The Application of Software Defined Radios in Unmanned Systems

I. Ivanov, A. Kolev, and S. Spasov

***Abstract* – The growing reliance on unmanned systems – ranging from aerial and ground vehicles to surface and underwater platforms—demands highly adaptable, secure, and efficient communication solutions. Traditional hardware-based radios often lack the flexibility required to operate in complex and dynamic spectrum environments. Software Defined Radios (SDRs) provide a transformative approach by enabling communication protocols and signal processing tasks to be implemented in software, allowing real-time reconfiguration, multi-band operation, and seamless interoperability across domains. This paper explores the integration of SDRs in various types of unmanned systems, highlighting their advantages in terms of spectrum agility, resilience to interference, and support for mission-specific waveforms. Use cases are discussed across domains such as UAV swarming, autonomous ground vehicles, maritime surveillance, and underwater exploration. Key technical challenges—including size, weight, and power (SWaP) constraints, processing latency, and security considerations—are analyzed. By enabling flexible and intelligent communication capabilities, SDRs are set to become a critical enabler for the next generation of autonomous and connected unmanned systems.** [1]

***Keywords*—UxS, Software Defined Radio (SDR)**

I. INTRODUCTION

In military affairs, growing needs of situation awareness and uninterrupted and reliable Command and Control (C2) from one side and availability of variety of unmanned platforms for air, land and maritime domain from other side, created explosion in usage of unmanned systems (UxS). Nowadays UxS is in the peak of the hype cycle of Gartner, where this technology is conceptually accepted as a solution of almost all problems. This creates a need for experimentations in order to justify engineering solutions.

Contemporary UxS heavily rely on communication. Most popular existing system concept is division of platform communication subsystem and mission subsystem (payload). According this concept multifunctionality (if needed) is achieved by changing of payload.

Previous related works considered only unmanned aerial systems (UAS) [1], [2], and from technology-centric perspective. The present study focuses on capability needs and appropriate solution for multi-mission combined radio-frequency system. Collection of functional requirements is done via scenario and use case. SDR technology is researched as part of the biggest concept of Software-defined Systems (SDS).

II. Scenario, use case and Functional Requirements

A. Scenario – Littoral ISR/EW Operations

Main missions of UxS in military domain are:

- Intelligence, Surveillance, and Reconnaissance (ISR);
- Combat missions – armed UAVs for precision strikes;
- Electronic warfare (EW);
- Logistics.

For current research following scenario with switching between ISR and EW is considered:

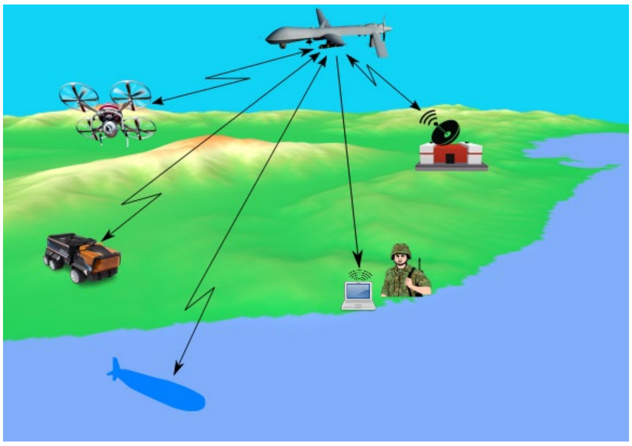

Fig. 1. High-level scenario diagram.

A joint military Intelligence, Surveillance, and Reconnaissance (ISR) operation is conducted in a strategic littoral zone, which includes islands, coastal terrain, urban sectors, and shallow waters. The mission involves the coordinated use of unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), and unmanned underwater vehicles (UUVs) to monitor enemy activity and collect tactical intelligence, as illustrated at Fig.1. The operational environment is RF-contested, with potential for electronic interference and jamming from hostile forces. In this setting, unmanned platforms must not only perform ISR but also be capable of dynamically switching to an Electronic Warfare (EW) role as the mission evolves – enabling rapid transition from passive surveillance to active disruption of adversary communications and navigation systems.

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B. *Use Case*

Based on scenario, following use case can be developed:

Use Case Name: Adaptive Multi-Domain ISR/EW and Communications

Goal: Ensure that unmanned systems (UAVs, UGVs, UUVs) can exchange data, adapt to RF conditions, and perform ISR and EW functions across air, land, and sea domains — dynamically, securely, and without manual reconfiguration.

Actors:

- UAV Operator
- Mission Planner
- Ground Command Center

Preconditions:

- The environment may be congested or contested (RF interference, jamming)
- Multiple types of unmanned systems are deployed simultaneously
- Mission tasks may shift from ISR to EW in real time

Main Functional Steps:

- Establish interoperable communications among UAVs, UGVs, UUVs
- Enable real-time transmission of multi-modal sensor data
- Monitor the RF environment and detect interference or jamming
- Dynamically adapt to spectrum changes (frequency, waveform, protocol)
- Transition unmanned assets from ISR role to EW role as the mission evolves
- Maintain distributed, resilient networking among platforms
- Ensure secure and low-latency links to the command center

Post conditions:

- Mission assets remain connected under changing RF and operational conditions
- ISR data is delivered continuously
- EW actions (e.g., jamming or deception) can be initiated without hardware change
- Network can scale as platforms join or leave.

C. *Functional Requirements*

Analysis of this scenario and the use case creates following functional requirements of the system:

- Interoperable communication across aerial, ground, and underwater platforms.
- Real-time exchange of sensor data (video, LiDAR, telemetry, acoustic).
- Adaptive use of the RF spectrum in contested or congested environments.
- Resistance to jamming and RF interference
- Reliable communication with a command station located inland.
- Distributed peer-to-peer networking among unmanned assets.
- Electronic warfare (EW) capabilities: detection, jamming, spoofing.
- Autonomous mission re-tasking (ISR ↔ EW switching).
- Scalability and dynamic node participation.

III. Unmanned Systems (UxS) Architecture, Software-Defined Systems (SDS) and Cognitive Systems

A. *Unmanned Systems (UxS) Architecture*

The most well developed architecture of military UxS is those of military UAS described in standard STANAG-4586 “Standard Interfaces of UA Control System (UCS) for NATO UA Interoperability” [3]. This document defines a unified framework that enables seamless integration, control, and information exchange between Unmanned Aircraft (UA) and their control systems across NATO member states. By standardizing the interfaces of the UCS, it ensures interoperability among different national platforms, reduces technical fragmentation, and facilitates joint operations. It specifies functional, data, and communication interfaces to support mission planning, execution, monitoring, and post-mission analysis. The standard plays a critical role in enhancing operational effectiveness, enabling coalition forces to share resources and information, and ensuring that unmanned systems can be rapidly integrated into NATO’s command and control structures.

At Fig. 2 the main components of a Unmanned Aircraft System (UAS), as defined in STANAG 4586, are shown[3]. Blocks, show in orange are additionally standardized in more details. Blocks in white have custom constructive solution.

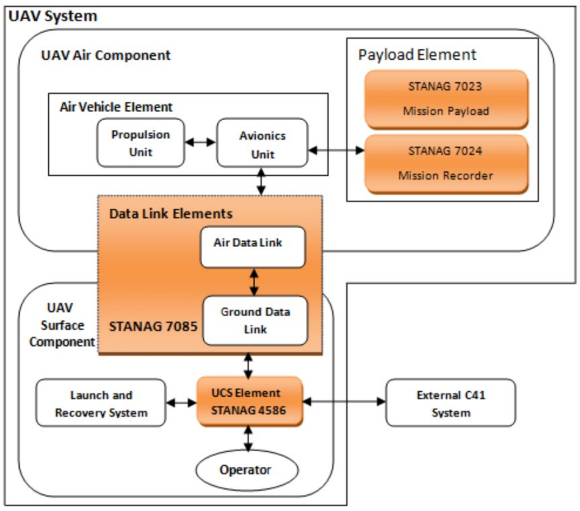

Fig. 2. UAS architecture according standard STANAG-4586.

According the standard STANAG-4586 the system divided into two major parts:

1.UAV Air Component, which includes:

- Air Vehicle Element – composed of the propulsion unit and avionics unit.
- Payload Element – containing the mission payload (e.g., sensors or weapons) and the payload recorder.

2. UAV Surface Component, which includes:

- UCS Element (Unmanned Control Station) operated by personnel and connected to external C4I systems.

- Launch and Recovery Element – specific to each UAV type.

Both components are linked through the Data Link Element, consisting of the Vehicle Data Terminal (VDT) onboard the UAV and the Control Data Terminal (CDT) on the ground or other platforms. This setup enables command, control, and data exchange between the UAV, its payload, and external systems.

B. Software-Defined Systems (SDS) and Cognitive Systems

Ubiquitous usage of computing devices and information technologies in almost every manmade objects created new paradigms in engineering new devices. The concept of Software-Defined Systems (SDS) stems from the trend of decoupling control logic from the underlying physical infrastructure in order to achieve greater flexibility, programmability, and adaptability. At its core, SDS represents the abstraction of hardware resources—whether computational, networking, storage, or even physical devices—and their centralized management through software. Early manifestations of this paradigm can be traced back to Software-Defined Radio (SDR), where traditional radio functions were implemented entirely in software [4]. The idea soon extended into radar systems, giving rise to the notion of Software-Defined Radar (SDRadar), in which radar waveforms, signal processing chains, and system modes are realized in software rather than rigid hardware. This provided the foundation for the more advanced concept of Cognitive Radar, as formulated by Haykin [5], where software programmability enables adaptive, intelligent, and learning-capable radar operation [6]. Later, the paradigm was adopted in networking under the form of Software-Defined Networking (SDN), which introduced a clear separation between the control plane and the data plane, enabling centralized orchestration of network operations [7].

Over the past decade, SDS has evolved in multiple directions, becoming a foundational paradigm for the design of modern information, sensing, and communication infrastructures. In the storage domain, this has led to Software-Defined Storage (SDS) [8]; in the automotive industry, to Software-Defined Vehicles (SDV) [9]; and in cloud and data center infrastructures, to integrated Software-Defined Data Centers (SDDC). Beyond these domains, SDS principles have been applied to advanced radar and sensing systems, where programmability enables multi-mode operation, real-time waveform adaptation, and the integration of cognitive processing. This expansion highlights the close relationship between SDS and the broader concept of cyber-physical systems (CPS), where intelligent control loops link sensing, computation, and actuation. In this sense, SDS serves as both a technological enabler and a conceptual framework, providing the programmability and abstraction necessary for building scalable, adaptive, and intelligent systems [8].

The natural progression of SDS leads toward the paradigm of cognitive systems, which combine software programmability with adaptive learning, reasoning, and decision-making. Cognitive systems are characterized by their ability to perceive the environment, interpret contextual information, and take actions that improve performance over time. A prominent example is cognitive radar, where the perception–action cycle enables the radar to sense the environment, learn from interactions, and adapt its transmission strategies accordingly [5], [6]. More broadly, cognitive systems extend these principles to communications, autonomous vehicles, industrial control, and defense applications, where adaptability and intelligence are critical. The synergy between SDS and cognitive systems lies in the fact that SDS provides the programmable, reconfigurable infrastructure, while cognitive methods supply the intelligence and autonomy needed for real-time optimization and decision-making [4], [5], [6]. As Industry 4.0 advances, the integration of SDS and cognitive systems is expected to play a central role in enabling resilient, efficient, and self-optimizing infrastructures.

IV. Software-Defined Radio (SDR) and its Application in UxS

A. SDR concept

According ontology created by working group P1900.1 of Institute of Electrical and Electronics Engineers (IEEE) “software-defined radio” is “…a radio in which some or all of the physical layer functions are software-defined” [10].

The foundations of the “software-defined radio” (SDR) paradigm are associated with research conducted by DARPA and the U.S. Air Force under the SpeakEasy project in the early 1980s, aimed at developing a prototype radio covering the frequency range from 2 MHz to 2 GHz and implementing approximately 10 communication standards [11]. Part of the results concerning the system architecture were published by Mitola in the early 1990s, where the author introduced the concepts of “software radio” [13], [14] and “software-defined radio” [15].

The successful development of a prototype software-defined radio under the SpeakEasy project served as a prerequisite for the launch of a large-scale program by the U.S. Department of Defense entitled the “Joint Tactical Radio System” (JTRS). The objective of JTRS was to establish a unified radio platform for all branches and services of the armed forces, capable of supporting more than 30 radiocommunication protocols [16]. The vast scope of the program, coinciding with the emergence of numerous successful communication technologies such as 3G, WiFi, and MANET, led to significant management challenges, primarily related to the constant expansion of user requirements. After multiple delays the program was subsequently terminated and reduced to more realistic objectives.

Notwithstanding the setbacks of JTRS as an undertaking—stemming from the challenges of the practical realization of software-defined tactical radio systems, as examined in [16] – the “software-defined radio” technology has demonstrated its vitality, continues to attract significant attention, and constitutes the foundation of paradigms such as the “cognitive radio” [17], the “cognitive radar” [5], the “software-defined radio technical system” [18], among others. Furthermore, SDR technology has experienced rapid adoption among amateur radio operators, largely due to the introduction of the low-cost RTL-SDR product, which enables the implementation of a software-defined radio receiver [19].

Generalized block scheme of SDR is shown at Fig. 3.

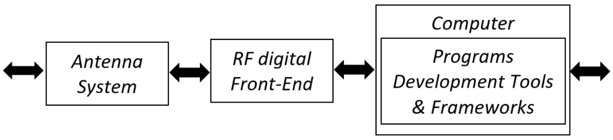

Fig. 3. Generic architecture of SDR.

The structure of a software-defined radio (SDR) includes three main components: the antenna system, the radio frequency (RF) front end, and a general-purpose computing platform (computer). The RF front end handles quadrature modulation and demodulation, performs analog-to-digital and digital-to-analog conversion (ADC/DAC), and carries out fundamental digital operations such as digital up/down conversion (DUC/DDC), decimation, and interpolation. The bulk of digital signal processing takes place on the computer. Popular software environments that support SDR operation on the computer include GNU Radio, MATLAB, LabVIEW, and SystemVue. Among these, GNU Radio is a widely used free and open-source framework that provides pre-built blocks for SDR as well as tools for creating custom ones.

Constructive view of one realization of SDR, based on single-board computer is shown at Fig. 4.

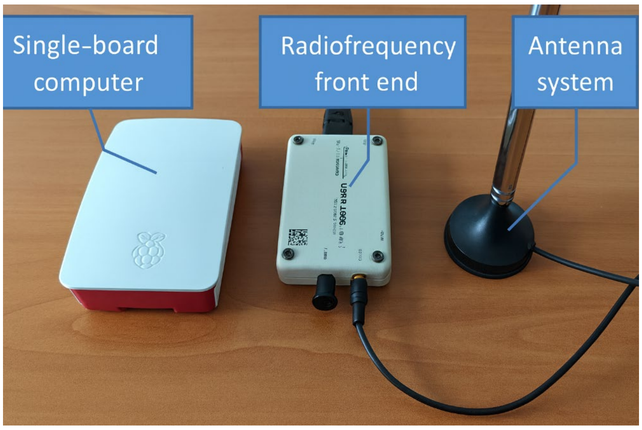

Fig. 4. Constructive view of SDR implementation.

This practical realization follows generalized block scheme at Fig. 3. There is tendency in future RF digital front-End and Computer, Operating System, Programs Development Tools & Frameworks to be combined in single constructive element[20].

Table I provides an overview of the key features of widely used radiofrequency front-ends for SDR implementation.

TABLE I
MAIN CHARACTERISTICS OF POPULAR RF FRONT-ENDS FOR SDRS

Platform	Frequency range	Channel bandwidth	Digital converters bit resolution	Digital interface	Number of Rx/Tx
Hack RF One	10 MHz - 6 GHz	20 MHz	8 bit	USB 2.0	1 Rx/1 Tx
Adalm PLUTO	325 MHz - 3.8 GHz	20 MHz	12 bit	USB 2.0	1 Rx/1 Tx
Ettus B210	70 MHz - 6 GHz	56 MHz	12 bit	USB 3.0	2 Rx/2 Tx
Ettus N210	10 MHz - 6 GHz	40 MHz	14-bit ADC 16-bit DAC	1G Ethernet	2 Rx/1 Tx
Ettus X210	50 MHz - 2.2 GHz, 400 MHz - 4.4 GHz, 1.2 GHz - 6 GHz	160 MHz	14-bit ADC 16-bit DAC	10G Ethernet, PCIe	2 Rx/2 Tx, 4 Rx
Ettus X310	10 MHz - 6 GHz	160 MHz	14-bit ADC 16-bit DAC	10G Ethernet, PCIe	2 Rx/2 Tx, 4 Rx
Lime SDR	100 kHz - 3.8 GHz	61.44 MHz	12 bit	USB 3.0	2 Rx/4 Tx
Pico SDR	70 MHz - 6 GHz	56 MHz	12 bit	PCIe	4 Rx/4 Tx, 4 Rx/8 Tx
RTL-SDR	24 - 1766 MHz	3.2 MHz (2.4 MHz typical)	8 bit	USB 2.0	1 Rx

The data indicate that these devices can cover a broad frequency span, including portions of the HF, VHF, and UHF ranges, and can process wide channel bandwidths of up to 120 MHz. They also enable high-speed data transfer to personal computer platforms—reaching rates of up to 10 Gbit/s—and support multiple coherent radio channels, among other capabilities. These characteristics allow the implementation of variety technologies such as GSM, LTE, DVB, FMCW Radar, MIMO, etc.

Advantages and disadvantages of SDR technology are summarized in following table.

TABLE II
ADVANTAGES AND DISADVANTAGES OF SOFTWARE-DEFINED RADIO (SDR)

Advantages	Disadvantages
Flexibility – supports multiple standards, modulations, and protocols within the same hardware.	Limited by the hardware front-end (antennas, filters, amplifiers).
Updates via software without changing hardware.	High power consumption and cooling requirements.
Capability to quickly adapt to new waveforms.	Possible processing delays (latency).
Supports a wide range of frequencies (with appropriate front-end).	More vulnerable to jamming and cyberattacks.
Multifunctionality – communication, monitoring, and analysis in a single module.	Complex development requiring highly skilled personnel.
Suitable for prototyping and research & development work.	High initial cost for high-performance systems. Size and weight may be problematic in mobile applications.

B. SDR application in UxS - Mapping SDR Capabilities to Functional Requirements

This section demonstrates how Software Defined Radios (SDRs) fulfill the functional requirements derived from the Adaptive multi-domain ISR and EW use case. While the use case does not impose any specific technical implementation, SDRs are a natural fit due to their reconfigurability, modularity, and adaptability. Below is a detailed mapping between the identified functional needs and the technical capabilities offered by SDR platforms.

TABLE III
FUNCTIONAL REQUIREMENTS MAPPING

Functional requirement	How SDR satisfies it
Interoperable communication across platforms	SDR supports multiple waveforms and protocols, allowing seamless communication between heterogeneous unmanned systems (UAVs, UGVs, UUVs).
Real-time sensor data exchange	SDRs enable high-throughput, low-latency transmission of telemetry, video, and sensor data using optimized modulation and bandwidth.
RF environment monitoring	Cognitive radio capabilities allow SDRs to scan the spectrum, detect interference or jamming, and assess spectrum availability.
Dynamic spectrum adaptation	SDRs can autonomously reconfigure frequency, bandwidth, and modulation to evade interference and optimize link quality in real-time.
ISR ↔ EW mission switching	SDRs can switch roles on-the-fly, from passive data collection to active jamming, spoofing, or electronic deception, all in software.
Distributed, resilient networking	With support for MANET and mesh topologies, SDRs provide dynamic, self-healing communication networks without fixed infrastructure.
Secure and robust command links	SDRs support encryption, authentication, and frequency hopping techniques to ensure secure and resilient C2 connectivity.

In the same time, disadvantages of SDR, summarized in Table II, put boundaries in system solution space and require future experimentations to prove the concept.

V. PREPARATION FOR EXPERIMENTAL WORK

We consider the Unmanned Aerial System (UAS) as a system composed of several distinct subsystems and modules. Fig. 5 shows the general layout of the UAS with the most essential components for the present discussion.

At the highest level, the UAS consists of a Ground Control Station (GCS), a Mobile Station (MS), and an air-based subsystem (UAV):

- Ground subsystem – The GCS performs functions related to pre-flight preparation, setting flight safety rules and emergency response procedures, generating a flight plan, and loading the flight plan into the onboard recorder. The operator of the ground control station initiates the UAV flight in either automatic or manual mode and monitors the mission according to the defined flight plan. If necessary, the operator switches to manual UAV control. The functionality of the MS involves receiving, processing, and applying information and data obtained from the UAV. The operator of the mobile station is a specialist with a profile suitable for the nature of the mission being carried out. Typical missions of modern UAS include reconnaissance, surveillance, and target designation;

- Air-based subsystem – A wide variety of technical solutions are possible both for the flight and propulsion components, as well as for the core and additional electronic equipment. In this discussion, we focus on the widely used aerial system of the "quadcopter" type. The core electronic equipment includes: flight controller, onboard recorder, Inertial Measurement Unit (IMU), Global Navigational Satellite System (GNSS), and telemetry radio channel (RC Telemetry). The additional electronic equipment is optional and is configured depending on the mission objectives. For surveillance and reconnaissance missions, the minimum required electronic components are: Single Board Computer (SBC), video camera (usually mounted on a gimbal), and a 3G/LTE modem to provide a digital data link to the MS. In specific cases, when observation and assessment of phenomena or adversary actions in the radio-electronic spectrum are required, a Software Defined Radio (SDR) module with its own antenna system is applied.

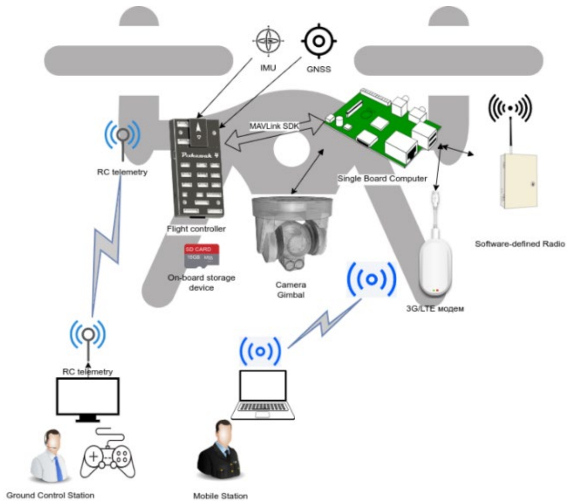

Fig. 5. General layout of the experimental UAS.

Fig. 6 schematically shows the data exchange between the core and additional UAV equipment.

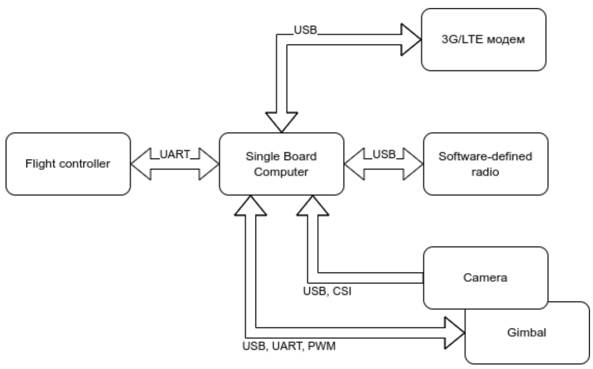

Fig. 6. Data flow and interfaces of experimental UAV.

The flight controller is the main and mandatory module in the UAV. During surveillance and reconnaissance missions, the flight controller receives navigation data about the position and spatial orientation of the UAV—yaw, roll, and pitch (YRP). For maintaining telemetry communication with the GCS, one applicable protocol is the Micro Air Vehicle Link (MAVLink) [21]. The SBC receives the full set of navigation data from the flight controller via the Universal Asynchronous Receiver-Transmitter (UART) serial protocol. To interpret the complete dataset, consisting of more than 1200 parameters, MAVLink SDK software is installed on the SBC [22]. In this way, the GCS operator, through the telemetry system, is able to control the additional electronic equipment.

The video camera is characterized by its interface capabilities, which in most practical cases are Universal Serial Bus (USB) or Camera Serial Interface (CSI). The gimbal allows camera orientation independent of the UAV's spatial position. Camera orientation can be set via USB, UART, or Pulse Width Modulation (PWM) interfaces. The imagery obtained from the video camera, tied to the navigation data at the moment of capture, is suitable for further processing with Post Processing Kinematic (PPK) [23].

The 3G/LTE modem component provides communication with the MS independently of the telemetry radio channel. Within the coverage of an existing cellular network, a standard network protocol is established. One widely used software architecture for such communication is Representational State Transfer (REST) [24], as well as file transfer or video streaming protocols. For secure communications in special missions, a Virtual Private Network (VPN) can be configured.

The SDR's RF front-end module communicates with the SBC via USB. Specialized software such as GNU Radio must be installed on the SBC [25]. On this program framework, dedicated flowgraph is running. The UAS thus gains the capability to analyze the radio frequency spectrum, enabling applications such as detecting GNSS spoofing, assessing adversary electronic warfare (EW) activity, or monitoring other radio frequency activities within the scope of the mission.

Practical realization of this concept is shown at Fig. 7. It follows concept from Fig. 5.

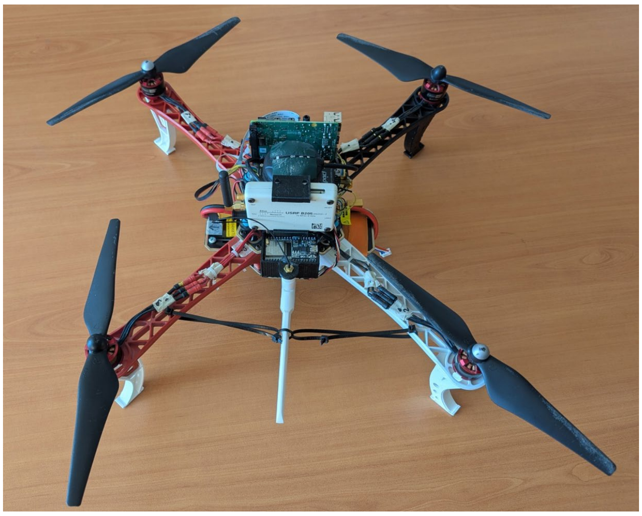

Fig. 7. The experimental UAV with SDR.

The use case described here in this work will be used for validation of the concept.

VI. Conclusion

In this work usage of SDR technology as affordance for UxS multimission system is investigated. Method of use case is used for functional requirements development. SDR technology as part of SDS is analyzed. Using mapping to functional requirements, usage of SDR in UxS is analyzed. Preliminary experimental works are reported. SDR technology seems viable for multimission scenarios.

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