Hardware architecture of a four-rotor UAV for USAR/WSAR scenarios

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Abstract. This paper presents a hardware architecture approach on employing UAVs in USAR/WSAR scenarios. The UAV presented in the paper is a four-rotor helicopter. The project aims to develop a flying platform capable of working in cooperation with different ground or surface unmanned vehicles. To realize the goal, a fusion of different sensors is implemented and a hardware architecture is developed which enables automatic hovering, control from other devices (platforms), obstacles avoidance, localization and navigation both for indoor and outdoor use. The test results of first flights demonstrated promising results and pointed out on some problems which have to be resolved in the nearest future. The set of sensors used for the project consists of 3 gyros, 3D inertial sensor and a compass, HOKUYO laser scanner. The data processing is performed on an Atmel 20 MHz microcontroller and a Gamstix microcomputer.

1 Introduction

Unmanned Aerial Vehicles (UAVs) that can operate autonomously in dynamic and complex operational environments are becoming more and more used. If before their application domains were of most demand in military sector, then recently the situation has changed with appearing on the market commercial UAV platforms. In the nearest future we can expect widespread usage of them in the civil and commercial sectors.

The requirements UAVs should meet to efficiently perform in the described scenarios present a great challenge for developers. The vehicles should be rapidly deployable, back-packable, light-weight, and easily controllable. An asset would be a possibility to work in cooperation with Unmanned Ground or Surface Vehicles (UGVs or USVs). The reason for the cooperation requirement follows from the imposed weight limitations. UGVs or USVs can carry more payload and hence can be equipped with better transceiver and used as docking stations in long-distanced missions. UAVs also can support ground or surface vehicles with a better scenery overview for an optimal navigation task.

To overcome mentioned limitations and drawbacks, our team in Fraunhofer IAIS, Germany is working on an Unmanned Ground and Aerial Vehicle (UGAV) consisted of teleoperated semi-autonomous UAV capable of working in cooperation with UGV [1]. This paper corresponds to the UAV part of the project and is organized as follows. In section Related work we describe what has been done in a field of UAVs related to our

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project's aim. The Quadrotor and Hardware architecture sections introduce the architecture of the quadrotor, describe characteristics and dynamics problems and approaches the solution. The modified configuration of the copter is then tested in the First results section and the arised problems are then discussed in the Conclusion and future work section.

2 Related work

UAVs are classified in the two categories: Lighter-then-air vehicles and heavier-then-air crafts. Lighter-then-air UAVs (presented by mostly blimps) have two major disadvantages: size/payload proportion and low resistance to wind. However they also can be used in some Search an Rescue missions [2]. But they are not rapidly deployable and require carrying balloons with the gas along with the control equipment. Heavier-then-air vehicles are better in this case. Those which are used in USAR and WSAR (Wilderness Search and Rescue) are relatively small and can start without runways. Among them there are fixed-wings airplanes, different modifications of helicopters and even kites [3]. Airplanes, in comparison with helicopters, have a lack of maneuverability and mostly can not hover (a hovering airplane is presented in [4]) but are capable to carry higher payload on larger distances. These make them mostly applicable in WSAR scenarios or in exploration of wide open areas with very few obstacles. In USAR scenarios VTOL crafts with their high maneuverability ideally support rescue workers. They are able to start at very small open areas. Unmanned copters vary in size according to their application. Some are quite big and able to carry heavy high-resolution equipment [5] while others can be small.

Helicopters employed in USAR missions are also different in their design, starting from conventional ones and ending with quadrotors or octa-rotors (four or eight rotors helicopters). Quadrotors and their variations have advantages over conventional helicopters due to absence of complex mechanical control linkages for rotor actuation [6]. Instead they rely only on fixed pitch control. Furthermore, they are capable of changing the moving direction by varying only the motor's speeds. But that simplicity in mechanics leads to higher computational effort to stabilize this highly nonlinear model [7] [8].

Because of the mechanical simplicity and high maneuverability, quadrotors became a field of interest of many researches. In particular there has been a boom during the last ten years, when new brushless motors and controllers became widely available on the market. These copters have enough payload to carry the necessary equipment for surveillance and navigation and are relatively extendable to perform many tasks, including USAR scenarios.

The quadrotor has two pairs of counter-rotating, fixed-pitch blades located at the four corners of the vehicle. Since the four-rotors helicopter is a highly non-linear and unstable platform and requires stability controllers to cope with its fast dynamics, the stabilization problem becomes a primary issue which is addressed in many articles [7–12] and mostly overcame to some extent. Because of natural drift of the used stabilization sensors (gyroscopes and inertial sensors) and constant air moving (wind, convention currents) it is difficult to achieve a stable hovering for a long period of time.

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This position drifting problem is manageable for outdoor environments by means of GPS [13–15]. However, in highly-dense urban areas or for indoor-use GPS becomes inapplicable. There are also difficulties because of limited payload of UAVs and integrated hardware which does not allow the platform to be easily extended with additional sensors. As a solution for indoor flights Roberts et al. [16] uses a platform equipped with sonar for altitude control and four infrared range finders for hovering control. Matsue et al. [17] employed three infrared range sensors to measure the height above the ground and the distances to two perpendicular walls. The former platform showed good hovering results in empty rooms and was able to avoid large obstacles while the last one could also follow walls. Kim [18] used 6 degrees of freedom inertial unit for hovering stabilization of a conventional helicopter.

Many approaches on the position drifting problem employ external sensing for position stabilization. Thus Castillo et. al [7] used POLHEMUS sensor for position tracking, Mori [19] processes on-board camera data on an external PC and Gurdan [20] performed experiments in a laboratory environment equipped with the indoor motion tracking system VICON that can measure the position vector of specific points on the body of the robot.

Although significant results were achieved, existing approaches lack of flexibility. Using external localization systems limits the copter's workspace to the area visible by that system. For avoiding collisions with obstacles and navigating in office buildings still no sufficient results have been demonstrated. However, for outdoor use the most promising solution is seen in fusing GPS and 6-DOF Inertial Measurement Unit (IMU).

3 Quadrotor

The quadrotor UAV is a four-rotors aerial platform that is capable of Vertical Take-Off and Landing (VTOL). Its flight control board is equipped with an inertial measurement unit consisting of 3-axes gyroscopes, 3-axes inertial sensors, 3-axes digital compass and a GPS module. For altitude control a pressure sensor is employed. Fusion of these sensors as well as the control of the four motors is done by means of an on-board $20\,\mathrm{MHz}$-microcontroller (Atmel ATMEGA644P) and four brushless motor control boards. The on-board microcontroller communicates with the four brushless controllers via $\mathrm{I^2C}$ bus.

The quadrotor has a size of $650 \times 650 \times 220$mm (L×W×H) and a weight of $590\,\mathrm{g}$. With an extra antenna the height increases to $550\,\mathrm{mm}$ and the weight increases to $600\,\mathrm{g}$. With fully loaded batteries ($2100\,\mathrm{mAh}$) it can operate for approx. $20\,\mathrm{min}$. Its maximum payload is $350\,\mathrm{g}$. The quadrotor is controlled either by the UGV or a human operator via WiFi, Bluetooth or an analog remote control unit.

The problem which is addressed to the drones in USAR scenarios is a possibility for a single human to simultaneously manage the aerial vehicle and its camera [21]. This requires the UAV to have some autonomous features to simplify the searching task of the personnel. This requirement and the necessity for the copter to accomplish tasks and return back or land safely in case of loosing a control signal is the basis for formulating the main goal of our project. The goal is to develop a multipurpose teleoperated VTOL platform with such autonomous features as automatic take-off and landing, position

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control, localization with return back function and obstacle avoidance. The platform should be suitable for both indoor and outdoor USAR applications and work in the collaboration with an UGV.

4 Hardware architecture

Concerning the selection of the proper platform for the research, the choice falls to a non-commercial open-source project *MikroKopter* [22] with available pre-assembled flight and brushless control boards and open-source software. The flight-control board contains a 3D accelerometer unit to calculate and align with the gravity of the earth. In order to provide automatic leveling of the copter, a complementary filter is implemented that processes the integrated angular velocity of three gyroscopes and the calculated Euler angles from the accelerometers. The output of the filter is used in a PID controller.

To make the platform usable in USAR scenarios and to achieve a higher stability and functionality it is equipped with additional sensors and computational units. Figure 1 shows the functional diagram of the quadrotor used in the project. The main component is the flight controller in the middle of the diagram. The flight-control board with the pressure sensor for altitude control, gyros and an accelerometer is running on an Atmel ATMEGA644p micro-controller and communicates with the four brushless controllers via I^2C bus. The brushless controllers in their turn are running on Atmel ATMEGA8 micro-controller and control the four brushless motors.

Rotation along central point (yaw) is eliminated with adding a 3D digital compass. Adding the compass is an important requirement for navigation. It allows us to fix the copter's orientation in space, in our case to the north. Knowing the orientation we can use GPS coordinates for navigation and hovering stabilization. In our model we used a widespread u-blox GPS receiver reprogrammed for sending coordinates in autonomous mode with $4\,\mathrm{Hz}$ frequency. GPS communication with the Flight Control board is established via second spare USART (Universal Synchronous/Asynchronous Receiver/Transmitter) of the ATMEGA644p micro-controller.

The quadrotor is controlled via a $40\,\mathrm{MHz}$ analog radio link. In order to achieve the vehicle's control compatibility with most electronic devices like laptops, mobile phones/smart-phones, pocket PCs etc., the quadrotor is equipped with the Free2move [23] Bluetooth and WiFi modules. The Bluetooth connection is performed via first USART of the on-board micro-controller and enables not only wireless data exchange but also program modification and flashing. Thus configuration parameters of the copter or the firmware can be changed "on-flight" or during a stop. The WiFi module is connected to a Gumstix [24] embedded computer. Gumstix is a $600\,\mathrm{MHz}$ micro-size computer running with Linux OpenEmbedded operating system. In addition to three RS232 ports it has an USB host controller and slot for external memory (micro-SD). It does not require special power supply because it uses $5\,\mathrm{V}$ which is standard for the helicopter's board. The weight of the Gumstix computer does not exceed 100 grams. Gumstix communicates with the Flight Control board by means of I^2C bus connection.

The problems with possible loose of control signal and crashing to obstacles can be solved by extending the autonomy of the quadrotor. For this purpose a HOKUYO [25]

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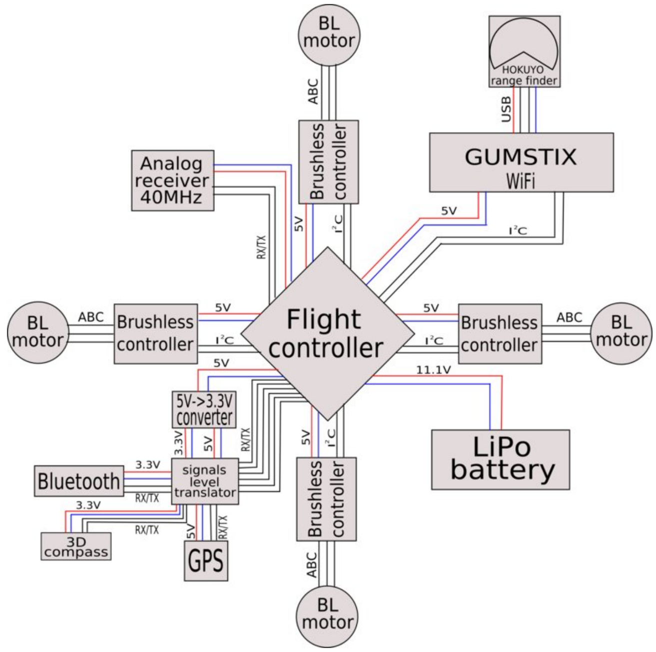

Fig. 1. The quadrotor's extended functional diagram. The Flight Control board utilizes the sensors data and computes the control signal for the Brushless Controllers. Communication between them and the Gumstix computer is established via I^2C bus. The signal level translator serves for normalizing different voltage levels of data signals.

laser range-finder is added. The laser scanner is needed for implementing collision avoidance function and will be used for indoor localization. Thus in case of loosing the control signal the helicopter should be able to find the way back using a built during the flight map and GPS position data. Data from the scanner is processed on the Gumstix computer. The collision avoidance function is served to prevent operator's control errors in USAR scenarios and focus him only on visual data from the on-board wireless camera. A comparison view of the HOKUYO range-finder, the wireless 2.4 GHz analog camera and the Gumstix computer is presented on Fig. 2.

Since the Bluetooth device and the 3D compass need only 3 V power supply, a 5 V to 3.3 V voltage converter is implemented. Signals are then translated via a signal level translator to satisfy flight-control microprocessor's requirements.

5 First results

At the current state of the project we have achieved significant altitude and attitude stability of the platform with 3-axes gyroscopes and accelerometers and an air pressure sensor. The copter is remotely controlled and able to fly indoor and outdoor with just

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Fig. 2. From the left to the right a HOKUYO URG-04LX Laser Range-Finder, a Wireless VisorTech GP-811T camera and Gumstix Verdex XL6P computer with 802.11(g) wireless communication module are shown. The display is detachable and is not needed during the flight.

a little adjustment of the flight trajectory by the operator. Altitude control is performed automatically according to the set point defined by the operator. Also by means of the 3D electronic compass the orientation is automatically controlled and turns the copter to the north after taking-off.

Experiments in the robotic laboratory at Fraunhofer Campus Birlinghoven showed some drawbacks of using the magnetic compass. Multiple power cables under the floor induce unstable magnetic vectors in nearly all directions. It causes the copter to search for north orientation and confuses the operator. Outdoors the performance shows excellent results. Manual landing on a small platform has also successfully tested at indoor and outdoor environments. Figure 3 shows the current prototype of the quadrotor[3].

GPS tests showed good results on the field. The helicopter was able to cope with wind and hover at one point with error up to 0.5 meter with 7 to 8 satellites in the field of view of the GPS sensor. At the same time some unexpected jumps in GPS coordinates were noticed. Showing quite still behaviour it could suddenly move fast to one direction and then return back. The fluctuations weren't always the case but when they occurred it caused significant oscillations in the quadrotor's hovering position. Further observations showed that the GPS jumps mostly occur when the receiver looses more than one satellite from the point of view. In other cases the signal readings show just slight drifting in coordinates. Refusing following the GPS coordinates readings in the control loop when there are less than six satellites in the field of view and limiting the pitch and roll angles partially reduces the copter's oscillations but have drawbacks

[3] Video links: `http://www.youtube.com/watch?v=48WVz9cEir8`,
`http://de.youtube.com/watch?v=476uiL7ouO0`,
`http://de.youtube.com/watch?v=Kh1SSfB2a5o`,
`http://de.youtube.com/watch?v=qFS85rR1qGI`

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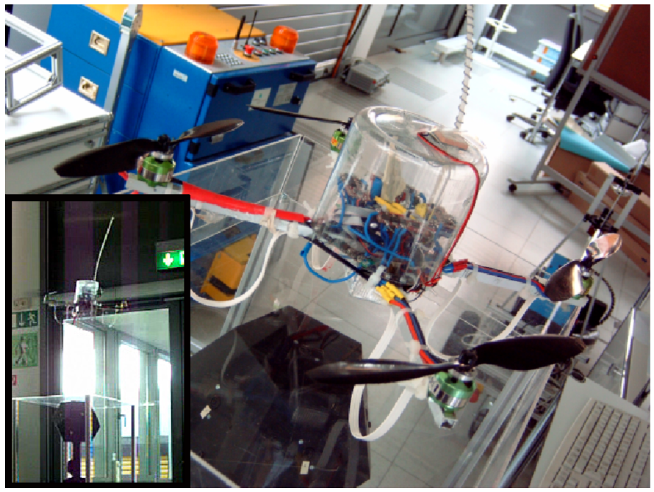

Fig. 3. A prototype of the quadrotor used for experiments. On the bottom-left figure the copter is tested for landing on a small platform in the Fraunhofer IAIS robotic laboratory.

when the wind is strong. A similar problem with the GPS data is noticed by Yun et. al. [15]. An example of a jump occured in the GPS signal is shown on fig. 4

In the campus area with low altitude $(0.5 - 1.5\,\mathrm{m})$ the number of satellites captured by the copter varied from 3 to $6 \cdot$ This leads to large 3D position errors of up to tens meters. The error is magnified by the fast dynamics of the quadrotor. The helicopter flying outdoor in the IAIS campus is shown on Fig. 5. From the picture we can see density of buildings in the testing area. In case of higher buildings the situation with GPS position error can be even worse.

To enable outdoor flight missions using GPS, a client program is written. The client is used to transmit GPS set-point coordinates to the quadrotor. In future, the programme is planned to be written platform independent to run on most mobile devices (platforms) and transmit also other different commands for the copter.

6 Conclusion

We have presented a hardware configuration of the quadrotor for USAR and WSAR scenarios. The platform's configuration reflects demands of such scenarious including cooperation with ground or surfaces unmanned platforms.

As shown by the first experiments the position drifting problem can not be totally eliminated with the chosen set of sensors. Since the platform can suffer from different deformations (which were actually the case after several crashes while performing first tests), external forces and control signal noise, precise horizontal leveling does not significantly reduce the drift. It is obvious that the copter lacks sensing along horizontal axes. GPS provides the solution but only for opened areas or high altitude flights.

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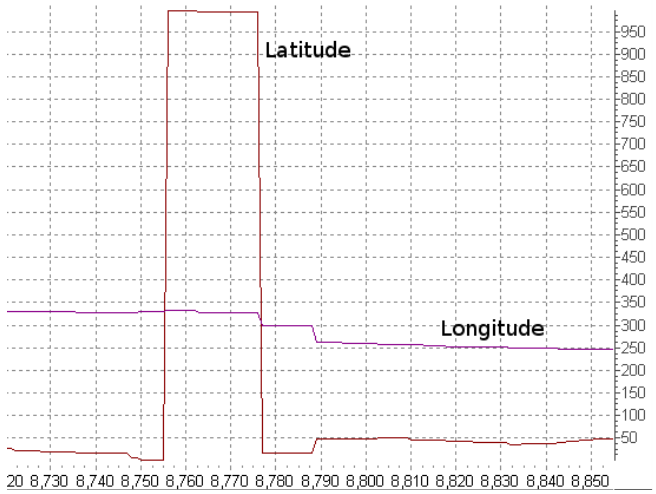

Fig. 4. The picture shows a spike in latitude GPS data reading occured with six satellites in the field of view. The vertical axis shows fourth to sixth digits in decimal degrees of the readings and the horizontal axis is the time step. One fourht digit in latitude is equal approx. to eleven meters and in longitude to 6.7 meters.

Fig. 5. The quadrotor (red square) is flying above the roofs and near a window at Fraunhofer IAIS campus. The large picture is taken from the on-board camera. The figure illustrates a possible search scenario in urban area like acquiring an interior overview through windows or scenery overview.

Although significant results have been achieved, the copter still requires operator presence in visible distance, especially indoor. The quadrotor is a valuable supplement in an USAR scenario especially if it cooperates with an UGV system. A simple interface should be provided to control it from any mobile device or other platforms like UGVs. This is a cooperative work within the UGAV project group.

In the near future the quadrotor will be equipped with a HOKUYO laser range-finder to pursue the goal of multiple obstacles avoidance along with solving the hovering drift problem for flying indoors. With more and more increasing density of integrated circuits and increasing computational power it becomes possible to overcome computational expenses for micro aerial vehicles.

To increase the altitude stability and hovering using GPS data different filtering techniques are planned to be implemented and analyzed.

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