Setup of a communication and control systems of a quadrotor type Unmanned Aerial Vehicle

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***Abstract*— This paper outlines the communication and control systems of a quadrotor type Unmanned Aerial Vehicle. The communication system comprises two different links, one for data and other for video signal, and all integrated by an autopilot module. The data link will be implemented using XBee modules and Mavlink communication protocol. The video transmission system will consist of two separate links which can work together avoiding interferences by using orthogonal polarization each other. It is also given some insights of the onboard software architecture, which is based on the Pixhawk autopilot.**

***Keywords*— UAV, quadcopter, autopilot, XBee, Mavlink, Pixhawk.**

I. Introduction

UAV (Unmanned Aerial Vehicle) or Drones are commonly employed in tasks where they have easy access to places that people do not. Due to their small size UAVs can be useful in hazardous conditions where human life is at risk and surroundings that are inaccessible to reach [1]. Its mobility is of key importance in several fields as surveillance, military application, documentation and monitoring purpose and image acquisition [2] [3] [4]. Nowadays, the most common UAV type for non-military application is the multicopter, and particularly the quadcopter [5] [6] which now have sufficient payload and endurance for this kind of tasks [7].

Among the advantages of copters over planes on these tasks is their ability to hovering. The multicopters offer, on the other hand, more payload carrying capacity than a helicopter of the same wingspan. It is known that multicopters controllability is better as there are multiple thrust vectors which renders the flight control simpler, allowing to hover at a constant level from ground by itself and at the same time allowing anyone to easily maneuver it [8], or also to achieve autonomous take-off and landing with little control software development effort from the autopilot point of view.

In general, they implement several flight modes, from less to more autonomous operation. The typical flight modes are:

- Manual: Roll, pitch, yaw and throttle controls are feed directly from the user input to the autopilot to calculate servo output values in an open-loop manner. This mode should not be available for multirotors.

- Stabilized: Roll, pitch, yaw and throttle controls are feed as setpoints to the autopilot, calculating servo output values in a close-loop with the attitude controller. Controls are in manual mode but the aircraft attitude is stabilized in the 3D space.

- Autonomous: The aircraft follows GPS waypoints set by base station.

It is needed both specialized hardware and software on a flight controller to achieve autonomous flight. In the case of hardware, IMUs (Inertial Measurement Units) are the most relevant module. An IMU is an electronic device that measures and reports on a craft's angular velocity, orientation, and gravitational forces, using a combination of three orthogonal accelerometers, three orthogonal gyroscopes, and three orthogonal magnetometers, enabling to estimate the UAV attitude. Quadcopters nowadays, besides the IMU, are also provided with barometers, vertical range sensors, airspeed sensor and GPS to obtain global position and make possible flying over waypoints.

Any variation on position, orientation and acceleration is detected by hardware devices, but data must be processed by the software onboard the craft to realize autonomous flight. There is great variety of projects where flight control algorithms are developed, as for example, those at the University of Zurich [9] and the Flying Machine Arena [10]. They make micro aerial vehicles (MAV) that even are able to do acrobatic flight.

When the flight mode is not autonomous, quadcopters need to receive control commands. In most of the commercially available devices, these commands are sent using RC systems such as the widely employed Futaba system [11].

This UAV prototype will be integrated into the robotic multiplatform ARGOS[1], consisting of long range and high-autonomy multi-robotic platform for performing complex missions in hostile environments. ARGOS project includes several robots capable of operate in different environments (on air or on land). The system is intended to operate when a natural disaster happens, such as earthquakes, and the zone becomes inaccessible.

The UAV will be a quadcopter of approximately 75 cm. from side to side. It will be able to carry payload of at least 3 kg and to fly over extended period of time, compared to other crafts similar in size. Mechanical design and controller software will provide the capacity to fly in a variety of conditions such as wind or rain. The quadcopter will be able to perform long range flights with LOS (Line Of Sight), but also fly in urban areas and inside buildings.

The quadcopter will be equipped with two video cameras which will transmit real-time signals. The first camera will be placed in the front of the vehicle and the other one will be hanging below, mounted on a pan/tilt/zoom module.

This paper describes the communication links between the UAV and GCS (Ground Control Station). It is divided into two different links, one for data and other for video signal, and all integrated by an autopilot.

Data transmission system: A bidirectional link is necessary to transmit control and telemetry data. Telemetry data will be sent from the aerial vehicle down to the GCS, and control data will take the opposite way.

Video transmission system: It will have two different links, one for each camera, both unidirectional. This means that it will have two individual transmitters. Control commands for cameras will be sent by the data transmission system.

Autopilot: module that controls both communication and flight stabilization.

The UAV prototype will be implemented using commercial modules, with versatility and system flexibility in mind.

This paper is organized in three main sections. First of all is the "System description", which is divide in other three subsections that describe the different modules of the UAV, those are: "Data transmission system", "Video transmission System" and the "Autopilot". On the next section a study of the autonomy of the system is done. And finally, a "Summary and conclusions" section.

II. SYSTEM DESCRIPTION

Fig.1 shows the general system diagram, with the modules and their interconnections. The autopilot and the XBee module will be connected by a bidirectional serial link. The autopilot will transmit telemetry information and will receive control commands through the XBee module. On/off switches of both cameras and the Pan/Tilt/Zoom system of the bottom camera will be controlled by the autopilot according to the received commands.

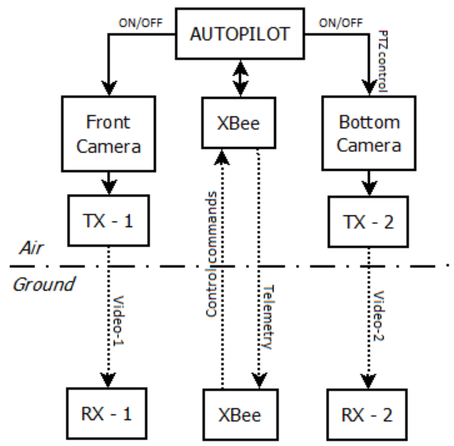

Fig. 1. General system diagram

A. *Data transmission system*

The communication data channel employs the Mavlink communication protocol [12]. Mavlink is a very lightweight, header-only messages marshaling library for micro aerial vehicles. It can pack C-structs over serial channels with high efficiency. Mavlink is bidirectional, so communication to and from UAV is possible. There is a common message set, but also it is possible to implement custom messages. Mavlink is LGPL (GNU Lesser General Public License) licensed so can be used in close-source and open-source projects.

The anatomy of Mavlink packet is inspired by CAN (Controller Area Network) and SAE AS-4 standards. The minimum packet length is 8 bytes for acknowledgement packets without payload, and the maximum packet length is 263 bytes for full payload. Taking into account worst case, all packets length 263 bytes, it is necessary a link speed of at least 105200 bps to transmit a frame every 20 ms. The next standard value for a link speed is 115200 bps. As the link is not always going to send full payload packets, a system with data rate of 115200 bps should be employed.

A suitable commercial RF device providing the required data rate in a bidirectional link are the XBee [13] modules, due to their low power consumption, lightweigh and low cost.

Devices operating at a frequency of 900 MHz are preferred over those at 2.4 GHz, mainly because their longest ranges, up to 45 km, depending on the implementation. At the same emitted power, the RF theory says that at lower frequencies longer ranges can be achieved due to propagation lost. Hence, 900 MHz systems should achieve better ranges than the same system operating on 2.4 GHz.

On the other hand, due to electromagnetic propagation characteristics, below-GHz signals are less susceptible to multipath fading. This is because signals can more easily pass through or around obstructions.

Among the drawbacks of using low frequencies is the limited bandwidth and the bigger size of the antenna. The antenna size increases with lower frequencies, for the same gain. A readily available dipole antenna at 2 dBi is chosen.

[1] Joint project between Robomotion and the HCTLab, Human Computer Technology Laboratory, of Universidad Autónoma de Madrid, under INNPACTO program published in ministerial bulletin ECC/1345/2012.

The XBee modules use a mesh networking protocol that provides an efficient way to route data between nodes. One of the most popular mesh networking protocols is ZigBee, in which three types of nodes are defined. In every Zigbee network there is a Coordinator node, some Routers and some End Devices. Each one has its own role to play. The selected XBee module uses another mesh network protocol, DigiMesh. This protocol is similar to ZigBee, but has several differences. DigiMesh has only one node type that simplifies network setup and provides more flexibility. Furthermore, DigiMesh achieves longer ranges and larger RF data rates than ZigBee protocol.

In addition, the selected device uses FHSS (Frequency Hopping Spread Spectrum) as a way to reduce interference effects. That also makes the link more robust to multipath fading. Spread spectrum communications improves privacy because the spreading code is only known by the transmitter and the receiver that are involved in the link.

B. Video transmission system

The video transmission system consists of two wireless links able to operate at the same time. Commercial wireless video transmission systems can be divided into two groups: analog and digital. Analog systems are used mainly by the hobbyist community, whilst digital systems, similar to those used in some television broadcasting cameras, are employed in the professional field.

Digital systems are more robust in the presence of interferences. Most of them use COFDM (Coded Orthogonal Frequency Division Multiplexing) modulation. The demodulated signal quality at the receiver is very good; these systems can transmit HD video signals by using H.264 or MPG-4 compression.

The bigger drawback of digital RF video links is the system cost. The less expensive digital transmitters have also some other problems, as big latency due to the time they need to compress video signal, or higher power requirements. Also, digital transmitters are bigger and heavier than analog transmitters.

Therefore, for this prototype, it has been opted for analog wireless PAL video transmitters. They use FM modulation like the ones used to do analog television broadcast.

Both analog and digital systems available in the market operate at the same frequency bands. The most common frequency is 5.8 GHz, but there are video transmitters that can also operate at 1.2 or 2.4 GHz. The best and newest video transmitters and receivers work on 5.8 GHz, thus, this frequency band is the selected one.

The main advantage of working on a high frequency is that there are no issues with the bandwidth. The chosen commercial system operates between 5740 MHz to 5860 MHz. It has seven channels separated 20 MHz each other. This module allows sending video signal and, optionally, one or two audio channels.

Other advantage of this frequency is that a bigger gain can be achieved with small antennas.

At this frequency, electromagnetic signals propagate largely in straight line paths. Thus, they are good for unobstructed line of sight communication. This propagation feature also makes system very susceptible to multipath fading. To reduce that effect, a diversity receiver with two antennas is going to be used. Both antennas receive the same signal but with different phase, and the receiver select the best signal from the two antennas.

Two different kind of circular polarized antennas will be used. One of them will be an omnidirectional 2 dBi antenna and the other a 12 dBi directional antenna, with a beam width of 60º. The directional antenna will always point to the UAV to get as long range as possible, and the omnidirectional one will be used to guarantee communication when the UAV flies near the receiver. Fig. 2 shows the radiation pattern of both antennas and how the main lobe of the directional one points to the null of the omnidirectional antenna.

It will be needed two video links operating together. To realize this configuration, each link will use a different polarization. One transmitter and receiver set will use RHCP (Right Hand Circular Polarized) antennas and the other will use LHCP (Left Hand Circular Polarized) antennas. So, they will be orthogonal minimizing interferences due to cross polarization discrimination.

C. Autopilot

The flight control system has to provide a semi-autonomous control to the UAV. It is needed a little and very lightweighted system as possible. Autopilot must be as flexible and versatile as possible and able to allow easy system integration to adapt it to this project.

One type of modification that is expected to do is the integration of new sensors and tasks automation. To do that, it is necessary a system that allows software modification and versatile interconnections.

This level of system versatility is easily found on open-source and open-hardware autopilot projects. The Pixhawk [14] is a powerful hardware-software autopilot suitable to be integrated into this project.

Pixhawk is an autopilot system designed and developed by PX4 project. It features advanced processor and sensor technology and a NuttX [15] real-time operating system. Pixhawk system include integrated multithreading and a Unix/Linux-like programming environment.

Px4 firmware is a continuous development project. This firmware is organized similarly to ROS [16] (Robots Operating System), but in a simpler way. It is made up of different modules or applications that run like independent threads or tasks. Communication among applications is carried out by uORB (micro Object Request Broker) topics, which are data

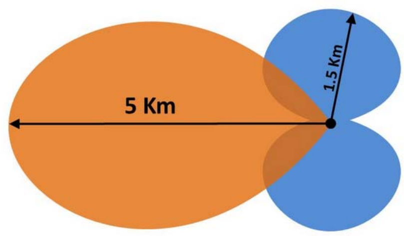

Fig. 2. Receiver antennas radiation pattern **[18]**.

structures. Applications can publish a message on a topic to send data, and can subscribe to a topic to receive data.

Pixhawk unit is combination of PX4FMU (PX4 Flight Management Unit) and PX4IO (PX4 Input Output) hardware modules. PX4IO is designed to driver interfaces to px4io and sends servo setpoints, while it receives battery voltage, current and RC input (Spectrum satellite protocol (DSM), Futaba S.Bus o PPM sum/CPPM). PX4FMU driver configures the FMU board. It controls the multi-function mapping of a number of pins that can be used with different functions such as send PWM servo data or receive PPM RC data.

Fig. 3 and Fig. 4 show a part of the software architecture where it is defined the way data go from RC receiver to motors. Applications are represented as blocks, and the lines that join the blocks represent the topics.

On the first figure (Fig. 3), input control values are published on the topic *input_rc* by either PX4FMU or PX4IO drivers. This topic communicates measured pulse widths for each of the supported input channels.

The SENSORS application subscribes to *input_rc*. In the case of a quadcopter, this application assign the normalized and scaled value of the four first channels to roll, pitch, yaw and throttle, and decides the switches modes (flight options) according to the value at the next four input channels. Other channels can be used command pan/tilt cameras. Calculated values are published on *manual_control_setpoint* topic.

Other possibility (Fig. 4), the one used in this project, is control setpoints are sent using Mavlink communication instead of the traditional RC remote controller.

The attitude controller, MC_ATT_CONTROL application in the case of a quadcopter, subscribes to *manual_control_setpoint*. The application combines the attitude setpoint and the current attitude of the UAV to generate the motor control signals, which are published on

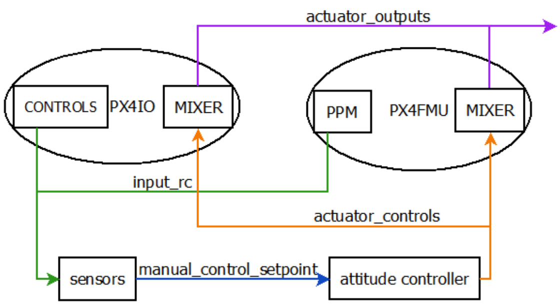

Fig. 3. Part of the software architecture when using RC control.

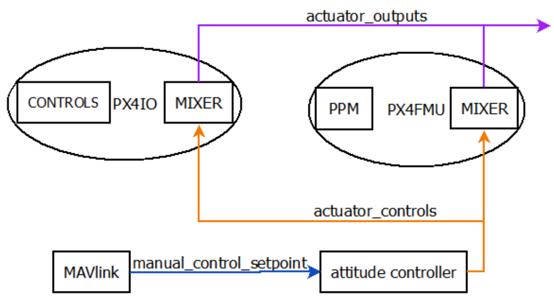

Fig. 4. Part of the software architecture when using Mavlink.

actuator_controls.

PXIO and PX4FMU drivers subscribe to *actuator_controls*. They use the MIXER to generate a set of outputs, used to update servo output and to publish the results on *actuator_outputs* topic for other modules to use. Multirotor mixer is specifically designed for mixing flight controls (roll, pitch, yaw and thrust) to produce motor speed control outputs suitable for multirotor air vehicles.

Fig. 5 shows the applications (modules) involved in the controller architecture when manual or stabilized flight mode is set. In that case, the attitude controller gets the attitude setpoint from the manual control input, while the current attitude is calculated by the attitude estimator according to the sensors data.

For the autonomous flight mode, the diagram that describes the system can be seen in Fig. 6. The attitude setpoints are generated by the position controller that combines navigator data, the current position and the attitude.

The COMMANDER application, present in both figures (Fig. 5 and Fig. 6), implements the main system state machine and publishes the flight control mode and the actuators status on the topics *vehicle_control_mode* and *actuator_armed*, respectively.

III. AUTONOMY STUDY

Two independent batteries are going to be employed to manage this UAV prototype. One will supply power to the motors and the other to the rest of the electronic. The motors have the most power consumption of all of the components on quadrotor type UAV, so that is why the autonomy is given by the motors battery. This is going to be an 8 cells LiPo battery with a capacity of 22000 mAh, which will provide between 25 and 30 minutes flight, considering that the UAV weigh 7.5 Kg including structure, batteries and electronics [17]. The electronics battery will be a 3 cells LiPo.

Table 1. summarizes the current consumption and weight of each electronic component used.

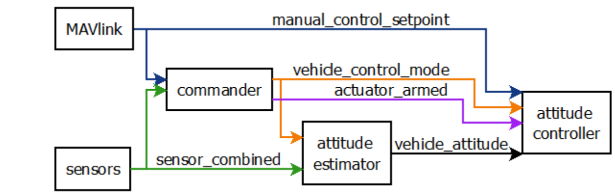

Fig. 5. Control architecture when manual or stabilized flight mode is set.

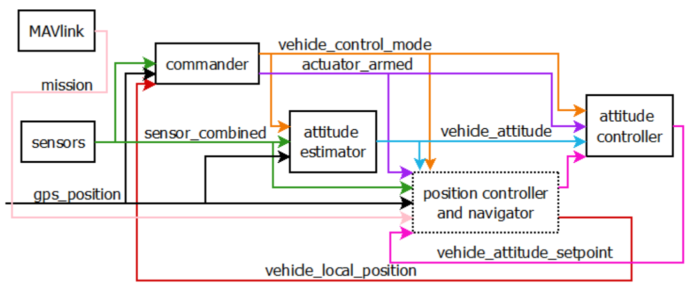

Fig. 6. Control architecture when autonomous flight mode is set.

TABLE I. ELECTRONICS CURRENT CONSUMPTION AND WEIGHT

	Current Consumption	Weight
Pixhawk	250 mA	38 g
GPS	40 mA	16.8 g
Airspeed sensor	3 mA	7 g
Sonar	100 mA	5.9 g
Front camera	250 mA	74 g
Bottom camera	400 mA	200 g
Servomotors	100 mA x 2 = 200 mA	60 g x 2 = 120 g
Video Tx	250 mA x 2 = 500 mA	18 g x 2 + 10 g = 46 g (with antennas)
XBee	215 mA	8 g + 10 g = 18 g (with antenna)
TOTAL	**1958 mA**	**525.7 g**

Total current consumption is about 1958 mA, hence, to achieve 30 minutes autonomy it is enough using a 1000 mAh capacity battery. It may notice that this is the worst case of power consumption because the bottom camera is not always going to be on and it has been considered peak current for the sensors, servomotors and the XBee module.

Furthermore, the battery weighs 97 g and motors, motors battery and the UAV structure will weigh around 6.5 Kg. If this is add to the electronics weight the result is 7.1227 Kg, which is less than the 7.5 Kg considered to estimate the autonomy of the motors, so this will also improve.

IV. SUMMARY AND CONCLUSIONS

This paper presents the integration of a complete communication system on a UAV which is able to operate safely in difficult environmental conditions. A quadrotor type UAV will be used due to its ability of hover at a constant level from ground by itself and because it has sufficient payload capacity and flight endurance. The communication system consists of one data transmission link and two different video links, all integrated by an autopilot.

XBee modules are used for data transmission link due to their low power consumption, light weight and low cost. The selected transceivers work on 900 MHz frequency and emit enough power to achieve medium ranges with 2 dBi gain antennas. Real experiments confirm that selected Xbee modules and antennas reach more than 3 km range with LOS. Mavlink communication protocol is used to allow bidirectional communication, to and from UAV. Mavlink protocol can pack C-structs over serial channels with high efficiency.

Commercial, readily available analog video transmission systems are used at two video links. These transmitters use FM modulation at 5.8 GHz frequency. To reduce multipath fading a diversity receiver with two antennas is used. Two different kind of circular polarized antennas are employed. One of them is an omnidirectional 2 dBi antenna and the other a 12 dBi directional antenna. To avoid cross-talk interference the two video links use orthogonal polarization each other.

To control both communication and flight stabilization it is used the Pixhawk system. The software for the Pixhawk autopilot modules runs on top of the very efficient small operating system NuttX. The Pixhawk software is made up of different modules or applications that run like independent threads or tasks. Communication among applications is carried out by publisher-subscriber scheme. This paper describes the software architecture section needed to be modified in this project to integrate a custom communication system and new sensors, as well as tasks automation.

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REFERENCES

[1] M. Kamran Joyo, S. Faiz Ahmed, D. Hazry, M. Hassan Tanveer, and F. A. Warsi, "Position controller design for quad-rotor under perturbed condition," Wulfenia Journal, vol. 20, nº 7, pp. 178-189, 2013.

[2] Shahida Khatoon, Dhiraj Gupta, Ahmad Saad Khan, "Assembly of an experimental quad-rotor type UAV for testing a novel autonomous flight control strategy," International Journal of Advanced Computer Research, vol. 3, nº 4, 2013.

[3] Haitao Jia, Wei Zhang, and Mei Xie, "UAV search planning based on perceptual cue," IEEE International Workshop on Microwave and Millimeter Wave Circuits and System Technology, Chengdu, China, 2013.

[4] Hrishikesh Sharma, Rajeev Bhujade, Adithya V and Balamuralidhar P., "Vision-based detection of power distribution lines in complex remote surroundings," IEEE Twentieth National Conference on Communications (NCC), Kanpur, India, 2014.

[5] M. Hassan Tanveer, D. Hazry, S. Faiz Ahmed, M. Kamran Joyo, Faizan. A. Warsi, "Design of overall stabilized controller for quad-rotor," Wulfenia Journal, vol. 20, no. 7, pp. 212-229, 2013.

[6] Michael C. Achtelik, Jan Stumpf, Daniel Gurdan, and Klaus-Michael Doth, "Design of a flexible high performance quadcopter platform breaking the MAV endurance record with laser power beaming," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), San Francisco, CA, USA, 2011.

[7] Inkyu Sa, and Peter Corke, "Vertical infrastructure inspection using a quadcopter and shared autonomy control," Field and Service Robotics - Results of the 8th International Conference, vol. 92, Brisbane, Australia, Springer Berlin Heidelberg, 2014, pp. 219-232.

[8] Bernard Tat Meng Leong, Sew Ming Low, Melanie Po-Leen Ooi, "Low-cost microcontroller-based hover control design of a quadcopter," ELSEVIER International Symposium on Robotics and Intelligent Sensors (IRIS), vol. 41, pp. 458-464, 2012.

[9] "ETH - IDSC - Institute for Dynamic Systems and Control," [Online]. Available: http://www.idsc.ethz.ch/. [Accessed 2014].

[10] "Flying Machine Arena," [Online]. Available: http://flyingmachinearena.org/. [Accessed 2014].

[11] "Futaba," [Online]. Available: http://www.futaba-rc.com/. [Accessed 2014].

[12] "Mavlink" [Online]. Available: http://qgroundcontrol.org/mavlink/start. [Accessed 2014].

[13] "XBee," [Online]. Available: http://www.digi.com/products/xbee/. [Accessed 2014].

[14] "PX4 Autopilot Platform," [Online]. Available: http://pixhawk.org/. [Accessed 2014].

[15] "NuttX Real-Time Operating System," [Online]. Available: http://nuttx.org/. [Accessed 2014].

[16] "ROS," [Online]. Available: http://www.ros.org/. [Accessed 2014].

[17] J. A. Benito, G. Glez-de-Rivera, J. Garrido, R. Ponticelli, "Design considerations of a small UAV platform carrying medium payloads" *DCIS*, Madrid, 2014.

[18] "Circular Wireless," [Online]. Available: http://www.circular-wireless.com/. [Accessed 2014].