Towards an Open-Source Simulation Platform for Counter-UAS Sensor Fusion

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***Abstract*—The Joint Research Centre (JRC) of the European Commission (EC) is developing the Sensor Data Fusion and Visualization (SeDaFuV) Counter-Unmanned Aircraft System (C-UAS) platform to enable and advance an open research on C-UAS multi-modal sensor fusion. An overview of the software is presented, together with key results and open challenges.**

***Index Terms*—Counter-Unmanned Aircraft Systems (Counter-UAS), Unmanned Aerial Vehicle (UAS) Tracking**

I. Introduction

The increasing discovery of drones in restricted airspaces is causing significant disruptions globally, requiring the development of effective Counter-Unmanned Aircraft System (C-UAS) solutions [1]. Within this context, C-UAS require advanced multi-modal sensor fusion techniques to accurately detect, track, and identify (DTI) drones [2] and guarantee sufficient reliability and robustness in complex environments. Given that current solutions often lack the capability to implement and/or simulate realistic multi-sensor environments, this contribution is aiming in developing a comprehensive simulation platform that models and evaluates multi-sensor DTI of drones, thereby assisting C-UAS research, development, and testing.

II. Software Overview

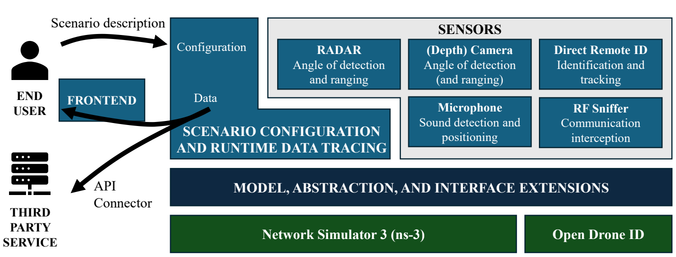

Fig. 1. Software architecture of the proposed contribution. The project's code relies on a strong foundation of libraries (blue), building a set of model extensions and abstraction interfaces (dark blue) to offer the characteristic high-level functionalities (green). Both end users and third party services can receive data through a dedicated frontend and APIs.

The Sensor Data Fusion and Visualization (SeDaFuV) simulator provides foundational classes to help build models for various sensor types commonly found in C-UAS solutions, including radio detection and ranging (RADARs), radiofrequency (RF) sensing devices, electro-optical and infrared (EO/IR) cameras, and microphone arrays. These models rely on physical propagation phenomena commonly found in these sensor modalities, which have been studied and implemented. The software architecture is shown in Figure 1.

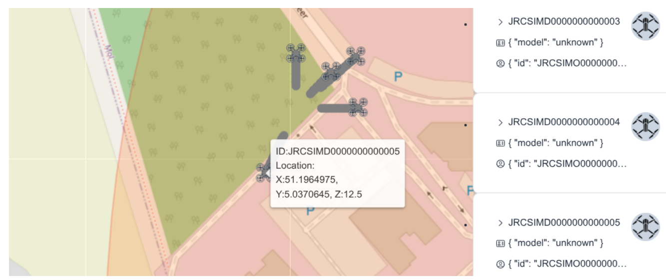

Fig. 2. Screenshot of the frontend interface map, showing five drones being detected through DRI. The position of the drone is displayed in a dedicated tooltip available when the user cursor hovers over a drone icon, while identification data are displayed on the right.

The drones are modeled as a set of complex multi-system entities, encompassing the possibility to be composed by one or multiple transmission modalities for an accurate construction of the RF signature. Moreover, they present additional properties in order to present their own RADAR cross section (RCS) and an association with a remote pilot, enabling realistic simulation of both line of sight (LoS) and beyond visual line of sight (BVLoS) flight operations. The simulated drones exhibit mobility patterns implemented as both stationary (i.e., hovering) or a 3D disc-bounded waypoint-based random walk, which helps defining realistic flight trajectories within defined operational areas.

Regarding the RADAR-based sensing, the simulator provides a foundational set of classes: starting from the RADAR itself, it is modeled as a parabolic rotating antenna that transmits a Chirp waveform signal. Such signal is modeled, by default, using the Friis equation propagating it at the speed of light. Such signal is reflected back by the drones, which acts as scatterers, thereby reflecting back the signal according to the drone RCS. All the models have a broad range of parameters to ensure a high degree of customizability, scenario design flexibility, and modeling extensibility.

978-3-903176-77-5

For what concerns RF sensing, instead, the software implements a hierarchical architecture, incorporating different sensing modalities, such as raw sniffing, Wireless Fidelity (Wi-Fi) telemetry interception, and DRI transmission and decoding. Raw sniffing is simulated by discretizing the electromagnetic spectrum into frequency bands defined by a starting frequency, an instantaneous bandwidth and a number of bands to analyze. Furthermore, the receiver implements a sensitivity threshold to detect incoming signals and evaluating their angle of arrival (AoA). The receiver is based on the uniform planar array model, enabling directional sensing capabilities, e.g., multiple signal classification (MUSIC), for precise direction finding. The raw RF receiver converts the received power spectral density measurements and AoA into timestamped detection events, which are sent to a detection application.

To comply with the design of the raw RF sensing device, an RF transmitter is provided, which implements a generic RF emission model that generates continuous-wave or modulated signals across specified spectrum bands. The transmitter supports both advanced antenna array configurations for proper beam forming and multiple input multiple output (MIMO) channel modeling. Regarding the Wi-Fi sniffing capabilities, the simulator's relevant classes are able to periodically transmit packets containing the position of the drone, augmented with configurable noise patterns. The transmitter obeys to IEEE 802.11 family standard with configurable power control mechanisms and sleep intervals, in order to simulate accurate resource-constrained Unmanned Aerial System (UAS) flights and protocol-aware sniffing operations. As an extension of Wi-Fi sniffing, a transmitter/receiver pair of devices are provided to simulate realistic DRI communications, modeled according to the ASD-STAN prEN 4709-002:2023 standard and encoding data as IEEE 802.11 neighbor awareness networking (NAN) frames. The implementation models a complete DRI protocol stack, including the drone basic identification data, location, authentication, self-identification, system information, and operator identification messages.

Concerning the EO/IR detection systems, the platform provides physical-based detection models that account for geometric field-of-view constraints, temporal sampling characteristics, and environmental detection limitations. Indeed, the optical detection subsystem is implemented through a hierarchical camera model that provides both 2D and 3D detection capabilities (with ranging). The camera models operate through a spherical coordinate detection evaluation, while ranging is implemented by considering its sampling rate, near-field occlusions, and far-field resolution limitations through a configurable set of parameters related to the camera capabilities, in order to abide to certain focal length limitations or atmospheric visibility conditions. Such modeling allows the simulation of a wide range of camera types, from classical lens-based sensors to light detection and ranging (LiDAR) and stereo vision configurations.

Regarding sound detection, instead, the simulator provides microphone array models that would allow the study of proximity-based detection algorithms and AoA estimation. The aforementioned sensors generate events that are handled at their own respective detection applications, which in turn feed data to a sensor fusion pipeline. This pipeline would rely on a representation fusion model encompassing one or multiple modalities. Finally, a report module allows the fused information to be encoded according to a JavaScript Object Notation (JSON) schema, which is then transmitted over Advanced Message Queueing Protocol (AMQP) and Hypertext Transfer Protocol (HTTP) server-sent events (SSE), allowing a wide compatibility with high-level user interfaces that can be developed with their own stack.

III. Technical Approach

The foundation of the technical implementation rests upon the open source Network Simulator 3 (ns-3) project*. The platform leverages a curated list of modules, extending them with new components and features to act both as a network-based and physical real-time simulator. This allows the usage of stable and established models, such as the spectrum propagation ones with realistic beam pattern simulation, directional gain characteristic, and spatial diversity modeling that reflects real-world antenna system behavior, while ensuring the adoption of a flexible and extensible software framework for C-UAS research purposes. The platform also includes the OpenDroneID library† to provide standard-compliant DRI support, in order to properly simulate regulatory-compliant communications. Moreover, the simulator adopts Apache Qpid Proton library‡ to publish detection reports over AMQP and cpp-httplib§ with SSE support for real-time web-based communications. Finally, modern C++20 language features were adopted to ensure memory safety and project extensibility.

IV. Conclusion, Limitations, and Future Work

The SeDaFuV platform has been briefly presented. It remains an ongoing work at the Joint Research Centre (JRC), as it is currently limited by the following aspects: (i) introduce multi-target tracking models with track association and pruning; (ii) integrate with advanced propagation models from ITU-R and Okumura-Hata; (iii) evolve ideal visual and sound detection strategies with more realistic models; and (iv) validate the introduced simulation models. Along with these limitations, future work activities will focus on the development of reference models for multi-modal sensor fusion.

References

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*https://www.nsnam.org/

†https://github.com/opendroneid/opendroneid-core-c

‡https://qpid.apache.org/proton/

§https://github.com/yhirose/cpp-httplib