TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 7
Number 2
June 2013

DOI: 10.12716/1001.07.02.11

# Integrated Communications System for the Remote Operation of Unmanned Aerial Vehicle

K. Kurek, T. Keller, J. Modelski, Y. Yashchyshyn, M. Piasecki, G. Pastuszak,
M. Darmetko & P. Bajurko
*Institute of Radioelectronics, Warsaw University of Technology, Warsaw, Poland*

ABSTRACT: The aim of the paper is to present the concept of the integrated system dedicated for communication and remote operation of the unmanned aerial vehicle (UAV). In the paper the concept and realization of this kind of wireless communications system is presented. The system consists of two integrated solutions – unidirectional broadcast transmission of video, audio and data from UAV to the operators within the mobile command centre and two-way communication with the telemetry and control subsystem. The systems are integrated within the single chassis and placed on the UAV to ensure proper operation of the flying robot. The specific elements of the system are presented as well as main requirements and connected with them development methods are also discussed in the paper.

## 1 INTRODUCTION

The paper is dedicated to present the concept of the integrated communication system for UAV (Unmanned Aerial Vehicle) data and telemetry transmission. UAV is one of the elements of the Proteus project, which is dedicated for developing an integrated system mobile system for counterterrorism and rescue operations. In the project Institute of Radioelectronics is mainly responsible for developing the entire communication system for all system components. The aim of this paper is to present general view at the concept of the system, which is the communication system for controlling the UAV and collecting the information from it. In the paper both the concept of the system and elements of its realization are presented.

## 2 PROTEUS PROJECT

The project "Integrated Mobile System for Counterterrorism and Rescue Operations" – PROTEUS is realized by consortium of leading science centers in Poland headed by Industrial Research Institute for Automation and Measurement PIAP [1]. The Proteus Project is aimed at development of a modern system, which in the future will be able to support operations of police, fire service and the other services responsible for security of our society. The designed system will include i.a.: three multi-functional robots, unmanned aircraft and mobile command centre. The Proteus is going to make use of a range of innovative technologies integration of which into one efficiently functioning system poses a serious challenge to engineers working on the project.

Intensification of violent weather phenomena, of terrorism and ever increasing dependency of a man on technology are the circumstances in which fire service and police have to reach for newer technological solutions, which can improve their operations. One of solutions like that will be the Proteus system.

## 2.1 *The aims of the Proteus Project*

The Proteus is a state-of-the-art integrated system intended for counter-terrorism and crisis management operations. Operations of the emergency services are to be supported by three multi-functional robots, unmanned aircraft and mobile command centre. The system is to be completely integrated, which is an innovation on a global scale and poses a serious challenge to engineers involved in the project.

Every device being a component of the Proteus performs a strictly defined function, and simultaneously is an integral part of the system. Elements of the Proteus are already used in rescue services and military structures, but bringing them together to create one operational unit is innovative even on a global scale. It is only the beginning for this kind of solutions to be developed in the world, and additionally they are created virtually exclusively for the military purposes. The IT system of the Proteus will allow for the presentation of the gathered data in a clear way, their comparison with reference data, and with aid of GIS systems (Geographic Information System is a system for acquisition, processing and presentation of data with reference to geographic location) it will enable, for instance, determination of direction in which spreads chemical contamination or fire. It will significantly enhance and speed up decision making processes, enabling the supervision and insight into the region under threat. Interconnection of existing elements and solutions into an integrated system capable of performing various tasks depending on the needs, is the essence of originality of the Proteus Project.

## 2.2 *System components*

After detailed research the potential requirements of future users of Proteus (the departments responsible for rescue operations and counterterrorism), Proteus system architecture and its components have been defined. As a result of many weeks of interviews with Fire Department personnel, police and counter-terrorism services, the main system concept was developed, consisting of the following main elements:

- Mobile Command Center MCC - the Proteus "brain", the large truck equipped with complex communications and operation systems. This is where, owing to data acquisition and interpretation, decisions affecting the action will be made. Apart from processing and integration of data coming from the system components taking part in action (robots, unmanned aircraft), the MCC will be in continuous communications with command posts of police, fire service and crisis management centers
- Mobile Robot Operator Centre MROC - to the site of operation all robots will be carried by Mobile Robot Operator Centre mounted (similarly as the MCC) on a chassis of a truck. It is equipped with devices for rapid loading and unloading of robots, portable robot operator stands (PROS) and a system of communications with command centre.
- Mobile robots - directly to the operation site three types of mobile robots are sent, every one of different functionalities and purpose. The Small Mobile Robot (SMR) is a robot of small dimensions and very high mobility, intended for operations in places of hard accessibility. In turn, main task of the Mobile Intervention Robot (MIR) is intervention. Larger and heavier, it will be equipped with manipulator and set of sensors intended for determination of threat levels. The largest of three robots will be the Mobile Enhanced Functionality Robot (MEFR). Mass of about 300 kg, capability of carrying weights of mass up to 40 kg with a manipulator of range of 2 meters, structure enabling the installation of additional devices: sensors, negotiation package or pyrotechnic guns;
- Unmanned Aerial Vehicle UAV – it is designed to provide on-line data from the operation site. Owing to cameras and other sensors installed on-board the person in command of action will have at their disposal a wide picture of situation from the place of intervention.

All components of the Proteus will be mobile, which will enable their transportation to the place of intervention, and modular structure of the whole allows for rapid adaptation to the specifics of the particular action. All system components will be equipped with a coherent communication system, which enables them to interact in the action, even in cases when they are deployed in different units. Thanks to the statement of the needs of the specific operation of different components, each time it will be able to be adapted to the nature of the threat and the scale and type of activities.

## 2.3 *Proteus communication system architecture*

The main objective implemented by the project PROTEUS communication system is to provide efficient and effective methods of communication between all elements of the integrated system to support counter-terrorism and anti-crisis activities. Based on "Tactical and Technical Assumptions" documents for the specific operations and on reference scenarios for different actions, the integrated architecture of the PROTEUS communication system has been developed [2].

Ensuring effective communication between system components requires the use of different systems for different applications. One of the primary tasks is to create a system that allows efficient transmission of image data, voice and telemetry from mobile robots and unmanned ship flying robots for both operators and the mobile position management the action. An equally important element is to propose a solution for the transmission of signals control the operation of robot.

In both of these systems important issues are both ranges, which are assumed to be achievable, as well as delays in transmission of signals in both directions (small enough to be able to smoothly control the operation of robots by means of video signals received from them). Due to the fact that there has been separation of the mobile control station from the position of the mobile robot operators, it is also necessary to design a dedicated radio link just to transfer between these system components, with the use of the transmission link which could be capable to transmit full information gathered from all the robots ( transfer stream of high bit-rate), also with strict restrictions on the ranges and delays. An important element of the system is also providing voice communication between the participants of the action and the communication system with the outside world.

Due to the complex structure of the system it was not possible to propose a single, integrated system that can combine different requirements. Therefore, to ensure the particular functionalities, the structure has been proposed composed from several complementary communications systems. Due to the demands of the need to ensure low latency data transmission and constant transmission of images from different robots it seems reasonable to divide the communication system for dedicated to each task subsystems:

- The system for transmission video data, voice and telemetry from UAV and mobile robots, based on broadcasting transmission, allowing to receive information from the robots both by operators and mobile robot operation centre;
- Low-rate communications system to transmit control data to the robot, also used for the transmission of telemetry data between system components;

The above two systems are integrated in one chassis and located at the UAV and mobile robots and are the main element of this paper. However, there are also three additional communication systems used for different applications:

- Mobile communication system for communication between mobile command center and mobile robot operator centre, dedicated to transfer information collected from all the robots to the command center, in order to illustrate the tactical situation;
- The system for voice communication, allowing for voice communication between the participants of the action and to transfer small data from the sensors (implemented as a system that resembles the functionality of radio communication trunking system ;
- The system for external communication which offers high-speed access to external network and capable of using both a variety of external sources (meteorological services, databases, external expertise, ...) as well as access to external departmental and telecommunications networks ;

The main challenges facing the designers of communication systems within the project , are related primarily with the need to ensure wireless transmission over long distances while providing very low latency and working in various, sometimes extreme environmental conditions. Established communication systems have to be flexible and modular solutions which meet the strict requirements for immunity, compatibility and overall dimensions.

Carried out work related to the latest developments in multimedia techniques (efficient hardware implementations of source encoders and multiplexing mechanisms of data) as well as with issues of radio communication (channel encoding, antenna systems, propagation). The project uses the advantages of various elements of the different network types (broadcast systems based on DVB-T / H radio networks, data transmission systems, telecommunication systems) for specific tasks and functionalities.

## 3 INTEGRATED SYSTEM FOR COMMUNICATION WITH UAV

The system for remote controlling and collecting the multimedia data from UAV is aimed to enable transmission of audio, video and data with a relatively high data rates. It is a system of video, voice and telemetry data transmission from mobile robots and UAV, based on broadcasting transmission. The information is transmitted to both operators and mobile robot operator centre. Based on Tactical and Technical Guidelines and reference scenarios of the potential actions (documents prepared by the emergency and security services), there have been basic parameters and requirements to be met by the specified communication system.

Basic requirements for the system indicate which particularly important parameters must meet the system to enable the application for receiving information from the UAV. The system should provide data rates of several Mbit/s at ranges in direct communication UAV - operator of up to 10km. Another very important requirement is the transmission delay - including the processing time in transmitter and receiver modules it shouldn’t exceed 100ms. The transmission should be encrypted using the AES128 protocol, and the modules should ensure proper operation at ambient temperatures from -30 to +50 ° C and relative humidity of up to 95%. An important limitation is the maximum size of the modules (limited due to the available free space in the UAV) and the weight. Below main elements of the system will be described.

### 3.1 *Source encoder*

To meet the high data rate requirement for the system some manner of source encoding was needed. The proposed encoder is compatible with H.264/AVC standard with Main or High Profile. However, the encoder does not have all the compression options consistent with these profiles, as it does not support MBAFF mode, the mode frame – field at the macroblock level, and only sequences consisting exclusively of the frames, or only from the fields. Furthermore, no B-frames are generated, which would result in the formation of a significant and unacceptable delays in the circuit video transmission. In the project there was assumed also, that the sequences are encoded in standard definition 720x576 (576p), using only the frames of type I and P. This allows to obtain the lowest delay between the time you collect video data and displaying them.

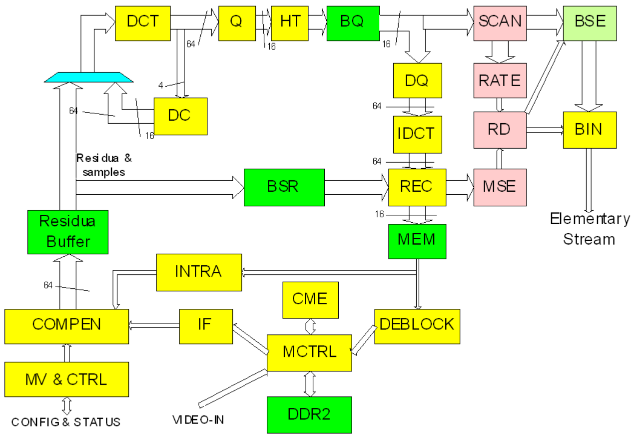


Figure 1. Block diagram of the H.264/AVC encoder

The encoder treated as an independent IP module should be scalable to 1080p HDTV resolution with increasing the clock frequency. It is assumed that a proposed resolution for PAL the clock of 100 MHz is sufficient. Control of the degree of compression ensures that the size of the stream does not exceed the capacity of the radio transmission path and the possible elements of a network.

Audio encoding is done in parallel to video encoding using MPEG4/AAC coding. Another device based on ARM microprocessor is used as a bridge between Ethernet and FPGA device. Ethernet is used both for sending control commands to encoder and for sending encoded stream to transmitter. Communication between FPGA and ARM is performed with use of EPI and I2C interfaces. ARM microprocessor translates commands sent to the encoder in AT standard to I2C signals controlling the device. Power-over-Ethernet (PoE) is used to deliver power to the device.

Functional diagram of the proposed encoder is shown in Figure 1. The basic processing unit adopted in the encoder is a macroblock, however individual modules can also operate on smaller blocks. The processing of macroblock was divided into five steps:

– rough estimation of traffic
– accurate traffic estimation and INTRA prediction
– the DSP loop
– mode selection
– binary encoder (entropy)

All these elements have been implemented, tested and verified in the laboratory environment and currently they are tested in the typical operation's conditions.

The target runtime platform of the source encoding/decoding subsystem is a set of printed circuit boards stacked on each other in the form of a "sandwich". Functional model was based on the combined kits FGPA Stratix 3 (DK-DEV-3SL150N) and ARM (DK-LM3S9B96). The encoding unit uses algorithms of high complexity, because of that achievement of the assumed parameters of the encoder is only possible with use of higher-end of FPGA devices. Final version of encoder is based on Altera Aria model FPGA devices.

## 3.2 *DSP Block*

Based on required parameters of transmission and knowing typical operating conditions, DVB-T [3] system was picked for video transmission between robots/UAV and operator or command center. Broadcast transmission was set as one of the requirements, and OFDM modulation used in the system helps to prevent harmful effects of multipath propagation, common in urban environments. DVB-T transmitter can be divided into two distinct parts: digital signal processing (DSP) block, and analog part of the transmitter.

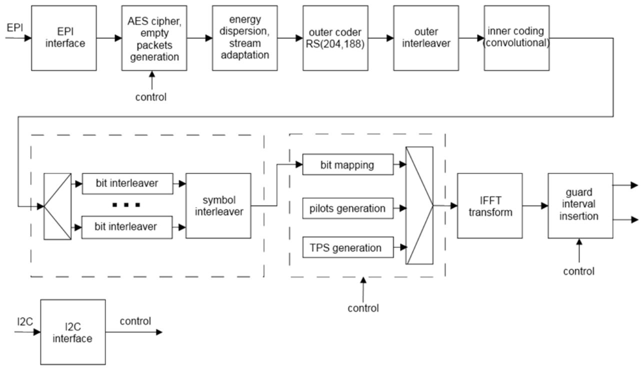


Figure 2. Block diagram of the PROTEUS transmitter's DSP block [4]

Digital part of the transmitter was based on the FPGA device, allowing for parallel execution of the algorithms [4]. The functional diagram of the DSP block is presented in Figure 2. EPI interface is used for incoming MPEG-2 transport stream, while I2C is used to receive commands form ARM microprocessor (implementing Ethernet controller as in encoder module). AES cipher is used to prevent receiving of the signal by off-the-shelf devices capable of DVB-T and MPEG4 decoding. AES algorithm is uses ECB mode, and 128 byte key. Channel coding and modulation is done according to DVB-T standard. All the code rates and modulation schemes are allowed, but transmission is limited to 2k mode (using 1512 active OFDM carriers). Hierarchical transmission options were also omitted, as not needed by the project requirements.

To ensure compliance with DVB-T standard and help validate DSP part of the transmitter gbDVB Simulator was used. Test platform for the system was based on the same devices as in encoder. The Stratix structures belong to the highest Altera series offering the greatest potential, but with high power consumption and price. Further evaluation of hardware resources occupied by the transmitter, allowed to pick much smaller and cheaper device as a target for final model. Altera Cyclone IV (EP4CE75F23I7) was chosen. Final model was done in the same "sandwich" technology as the encoder.

## 3.3 *RF radio transmitter*

One of the elements of the transmission system for video, audio and data signal is a radio transmitter, which enables the one-way wireless link between mobile robot and the operator and the command center. This link is a transmission channel for video signals from cameras installed on the RM, making it possible to use them to conduct follow-site or remotely control a robot, it is therefore of fundamental importance for the realization of the most significant functionality of the system.

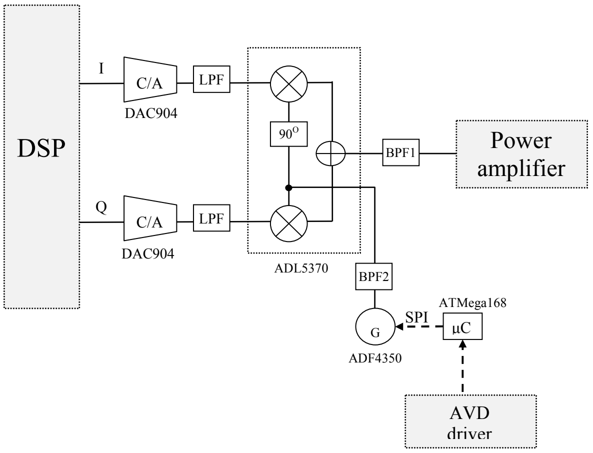


Figure 3. Block diagram of the RF transmitter

AVD transmitter was carried out according to the flowchart shown in Figure 3. The input of the device are the two paths I and Q in the form of 14-bit parallel bus. These buses are used for sending samples of I and Q components of the OFDM signal generated by the DSP block. The digital signals are converted into analog signals using digital to analog converters (DAC). These converters, Analog Devices AD9772A [5] are characterized by the achievable processing speed of not less than 150 MSPS (million samples per second), which is the value which gives the analog signal with bandwidth wider than expected width of the channel (8 MHz ). Important quality of those converters is built in 2x interpolation filter, allowing for oversampling in time domain. Oversampling is essential for generating OFDM signal with good spectral characteristics. Most importantly, it allows for filters of lesser order to be used.

Analog signals generated at the output of the transducers are subjected to low-pass filter with two identical low-pass filters (LPF) with a bandwidth corresponding to the width of the channel. Obtained in this way signals are given to the input I and Q quadrature mixer (ADL5370 module [6]). The mixer output signal is subjected to filtration (BPF1) deleting the out-of-band mixing products, and passed to the amplifier block.

As a carrier wave generator (G), a module ADF4350 [7] has been used. This generator characterizes with a compact design, in which is integrated controller PLL loop and VCO generator in order to significantly simplifying the design of the transmitter. Choosing the carrier frequency is possible by appropriate programming of the generator, which is done via SPI compatible interface. Produced signal is characterized by a low phase noise and a significant level of harmonics. In order to remove harmonic products, there was used the bandpass filter at the output of generator (BPF2).

For described above transmission path there is a microprocessor controller (µC) assigned, developed on ATmega168 microcontroller [8] on the board LO-TV-AS-P. Its task is programming of the ADF4350 generator according to the instructions coming from the controller. This solution increases the flexibility of the structure of the transmitter. It allows for moving the issue of track configuration the programmable electronic components to a higher level of abstraction, allowing the driver software does not need to take into account the structural details, and only care about the fulfillment of functional requirements. An additional advantage of this approach is that the AVD controller software will not require any changes to modify the transmission track construction are not due to expansion of functionality, but made for example, to upgrade the transmitter or the optimization of its parameters.

### 3.4 *TCTM subsystem*

The aim of the TCTM subsystem is to enable the transmission of the control signals to robots and telemetry data from robots to the operators and command centre. The transmitted data are relatively low bit rates. The main task of this subsystem is to ensure the control of mobile robots by operators via the operator console, or directly from MROC. This system is also responsible for the transmission of telemetry data from sensors placed on the robots.

As for basic parameters of the planned system, it was decided to use Ethernet 100Mb / s (RJ45). The system should be able to provide telemetry data transmission and control with bit rate 20kbit/s obtaining ranges analogous to the ranges of video transmission system. Transmission system operates in the ISM band (use of radio equipment in the band freed does not require a radio license). The required standard 128bit AES encryption, the keys are provided by the control unit.

For the purpose of the control and telemetry system there has been selected range of 863-870 MHz In this range radio equipment can operate with power 25 mW erp , the only exception is the subrange 869.40 - 869.65 MHz where the equipment is authorized to work with the power of up to 500mW. It should be noted that these frequency ranges are also intended for ISM equipment. Devices operating in this band must accept harmful interference which may be caused by ISM equipment and other radio devices.

In view of the determined requirements for the subsystem TCTM there were analyzed available on the market and currently developed technical solutions for their fulfillment.

Controlling of the module and using the interfaces is based on the ARM microprocessor. Due to use the Ethernet, USB and possible CAN interfaces there has been chosen microprocessor with built-in support for these peripheral interfaces. In addition, due to the large amount of software needed to support AES encryption, a module with hardware implementation of the encryption has been used. The required transmission speed is slow , so there is possible to use an ARM7 processor architecture with reduced to 48MHz. The processors in the ARM 7 architecture are now widely available from many manufacturers, including minimization of dimensions of the application allows control unit, minimization of power consumption and portability of the code in case of need for faster systems.

RF part used in the system should allow a change in a wide frequency band. In addition, radio structures should be capable of regulating flow rate and provide high sensitivity at low bit rates. It was also recommended the use of mass-produced solutions, thus ensuring repeatability of technical parameters and reduce the costs of modifications. For the project there have been proposed two sets of radio modules, one of which offers acceptable parameters of radio and the ability to configure high-speed transmission and frequency range. The second of the selected systems are characterized by very good radio parameters, however, limited possibilities of changing the frequency of the system.

Because of the complexity of the system there was assumed a modular approach to the selection of the target architecture that allows independent design, selection of manufacturing technology, measurement and testing. At any point it can easily be changed in each system module. This solution will also simplify the process of service in the future. Below general architecture of telemetry and control system includes functional blocks of the modules is presented. Operation of the subsystem is as follows

Transport stream is sent over Ethernet network to the selected port of the TCTM system. The system is performed an optional the TCTM encryption the data stream, division of data, addition of redundant code enabling correction of corrupted data after the radio transmission path. The prepared data to are transmitted radio circuit. For the higher-level module the transmission is transparent and the TCTM module only causes a delay, which should not exceed 20ms.

Due to the additional protection time and data redundant minimum bit rate for a single radio channel should not be less than 100kb / s. Another pair of systems the TCTM work in radio channels that will enable ensuring adequate frequency separation.

Ensuring proper synchronization of time slots for the transmission of individual packets between pairs of the TCTM can be possible with use of the radio transmission or via an external sync signal from eg GPS.

Single and narrow band of operation possible for use by the TCTM module makes it impossible to use frequency duplex (FDD). It is necessary to use time-division duplex and the work of individual pairs of units in alternating time slots.

### 3.5 *Antenna system for the airplane*

One of the very important elements of the communication system dedicated for exchanging information between an UAV and the operator is the antenna system. The antenna system for airplane consists of two antennas, each for other communication subsystem. Due to constructional reasons the antennas might be mounted on the fuselage, whereas the wings are destined for fuel tanks [9]. The antennas are situated in the lower part of the fuselage, as it is depicted in Figure 4.

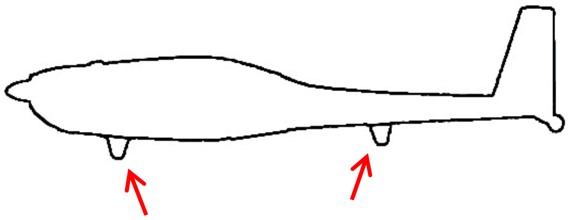

Figure 4. Placement of antennas under the fuselage [9]

The antennas are enclosed in glass-epoxy laminate housings, having form of keel. This ensures protection of the antenna from mechanical and environmental risks. Electrical properties of the housing material have been verified at system operating frequencies. The permittivity of the material is in the range 4.16 ÷ 4.33, and the loss tangent is approx. $1.1 \bullet 10^{-2}$.

The monopole antenna design with extended frequency band has been chosen for the communication system on the airplane. The monopole antenna requires conducting ground plane to operate properly and thus the inner side of airplane's sheathing has to be metalized in the part neighboring to the antenna. The metallization also improves electromagnetic shielding between the antenna and the airplane's equipment.

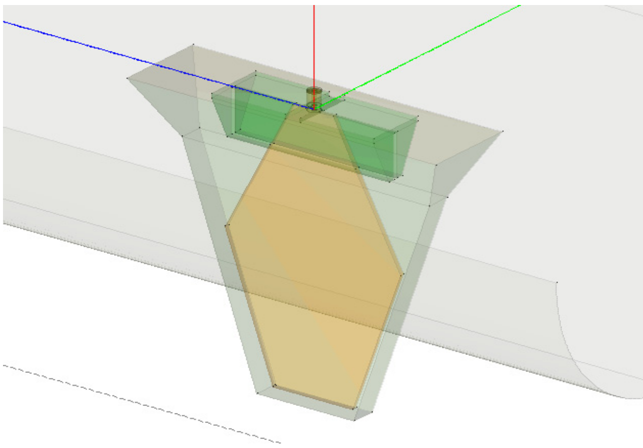

Figure 5. Mechanical construction of the antenna. [9]

In order to obtain the extended frequency band the monopole antenna has a form of fin, which is also streamlined. Figure 5 presents construction of radiating element of the antenna. It is supported with a special elements providing mechanical stability.

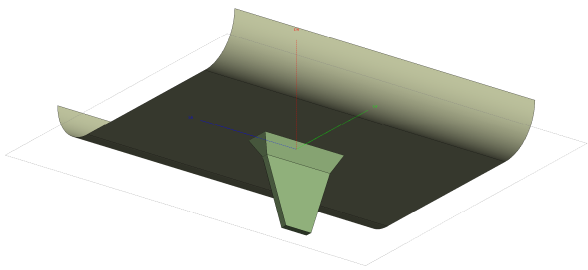

Figure 6. Simulation model of the antenna [9]

The antenna performance has been tested using electromagnetic simulator, namely FEKO software [10]. Figure 6 presents the simulated antenna model, comprising the radiating elements and its mechanical support, the housing and the grounded part of sheathing. The antenna is fed via SMA junction. Simulations have been also employed to optimize the reflection coefficient characteristic. After the design process the antenna has been manufactured and its characteristics have been verified experimentally.

Results of simulation, obtained with the Method of Moments implemented in FEKO software [10], are given in Figures 7-8. The reflection coefficient presented in Fig. 7 is compared with measurement results. Excellent agreement may be observed. Fig. 8 presents 3-dimensional view of the radiation pattern. The radiation is omnidirectional, which is typical for the monopole antenna. The ground plane causes slight deflection of the beam to the bottom, being beneficial for this application.

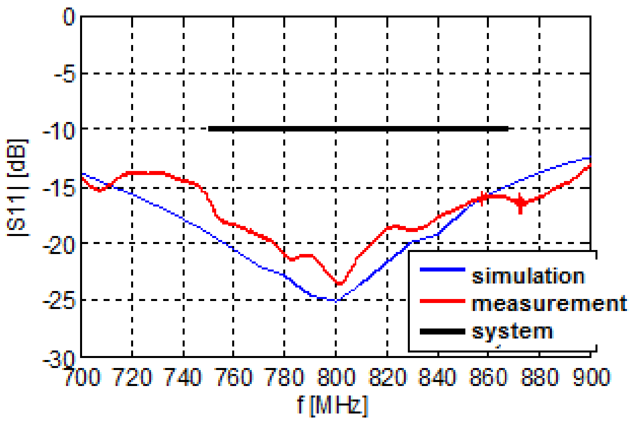


Figure 7. Reflection coefficient of the antenna

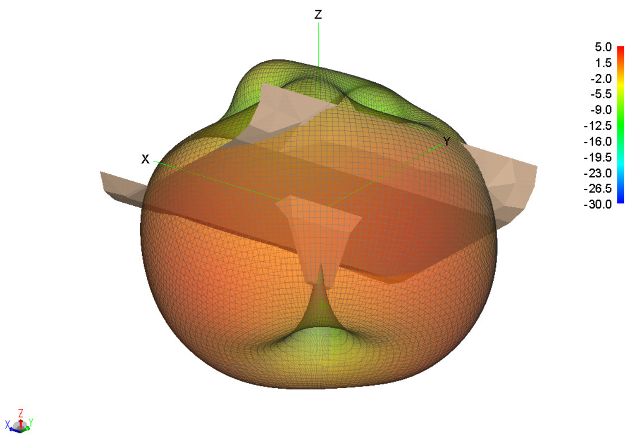


Figure 8. Radiation pattern of the antenna (dBi). [9]

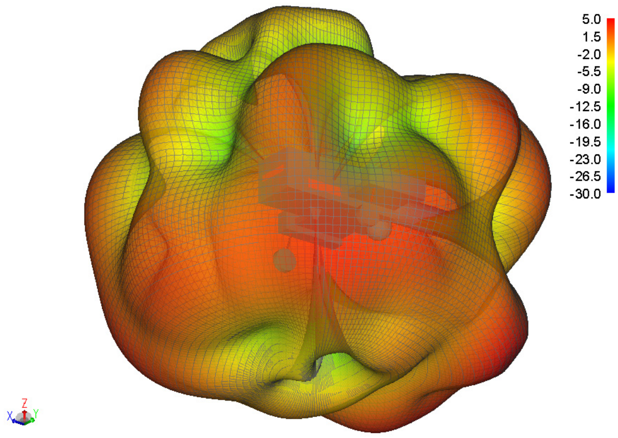


Figure 9.Radiation pattern of the antenna placed on the airplane. [9]

In real scenario the radiation pattern is distorted by particular components of airplane, thus the radiation intensity is not equally distributed in all directions. Further simulations have been conducted in order to determine expected typical deviation of the radiation intensity. The antenna model has been combined with simplified model of the airplane and simulated in such arrangement.

The obtained radiation pattern is presented in Fig. 9. It can be observed that the radiation pattern is remarkably deformed. The result is obviously solely the example of possible distortions. The final radiation pattern depends on airplane's equipment and details of construction. However the simulation results of the antenna operating on the model of airplane allow determine that typical deviation amplitude is less than 5 dB. Therefore, under the assumption that the maximum airplane's tilt is less than 30°, the communication link is ensured for all positions of airplane. The possible fading during airplane's maneuvers is expected to be temporary and having insignificant meaning for the communication system.

## 4 SUMMARY

In the paper the concept and realization of the integrated system for unmanned flying vehicle's communication is presented. The system consists of two integrated solution – unidirectional broadcast transmission of video, audio and data from mobile robots to the operators and two-way communication with the telemetry and control subsystem. The systems are integrated within the single chassis and placed on the mobile robot to ensure proper operation of the mobile robot. The specific elements of the system were presented as well as main requirements and connected with them development methods were also discussed.

The work is related to both the latest developments in multimedia techniques (efficient hardware implementations of source encoders and data multiplexing mechanisms) as well as with issues of radiocommunication (channel encoding, antenna systems). Within the project there are different components created using the advantages of different types of networks (DVB-T / H broadcast systems, radio networks, data transmission systems, telecommunication systems) for specific tasks and functionalities.

## ACKNOWLEDGEMENT

The work is a part of the project "Integrated mobile system for counterterrorism and rescue operations", co-financed by the European Regional Development Fund within the framework of the 1. priority axis of the Innovative Economy Operational Programme, 2007-2013, submeasure 1.1.2 "Strategic R&D Research". Contract no. POIG.01.02.01-00-014/08.

## REFERENCES

[1] Proteus Project homepage, http://www.projektproteus.pl
[2] T. Keller, A.Kurek, K. Kurek, J. Modelski, M. Piasecki, G. Pastuszak, R. Szumny, K. Bryłka, „Wireless communications and TV monitoring systems in the PROTEUS project", Przegląd Telekomunikacyjny i Wiadomości Telekomunikacyjne, nr 12/2010 („Systemy łączności radiowej i monitoringu telewizyjnego w projekcie PROTEUS", in polish language).
[3] ETSI 2009, ETSI EN 300 744 v 1.6.1 Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for digital terrestrial television
[4] M. Darmetko, M. Klocek, B. Majewski, K. Kurek, T. Keller, M. Piasecki, „Realization of the Digital signal processing block of the DVB-T transmitter with use of FPGA structures", Przegląd Telekomunikacyjny i Wiadomości Telekomunikacyjne, nr 6/2011 („Realizacja toru cyfrowego przetwarzania sygnału dla nadajnika DVB-T w strukturze FPGA", in polish language).
[5] Analog 2008a, http://www.analog.com/static/imported-files/data_sheets/AD9772A.pdf
[6] Analog 2006, http://www.analog.com/static/imported-files/data_sheets/ADL5370.pdf
[7] Analog 2008b, http://www.analog.com/static/imported-files/data_sheets/ADF4350.pdf
[8] Atmel 2011, http://www.atmel.com/dyn/resources/prod_documents/doc2545.pdf
[9] P. Bajurko, Y. Yashchyshyn, "The DVB Antenna for Un-manned Plane Destined for Remote Monitoring", Przegląd Telekomunikacyjny i Wiadomości Telekomunikacyjne, nr 6/2010, pp. 604-607 („Antena do transmisji sygnału DVB z samolotu bezzałogowego przeznaczonego do celów zdalnego monitorowania", in polish language).
[10] U. Jakobus, M. Bingle, M. Schoeman, J. J. van Tonder, F. Illenseer, "Tailoring FEKO for micro-wave problems", Mi-crowave Magazine, IEEE, December 2008, pp. 76-85.