BSENSED – A Multi-Sensor-based Digital Twin Framework for Enhanced Border Surveillance and Situational Awareness

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***Abstract*—In this paper, we present BSENSED, a currently under-development digital twin framework for enhanced border surveillance and situational awareness. Built from publicly available geospatial data and continuously updated with information acquired by a multi-sensor payload deployed on fixed infrastructure and/or vehicles, BSENSED aims to maintain an up-to-date virtual representation of the environment. The framework is designed to support border surveillance through the detection and localization of people and vehicles, while also enhancing operator situational awareness and enabling the teleoperation and training of uncrewed robotic platforms operators.**

***Index Terms*—Digital Twin, Environment Reconstruction, Data Fusion, Object Detection, Uncrewed Ground Vehicles.**

I. Introduction

Border surveillance, whether on infrastructure or in natural terrain, is a complex and demanding task. Modern surveillance systems can generate a vast amount of heterogeneous data, often overwhelming operators and making real-time situational awareness difficult to maintain. Robotic platforms, such as uncrewed ground vehicles (UGVs), may assist personnel in surveillance and reconnaissance missions. However, their successful deployment requires adequate operator training and confidence in the system's capabilities.

Digital twin technology is emerging as a crucial tool for integrating physical and virtual systems, with applications in various domains including manufacturing [1], healthcare [2], or agriculture [3]. By combining real-time data acquisition with high-fidelity virtual representations, digital twins can support enhanced situational awareness, risk assessment, and decision-making. Despite recent advances, the application of digital twins to border surveillance remains underexplored and presents several research challenges, including real-time environmental reconstruction, multi-sensor fusion, and the integration of robotic platforms.

To address these challenges, this paper presents BSENSED, a digital twin framework for enhanced border surveillance and situational awareness. By combining *a priori* geospatial information with real data acquired from a multi-sensor payload, BSENSED continuously updates a virtual representation of the environment. This capability aims to support border surveillance, improve operator awareness, and facilitate the teleoperation and training of robotic systems.

As a work in progress, this paper presents the overall architecture of the BSENSED framework and discusses the current implementation status of its main components, including the digital twin environment and the multi-sensor payload.

The main contribution of this work is the proposed architecture that enables continuous digital twin updates through the fusion of *a priori* geospatial information and real-time multi-sensor data for border surveillance applications.

II. BSENSED Framework

Figure 1 presents the framework for the BSENSED project. This framework consists of two main components: the digital twin and a standalone multi-sensor payload that gathers, processes, and fuses data to provide real-time complementary information.

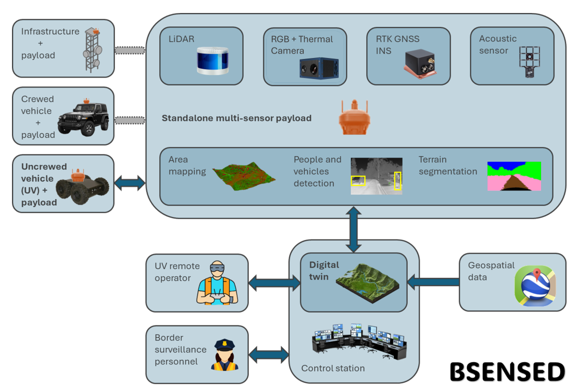

Fig. 1: The BSENSED framework.

A. Digital Twin Environment

Currently being developed in *Unreal Engine 5*, a state-of-the-art game engine that is able to render realistic scenes in real-time, the digital twin environment is built in two stages:

- Firstly, publicly available geospatial data are used to create an *a priori* digital environment of our world. These

data can include terrain elevation and other georeferenced features, such as buildings, roads, and trees. The resulting world will serve as an initial estimate for our digital twin.
- Then, data from a multi-sensor payload are collected and processed in real-time so that the *a priori* digital twin can be updated. This includes not only updates to the static digital environment (for example, the addition of features not present in the original geospatial data and changes to terrain and/or existing features), but also the inclusion of detected dynamic objects, such as people and vehicles.

Deployed within a control station, this digital twin serves a dual purpose: it ensures effective monitoring and border surveillance while delivering an enhanced teleoperation experience for remote operators of UGVs. In addition, the digitally reconstructed environment can serve as a low-cost and risk-free offline simulation environment for personnel training.

B. Multi-Sensor Payload

The multi-sensor payload is one of the main sources of information for the digital twin (see Figure 2a). It is composed of a set of sensors, including a 3D LiDAR, 3 visible and 1 thermal cameras, a high-precision inertial navigation system (INS) and an acoustic sensor. Due to its lightweight and modular design, it can be attached to any vehicle (crewed or uncrewed) or to fixed infrastructure. Powered by an *Nvidia Jetson Orin AGX* onboard computer, it can run a multitude of data-processing algorithms, such as simultaneous localization and mapping (SLAM) and object detection. Both raw and processed sensor information can be fed into the digital twin via WiFi or mobile communications.

(a) Multi-sensor payload.

(b) Digital environment reconstruction.

Fig. 2: Preliminary developments.

III. Preliminary Developments

Several core components of the BSENSED framework have already been implemented. Regarding the payload, it has been assembled, as shown in Figure 2a, and all the sensors have been integrated with the onboard computer. It is capable of acquiring synchronized multi-sensor data, which can be directly integrated into the project pipeline and also serve as a benchmark for the validation and comparison of algorithms. In addition, the payload currently supports real-time SLAM via FAST-LIVO2 [4] and real-time detection of people and vehicles using visible and thermal imagery, based on [5].

As for the digital twin, it is currently initialized using a high-resolution digital elevation map (DEM), which is overlaid with publicly available satellite imagery. Then, the static environment of the digital twin is updated in real time based on the 3D point cloud map generated by the SLAM algorithm, as shown in Figure 2b. The payload is also dynamically represented within the digital twin through the SLAM algorithm's output pose.

IV. Conclusions & Future Work

In this paper, we presented BSENSED, a digital twin framework for border surveillance and enhanced situational awareness. The current implementation integrates a multi-sensor payload for real-time perception and data acquisition with a digital twin environment initialized from geospatial data and continuously updated with SLAM-derived information.

Preliminary results demonstrate the feasibility of the proposed approach, while also revealing limitations in reconstruction fidelity when relying on point-cloud-based representations. To address this limitation, current research focuses on improving scene reconstruction using 3D Gaussian Splatting [6], specifically through the Gaussian-LIC framework [7]. Future work will also focus on fusing *a priori* with real-time data, incorporating dynamic objects such as people and vehicles into the digital twin, integrating the framework with UGV platforms, and developing a digital-twin-based training simulator for UGV operators.

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