Real-Time Localization of Objects using Radio Frequency Propagation in Digital Twin

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***Abstract*—A digital twin is a virtual representation of a physical object, system, or process that is used to simulate, predict, and optimize its performance in real-time. This digital counterpart is created using data from sensors and other sources to reflect the state and behavior of the physical counterpart. In this demo paper, we introduce an innovative real-time object localization system within a digital twin, designed to detect and locate objects within an environment. We demonstrate our system using a digital twin setup that leverages Blender tool and RF propagation with NVIDIA's Sionna RT. Our results illustrate that real-time object localization can be effectively achieved through our framework. This demo offers valuable insights into the potential of our framework as a reliable and efficient method for performing real-time object localization.**

***Index Terms*—Digital Twin, RF propagation, Object localization.**

I. Introduction

Precise localization in an environment provides significant benefits, boosting functionality and efficiency in fields such as robotics and automation, augmented reality and virtual reality, smart homes and Internet of Things, as well as security and surveillance. The capability to accurately pinpoint the position and orientation of objects is crucial for technological advancement and enhancing the quality of numerous applications that require detailed spatial awareness and control.

Machine learning (ML)-based objects localization. Such precise object localization involves using machine learning-based algorithms and models to identify and locate objects within images or videos [1]. Also, the rapid advancement of object localization techniques have been largely credited to the development of deep convolutional neural networks and the enhanced computing power of GPUs [1]. By training on large datasets, these models learn to recognize patterns and features that distinguish different objects.

Concerns with ML-based object localization. However, training those ML models requires availability of relevant data in large scale. For example, for a ML-based model to detect and localize a 'Table' or a 'Chair', we need to have access to thousands of labeled images which include those objects [1]. This requirement makes the machine learning based methods prone to security risk and adversarial attacks where the attacker can manipulate the training data to degrade the localization performance [2]. Additionally, the ML-based object localization using images has limitations in capturing objects that are within non-line-of-sight (NLOS).

Digital twin-based object localization: motivation and contributions. Motivated by the previous challenges, the research

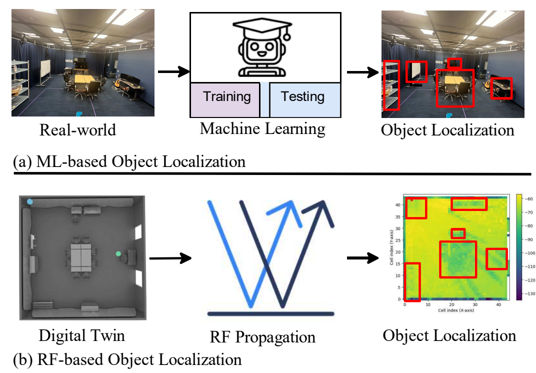

Fig. 1. ML-based object localization vs. RF-based object localization.

community is now investigating the use of digital twins for localizing objects within the digital space [3]. Essentially, a digital twin serves as a dynamic digital counterpart to a real-world scenario, bridging the gap between physical systems and digital environments. In this paper we introduce a real-time object localization framework which uses the RF propagation modeling to detect objects within a digital twin. The proposed approach does not require large training datasets and excels at capturing NLOS scene objects through accurate configuration and positioning of the scene's radio devices. This technique uses ray-tracing (RT) which simulates advanced lighting effects such as reflections, refractions, diffractions, and scatterings with high fidelity and realism [4]. Our proposed approach comes with an initial cost of setting up a digital twin of the real world, or can be integrated to any existing digital twin environment. The illustrative benefits of employing the proposed RF propagation for object localization are shown in Fig. 1. Overall, the paper contributions are as follows:

1. Designing digital twin scenarios and RF propagation models using publicly available Blender [5] and NVIDIA's Sionna RT [4] tools.

2. Generating propagation characteristics through a systematic methodology by utilizing ray-tracing within the digital twin.

3. Detecting and locating real-time objects using our indoor lab setup as example scenes.

II. SYSTEM DESIGN AND IMPLEMENTATION

We design and implement this work on an Intel (R) Xeon w7-2495x, Windows 10 system, the setup incorporates Blender LTS v3.6.12 [5], and NVIDIA's Sionna RT [4]. The overall flow of system design is shown in Fig. 2.

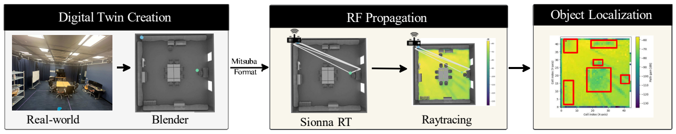

Fig. 2. The overall pipeline of the proposed design.

Digital twin creation. We use Blender tool to digitally replicate two real-world lab indoor environments. We then assign electromagnetic properties to all the objects in both scenes to ensure accurate calculations and realism. These scenes are subsequently exported to Sionna RT using the `Mitsuba (.xml)` format. Note that Blender is exclusively used for generating digital twins and does not play any role in object localization. The process of creating digital twins is detailed in our previous works [6], [7]. The digital twins of both scenes are displayed alongside their real-world counterparts in Fig. 3.

Propagation modeling using Sionna RT. The created scenes are imported into Sionna RT for propagation modeling. For each scene, we include characteristics such as the transmitter array, receiver array, camera, scene transmitter, and receiver. To ensure precise propagation, each scene transmitter is placed on the ceiling and the receiver is positioned on the floor. The optimal configuration for both scenes after optimization is `max-depth = 5` and `num-samples = 65`.

Object localization. When signals are transmitted from the transmitter and interact with objects in the environment, their material properties (such as wood, metal, concrete, and brick) cause signal interference, resulting in distinct shapes on the map. These shapes, highlighted in green, indicate the presence and characteristics of obstacles based on their interference patterns. Additionally, the shapes provide insights into the types of objects present in the environment. From the Fig. 3 (d) and (h), we observe 6 and 14 number of objects in Scenario 1 and 2, respectively. Out of 14 objects in the Scenario 2, 11 of them looks small square shaped, which matches with the 11 chairs present in the real-world scene. On the other hand, we could only detect 7 objects out of 14 real-world objects within the Scenario 1, due to the fact that the RF propagation of the 8 small chairs got merged with the propagation of the big center table. The coarse shapes of the detected objects in digital twins resembles the shapes of the furniture present in the real-world images.

III. Demonstration

For our demo, we will set up a laptop using Jupyter Notebook as the integrated development environment (IDE) with NVIDIA's Sionna RT installed to carry out the propagation characteristics of different environments. Attendees will observe the importation of two distinct indoor scenes from Blender into Sionna RT, along with the use of machine learning libraries for visualization. We will demonstrate how to load the scenes and perform ray-tracing for radio propagation by configuring the antenna arrays for all transmitters and receivers, and adding the respective transmitters and receivers for these scenes. Then the carrier frequency for both scenes will be set to 2.4 GHz. Next, we will compute and display the propagation paths within these scenes. Lastly, we will simulate coverage maps to illustrate how the signal interacts with objects within the scenes. Attendees will have the opportunity to compare real-world scenes with their digital twin counterparts, demonstrating real-time object localization by clearly identifying the location and orientation of objects in the digital twin scenes.

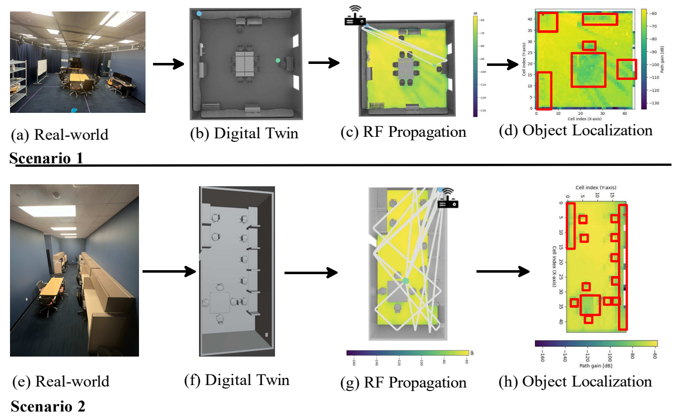

Fig. 3. Illustration of the scenes created for object localization from the real-world environment. In each scene, the transmitter is mounted on the room's ceiling, while the receiver is placed in an open space on the ground. The red boxes in both created scenes accurately depict the objects, highlighting their shapes, sizes, and positions.

IV. Conclusion

This demo paper presents an innovative system for real-time object localization using RF propagation within an environment. Our approach involves creating a digital twin of the physical space, performing propagation characteristics, and identifying object locations and shapes within that space. Through extensive experimental validation in two scenarios, we demonstrate that our system can accurately determine objects shapes and orientation without requiring training data. Future research will focus on incorporating both real-world and digital twin scenes to characterize other properties of an object by fusing image-based machine learning and RT-based RF propagation modeling.

References

[1] Z. Zou, K. Chen, Z. Shi, Y. Guo, and J. Ye, "Object detection in 20 years: A survey," *Proceedings of the IEEE*, vol. 111, no. 3, pp. 257–276, 2023.
[2] I. Goodfellow, J. Shlens, and C. Szegedy, "Explaining and harnessing adversarial examples," in *International Conference on Learning Representations*, 2015. [Online]. Available: http://arxiv.org/abs/1412.6572
[3] J. Morais and A. Alkhateeb, "Localization in digital twin mimo networks: A case for massive fingerprinting," *arXiv preprint arXiv:2403.09614*, 2024.
[4] J. Hoydis, F. A. Aoudia, S. Cammerer, M. Nimier-David, N. Binder, G. Marcus, and A. Keller, "Sionna rt: Differentiable ray tracing for radio propagation modeling," *arXiv preprint arXiv:2303.11103*, 2023.
[5] B. O. Community, *Blender - a 3D modelling and rendering package*, Blender Foundation, Stichting Blender Foundation, Amsterdam, 2018. [Online]. Available: http://www.blender.org
[6] S. Amatare, M. Samson, and D. Roy, "Testbed design for robot navigation through differential ray tracing," in *2024 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2024, pp. 173–174.
[7] S. Amatare, G. Singh, M. Samson, and D. Roy, "RagNAR: Ray-tracing based Navigation for Autonomous Robot in Unstructured Environment," in *IEEE Global Communications Conference*, 2024.