DEVELOPMENT OF AN AERIAL CYBERNETIC IOT SYSTEM BASED ON LTA-UAVS FOR MULTIFACETED APPLICATIONS

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Abstract

This paper presents the development and implementation of a cybernetic IoT system based on a fleet of LTA-UAVs with different payload capacities. The system integrates a variety of sensors. The use of a single-board computer with functional adaptations allowed the implementation of a full Linux distribution on the UAVs, enabling efficient data processing and analysis. The integration of multiple wireless data transfer interfaces ensures reliable and uninterrupted data transmission. The multichannel routing environment enables the delivery of data streams with varying quality over different interfaces in a timely and redundant manner. The system has been successfully tested in various proof-of-concept scenarios, including 3D modeling of monuments, traffic monitoring, and detection and labeling of moving objects from the air. Future applications of the system are planned in areas such as earth observation and smart cities. In conclusion, the developed IT system based on LTA-UAVs presents a promising solution for a wide range of applications. The system's capabilities, such as long-range operation, low noise emission, and high payload capacity, make it ideal for environmental inspection and wildlife search. The versatility and flexibility offer potentials for future developments.

Keywords: LTA, UAV, IoT, EO, Real-Time, Data, Connectivity, LTE, 5G, SatCom, Multi-Channel, Cybernetics

INTRODUCTION

The world is witnessing a paradigm shift in the realm of unmanned aerial vehicles (UAVs) as innovative technologies continue to redefine the possibilities of flight. In this context, this paper unveils the development of a cybernetic Internet of Things (IoT) system, strategically deployed through a fleet of Lighter Than Air Unmanned Aerial Vehicles (LTA-UAVs) with varying payload capacities. Our journey into this realm is motivated by the imperative need for versatile, sustainable, and resilient solutions that can address multifaceted challenges. In recent years, the convergence of cybernetics and IoT has unleashed unprecedented potential in the field of aerial systems. The capacity to integrate a multitude of sensors, coupled with advancements in computing and data transmission, has opened doors to a new era of exploration, monitoring, and problem-solving from the skies.[1,2,3]

It's within this context that we present our innovative system, which capitalizes on the innate qualities like long-range operation, minimal noise emissions, and substantial payload capabilities.

Figure 1 h-aero® one, 3kg payload, 5h endurance

[1] Singer, Cs.: "Ultralight Solar Powered Hybrid Research Drone", NASA Astrophysics Data System, June 2012
[2] Singer, Cs.: „Aerial 3D Reconstruction of Antique Buildings via LTA UAV", DGLR, 13.03.2020
[3] Harithuddin et al.: "Lighter-than-air (lta) unmanned aerial system (uas) carrier concept for survaillance and disaster management", UPM Space Systems Laboratory, Malaysia, 2018

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We briefly describe, which system architecture we have chosen for the development and practical implementation as well as which arsenal of sensors the h-aero® flight systems incorporate. Subsequently we outline the framework for secure and efficient data transfer via a spectrum of wireless interfaces, encompassing Wireless Local Area Network (WLAN), Long-Term Evolution (LTE), radio modems, and Satellite Communications (SatCom).

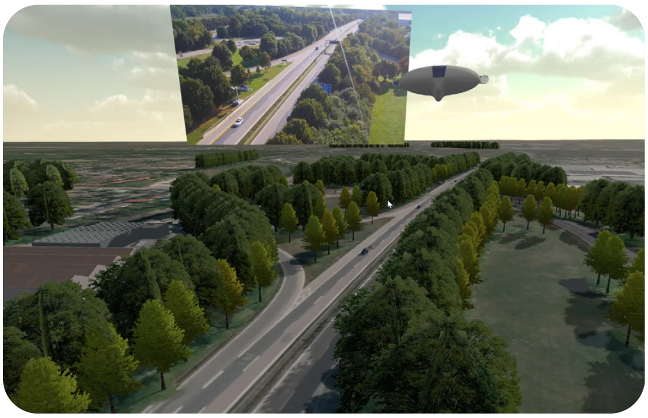

Figure 2 Dynamic 3D Model based on 4K video

In this documentation our primary objective is to showcase the potential of LTA-UAVs across various domains in real-world scenarios and to manifest them based on this as robust solution for challenges spanning from environmental monitoring and wildlife conservation to urban planning and traffic management.

SYSTEM ARCHITECTURE AND COMPONENTS

Description of LTA-UAV Fleet and Capacities

A cornerstone of our system is the deployment of a fleet of LTA-UAVs, each meticulously designed with varying payload capacities.

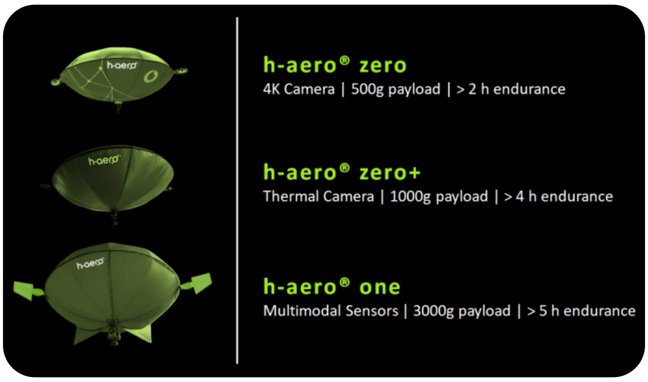

Figure 3 Available h-aero® LTA-UAV models

From compact lenticular models optimized for agility to larger variants our fleet encompasses the following spectrum of operational capabilities such as:

- Free Flight up to 15km/h true airspeed
- Tethered with 30km/h wind resistance
- Aerosol Mode (BVLOS), work in progress

Integration of Sensors:

The array of sensors which the h-aero® LTA UAV systems integrate is extensive. These sensors serve as the eyes and ears of our LTA-UAV fleet, providing real-time data and feedback critical for decision-making and analysis. The sensor suite includes GPS for precise positioning, accelerometers for motion monitoring, voltage and current sensors for power management, compass for orientation, barometers for altitude measurement, thermometers for temperature tracking, hyperspectral cameras for detailed imaging, 360-degree cameras for panoramic views, thermal cameras for heat detection, and radar for object detection.

Single-Board Computer Implementation

The data processing capabilities lies in the innovative adaptation of single-board computers. This empowers our LTA-UAVs facilitating efficient data processing and analysis directly onboard. The integration of single-board computers is a technological advancement that has streamlined our operations, enabling real-time data interpretation and decision-making during flight missions.

Another defining feature is the deployment of full Linux distributions on our UAVs. This technological innovation marks a significant departure from traditional UAV systems, where data processing typically occurs post-flight. By installing complete Linux distributions on our vehicles, we have ushered in a new era of real-time data processing and analysis capabilities, setting a new standard for operational efficiency and effectiveness.

Efficient Data Processing and Analysis Capabilities

The IT integration on our UAVs empowers our aerial platforms with data processing and analysis capabilities. Unlike conventional systems that rely on data transfer to ground stations for processing, our vehicles can independently process incoming data streams during flight. This not only reduces latency but also provides a crucial advantage in time-sensitive applications such as emergency response and surveillance.

The integrated onboard computers are equipped with powerful processors and memory, allowing for complex computations and data manipulation in real-time. This means that data collected by the sensors on our LTA-UAVs can be swiftly transformed into actionable insights, enabling rapid decision-making and response.

Whether it's monitoring environmental parameters, identifying objects of interest, or conducting 3D modeling, our system is engineered to excel in diverse operational scenarios.

The respective sketch of the system architecture is depicted in Figure 4.

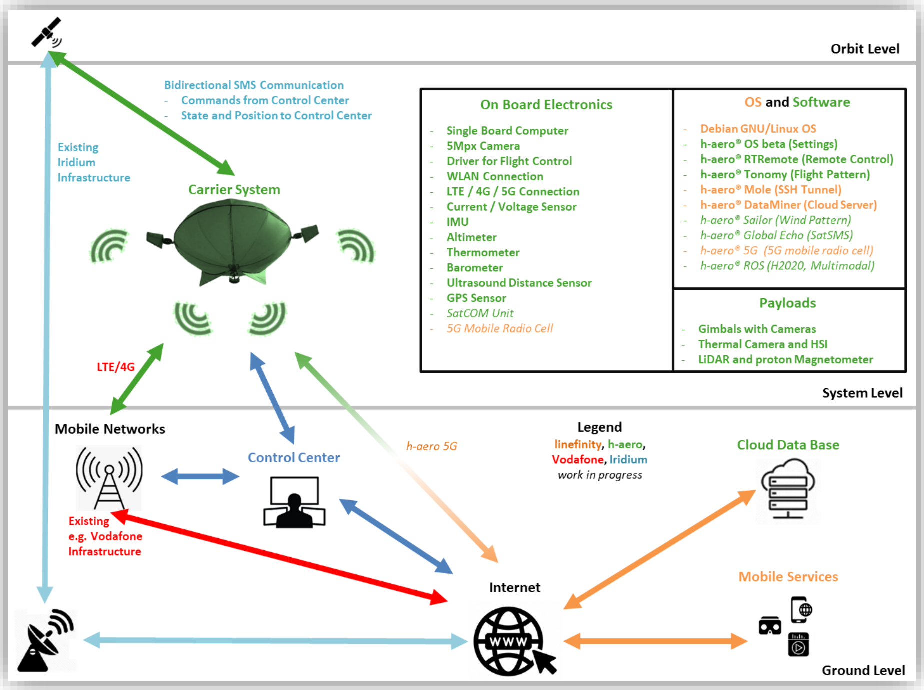

Figure 4 System Architecture and Components

Benefits for Real-Time Data Handling

The adoption of Linux distributions brings forth a multitude of benefits for real-time data handling. These advantages include:

Flexibility: Linux's open-source nature enables us to customize and adapt the operating system to suit our specific requirements. We can integrate a wide range of software tools and libraries to cater to various applications seamlessly.

Stability: Linux is renowned for its reliability and stability, critical factors when operating UAVs in demanding environments. This ensures that our system can consistently perform even under challenging conditions.

Security: Security is paramount, particularly when handling sensitive data. Linux distributions offer robust security features and the ability to apply stringent access controls to protect data integrity.

Scalability: As our system evolves and expands, Linux provides the scalability required to accommodate growing computational demands. This scalability ensures that our system remains agile and adaptable to future advancements and requirements.

Figure 5 RPi-Cam with live stream over Aichtal

WIRELESS DATA TRANSMISSION INTERFACES

The effectiveness of LTA-UAVs rely heavily on the seamless flow of data between the fleet and ground station(s). To facilitate this, we have meticulously integrated a comprehensive suite of wireless data transmission interfaces, ensuring uninterrupted and reliable data transmission even in the most challenging operational environments.

Integration of WLAN

For short to medium-range data transmission we equipped our LTA-UAVs with WLAN capabilities, enabling swift and secure communication with ground stations and other networked devices within the operational vicinity. The programming, maintenance, analysis and testing of the systems are mainly carried out in the WLAN environment. The user can connect his end device with the board computer of the LTA-UAV via an Access Point while also IP forwarding is enabled. This provides an internet connection to the user's end device if the hovering h-aero® is connected to the internet for example with an integrated LTE Stick.

Incorporating LTE for High-Speed Data Transfer

For high-speed data transfer applications and extended coverage, we apply LTE connectivity. We use this high-speed capability for scenarios like live video streaming, remote sensing, and continuous data feed to central command centers. In Figure 5 a BVLOS test flight's live stream is captured with a RPi-Cam while in Figure 6 the visualization of the over the LTE network sent data is visualized in Grafana near real-time. With this we aim to quantify the altitude specific mobile field coverage.

860MHz & 2.4GHz Type Radio Modems

As an alternative communication option, in the case of not existent LTE network, we integrated 860MHz and 2.4GHz Type free license Radio Modem pairs into the air and ground unit to be able to remote control our systems over wide distances up to 300km range. These modems facilitate robust communication between UAVs operating in close proximity, enabling coordinated efforts in tasks such as swarm operations, collaborative mapping, and search and rescue missions. The inclusion of radio modems enhances the redundancy and reliability of our communication network.

SatCom for Global Connectivity

Worldwide connectivity is achieved by incorporating Satellite Communications (SatCom). Our systems establish direct communication with readily accessible commercial satellite networks. This ensures continuous communication even in remote or geographically demanding aerial. The global reach expands the potential applications, encompassing a wide array of missions, such as international disaster response and environmental monitoring. The data interpretation onboard, facilitated e.g. by OpenCV, significantly enhances the system's effectiveness.

Uninterrupted and Reliable Data Transmission

The integration of multiple wireless data transmission interfaces ensures the reliability and continuity of data transfer. Redundancy mechanisms are in place to seamlessly switch between communication modes if one encounters interference or disruption. For this, amongst others, e.g. Multipath IP Routing algorithms are required.

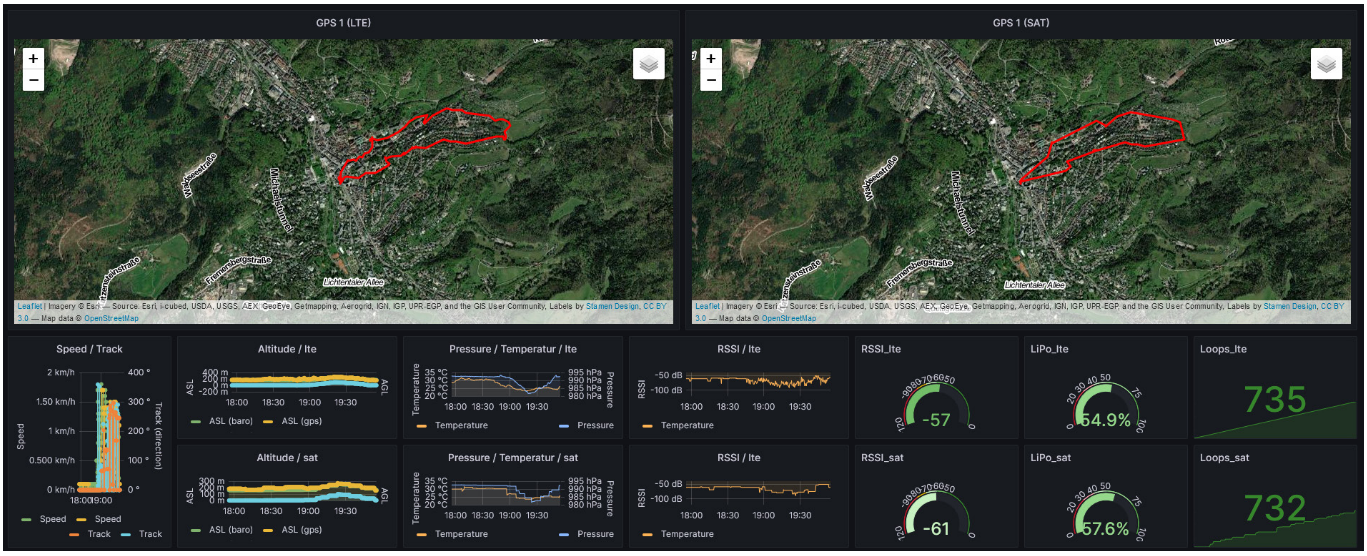

Figure 6 **Time Series Database and Near Real Time Data Visualization (left GPS: LTE, right GPS: SatCom)**

MULTICHANNEL ROUTING ENVIRONMENT

Our communication strategy comprises the establishment of a sophisticated multichannel routing environment. The various technologies (e.g. terrestrial networks (4G/5G), Wi-fi, LEO and GEO satellites) being in use to connect the LTA UAV to the cloud have different properties with regards to connection quality (jitter and data rate) as well as reliability. For transferring large amounts of payload data as well as establishing a reliable command-and-control channel a solution is needed, that accommodates varying data stream qualities over those different interfaces.

To achieve this, our multichannel routing environment employs a set of strategies that adapt in real-time. When faced with challenging conditions or unexpected interface disruptions, the system automatically switches to alternative channels or modes to guarantee continuous data flow.

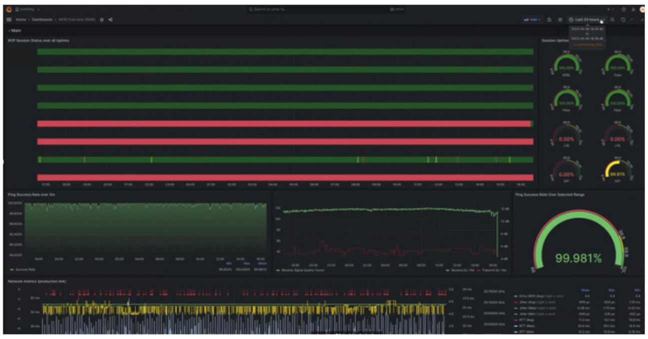

Figure 7 Multi-Channel Monitor

Each interface gets a priority assigned and the data flow is continuously monitored using standardized protocols like BGP and BFD. Those packet flows allow us to calculate link metrics like jitter and packet loss, which can then, separately, influence routing decisions for command and control traffic or multiple classes of payload traffic. Furthermore the traffic can be shaped on both sides, so for each side (uplink and downlink), we can define a bandwidth value that we assume to be available on a link. If the link offers guaranteed quality metrics (e.g. guarantees regarding max. allowed packet loss), this allows ensuring certain quality metrics for particular flows (real-time data), while other flows are down-prioritized if needed to keep the overall data rate below the defined limit. Even for links, that do not guarantee certain quality metrics (best effort links), we can avoid link saturation by shaping to a (much) lower data rate, which is then more eligible to carry flows with higher requirements regarding the link quality: because a lower data rate is more likely to be available than a higher data rate, especially if saturated by lower-priority traffic.

For interconnecting a fleet of multiple LTA UAVs we can make use of recent network meshing technologies. Depending on the requirements, low-power, lower-layer mesh-protocols like thread are appropriate or higher layer meshes for Wifi-links like batman for high data rate applications.

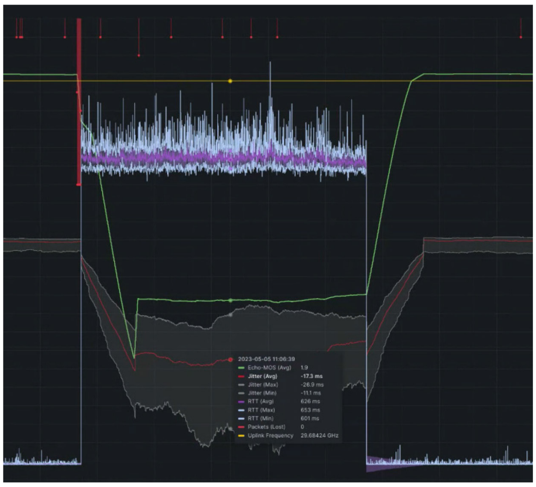

Figure 8 Multi-Channel Signal Analysis

Our priority is the integration of those protocols in a single device to avoid extra weight: this is possible by choosing and adapting proven open source based solutions only that allow us to integrate the software solution on the linux-based system, which is already carried by the UAV.

PROOF-OF-CONCEPT SCENARIOS

To validate the capabilities of the developed LTA-UAV system incl. IoT features and redundant connectivity, we carried out proof-of-concept (PoC) missions in the context of real-world applications.

<u>Overview of Testing and Implementation Scenarios</u>

Since the foundation of the HAT GmbH we carried out over 100 flights for PoC projects following the principle of bootstrapping. The successful PoCs can be classified into the categories Exploration (e.g. Resource Exploration, Cultural Heritage, GPR-, Radar- and HSI Measurement), Communication (e.g. Video Live Stream, 5G WLAN Access, Events, Airport Terminal) and Observation (e.g. Tunnel Inspection, Thermal 3D City Maps, Cultural Heritage, Agriculture, Forestry, EO, Events). The application fields are more or less scalable depending on the market segments' needs. In the following we briefly describe three use-case examples bearing strongest scaling potentials with the current state of the art technology. The description of all the PoCs will be the scope of upcoming scientific documentation.

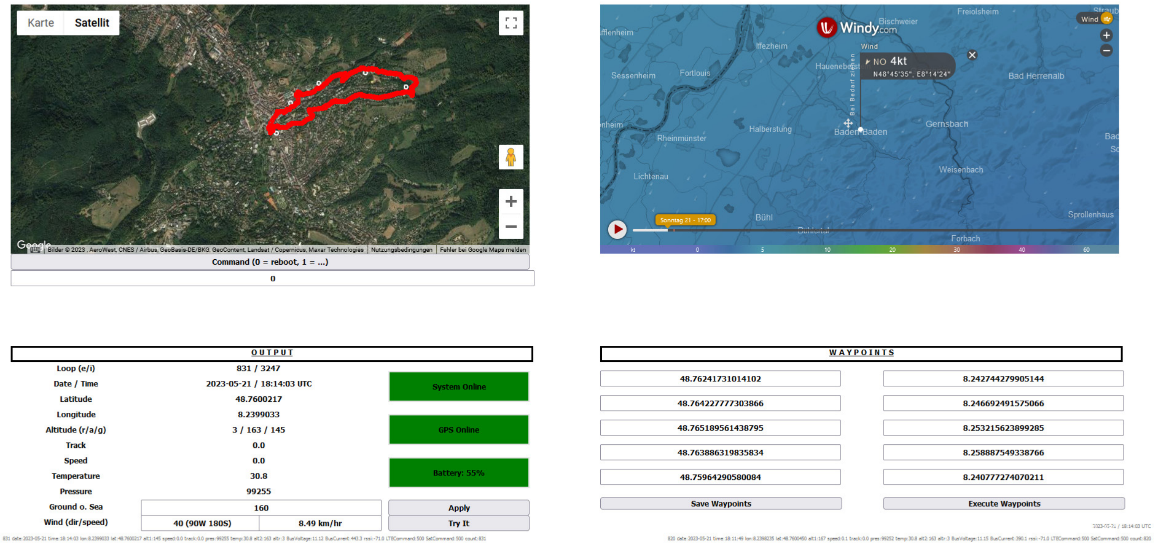

Figure 9 **GUI with Integrated Waypoint Selection and Wind Database**

3D Modeling of Cultural Heritage[2, 4]

We collected with a LTA-UAV equipped with a 4K gimbal camera as many optical datasets from an old church's inventory and walls as possible in one flight and used the collected pixel matrices to stich the optical information to virtual 3D Model Objects that can be displayed on a screen of a personal computer.

Traffic Monitoring and Congestion Analysis[5,6]

We applied our system in the tethered balloon mode equipped with a 4K camera incl. tracking abilities and performed in multiple 3h sessions traffic monitoring and data acquisition. Subsequently we generated out of the collected digital information dynamic and interactive 3D Models that show the traffic's behavior and allow model interaction.

Detection and Labeling from Aerial Perspective[7,8]

With the aforementioned dataset we could also show the accurate classification, labeling and counting of the traffic's participants.

FUTURE APPLICATIONS

With the collected experience to build our systems and apply them, the future directions of the technology can be assumed and discussed. This is also valid related to the opening up array of new and not yet carried out applications based on the system's adaptability and versatility.

Prospects in Earth Observation and Smart Cities

Equipped with various sensors, such as thermal cameras, hyperspectral imaging, and radar the developed systems can be used for environmental monitoring and be operated in Beyond Visual Line of Sight (BVLOS) flight modes. To use them effectively, certain technical requirements must be met. These requirements include reliable routines for outdoor operations, the presented redundant communication systems, on-board data processing capabilities, remote control options with applicable waypoints and the use of an integrated real-time wind database, as illustrated in in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

Environmental Inspection and Wildlife Search

The ability to operate quietly and without disturbance, coupled with the high payload capacity, allows for efficient surveys in swarms. Whether it's monitoring the health of forests, identifying and tracking wildlife populations, or conducting aerial surveys of aquatic ecosystems, LTA-UAVs can play a vital role in safeguarding the environment. By minimizing disruption and providing valuable data, it contributes to our understanding of ecological systems and supports conservation efforts.

[4] https://youtu.be/kbYZu0tjGmo
[5] https://youtu.be/sMA1SQ8TSIE
[6] https://youtu.be/XuUf1e05-6Y
[7] https://youtu.be/59B_Dr5qMbs
[8] https://youtu.be/cxgY_1P2SmU

Extending System Versatility to New Applications

The adaptability and flexibility of the presented development mean that it can be tailored to address emerging challenges across diverse domains. From disaster response and emergency services to precision agriculture and infrastructure inspection, the possibilities are limited only by our imagination. By continuously innovating and collaborating with partners and stakeholders, we aim to extend the system's versatility to new horizons. We welcome the opportunity to explore novel applications and refine our technology to meet evolving needs.

CONCLUSION

In summary the achievements and contributions of the herein disclosed development reflect the innovative capabilities it brings to the forefront. Future developments and innovations based on LTA-UAVs bear a long list of new technical options.

Summary of Achievements and Contributions

We have explored the development and implementation of an innovative cybernetic IoT system built upon a fleet of LTA-UAVs. Some of the key achievements and contributions include:

- **Integration of Multifaceted Sensors**
- **Efficient Data Processing**
- **Robust Data Transmission**
- **Multichannel Routing**
- **Successful Proof-of-Concept Scenarios**

General Capabilities

The showcased capabilities with metrics are:

Long-Range Operation:

Endurance:	5 h
Velocity:	20 km/h
Range:	100 km

Low Noise Emission:

Noise:	< 40 dB

High Payload Capacity:

Payload:	up to 3 kg

Interfaces for Adaptability and Versatility:

USB | USB-C;

LAN | WLAN | LoRaWAN

3G | 4G | 5G | 5G IoT | SIM;

SatCom;

RS232 | UART | I2C;

SD (1TB).

Potential for Future Developments and Innovations

The evolving landscape of technology and the growing demands of various sectors create opportunities for continuous refinement and expansion.

In closing, the developed cybernetic IoT system based on LTA-UAVs represents a promising solution with a broad range of applications. Its achievements, capabilities, and potential for future growth set the stage for a dynamic journey of exploration and innovation.

ACKNOWLEDGMENTS

We would like to extend our heartfelt thanks to the organizations that played a pivotal role in the success of the respective projects.

Extraordinary thanks, appreciation and respect go to the team of Linefinity GmbH & Co. KG, who not only supported us with the IT architecture, operating system, networks and multichanneling, but also stood by us with best advice at any time.

Our gratitude goes to LandPlan OS for their invaluable assistance in creating the 3D traffic model. We also want to acknowledge Infolks for their expertise in data labeling, which significantly improved the quality of our results. Special thanks are due to Autobahn GmbH for providing crucial scenarios that enriched our research and to the Cathedral Provost of the St. Peter and Paul Church Puck for generously sharing a sample of the church model, which proved instrumental in our work. We furthermore wish to express our deep appreciation to our dedicated team, whose unwavering support and tireless efforts were indispensable throughout this endeavor. We also want to acknowledge and thank all those who contributed, directly or indirectly, to the respective projects. Their collective efforts were instrumental in helping us achieve our goals.