the experiment video. The ground robot drove approximately 10 meters, stopped and turned 40 degrees left and continued driving forward.

The second task started with a straight drive of about 7 meters and ended with the UGV arriving close to an obstacle. The LinkMAV was commanded to climb several centimeters above the box. After that, the UAV was commanded to fly 1 meter forward to reach behind the obstacle. Despite turbulence generated by a close distance between the UAV and the obstacle, the flight was autonomous at all times. After the person behind the obstacle was spotted by the ground operator, the UGV was commanded to return to the starting position. Three sample frames of the video are presented in Figure 9B. The bottom-left image presents a frame from the onboard UAV thermal video with the identified human body.

The pose estimation algorithm runs at a frame-rate of around 20Hz and allows for controlling the UAV purely by vision. The use of a first order low-pass filter and a PID controller allows for an autonomous flight within the envelope described in Section 3.

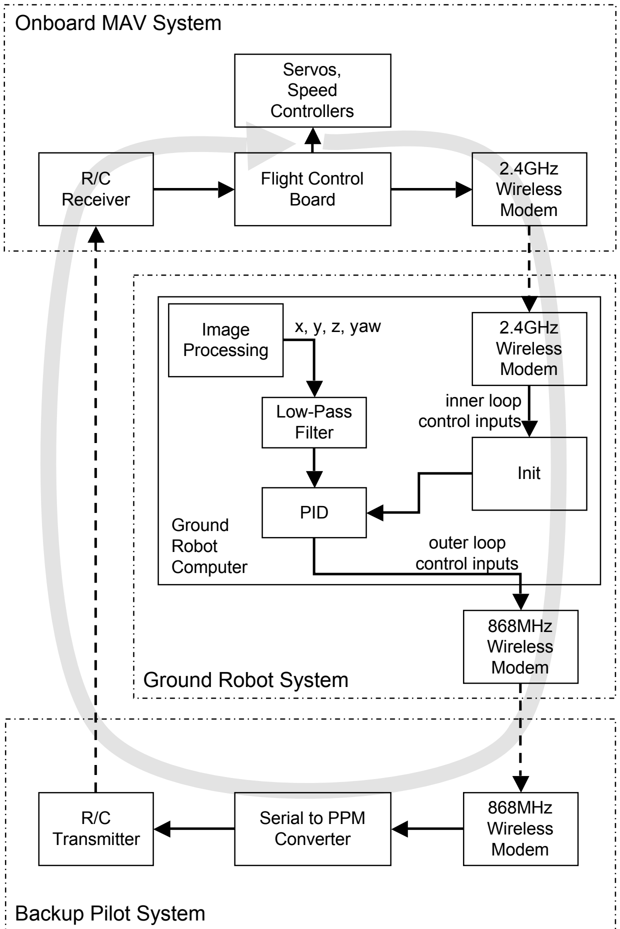

Figure 8. Control flow diagram. The greyed arrow depicts outer loop closure.

7. Conclusion and future work

We have presented a deployed system which allows for micro UAV indoor flight in cooperation with a ground robot. The technique allows for navigation in unknown environments without additional infrastructure. Several hours of flight tests were performed in order to validate the technique in real environments. The pose estimation technique can be extended to other setups and other platforms.

Future work will include extending the system to include a Simultaneous Localization And Mapping (SLAM) technique performed by a ground robot based on a laser scanner. This will enable the system to perform fully autonomous exploration missions where the UAV will provide an additional input from an onboard laser scanner to map parts of the environment out of reach of a ground robot's sensors. Another improvement will be introduced by means of a Kalman filter to fuse vision and inertial data onboard the UAV to allow the system to function at arbitrary yaw angles.

Acknowledgments

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Gianpaolo Conte obtained the MSc in aerospace engineer in 2001 from Turin Polytechnic. He received the Licentiate degree in 2006 from the University of Linköping where he is working on navigation related issues for UAVs. He is also a PhD candidate at the same University.