Implementation of Micro Airborne Radio Relay

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Abstract:
This paper presents results of Micro Airborne Radio Relay implementation designed to extend range of mobile robots in search and rescue missions. Architecture of routing device with hardware based on ARM development board is presented, as well as overview of based on mbed-rtos software. Selected radio solution with radio modem and antennas is described. Paper presents results of proposed system field tests.

Keywords: *UAV, telemetry, telecommand, mobile robot, radio relay*

1. Introduction

Unmanned Aerial Vehicles are commonly used in various fields. UAVs come in variety of forms, sizes and degrees of autonomy. Some of them are remotely controlled by pilot with or without use of video stream from onboard camera. Others vehicles fly automatically or even semi autonomously. In all ceases operator of unmanned aircraft needs some sort of telecommand and telemetry to and from the vehicle.

Military, which is main user of Unmanned Aerial Vehicles, is in privileged position as it has access to various unavailable to civilian user means of telecommunication. Such technologies are for example: high bandwidth satellite links or high power, restricted frequency transmitters. These means of communication allow for seamlessly executed missions beyond visual line of sight (BVLOS).

Civilian users operate in much more restricted environment. They must comply witch many laws regulating operations of UAVs. One of them is regulation of radio equipment e.g. CLASS 1 devices [1]. In current legislation there are no specific rules for radio communication of unmanned aerial vehicles, so they operations are based on common rules. There is possibility of acquiring special permission for use of high performance radio communication system, but it is complicated because common rules are incompatible with requirements of UAV applications such as exclusiveness (there should be some specific fragment of radio band for specific operation) and mobile nature of UAVs operations.

1.1. Motivation

Currently, legislation in Poland allows for operating unmanned aircraft beyond visual line of sight (BVLOS). With this type of mission one of the factors limiting the range is radio communication. Radio waves carries the telemetry of aircraft such as altitude, speed and position as well as commands for the autopilot system and information specific to the mission goal e.g. acknowledgment of detected object. Such communication is a prerequisite for safe conduct of the flight and successful completion of the task.

Radio communication range can be expanded using better radio modems, but this is not always the right solution. For example, further increasing of the transmitter power may be restricted by law or technical conditions of the plane – insufficient power supply or excessive weight.

For technical reasons, UHF band is used for communication with unmanned aerial systems (size of antennas, propagation conditions and the availability of bandwidth). Radio communication in this frequency band is strongly influenced by obstacles. Such an obstacle can completely prevent direct communication, even if in the line of sight coverage is sufficient. In some cases even curvature of Earth could incapacitate surface-to-surface communication.

Such issues are faced by MelAvio – team of students representing Warsaw University of Technology in UAV Challenge 2016 – Medical Express [2]. Script of the competition includes the necessity of landing unmanned aerial system at a distance of more than 10km from the ground station. Throughout the mission it is necessary to maintain continuous radio communications. MelAvio, during the start of in the UAV Challenge 2014 – Outback Rescue competition, was able to maintain the surface-to-surface communication at the distance of 5 km and surface-to-air at the distance of 8 km. These results indicate that it will not be possible to meet the requirements using current method of direct radio communication, so airborne radio relay was proposed as a solution to the issue.

1.2. State of Knowledge

Today, radio communication is widely used in various fields of life. Television, mobile phones, wireless Internet access are all examples of radio technologies. Radio communication, like everything has restrictions. Some of them are physical, but some of them are legal based. This results often in worse than desired performance, like too low range. In some cases usage of radio relay could boost performance of radio link to sufficient level. One possibility of placing radio relay is embedding it in an aircraft. The main advantage of this approach is high mobility of aircraft.

Using airplanes as radio relays has long history. One of earliest reported use cases of airborne radio relay is Battle of Ia Drang Valley in 1965 in Vietnam. Since then airborne radio relay technology is in continuous development. Main field of operation is still military operations because of high cost of operation. Using small unmanned aerial vehicles as a carrier could significantly reduce cost in comparison with manned aircraft.

Total mass of aircraft is about proportional to it's payload capacity. As CLASS 1 compatibility limits maximum performance of radio relay, it could be designed as light, as 1 kg without additional penalties. It is fraction of human pilot mass, so purposely build unmanned aircraft could be at least order of magnitude lighter then small manned vehicle. Such reduction in weight reduces cost of operation and increases accessibility.

There are currently available radio relay modules build for UAVs such as STAR from Thales Communications[3]. This solution is limited to military users, as it uses restricted frequency.

There are also academic research of airborne radio relays. Some of them focuses on general network communication like ones used in computer communication. In those research IEEE 802.11 (Wi-Fi) network devices are used. This results in high bandwidth at the expense of range [4], [5].

Other research focuses on similar topic to presented in this paper, but are limited to simulations without physical implementation [6].

2. The System Architecture

2.1. Frequency bands

Three frequency groups where considered for usage in radio relay:

- 2400 MHz
- 900 MHz
- 450 MHz

The 869MHz frequency band was chosen as final frequency. Receivers in this band has better sensitivity then ones for 2400 MHz (-110dBm vs. -100dBm). Antenna size is still small enough (180mm for coaxial half-wave dipole with connector) to fit on sub 5kg UAV, where 450MHz antenna will be too big.

Higher frequency bands have also smaller Fresnel zone, which should by clear from obstructions for good communication. To achieve this, antennas should be placed high above the ground. On the relay UAV this is no issue as it could fly up to 120m above ground level (limited by law). On the ground we can use antenna mast, but to retain mobility it's height must be limited to about 7m, which would be too low for 450MHz.

2.2. Radio Modem

Several radio modems was considered. There are many available radio communication solutions on the market in different form factors from integrated circuits to modules. RFDesign RFD868+ was chosen as it has sufficient output power (1 W) to achieve maximum legal in Poland EIRP (29 dBm for Class 1 device [7]). This module has several additional features which are beneficial in radio relay application. Firstly they are compatible with MP-SiK firmware which enables them to work with more than two modems in network, but they don't provide any routing capabilities, just conflict free operation. This is essential feature as airborne relay aircraft can work with just one radio modem to support communication channels: between itself and ground station and between itself and mobile robot executing primary mission. This also enhance reliability, as potentially any node can work as relay. To achieve similar results with simple point-to-point modems every node should have two modems (for three node network, as proposed in this paper).

Secondly RFD868+ uses FHSS technology which helps mitigating noise. It has built in two way diversity which enables connection of two antennas to one modem and automatical switchover to one which provides better signal.

This modem has also average in class sensitivity of -121 dBm at low data rates and about -110 dBm at data rates used in Micro Airborne Radio Relay.

Radio modems are configured to use 64 kbps FSK modulation. They use duty cycle of 10% to comply with Sub-class 30 of Class 1 device [7].

This solution should provide signal to noise ratio of 24 dBm at 15 km range.

2.3. Antennas

For the best usage of diversity function of RFD868+ modems it was chosen to use two half-wave dipole antennas in horizontal position mounted with 90° angle between them. This configuration results in horizontal polarization of radio waves and spatial diversity – each antenna supports two opposite quarters of horizon. This configuration is used in relay aircraft and in mobile robot. It results in 3 dBi gain in antenna subsystem.

On the ground there is horizontally mounted Yagi-Uda antenna with two directors – 6 dBi gain. It has usable cone of 60° (included angle) which main purpose is providing spatial selectivity on ground node. Antenna mast have no active antenna tracking capabilities, as manual aiming antenna turn out to be sufficient, because in most cases direction to region of interest is well defined. Second antenna on the ground is half-wave dipole to provide connectivity in ground node proximity and protect otherwise unused antenna channel from overload by reflections of unterminated connector.

2.4. Hardware

System requires at least three channels of communication:

- To the vehicle autopilot;
- To the radio modem;
- To the payload.

The hardware is based on NUCLEO-F446RE development board and custom daughterboard. The Nucleo board is based on STM32F446RET6 microcontroller with ARM Cortex-M4 core clocked at

180 MHz. This MCU provides all necessary interfaces (Fig. 1). Development board provides all necessary components for running micro controller – power regulator, decoupling capacitor network, clock source as well as embedded debugger. The daughterboard contains power preregulator which enables usage of 2S to 4S Lithium-Polymer battery packs commonly used for powering small mobile robots. Second function of the supplementary board is mechanical support for connecting wires. To ensure high reliability on board of research UAV each wire connected to board is firstly through-hole soldered, then passed through strain relief hole on PCB and tight to board in harness with zip tie. There are also three LED on the board for status indication.

The daughterboard contains also UART to USB bridge. It is built around FTDI FT230XS integrated circuit. It provides reliable mean of communication with payload computer.

As area of board is constrained by design of Nucleo baseboard, so several features was added in free space for future use: SPI bus for Ethernet connectivity or secondary radio module, footprint for I2C EEPROM, two standard servo outputs for antenna tracker functionality, additional UART with timer input for GPS (position and precise clock reference).

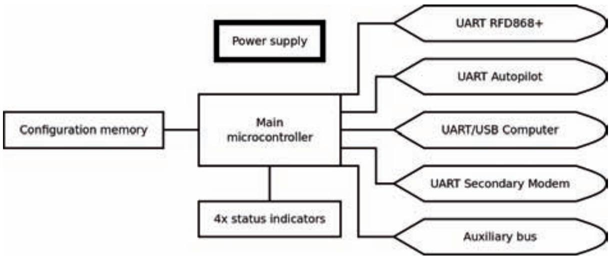

Fig. 1. Controller Block Diagram

2.5. Software

Mbed platform was chosen for writing the software for the relay. It is cloud based IDE for ARM Cortex-M microcontrollers. Mbed is based on C++ language. It supports mainly development boards like ST NUCLEO-F446RE used in this project. It provides complete SDK with compiler, HAL type peripheral library, RTOS and various third party libraries. This cloud IDE provides version control system based on Mercurial and export options for all major ARM toolchains.

Mavlink was chosen for use as telemetry protocol for its universality and commonness. It is telemetry and telecommand protocol used by many autopilots on the market, for example Pixhawk with PX4 software, VRBrain with Ardupilot, Parrot AR.Drone and many more. It is also supported by various ground control stations like Qgroundcontrol, MissionPlanner or Tower.

2.6. Relay algorithm

Relaying data is realized as a pipeline (Fig. 2). Each role in the pipeline is a class. Every object in pipeline has own thread for specific task. Communication between threads is provided by Mbed RTOS mail mechanism.

Firstly, incoming data are received by HAL driver. Then they are delivered to Packet Preparator. Each HAL driver has its own instance of Packet Preparator with own thread. It detects packet boundaries and identifies its type. It also checks correctness of data by use of CRC. Packet Preparator is responsible for wrapping data in Message structure which contains following information:

- Type of message (e.g. Mavlink2 or Payload Control);
- Length;
- Source(which input device received it);
- Unique fingerprint;
- Priority;
- Message content.

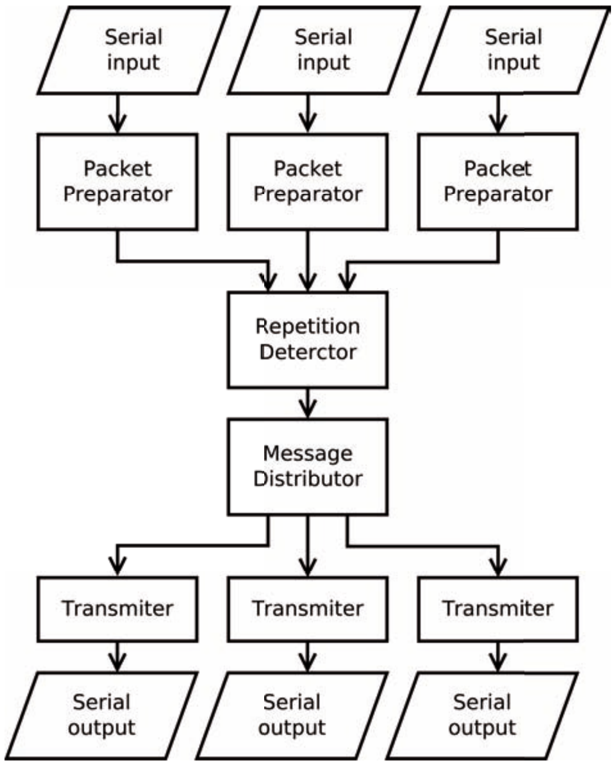

Fig. 2. Data Flow Pipeline

In the next step of pipeline message is *Repetition Detector*. It keeps track of 128 recently processed messages. If the message was already processed it would be discarded. Its role is to prevent looping of packets between nodes and uselessly wasting limited bandwidth. Single, common Repetition Detector is implemented in the pipeline.

Then message is moved to the Message Distributor that decides which transmitters should emit the message. The decision is made with use of routing table. It classifies the message by source and type. There is single, common Message Distributor in the pipeline.

In the end the message is routed to one or couple Transmitters. They are responsible for feeding output HAL drivers with data. Transmitter may also drop the message if the output device is clogged up or if it is a command issued for other vehicle.

3. Results

3.1. System Properties

Total mass of the system is 212.9 g (Table 1) with enough battery capacity for over 2 hours of continuous operation. Average current consumption of radio modem is 300 mA at 5 V. Router module consumes on average 120 mA also at 5 V. That makes average power consumption of 2.6 W from battery (including conversion losses). Dimensions of the complete router stack are 70 mm by 83 mm by 25 mm (WxDxH) (Fig. 3).

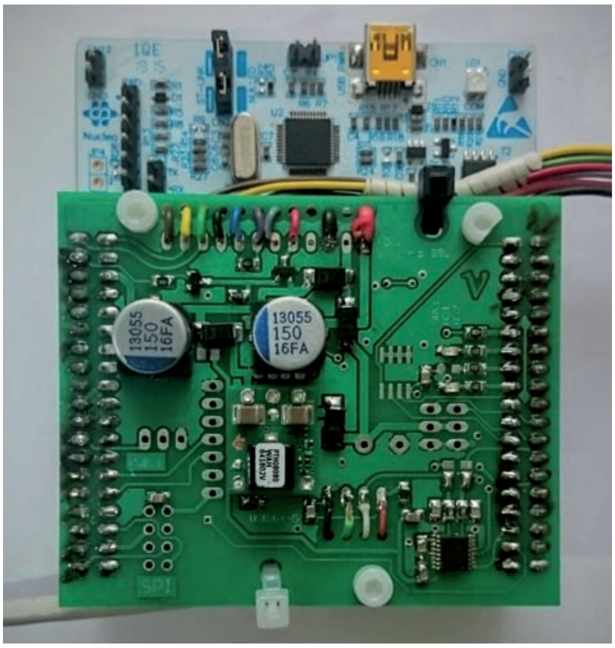

Fig. 3. Router module

Table 1. Mass of system components

Component	Mass
Daughterboard with harnesses	63.3 g
Nucleo board	34.3 g
Radio modem	15.3 g
Two half-wave dipole antennas	51 g
Battery pack (800 mAh, 7.4 V)	49 g
TOTAL	212.9 g

Router section of the system weights 111 g (including its share in battery mass). All UAVs needs telemetry and telecommand connection for safe operation, so already needs radio modem, antennas and power source for it. In this case implementation of relay functionality with this implementation is just addition of 111 g to existing aircraft. Required volume is more disturbing, as current implementation has volume of about 0.2 l, which in most UAVs will be mayor difficulty of implementation.

3.2. Range tests

Range tests were conducted in simulated scenario of Beyond Visual Line of Sight mission, because of real BVLOS flight requires special license and permission. Instead, there were used two ground stations – one with pilot and primary ground station operator, and

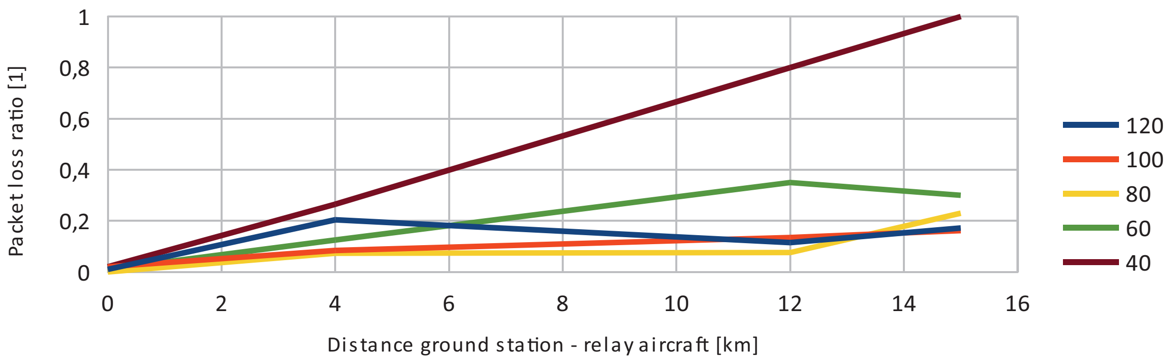

Fig. 4. Packet loss ratio for different airborne relay flight altitudes [m]

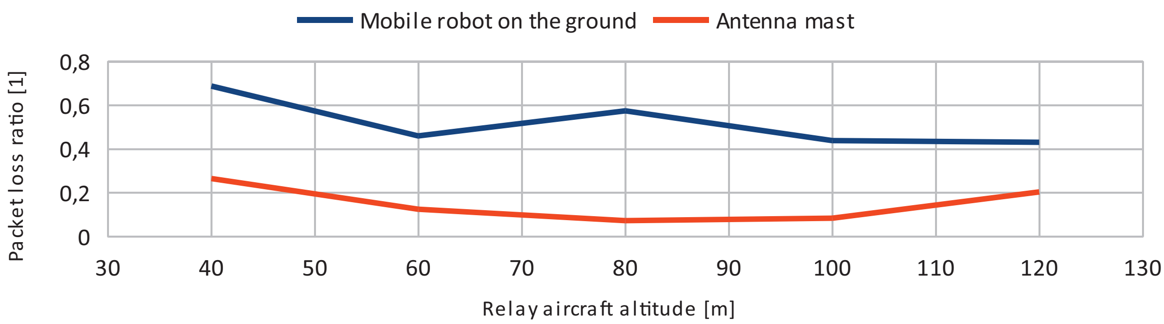

Fig. 5. Packet loss ratio at 4 km from airborne relay

second simulated ground station with antenna mast and all required hardware. This station was set up in several locations and used to collect measurement data. Fig. 4 presents results of study on relay flight altitude on transmission range. Best results are achieved at 100 m above ground level. Altitude of 40 m was determined to be insufficient for communication over 10 km.

Fig. 5 shows result of comparison between on ground mast and proper antenna versus two half-wave dipole antennas 0.25 m above ground in mobile robot. Measurements were taken 4 km from relay aircraft. It is maximum usable range between relay and mobile robot on the ground, as it results in about 50% packet loss. High flight altitude of relay is clearly beneficial for link quality.

4. Conclusions and Future Work

Measurements results shows, that ability to elevate antenna to 100 m above ground helps achieve long communication rage. 200 g system could fly for an hour on board of 4 kg electric airplane at 100 m above ground. That kind of system could be built for about 10000 EUR and could operate at cost of electric energy to recharge batteries, while being mobile in opposition to 100 m antenna mast. It is also significantly cheaper than manned aircraft radio relay. It is clearly competitive solution for communication ranges up to 15 km.

In the future system could be further improved in various ways:

- Reduction of router module volume,
- Support for authentication of passed data,
- Addition of second, redundant transmission channel to increase reliability.
- Implementation of payload communication protocol for mobile robot, as current work was focused on telemetry and telecommand for autopilot systems.

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