Testbed Design for Robot Navigation through Differential Ray Tracing

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***Abstract*—In recent years, there has been a surge in interest towards the refinement of autonomous systems, with a specific focus on advancing robot navigation through the effective utilization of sensing data. However, this heightened focus has brought forth significant privacy concerns. To address these issues and concurrently harness the advantages of sensing-based robot navigation, this paper introduces a testbed, designed to facilitate robot navigation via the application of a Differential Ray Tracing (DRT) approach. We delineate a systematic pipeline for constructing such a testbed, employing Lidar sensors from commercially available handheld devices. The acquired data is integrated into NVIDIA's Sionna tool. This integration process serves to enable the formulation of Radio Frequency (RF) propagation models tailored for mobile robots operating within indoor environments. This paper represents a significant stride toward the practical implementation of robot navigation by employing the RT-generated RF propagation of the environment. Through our proposed testbed, we contribute to the development of a robust and privacy-preserving approach for robot navigation in autonomous environment.**

I. Introduction

Sensor-Enabled Robot Navigation. Ongoing efforts led by 3GPP aim to broaden performance criteria tailored for various vertical applications, spanning vehicle-to-everything communication, uncrewed aerial vehicles, and industrial robotics, to name a few. [1]. Complementarily, 3GPP's active stage-1 study within Release 19 concentrates on identifying critical gaps crucial for coordinating collective operations among multiple service robots navigating unstructured environments [2]. Unstructured settings lack predetermined spatial layouts, characterized by irregularities and unpredictability, posing challenges for navigation. Service robots confront these challenges by employing an array of sensors such as cameras and Lidar, empowering autonomous decision-making grounded in sensor-derived data. 3GPP's endeavors underscore the necessity of adapting autonomous systems to intricate surroundings, emphasizing the urgency for adaptability and superior decision-making capacities to navigate such diverse terrains effectively.

Concerns with Sensor-enabled Robot Navigation. The utilization of sensing data in service robots brings forth pertinent privacy risks, encompassing unauthorized surveillance and potential data breaches. Mitigating these risks involves the implementation of robust data protection protocols, explicit user consent acquisition, and transparent data usage policies during service robot development and deployment stages [3], [4]. These are essential for ensuring user privacy and complying with data management frameworks in autonomous systems.

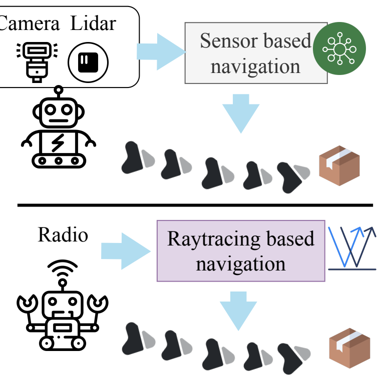

Fig. 1. Sensor-based navigation vs. DRT-based navigation.

Privacy Preservation through Differential Ray Tracing (DRT). In the realm of privacy-preserving environmental sensing, RF Ray Tracing emerges as a method adept at selectively capturing and processing visual and spatial data from the surroundings. Ray Tracing works on the principles of geometric optics by conceptualizing the electro-magnetic waves as individual rays travelling in straight paths until they encounter various objects, prompting reflection, refraction, diffraction, or scattering. Specifically, DRT facilitates precise sensitivity analysis of the environment, surpassing the conventional approach of tracing individual rays for pixel color [5], [6]. It focuses on computing minute variations in scene parameters, enabling efficient analysis of how alterations in scene geometry, lighting, or camera viewpoint impact the rendered image. Consequently, DRT adeptly extracts essential environmental features crucial for generating precise actuation directives in unstructured environments, pivotal for robot navigation. The illustrative benefits of employing DRT-based robot navigation are shown in Fig. 1.

Motivation and Contributions. Validating the novel use of DRT for robot navigation demands a specialized testbed setup that emulates real-world scenarios while facilitating digital scene creation. This paper introduces a streamlined testbed design involving the creation of a realistic digital scene, integrated into the NVIDIA's *Sionna RT* software [5]. This integration enables the analysis of propagation characteristics within the digital scene, crucial for comprehensive ray tracing-based simulations. This testbed is instrumental in validating the practicality of DRT for precise and efficient robot navigation in complex environments. The paper contributions are:

C1. Proposing a DRT-based privacy-preserving robot navigation concept and outlining a systematic testbed creation methodology.
C2. Designing a specialized testbed employing DRT on digital scenes through NVIDIA's Sionna RT [5] and Blender [7] tools.
C3. Releasing the codebase facilitating testbed creation for broader community use, available in [8].

II. Testbed Design

Implemented on an Intel i7, Ubuntu system, the setup integrates Polycam, Blender LTS v3.6.12 [7], and NVIDIA's Sionna RT [5]. The testbed includes scene creation and subsequent ray propagation characterization using Sionna RT, Fig. 2.

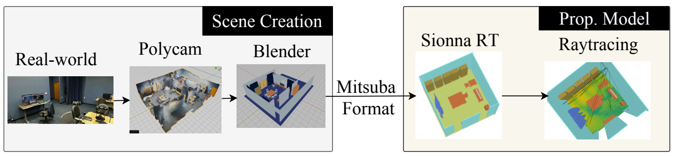

Fig. 2. The overall pipeline of the proposed testbed design.

Scene Creation. We use Polycam's Lidar feature and Blender tools to replicate a real-world indoor environment digitally. This digital *scene* undergoes meticulous importation into Sionna RT [5] from Blender employing `Mitsuba 3`, facilitating precise `.xml` format utilization. Sionna categorizes all scene components as *radio materials* for accurate calculations and *radio properties*. Subsequent optimizations in scene simplification aim to refine ray transmission and propagation accuracy for enhanced robot navigation, as visualized in Fig. 2. Note that the role of Polycam involves testbed creation only, not in the robot navigation decisions for future research.

Propagation Modeling using Sionna RT. Following scene creation, the propagation modeling process in Sionna RT begins by integrating Sionna with the *LLVM toolchain* for seamless compatibility. This integration ensures the systematic inclusion of receivers and transmitters, replicating real-world scenarios within the scene. Computational algorithms compute signal paths, generating comprehensive coverage maps visualizing signal propagation patterns. Precision in the environment involves fine-tuning critical parameters like `max-depth` and `num-samples`. The optimal configuration, with `max-depth = 5` and `num-samples = 200`, is determined through iterative optimization. This meticulous calibration guarantees high fidelity, capturing intricate signal propagation nuances within the scene, aligning precisely with our research objectives. Fig. 3 displays a sample of the generated propagation model.

A. Applicable Research Directions

- The proposed testbed offers a tangible pathway to create datasets akin to authentic RF maps, crucial for effective robot navigation. The utilization of reinforcement learning methodologies enables exact metrics for guiding the robot's maneuvers. These metrics rely on the RF propagation characteristics acquired from the ray-traced environment, ensuring accurate and informed robot navigation. Diverse data, including channel impulse responses, angle of departure, and angle of arrival, can be effectively captured from the propagation paths observed within our experimental testbed.

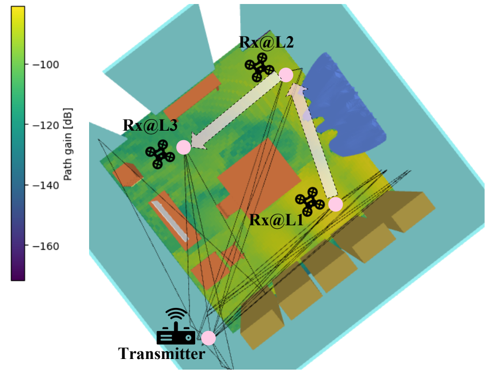

Fig. 3. Illustration of the propagation characteristics generated in Sionna RT. The transmitter is situated at the room's ceiling (bottom left corner), while the receivers are located on robots positioned across three distinct room areas (L1, L2, and L3). These simulations demonstrate varied robot navigation scenarios, showcasing how DRT and RF propagation alter concerning different robot positions.

- The convergence of computer vision and radio material properties unveils a new direction. By using Sionna RT to map rays onto hazardous objects, machine learning distinguishes between harmful and harmless entities. This novel direction transforms object classification beyond camera-based methods which introduces a transformative paradigm in object classification, steering away from traditional camera-based methods and leveraging radio material traits for enhanced precision.

III. Conclusion

In this paper, we underscore the privacy concerns entailed in service robot navigation, emphasizing the avoidance of privacy-sensitive data collection via cameras or Lidar sensors. Our proposed testbed design process, employing open-source tools, facilitates the generation of an environment's propagation model while preserving privacy. Our imminent focus includes advancing a reinforcement learning-based approach, leveraging raytraced data to precisely generate actuation data. This advancement ensures robust and privacy-conscious strategies for future service robot navigation.

References

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