Unmanned Aerial System Architecture for Maritime Missions. Design & Hardware Description

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***Abstract*—The growing interest in Unmanned Aerial Systems (UAS) research, alongside with increasingly affordable hardware, creates great opportunity for research facilities to compare algorithms and simulation results with applied in-flight performance. However, developing the necessary equipment for such endeavour requires significant effort, often beyond available resources and the main research focus. As a solution, a system architecture for enabling advanced experiments is presented, allowing researchers to reduce the amount of required effort in developing a UAS. The proposed architecture is compatible with current state-of-the-art research facilities and standards, promoting an increased cooperation between experts in the field. The capabilities of the presented setup have evolved and been verified during intensive field experiments over the past two years, considering various algorithms and distinct equipment. This paper provides a detailed description of both the architecture and implementation details, such as the used hardware and software, being therefore a potential reference for the research community and for facilities planning the development of their own UAS.**

I. Introduction

Unmanned Aerial Systems (UAS) became a popular subject of research in recent years. Currently available publications describe UAS architectures with different levels of details. Some authors focus on general description of a system [21] while other focus more on details of a platform design and used hardware [9]. Other available works elaborates multi- Unmanned Air Vehicles (UAVs) software and simulation architecture [13], avionics [19], or software architecture [25]. Often a full system design and practical performance verification is provided in papers discussing experiments results (i.e. [12], [26], [27].

Unfortunately, a number of UAS is developed by academic community only for the purpose of internal work, and only a few systems were created specifically for maritime environment research [11]. On the other hand Unmanned Aerial Vehicles cooperating with other vehicles under one system proved its value for ocean research [14].

For this reason, an UAS architecture compatible with other research facilities standards, that can be easily applied by departments planing to build and perform experiments with their own Unmanned Aerial Systems, can increase researchers cooperation and knowledge sharing process.

One of the key aspects of the successful UAS is a mechanism of easy integration of existing and future technologies. The system should provide stable and well defined foundations, so newcomer researchers could quickly familiarize with the setup. At the same time, the platform should be low cost, based on easily accessible hardware and software, still supporting sophisticated operations and functions. It should also satisfy safety requirements. This imply system modularity, scalability and flexibility.

The architecture described in this paper fulfills the mentioned needs, therefore it can both provide other research facilities a head start and contribute to the overall increase of knowledge in the UAS discipline. The defined setup allows scientists to focus on the main goal of their project - which is often practical verification of simulation results, or acquisition of payload sensor data - instead, expediting development and tests.

In addition the architecture is compatible with the LSTS Toolchain – a flexible and scalable, open-source software, supporting integration and control of various types of unmanned vehicles [22]. Thanks to that, the system can be easily integrated with technologies used at other research facilities that use the same standard, i.e. researchers groups at University of Porto, and the Norwegian University of Science and Technology. Additionally, users gain access to advanced tools, often used in projects, i.e. data analysis tools with charting and export to Matlab files.

The development of the presented system required experience in various disciplines including computer science, electronics, aerodynamics and mechanics, as well as investment of time and resources. The setup is the result of two years of work and number of intensive field tests in various research areas, examples are:

- a light-weight thermal camera payload with georeferencing capabilities that automatically detect and track object on the ocean surface [17] [18]
- UAV integration with an anti-icing and de-icing nanomaterial-based wing temperature control system [24] which aim is to allow flight in harsh weather conditions
- prototype autonomous net recovery landing system using RTK GPS [23] and deep-stall landing [20]

- data acquisition and signal relaying experiments of Floating Wireless Sensor Node [10]
- relay communication between Autonomous Underwater Vehicle (AUV) HYDROID REMUS 100 and its Ground Control Station using UAV [16].

The paper provides a detailed hardware and functional description of all UAS components. Section II of the paper provides overview of the proposed system architecture. In sections III each module is described with more technical details. Additionally, section III-D includes a table of technologies used in the presented solution.

II. System architecture overview

The components of the presented architecture are grouped into segments with respect to their function. These are:

A. Unmanned Aerial Vehicle
B. Ground Segment
C. Radio-communication

Unmanned Aerial Vehicle and Ground Segment are physically separated groups, while Radio-communication segment overlaps communication equipment of both. The diagram of the architecture is shown on Figure 1.

A. Unmanned Aerial Vehicle

The Unmanned Aerial Vehicle consist of following modules:

- Airframe – mechanics of the aircraft
- Flight Management System (FMS)
- Payload – custom module

1) Airframe: Development of an aerial vehicle for research in the discipline of unmanned aviation – often incorporating learning process of students and researchers – puts multiple counterbalanced requirements on the airframe selection. On one hand, in order to perform a variety of advanced scenarios, the plane needs to be modern and agile. On the other hand, operational and maintenance cost (including repair) should be as low as possible. An airframe should be selected according to researchers' needs. Parameters, such as aerodynamic configuration, size, Maximum Take-Off Mass, or propulsion has to be defined with respect to planned use scenarios.

2) Flight Management System: The idea behind a Flight Management System (FMS) is to gather into a standalone device core electronic components, necessary to perform safe, automatic flight. The FMS module is designed to be the same in all planes. This speeds up aircraft production process and tests, as well as it supports safe integration of researchers modules into the UAV. Key elements of the unit are an autopilot, elementary sensors and actuators. Additionally, the module includes radio equipment and Power Management Unit. The airframe and the FMS together allow to perform both remotely controlled, and automatic flight.

3) Payload: A Payload is researchers' main point of focus and is custom made for every project. It incorporates sensors, actuators, peripherals, and a processor unit selected for the experiment. The Payload should also be equipped with an independent power supply. The module joins onboard equipment necessary to perform experiments, but not required to perform a safe, automatic flight. In case of malfunction, this module does not influence flight safety and can be turned off by a Crew.

B. Ground Segment

The Ground Segment gathers all elements required to perform flight of aerial vehicle, while not being part of the aircraft itself. Key groups of this segment are:

- Crew – a group of people involved in UAV operation
- Control Station – computers used to control vehicles and process aircraft data
- Antenna System – set of devices enabling radio-communication with the plane
- Standalone Radio Equipment – radio equipment used directly by the VLOS Pilot and the Operator
- Accessories – equipment not directly involved in UAV flight, but required to perform it

1) Crew: The Crew structure, positions and responsibilities depend on a local Civil Aviation Authority (CAA) regulations, specific to each country. For example in Norway UAV flight can be performed under few categories, with different regulatory limits [4]:

- VLOS – Visual Line of Sight, where pilot keeps direct unaided visual contact with plane, and altitude is lower than 400 feet.
- E-VLOS – where altitude can exceed 400 feet and/or flight outside pilots visual line of sight, normally requiring additional observers.
- Beyond LOS – where no unaided visual contact is kept neither by pilot nor observer. Description of BLOS operations can be found in [15].
  - BVLOS – the same criteria as BLOS.
  - BRLOS – Beyond Radio Line of Sight, where there is no direct telecommunication link between plane and control station, but third party communication infrastructure is used.

According to these regulation as well as to practical matters, the proposed system is controlled by at least two people. A Remotely Piloted Aircraft System Operator and a Visual Line of Sight Pilot (VLOS Pilot). Additionally the Crew can be extended by a member called User. Regarding hierarchy, the Operator can be considered as Pilot-In-Command (PIC) while the VLOS Pilot is Second-In-Command (SIC).

The Operator's role is to monitor and control flight, as well as to detect and react on emergency/abnormal situations. In general he defines and modifies flight plan to reach mission objectives. Additionally, the Operator keeps communication with the rest of the Crew, Air Traffic Control (ATC) and other airspace users. Prior to take-off, the Operator does checklist, tests elements of Ground Segment (i.e. Control Station, power generators), tests Radio-communication, Flight Management System and Payload proper work. Moreover, the Operator is responsible for filling out a logbook after flights.

The VLOS Pilot's main responsibility is to manually control the vehicle during certain flight phases, i.e. catapult take-off and landing. Additionally, he takes control in emergency/abnormal situations if the vehicle is within VLOS. Prior to take-off the Pilot prepares and inspects structure assembly, battery state, sensors and actuators. Moreover, he tests some elements of the Ground Segment (i.e. catapult launcher, RC transmitter) and verifies if weather conditions are within safety margins. After take-off, he performs in-flight checks and gives permission to enter automatic flight. At the end of the mission pilot lands the plane and consequently secures and checks it after flight.

Last but not least member of a crew is the User. Position can be represented by multiple people, usually researchers. Users goal is often to monitor/operate the Payload during UAV flight. In some scenarios, the User can get access to plane controls via the Payload, i.e. when testing new navigation algorithms. The system architecture provides such functionality, however it can be used only if the Operator and the VLOS Pilot were notified and can instantly regain control over the aircraft.

2) Control Station: The Control Station is used by the Crew to control the UAV and its Payload. Its elements are:

- UAV Operator Station – computers used by the Operator to control the Flight Management System
- User Station – computers used by the User to monitor/control the Payload
- Network Router – used to connect the Ground Segment and the Radio-communication Segment together

Computers have installed and configured a Command and Control (C2) software compatible with the FMS and the Payload. The Operator Station enables monitoring, and provides direct control over all flight parameters, such as flight plan, speed, or altitude. On the other hand the User Station software functions depends fully on the Payload setup and capabilities.

3) Antenna System: The Antenna System is used by the Operator and the User to communicate with the plane. It consists of two units:

- Antenna Pan-Tilt Unit (PTU) – a device positioning a directional antenna
- PTU Controller – a controller of the Antenna PTU

The Antenna PTU is necessary to extend range of a high-throughput, Super High Frequency, data-link, that required Line-of-Sight (LOS) between transceivers antennas. The PTU

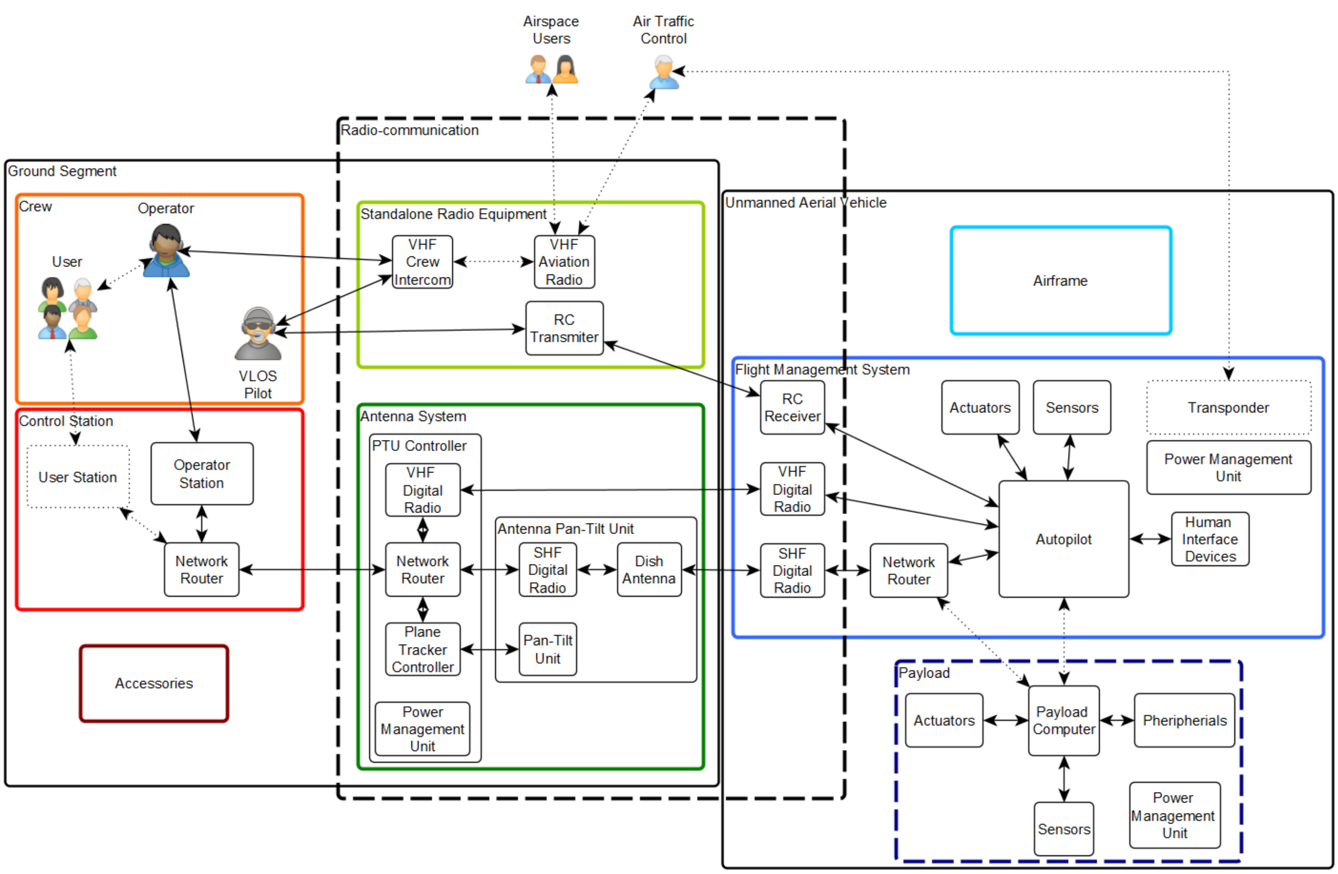


Fig. 1: System Architecture Diagram (dotted line – optional connection/element)

can rotate in pan and tilt axes and is aiming the dedicated dish antenna in the direction of the aerial vehicle. The Antenna PTU requires special controller – a separate module, calculating desired motion and position of the PTU, and powering the unit. Additionally, the PTU Controller has built in a long-range VHF Digital Radio, and provides the interface between the Antenna System and the Control Station.

4) Standalone Radio Equipment: The Standalone Radio Equipment includes radios used directly by the VLOS Pilot and the Operator. Main element of the group is a RC transmitter used by the VLOS Pilot to manually control the aircraft. Additionally, the group includes a crew intercom and transmitters necessary to contact with Air Traffic Control and other airspace users over voice.

5) Accessories: Other devices, not directly involved in UAV operations, but necessary to perform it, are marked as Accessories. This group includes elements such as: UAV catapult launcher, power generators, battery chargers, or transport cases.

C. Radio-communication

The Radio-communication group of the presented architecture is overlapping both the Ground and the UAV segment elements. It provides multiple communication channels for the vehicle control and monitoring, the Payload data transfer, as well as for the voice communication between the Crew, the ATC and other airspace users. These channels are:

- Voice intercom – providing communication between the Operator and the VLOS Pilot
- Aviation radio – enabling the Operator voice communication with the Air Traffic Control (ATC) and other airspace users
- Short-range manual Remote Control – used by the VLOS Pilot to manually control the plane
- High-speed, middle-range, digital data/telemetry radio – providing high-data-rate radio link for data transmission
- Low-speed, long-range, digital telemetry radio – used to control the autopilot over a long distance (BLOS)

Field tests have shown that the Operator and the VLOS Pilot are often in a significant distance from each other, and unaided voice communication is not possible. The problem is especially visible in the take-off phase, when the airplane engine noise can drown out Pilot's voice. To secure safe and reliable communication both the VLOS Pilot and the Operator are equipped with a dedicated headset of the wireless voice intercom. Additionally, the intercom can be integrated with the aviation radio that is required during flights in most of airspace classes. It provides contact with Air Traffic Control (ATC) and other aircraft in the vicinity.

To control the plane when automatic flight is disengaged the VLOS Pilot uses the manual Remote Controller (RC). Its range covers the distance over which no-aided, visual control of the plane is still possible.

For the bidirectional transmission of the Payload and the FMS data, the UAV system should be equipped with primary, middle range (several kilometers) radio-link. In addition, the long-range, low-speed radio-link should be used for safety reasons. The secondary communication channel is providing direct data transmission between the autopilot and the Ground Segment. It is used in case of the primary data-link connection lost or malfunction.

D. Failure modes

Each component of the entire system might experience an in-flight malfunction. Therefore an analysis of failure modes is an important aspect of the system description. The core idea of the presented architecture is to separate flight critical elements (the FMS) from the Payload. The payload malfunction should not influence flight safety, although it may reduce scientific value of the flight. To increase the FMS reliability, the module is equipped with redundant autopilot access channels, and the autopilot itself provides multiple failsafe procedures.

The single-points-of-failure of the system are: power supply, the autopilot including embedded and airspeed sensors, the control surface actuators and the propulsion.

The power supply reliability is the key aspect influencing the flight safety. The presented solution bases entirely on batteries providing power to every system component. For this reason separate battery packs for the FMS and the Payload should be used. Such configuration reduces probability of the FMS failure in case of the Payload electric malfunction (i.e. short circuit, abnormal energy consumption).

The autopilot is equipped with a number of failsafe functions, therefore failure of the remaining FMS components may influence the mission scenario, but should not lead to uncontrolled flight termination. The primary autopilot failsafe mechanism bases on Return-to-Launch-point action (RTL). The autopilot is able to detect loss of: the RC signal, the Command & Control software telemetry, or the GPS signal [2]. Moreover, the basic failsafe mode can be triggered by low battery voltage or by the total-used-energy-meter embedded in the autopilot.

In addition, a geofence function can be used as well [3]. The geofence defines the area that plane must not leave during the flight. If the border is reached, planes turns back to the predefined return location.

The autopilot is also equipped with an Advanced Failsafe (AFS) [1]. It enables automatic flight termination, so the plane is forced to enter spin and crash. The mode can be triggered manually by the Operator or set up to be executed when one of the following events occurs:

- Geofence breach
- Maximum pressure altitude breach
- GPS loss combined with the Ground Control Station communication loss ("Dual loss")
- RC loss

From the operational perspective the autopilot failsafe modes are dedicated mostly for the BLOS flights. If a malfunction occurs during the VLOS operations, the Pilot takes manual control over the UAV using the RC channel. Still, the RC communication might fail as well. If the RC receiver detects such event, the autopilot can be configured to guide the UAV to the launch point.

To provide the control and the communication redundancy, the Crew can access the autopilot functions using various communication chains. These are summarized on Figure 2.

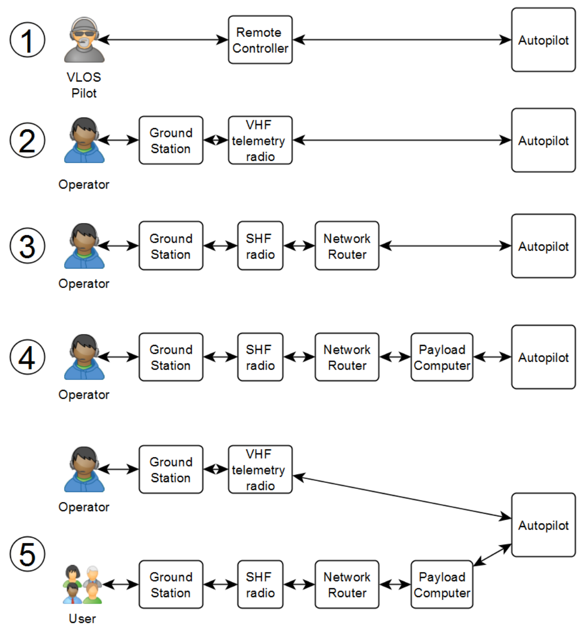


Fig. 2: Autopilot access chain diagram

The case ① shows the mentioned VLOS Pilot manual control over the UAV. This is the core mechanism of controlling the aircraft but its use is limited to VLOS flights.

The Operator can use multiple communication channel to control the plane. At the same time a set of redundant chains ② & ③, or ② & ④ can be used. In case of chains ② & ③ the Operator is keeping control over the autopilot using autopilot standard Command & Control software. The case ② shows use of the long-range radio which is directly connected to the autopilot, while the case ③ uses SHF datalink.

If the Operator wish to use the LSTS Toolchain in addition to standard C2 software, the system can be configured to use set ② & ④. Control chain ② still uses standard autopilot Command & Control to operate the UAV. While in ④ the Operator uses the LSTS Toolchain C2 software. Both solutions can run at the same time, however the Operator has to pay attention as both software can overwrite each other commands. Similarly, the case ⑤ shows combined operation of the Operator and the User.The Operator uses ② and autopilot standard Communication & Control software, while the User uses the communication chain ④ and the LSTS Toolchain. Both have access to the autopilot functions at the same time and can overwrite each other commands. For this reason proper crew communication is crucial.

To reduce in-flight risk, a dedicated set of manuals and checklist has been created basing on user experience and known best practices, describing possible in-flight events, the crew members responsibilities and actions. The documents has been approved by the CAA and are used during all UAV operations. Before each flight the proper operation of all system components must be verified with respect to the preflight checklist. Similarly, the Crew can switch from the manual to the automatic flight mode only if the in-flight test performed at the beginning of the flight were successful. While the aircraft is performing automatic flight, the Crew constantly monitors the UAV behaviour and react on any unexpected event according to the manual.

Additionally, every system may experience phenomena that can affect all electronic components work. A good practices of a hardware design should be applied to minimize the negative effects of interference, vibrations, temperature and humidity/water ingress.

The interference impact can be reduced by careful selection of radio/transmission frequencies and use of shielded data-wires. Vibrations can affect the Inertial Measurement Unit readings and cause mechanical damage of connectors. Both components sensitive to vibration as well as elements causing them should be attached to the aircraft structure using dumpers. Too high or too low temperature may cause modules malfunction, shutdown or even permanent damage. Therefor appropriate cooling airflow, radiators or heaters shall be considered in the design. Finally, protection against the humidity/water ingress can be additional coating layer of electronic components or sealed casing, however such solution may influence heat dissipation properties.

Last but not least, a mechanism of turning off non-flight critical components (i.e. relays cutting power, fuses) should be applied in the system to increase overall system safety.

III. Hardware Description

The components of the presented architecture have been selected and tested over a period of two years of intensive field experiments. This section provides detailed description of all key elements in the same order in which they were introduced in section II.

A. Unmanned Aerial Vehicle

The presented architecture can be applied to various aircraft, however paper focuses on UAVs based on a Skywalker X8 airframe (Fig. 3).

Fig. 3: Skywalker X8 based UAV in flight

1) Airframe: The X8 is a Do-It-Yourself type flying-wing. The plane Maximum Take-Off Weight is 4.2 kg, including 1 kg for the Payload. The Skywalker cruise speed is 18 m/s and the flight endurance is between 45 and 60 minutes. Additionally, the aircraft has small take-off/landing sites requirement, can take-off from a catapult launcher and land in a net. Construction of the X8 provides great flexibility both in terms of the mechanical customisation and equipment integration. The airframe is made out of an Expanded Polyolefin foam (EPO), which offers easy customization and repair, and high durability. All these makes it the perfect vehicle for experimental projects with modest requirements.

2) Flight Management System: The Flight Management System module (Fig. 4b) should be common to all aircraft and be possible to be quickly replaced when needed. The FMS consist of the autopilot with its peripherals, communication assets and the power management unit.

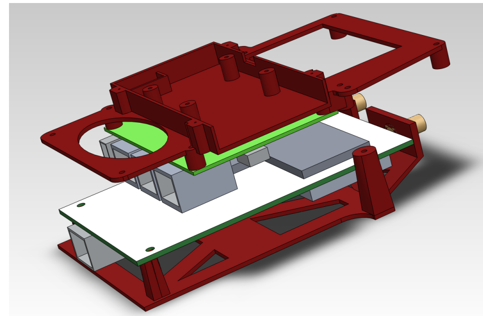
The autopilot is the central element of the FMS. In this role a 3DR Pixhawk with an ArduPilot ArduPlane software is used. The ArduPlane uses a MAVlink telemetry protocol, therefore it is compatible with the LSTS Toolchain. The 3DR Pixhawk is based on the 168MHz, 32-bit ARM Cortex M4 core with a FPU [6]. Additionally, it is equipped with a 32-bit failsafe co-processor. The device provides dedicated connector for Remote Controller and 3 input/output telemetry ports (2x UART TTL, 1x USB). The autopilot has a built-in IMU and barometric sensors. In addition a 3DR Pixhawk dedicated GPS with compass, and airspeed sensors are installed in the appropriate areas of the airframe. The Pixhawk Human Interface Devices (HID) enable the Pilot to activate/deactivate propulsion (button on fuselage), and inform about plane status (LED, buzzer). Aircraft control surfaces and propulsion are driven by autopilot PWM outputs. Actuators are RC servomechanisms HiTec HS-5125MG, while the plane propulsion is an electric, BLDC, Hacker A40 motor, driven by the Jeti MASTER SPIN 66 PRO Engine Control Unit (ECU). Still, servos, the motor and the ECU should be selected according to the user preferences, and the airframe type.

During some experiments, the Payload Computer may need access to the autopilot telemetry data - i.e. to register sensor readings, or actively modify the flight plan to reach mission objectives. It can be done twofold. First option is to connect the Payload Computer directly to the telemetry port of the autopilot. Second way is to connect the Payload Computer using the Ethernet interface with the Network Router of the FMS. The Network Routers, equipped with USB-to-UART adapter and dedicated software, converts the Pixhawk telemetry serial port making it accessible via a network socket.

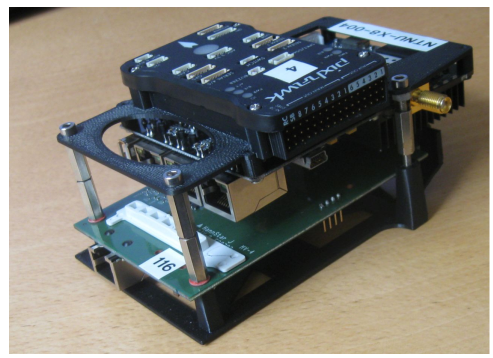
The Power Management Unit is a set of voltage regulators and DC-DC converters providing power supply to all FMS components. A power source is a Lithium-Polymer (Li-Pol) 14.8V, 10Ah battery.

Another important part of the FMS is radio equipment that enables communication with the Ground Segment. All radio-communication units are described with more details in section III-C.

To keep all elements together, and enable easy replacement of the module, components are placed on a dedicated 3D printed assembly (Fig. 4a).



(a) CAD drawing



(b) Built device

Fig. 4: Flight Management System

3) Payload: The Payload is meant to be custom made for every project. Although its modules vary depending on experiment objectives, some unification in terms of the Payload Computer is beneficial. A common central unit reduces time needed to prepare and configure the operating system and the software. An example of the Payload Computer can be a BeagleBone Black (BBB) Single Board PC (SBPC). It provides sufficient computation power, low energy consumption and variety of communication interfaces. BBB can run various operating system including Debian, Ubuntu, Android. In addition, its architecture is compatible with the LSTS software Toolchain mentioned earlier in this paper.

The board is based on an AM335x, 1GHz ARM Cortex-A8 processor, with a NOEN floating-point accelerator and two 32-bit Programmable Real-Time Units (PRU) microcontrollers. The BBB offers 512MB RAM and 4GB on-board flash storage. The unit provides multiple interfaces: USB host 2.0, Ethernet, 4x UART, 8x PWM, LCD, GPMC, MMC1, 2x SPI, 2x I2C, A/D Converter, and 2xCAN Bus. To speed up the process of hardware integration and make access to BBB interfaces easier an extension board called ”CAPE” has been developed. It defines connectors and wiring standards for all projects, and extends BBB functions with additional components (i.e. Real-Time clock, more powerful voltage regulator). Of course, the BeagleBone Black is not the only solution suitable for the Payload Computer role. In some experiments a PandaBoard [17] or an Arduino Uno R3 [24] were used in this role.

B. Ground Segment

In terms of the compatibility with the presented architecture, the Ground Segment hardware choice is very flexible. Some of the components can be replaced by less powerful and more affordable solutions (i.e. fully rugged PCs, or high-end Pan-Tilt Unit). This section presents the reference hardware used during UAV operations, which can be modified according to user needs.

1) Control Station: The UAV Operator Station is a Dell Latitude 14 Rugged Extreme (7404) PC running Ubuntu 14.04LTS or Windows 7 operating system. It has installed and configured an autopilot control software: ArduPilot community Mission Planner and APM Planner 2.0, used to directly control the Pixhawk autopilot. In addition it is equipped with a LSTS Neptus Command & Control software being part of the LSTS Toolchain. Depending on mission objectives and the Payload configuration, the Operator can chose which software is going to be used during flight.

The User Station configuration depends on the on-board equipment and flight scenario. In most cases this role is covered by a PC running Linux operating system, with the LSTS Neptus installed. The software provides the Payload control, data collection and analysis mechanisms. However, in some cases, when the Payload is not using the LSTS Toolchain, other control software can be used.

2) Antenna System: The Antenna PTU is a FLIR D300E unit is positioning dish antenna, providing long-range, high-bandwidth data-link (Fig. 5a). To track the aircraft, the GPS positions of both Antenna PTU Unit and vehicle are required. The GPS position of the aircraft is delivered with the autopilot telemetry over radio-link. The D300E provides unlimited horizontal and limited vertical rotation. The device can handle load of 32kg, and reach speed of 100°/sec. The PTU is placed on a Manfrotto M528XB heavy-duty tripod with a custom made mechanical adapter.

The PTU Controller is a separate box with custom electronics, controlling and powering the Antenna PTU Unit (Fig. 5b). The device provides an interface between the Antenna System and Ground Station. Additionally, the VHF Digital Radio can be placed inside this unit.

(a) Antenna PTU Unit

(b) PTU Controller

Fig. 5: Antenna System

C. Radio-communication

The Radio-communication segment include communication equipment of both the Ground and the UAV segments. These equipment includes technologies used for voice communication, remote control of the vehicle and digital data transceivers.

1) Voice communication: To provide safe and reliable communication of the Crew, a David Clark EMS wireless intercom system is used. The VLOS Pilot is equipped with a H9941 single-ear headset, while the Operator uses a H9940 unit. Transmitters are U9910-BSW belt stations, and a U9920-G38 provides a gateway node service. The VLOS Pilot need to use both hands for plane control, therefore transmission is activated using VOX mechanism.

Intercom can be integrated with aviation radio, providing contact with Air Traffic Control (ATC) and other air traffic in the vicinity. It is important to note that use of aeronautical voice communication frequencies (118 136.975 MHz) may require operators license.

2) Remote Control: For the Pixhawk autopilot few RC solutions are recommended [6], namely:

- FrSky ACCST
- Graupner HOTT
- Futaba/Robbe FASST/RASST
- Spektrum and DSM Compatible Receivers

Basing on available devices functionality and price, as well as the VLOS Pilot preferences, Spektrum DX7s transmitter and AR8000 micro receiver were selected for the setup. A 2.4 GHz, licence free frequency band is used, therefor interference from other devices need to be taken into consideration, i.e. Bluetooth or Wi-Fi. To reduce interference with other devices, the Spektrum system provides a DSM-X interference resistance mechanism. The DSM-X combines both Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS).

3) Telemetry transceivers: As a primary data-link the system uses a digital, Super-High Frequency (SHF) Ubiquiti AirMax radios. The data-link is based on a Ubiquity Rocket

M5, 2x2 MIMO, 5.8 GHz, 150+ Mbps base stations. The Rocket provides up to 27 dBm transmission power and -96 dBm receiver sensitivity [7]. The device is equipped with the Ethernet interface. While one transceiver is integrated into the FMS of the plane, the second radio is a part of the Antenna System described previously in this document. The dish antenna of the Antenna System is a Ubiquiti RD-5G34, suitable for frequencies range between 5.1 and 5.8 GHz, providing gain of 34 dBi, and HPOL/VPOL beamwidth of 3° [8]. Using such setup, the data-link range of 10 km was verified experimentally. Link can transmit the complete set of the aircraft data, including both the autopilot telemetry and the payload data.

A secondary radio transceiver is used in order to increase system safety. A digital 140-170 MHz VHF, Point-to-Point, Software Defined Radio (SDR) provides range of 100 km. Because it uses VHF band it is less influenced by terrain and other obstacles in the LOS path than SHF communication, for this reason it enables operations when there is no direct line of sight between UAV and Ground Segment antennas. The radio provides transparent serial communication port, with speed of 9600 bps, sufficient for basic telemetry transmission and control. When the SHF radio connection is lost, the VHF radio becomes the only communication channel. Note that in the FMS, the VHF radio is connected directly to the autopilot. For this reason it cannot directly control the Payload, nor transmits its data.

The frequency band of the VHF radio cannot be used without a valid licence. Alternative for licenced radio-bands can be transceivers operating within the Industrial, Scientific and Medical (ISM) band.

Last but not least, depending on regulations a Mode C or S Transponder and possibly ADS-B out transmitter may be required during flights.

4) Network Router: The Network Routers are in multiple places of the setup. Due to the airframe weight, space and power limitations, the router need to be small and power efficient. An OpenEmbed SOM9331 device meets these requirements. The router is based on 400MHz Atheros AR9331 System-on-a-Chip (SoC), with 64 MB RAM, and 8MB SPI flash [5]. There are various versions of this module, however in the setup the one with 3 Ethernet ports and USB host is used. The SOM9331 is equipped with build-in antenna and can work as a 2.4 GHz Wi-Fi access point. This function is beneficial on sites where the available Ethernet cable length or its placement are an issue. The device is controlled by a custom-built OpenWrt BarrierBreaker (14.07) GNU/Linux for embedded devices. The operating system enables high degree of network settings customization, including use of Delay-Tolerant and IEEE 802.11s mesh networks.

D. Hardware look-up-table

Table I provides a quick overview of technologies selected and tested during development of the discussed system. Table can be used as a reference point to researchers building own Unmanned Aerial System.

TABLE I: System components summary table

Component	**Used technology**
UAV airframe	Skywalker X8
X8 Autopilot	3DR Pixhawk
Sensors	3DR uBlox GPS with Compass Kit Pixhawk Airspeed Sensor Kit
Servos	HiTec HS-5125MG
Motor	Hacker A40
ECU	Jeti MASTER SPIN 66 PRO
Main battery pack	Li-Pol, 14.8V, 10Ah
Primary digital data link	SHF, Ubiquiti Rocket M5 radios
Secondary digital radio	Owl 140-170 MHz VHF Software Defined Radio (SDR)
RC controller	Spektrum DX7s
RC receiver	AR8000
Crew Intercom	David Clark EMS H9941 (VLOS Pilot) H9940 (Operator) U9910-BSW U9920-G38
Network router	OpenEmbed SOM9331
Pan-Tilt Unit	FLIR PTU D300E
PTU tripod	Manfrotto M528XB
Dish antenna	Ubiquiti RD-5G34
Payload computer	BeagleBone Black
Operator Station	Dell Latitude 14 Rugged Extreme
Autopilot control software	APM Planner 2.0, Mission Planner
High Level Software Toolchain	LSTS Toolchain
UAV launcher	Catapult

IV. CONCLUSION

With the growing popularity of Unmanned Aerial Systems research and increasing availability of related hardware, there is also the need and opportunity for the research community to verify theoretical and simulation based results in practice. Nonetheless, the development of such a system from scratch often exceeds projects' time frame and available resources.

The solution presented in the paper enables scientists to set main focus on the their research objectives. This allows them to solely focus on the integration of specific equipment related to the research goals, keeping the majority of the hardware already defined. The architecture is able to accommodate advanced flight algorithms while keeping high-level of safety, providing a separation between flight-critical elements, as much as possible, from the equipment being tested.

The defined architecture ensures compatibility with the high-level software toolchain designed to be used with various types of Unmanned Vehicles, and is able to provide a complete solution inter-operable with other research facilities' projects.

Throughout two years of intensive field experiments, including several research problems, the presented setup proved its suitability and robustness. These positive results suggest that it can be used as a reference point for facilities planning to develop their own UAS, or as a benchmark tool for comparison with groups already performing field experiments with UAVs.

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