Semantic Interoperability of UAV Control Systems using an Ontology and Multi-Protocol Mapping

Yorghos Voutos, Phivos Mylonas
Department of Informatics and Computer Engineering
University of West Attica, P.C. 122 43
Egaleo, Greece
{gvoutos, mylonasf}@uniwa.gr

Abstract **- Unmanned Aerial Vehicles (UAVs) are increasingly deployed in both civil and defense domains, yet their integration is hindered by the lack of interoperability across heterogeneous control protocols such as STANAG 4586, JAUS, and MAVLink. While STANAG 4586 provides NATO-compliant interoperability, it is often complex and resource-intensive for smaller UAVs, whereas MAVLink is lightweight and widely adopted but lacks robust security features. JAUS, in turn, offers modularity but introduces challenges in semantic consistency. This paper proposes an ontology-based semantic interoperability framework to bridge these protocols, enabling unified command, control, and telemetry integration. The ontology leverages formal representation of UAV platforms, sensors, commands, and telemetry messages, ensuring semantic alignment across heterogeneous systems. Protocol mapping is supported through ontology object properties that capture message equivalences and context dependencies. The proposed framework also incorporates semantic concepts derived from EUROSUR and CISE to extend interoperability towards maritime security and border surveillance applications. Case studies demonstrate mapping of representative commands and telemetry (e.g., TakeOffCommand, Waypoint navigation) across protocols. This ontology-based approach improves semantic consistency, reduces integration complexity, and supports multi-domain UAV operations.**

Keywords - Ontology, UAV, Interoperability, STANAG 4586, JAUS, MAVLink, Semantic Web, EUROSUR, CISE.

I. INTRODUCTION

The rapid proliferation of Unmanned Aerial Vehicles (UAVs) in military, civilian, and commercial domains has highlighted the pressing challenge of interoperability. Modern UAV ecosystems encompass a wide range of vehicles and Ground Control Systems (GCSs), often relying on diverse Command and Control (C2) protocols such as STANAG 4586, JAUS, and MAVLink. Although these protocols share conceptual similarities, they differ significantly in structure, message sets, and implementation contexts, which creates barriers to joint operation and data exchange.

STANAG 4586, developed under NATO Standardization Agreements, was designed to ensure interoperability among coalition forces, defining Levels of Interoperability (LoI) and standardizing data exchange between GCSs and UAVs. However, its complexity and limited availability of open-source implementations restrict its adoption outside defense operations. MAVLink, by contrast, has become the de facto standard for lightweight UAVs due to its simplicity, openness, and community-driven evolution, but it suffers from limited semantic richness and security vulnerabilities. JAUS, meanwhile, provides modularity and extensibility for unmanned systems but poses difficulties in aligning semantics with mission-specific ontologies.

To address these challenges, recent works have explored bridging mechanisms between MAVLink and STANAG 4586, comparative analyses of C2 protocols, and mission message handling under STANAG frameworks. However, most solutions remain syntactic, lacking a semantic layer capable of aligning concepts, commands, and telemetry data across protocols. The absence of semantic interoperability impedes consistent interpretation of mission objectives, payload operations, and situational awareness data across heterogeneous UAV platforms.

This paper proposes an ontology-based semantic interoperability framework for UAV control systems. The ontology formalizes UAV platforms, sensors, commands, and telemetry, while explicitly modeling mappings across STANAG 4586, JAUS, and MAVLink. Semantic object properties (e.g., `mappedTo`, `generatesTelemetry`, `sendsControlMessage`) enable representation of equivalences across protocol constructs. Furthermore, the ontology integrates semantic elements inspired by EUROSUR and CISE frameworks, extending applicability to border surveillance and maritime security domains. In this sense, our paper makes three primary contributions. First, we present a novel ontology designed to model the key entities and relationships within UAV systems, establishing a common semantic ground across diverse command and control protocols. Second, we build upon this foundation to create a practical framework that maps and demonstrates semantic equivalence between core commands and telemetry data in STANAG 4586, JAUS, and MAVLink. Finally, we validate the entire approach through a series of detailed case studies, illustrating how these semantic mappings function in representative UAV missions and sensor integration scenarios.

The remainder of this paper is organized as follows: Section II reviews related work; Section III presents the ontology design and implementation; Section IV discusses use-case scenarios and protocol mappings; Section V provides evaluation and discussion; and Section VI concludes with future research directions.

979-8-3315-8704-8/25/$31.00

II. Related Work

Interoperability in UAV systems has been studied from multiple perspectives, ranging from standardization frameworks to protocol bridging solutions and ontology-based approaches. This section reviews representative contributions relevant to STANAG 4586, JAUS, and MAVLink integration.

A. Ontology-Based Approaches

Early research has investigated semantic models for UAV interoperability. Zafeiriadou et al. [1] proposed an ontology-based representation of STANAG 4586 concepts, employing OWL and Protégé to model messages and bridge interoperability gaps between heterogeneous Ground Control Stations (GCSs). Their work demonstrated that semantic alignment can enhance interoperability beyond syntactic message translation, but it focused primarily on STANAG-specific structures rather than multi-protocol integration. Similarly, graph-based semantic approaches have been applied in social media analysis by G. Drakopoulos et al. [2] to assess affective coherence and contextual relationships, which could inspire future extensions of UAV ontology models to include emotional or contextual awareness in mission planning.

B. Protocol Bridging Efforts

Bridging between MAVLink and STANAG 4586 has been extensively studied. Marques et al. [3] developed a gateway as part of the ICARUS project, enabling MAVLink-based UAVs to communicate with STANAG-compliant GCSs using a lightweight Raspberry Pi bridge. This approach facilitated NATO-level interoperability for smaller UAVs but remained bound to specific message translation rules. Similarly, Khan et al. [4] proposed an algorithmic mapping framework from MAVLink to STANAG 4586 with an emphasis on security and reliability of communication. Their method provided formal translation rules but did not extend to semantic equivalences across heterogeneous systems.

C. Comparative Analyses of Protocols

Other studies have focused on systematic comparison of C2 protocols. Nam et al. [5] analyzed the strengths and weaknesses of STANAG 4586 and MAVLink, identifying complementarities that could support unification of interoperability frameworks. More recently, Reichstein et al. [6] compared the protocols with respect to autonomy support, mission transfer, and robustness, concluding that both introduce conceptual limitations that hinder seamless interoperability. Such analyses provide valuable input for identifying semantic alignment requirements.

D. Mission Data Handling and Extensions

Work on message handling under STANAG 4586 has also contributed to interoperability research. Heimsch et al. [7] developed a mission data-handling algorithm to interface UAV flight guidance systems with GCSs via STANAG 4586 AEP-84 messages. Their modular design demonstrated interoperability at the mission data level, though it remained confined to STANAG 4586 without extending to other protocols.

E. MAVLink Survey and Security Concerns

MAVLink's popularity has led to several technical surveys. Koubaa et al. [8] presented a comprehensive overview of MAVLink versions, applications, and vulnerabilities, highlighting its widespread use in ArduPilot and PX4 ecosystems. Their analysis underscored MAVLink's lightweight efficiency but also exposed significant security weaknesses, reinforcing the need for semantic and secure interoperability frameworks.

At this point it should be evident that relevant existing research approaches have made significant strides in bridging and analyzing UAV control protocols. However, most of them focus on syntactic translation or protocol-specific solutions. The herein proposed work differs significantly by introducing a semantic ontology-based framework that unifies STANAG 4586, JAUS, and MAVLink, thereby extending interoperability beyond translation toward semantic consistency and knowledge integration.

III. Ontology Design and Implementation

Ontology engineering offers a structured approach to model the semantic relations among heterogeneous systems. In the proposed framework, the ontology provides a formal representation of UAV platforms, sensors, commands, telemetry, and communication protocols, thereby enabling semantic interoperability across STANAG 4586, JAUS, and MAVLink. The design process followed standard ontology development methodologies, with emphasis on modularity and extensibility.

A. Ontology Scope and Objectives

The ontology is designed to:

i. Represent UxV platforms (UAVs, UGVs, USVs, UUVs) and their associated sensors.

ii. Model control commands and telemetry messages in a unified manner.

iii. Enable protocol mapping across heterogeneous standards.

iv. Support integration with EUROSUR and CISE frameworks for maritime security and border surveillance.

By formalizing these elements, the ontology ensures that command semantics, telemetry data, and mission objectives are consistently interpreted across different C2 environments. This approach aligns with established practices in multimedia semantic indexing, where ontologies are used to represent and retrieve complex content structures across heterogeneous sources [9].

B. Ontology Classes

Core classes include:

- **Vehicles**: `UAV`, `UGV`, `USV`, `UUV`, `UxV` (generic unmanned vehicle).
- **Sensors**: `LidarSensor`, `RadarSensor`, `SonarSensor`, `ElectroOpticalSensor`, `InfraredSensor`,

979-8-3315-8704-8/25/$31.00 ©2025 IEEE

MagneticAnomalyDetector, AcousticSensor.

- **Telemetry and Reports**: TelemetryData, MissionStatusReport, PositionReport, VelocityReport, BatteryStatus, SensorStatus.
- **Control Commands**: TakeOffCommand, LandCommand, WaypointCommand, SpeedOverride, EmergencyStopCommand, FlightModeChange.
- **Protocols**: MAVLink_Command, STANAG_4586_Command, JAUS_Command.

This taxonomy reflects the operational entities of UAV ecosystems and is aligned with specifications in STANAG 4586, MAVLink, and JAUS.

C. Object Properties

Object properties capture semantic relationships among entities:

- **isMountedOn**: links sensors to vehicles.
- **generatesTelemetry**: associates systems with their output data.
- **sendsControlMessage/ receivesControlMessage**: model the exchange of commands.
- **mappedTo**: enables cross-protocol mapping of equivalent commands or telemetry messages.
- **monitorsArea/ monitorsSensor**: describe observation tasks.
- **providesData**: links a sensor to the system consuming its output.

These relationships provide the foundation for semantic reasoning about interoperability. The use of context-aware object properties (e.g., monitorsArea, providesData) is inspired by our earlier work in context modeling for multimedia analysis, which emphasizes the role of contextual relationships in semantic interpretation [10].

D. Data Properties

Data properties capture measurable attributes:

- **hasAltitude, hasLatitude, hasLongitude** (spatial position).
- **hasSpeed, hasRange, hasResolution** (performance parameters).
- **commandID, hasPriority** (command metadata).
- **hasTimestamp** (synchronization).

By linking ontology instances to these attributes, the framework allows precise specification of UAV states and commands.

E. Protocol Mapping Mechanism

A key contribution of the ontology is the semantic mapping of protocol messages. For example:

- A MAV_CMD_NAV_TAKEOFF message in MAVLink is mappedTo a TakeOffCommand in STANAG 4586.
- A JAUS_Telemetry packet is mappedTo a MAVLink TelemetryData message.

This enables interoperability between heterogeneous GCSs and UAVs without requiring rigid translation engines, since reasoning engines can infer equivalences through ontology mappings.

F. Integration with EUROSUR and CISE

The ontology incorporates concepts from EUROSUR and CISE, which support information sharing in European border and maritime surveillance. By aligning with these frameworks, the ontology extends beyond UAV-specific semantics to cover multi-domain situational awareness, enabling future integration with broader security ecosystems.

G. Implementation

The ontology was developed using OWL 2 in Protégé, with reasoning support for consistency checking and semantic query execution. Protocol message definitions were formalized as ontology classes and object properties, while instance-level mappings illustrated cross-protocol interoperability. This modular design ensures extensibility as new UAV protocols or standards emerge.

IV. Case Studies and Scenarios

To validate the applicability of the proposed ontology-based interoperability framework, representative scenarios were defined. These scenarios demonstrate how semantic mappings enable communication between heterogeneous protocols and ensure consistent interpretation of UAV commands and telemetry.

A. Command Mapping Across Protocols

A fundamental use case is the execution of flight control commands across different communication standards.

- In MAVLink, the MAV_CMD_NAV_TAKEOFF message is issued to initiate a UAV takeoff.
- In STANAG 4586, an equivalent TakeOffCommand message is defined with additional attributes such as altitude and mission phase identifiers.
- In JAUS, takeoff is represented as a generic PrimitiveDriver_SetWrenchEffort message with vehicle control parameters.

Through the ontology's mappedTo property, these commands are semantically aligned, allowing a Ground Control Station (GCS) operating in one protocol to issue commands that are understood by UAVs controlled through

979-8-3315-8704-8/25/$31.00 ©2025 IEEE

another.

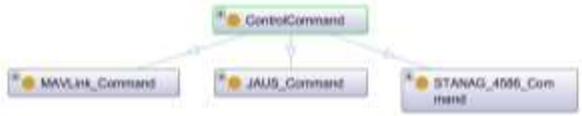

Fig. 1. Illustrates the ontology-based mapping of Control commands across MAVLink, STANAG 4586, and JAUS.

B. Telemetry Data Integration

Another scenario involves telemetry data harmonization. UAV platforms typically transmit position, velocity, and system health through protocol-specific message structures:

Another scenario involves telemetry data harmonization. UAV platforms typically transmit position, velocity, and system health through protocol-specific message structures:

- **MAVLink** provides `GLOBAL_POSITION_INT` and `BATTERY_STATUS`.
- **STANAG 4586** defines `PositionReport`, `VelocityReport`, and `BatteryStatus`.
- **JAUS** offers telemetry through `ReportGlobalPose` and `ReportStatus` messages.

Using the ontology, these heterogeneous telemetry messages are unified under abstract classes such as `TelemetryData`, enabling semantic reasoning for situational awareness.

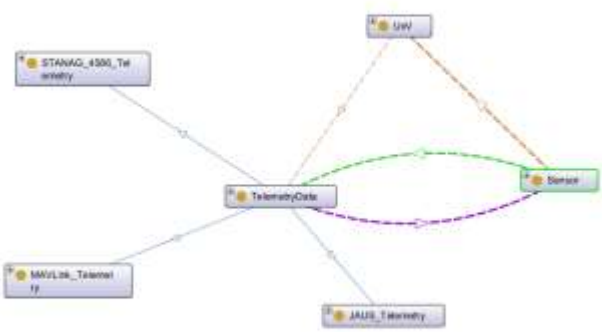

Fig. 2. Presents the ontology-driven integration of telemetry messages from multiple protocols.

C. Multi-Sensor Fusion Scenario

The ontology also supports scenarios involving multi-sensor payloads. For example, a UAV equipped with `RadarSensor` and `InfraredSensor` can report environmental observations:

- Radar detects moving objects in a monitored area (`monitorsArea`).
- Infrared provides complementary thermal signatures (`monitorsSensor`).

Ontology alignment ensures that these sensor outputs are semantically integrated and can be interpreted consistently by GCS applications, regardless of whether data was transmitted through MAVLink, JAUS, or STANAG 4586. This fusion process is analogous to traditional knowledge-assisted image analysis systems that leverage context and spatial optimization to improve semantic interpretation of visual data, like the one introduced by Papadopoulos et al. [11].

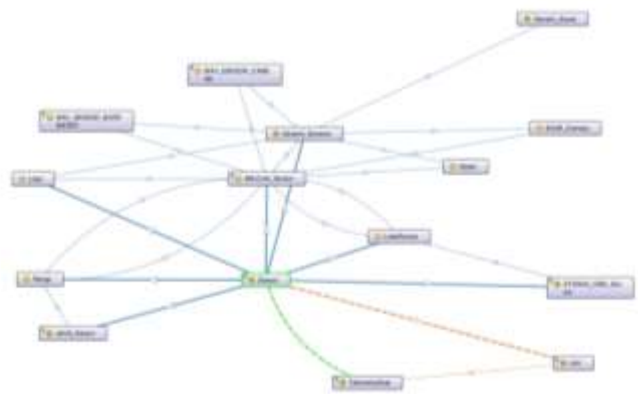

Fig. 3. Depicts the ontology-based integration of sensor data in a multi-protocol UAV environment.

D. Maritime Surveillance Application

A domain-specific application scenario highlights the integration of UAV data into broader situational awareness frameworks such as EUROSUR and CISE.

- UAVs collect surveillance data over maritime borders using MAVLink-enabled drones.
- Through ontology mappings, the data is translated into STANAG 4586-compliant reports.
- The extended ontology aligns these reports with EUROSUR event and asset models, enabling seamless integration with multinational maritime surveillance systems. Such integration can be further enhanced by geo-clustering techniques that detect and semantically characterize areas-of-interest, as demonstrated by Spyrou et al. in spatial data analysis for surveillance applications [12].

This scenario underscores the framework's potential for extending UAV interoperability into multi-domain security applications.

These case studies demonstrate that the proposed ontology provides semantic mappings for UAV commands, telemetry, and sensor data, enabling interoperability across MAVLink, JAUS, and STANAG 4586. By incorporating EUROSUR and CISE concepts, the ontology further extends interoperability toward cross-domain surveillance and defense applications.

V. Evaluation and Discussion

The evaluation of the proposed ontology-based interoperability framework focuses on three aspects: (i) comparative analysis with existing bridging solutions, (ii) semantic expressiveness and extensibility, and (iii) security and operational considerations.

A. Comparison with Bridging Solutions

Prior efforts have predominantly relied on protocol bridges or gateways to enable interoperability. Marques et al. implemented a hardware-based MAVLink-STANAG 4586 gateway within the ICARUS project, enabling NATO GCSs to control MAVLink-based UAVs. Similarly, Khan et al. [4] proposed an algorithmic mapping from MAVLink to STANAG 4586, emphasizing encryption and secure message handling. While effective, these solutions remain syntactic translations, requiring predefined mappings for each message type.

In contrast, the ontology-based approach provides a semantic abstraction layer. Instead of directly translating messages, commands and telemetry are mapped to higher-level concepts (e.g., `TakeOffCommand`, `TelemetryData`), which can then be instantiated in different protocols. This reduces duplication and allows new mappings to be integrated without modifying existing translation rules.

B. Comparative Protocol Analyses

Nam et al. conducted a detailed comparison of STANAG 4586 and MAVLink, highlighting complementary strengths: STANAG offers robustness and doctrinal completeness, while MAVLink emphasizes simplicity and real-time efficiency. Schopferer and Jünger [6] further showed that both protocols impose conceptual limitations on autonomy, mission transfer, and extensibility.

The proposed ontology mitigates these limitations by providing protocol-independent abstractions. For example, the semantic definition of a `WaypointCommand` captures essential mission semantics, even if STANAG and MAVLink encode the data differently. Thus, autonomy-related extensions can be supported at the ontology level, independent of protocol constraints.

C. Mission Data Handling and Extensions

Recent work by Heimsch et al. [7] demonstrated the value of modular mission data handling using STANAG 4586 AEP-84 for UAV–GCS communication. Their algorithm enabled consistent mission definition, but was limited to STANAG-compliant architectures. In contrast, the ontology generalizes mission semantics, allowing equivalent mission definitions (e.g., takeoff, loiter, return-to-base) to be mapped across STANAG, JAUS, and MAVLink. This flexibility extends mission-level interoperability to heterogeneous UAV fleets.

D. Security and Reliability Considerations

MAVLink’s vulnerabilities have been widely documented, including susceptibility to eavesdropping and command hijacking. Khan et al. [4] addressed these issues by proposing encryption-based secure mappings, but this still relied on message-level translation. By introducing a semantic layer, the ontology allows security mechanisms to operate at higher abstraction levels—for instance, reasoning engines can validate whether a received command is semantically consistent with mission objectives before execution.

E. Semantic Expressiveness and Extensibility

Unlike bridges, which must be re-engineered for each new protocol, the ontology can be extended incrementally. For example, emerging standards (e.g., for swarm UAV coordination) can be modeled by adding new ontology classes and properties without disrupting existing mappings. Moreover, by aligning with EUROSUR and CISE models, the ontology expands UAV interoperability into multi-domain surveillance ecosystems, a capability not addressed by existing approaches.

The proposed ontology-based framework advances beyond traditional gateway approaches by enabling semantic interoperability. It ensures protocol-agnostic representation of UAV entities, supports extensibility for new standards, and offers opportunities for semantic validation and enhanced security. While bridging solutions provide practical short-term interoperability, the ontology establishes a scalable foundation for long-term integration across heterogeneous UAV systems.

VI. Conclusion and Future Work

This paper proposed an ontology-based semantic interoperability framework for UAV control systems, addressing the challenges of integrating heterogeneous communication protocols such as STANAG 4586, JAUS, and MAVLink. By formalizing UAV platforms, sensors, control commands, and telemetry into an ontology, the framework enables consistent semantic alignment across protocols. The use of object properties such as `mappedTo`, `generatesTelemetry`, and `sendsControlMessage` provides a structured mechanism for expressing cross-protocol equivalences, while data properties capture essential operational attributes.

Case studies demonstrated the framework’s ability to unify flight commands (e.g., `TakeOffCommand`), telemetry streams, and multi-sensor payload data across diverse protocols. Furthermore, the integration of EUROSUR and CISE concepts extends the framework to maritime security and border surveillance domains, illustrating its applicability to multi-domain operations.

In comparison with existing bridging solutions, the proposed ontology-driven framework offers several key benefits over conventional bridging techniques. First, it establishes a consistent semantic layer that captures the core meaning of mission commands and data, making them independent of any specific protocol's syntax. This decoupling ensures that intent is preserved across different systems. Furthermore, the design is inherently extensible; integrating a new protocol or a novel mission construct doesn't require building a new gateway from scratch. Instead, it can be accommodated by extending the ontology, making the system adaptable to future technologies. Finally, the semantic foundation opens the door to enhanced security measures. By understanding the context and meaning of a command, the system can perform logical validation against the current mission state, providing a crucial layer of security that works in tandem with traditional cryptographic methods.

Despite these advantages, some limitations remain. The ontology currently assumes abstract representations of UAV platforms without detailed hardware-specific specifications. In addition, real-time performance evaluation of semantic reasoning in operational UAV missions has yet to be assessed. Thus, our future research will progress along three main paths. The immediate next step involves building a functional prototype to test the ontology within a middleware system. This will allow us to evaluate its performance and interoperability in live, multi-UAV environments. Alongside this, we plan to bolster the framework's security by weaving semantic validation checks directly into the command pipeline. This approach would add a logical layer of defense to counter the vulnerabilities found in lightweight protocols like MAVLink. Finally, we intend to broaden the ontology's scope to address new operational challenges, such as coordinating UAV swarms, enabling autonomous mission bargaining between systems, and facilitating seamless integration with the wider ecosystem of IoT devices. By introducing semantic interoperability, this work contributes to a scalable and future-proof foundation for integrating UAV systems across heterogeneous standards and domains.

Acknowledgments

The financial support by the European Union and Greece (SA/2021-2022/Innovation for sea/shore, and/or land border surveillance (operational testing in pilot projects), under the Instrument for Financial Support for Border Management and Visa Policy (BMVI), for the project "REal-time ArtifiCial InTellIgence for BOrders Surveillance via RPAS data aNalytics to support Law Enforcement Agencies - REACTION" with MIS code: 6005579, is gratefully acknowledged.

The authors also acknowledge the use of OpenAI's ChatGPT in assisting with the language editing of this manuscript, in compliance with IEEE guidelines on AI-generated text. All intellectual contributions, conceptual design, and research content are original to the authors.

References

[1] Z. Zafeiriadou, P. Kosmopoulos, and S. Christodoulou, “Ontology-based Integration of STANAG 4586 for UAV Interoperability,” in Proc. Int. Conf. Military Communications and Information Systems (ICMCIS), IEEE, 2018.

[2] G. Drakopoulos, I. Giannoukou, Ph. Mylonas, S. Sioutas, “A graph neural network for assessing the affective coherence of Twitter graphs,” 2020 IEEE International Conference on Big Data (Big Data), 3618-3627, 2020.

[3] H. Marques, L. Marques, and J. Barata, “ICARUS Project: A STANAG 4586 Gateway for MAVLink-based UAVs,” in Proc. OCEANS 2017 – Aberdeen, IEEE, 2017. doi: 10.1109/OCEANSE.2017.8084866.

[4] N. A. Khan, N. Z. Jhanjhi, and S. Brohi, “Proposing an Algorithm for UAVs Interoperability: MAVLink to STANAG 4586 for Securing Communication,” in Proc. of International Conference on Advances in Cyber Security (ACeS), pp. 515-525, Springer, 2021. doi: 10.1007/978-981-16-3153-544.

[5] G. Nam, J. Go, C. Kwon, and S. Jeong, “A Study on the Analysis and Improvement of STANAG 4586 / MAVLink Protocol for Interoperability Improvement of UAS,” Journal of the Korea Institute of Military Science and Technology, vol. 23, no. 6, pp. 618–638, Dec. 2020. doi: 10.9766/KIMST.2020.23.6.618.

[6] L. Reichstein, S. Schopferer, and F. Jünger, “A Comparison of Command and Control Communication Protocols for Unmanned Aircraft: STANAG 4586 vs. MAVLink,” in Proc. Int. Conf. Unmanned Aircraft Systems (ICUAS), pp. 1413–1422, IEEE, June 2022. doi: 10.1109/ICUAS54217.2022.9836194.

[7] D. Heimsch, M. Speckmaier, D. Gierszewski, F. Schwaiger, Z. Mbikayi, and F. Holzapfel, “Development and Implementation of a Mission Data-Handling Algorithm for an Automatic Flight Guidance System,” Aerospace, vol. 11, no. 2, p. 115, Jan. 2024. doi: 10.3390/aerospace11020115.

[8] A. Koubaa, A. Allouch, M. Alajlan, Y. Javed, A. Belghith, and M. Khalgui, “Micro Air Vehicle Link (MAVLink) in a Nutshell: A Survey,” IEEE Access, vol. 7, pp. 87658–87680, 2019. doi: 10.1109/ACCESS.2019.2924410.

[9] Ph. Mylonas, T. Athanasiadis, M. Wallace, Y. Avrithis, S. Kollias, “Semantic representation of multimedia content: Knowledge representation and semantic indexing,” Multimedia Tools and Applications 39 (3), 293-327, 2008.

[10] Ph. Mylonas, Y. Avrithis, “Context modelling for multimedia analysis,” in Proc. of 5th International and Interdisciplinary Conference on Modeling and Using Context (CONTEXT 2005), Paris, France, 2005.

[11] G. T. Papadopoulos, Ph. Mylonas, V. Mezaris, Y. Avrithis, I. Kompatsiaris, “Knowledge-assisted image analysis based on context and spatial optimization,” International Journal on Semantic Web and Information Systems (IJSWIS) 2 (3), 2006.

[12] E. Spyrou, M. Korakakis, V. Charalampidis, A. Psallas, Ph. Mylonas, “A geo-clustering approach for the detection of areas-of-interest and their underlying semantics,” Algorithms 10 (1), 35, 2017.