

**AGENT-BASED MODELLING AND SIMULATION OF SIDEWALK
DELIVERY ROBOTS' INTERACTION WITH PEDESTRIANS.**

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Abstract

In modern urban landscapes, the rising prevalence of Sidewalk Autonomous Delivery Robots (SADRs) necessitates a deep understanding of their interactions with pedestrians. Moreover, developing tools to simulate and analyze these interactions is equally vital. To this end, this thesis not only delves deep into understanding these dynamic interactions in shared spaces but also introduces a novel methodology for constructing a web-based simulator designed to emulate interactions between SADRs and pedestrians.

This research is anchored in a GIS-enhanced digital twin that replicates a campus-sized urban setting, capturing its multifaceted complexities. This digital twin, which incorporates detailed topographical, infrastructural, and environmental data, serves as an accurate mirror of the real world. The "TwinWalk" simulation framework, a cutting-edge web-based tool, is introduced to dissect the intricacies of interactions among robots, pedestrians, and wheelchair users. Specializing in agent-based modeling of multi-agent systems, TwinWalk incorporates steering behaviours and the Predictive Avoidance Model (PAM) to adeptly navigate collision avoidance scenarios. Hence, TwinWalk not only brings our digital twin to life but also offers a rich depiction of human-robot interactions, yielding insights that mirror real-world

complexities.

Experimental findings, derived from the agent-based methodology combined with multi-agent steering behaviors and PAM, reveal intriguing patterns: SADR generally uphold safety buffers and minimize sidewalk congestion but display a heightened risk of collisions. Interestingly, pedestrians often fail to maintain recommended safety distances, positioning them as the primary agents in proximity infringements. Such revelations underscore the urgency for continued research and the formulation of specialized safety protocols.

This research provides an indispensable simulation tool for urban planners, policymakers, and fellow researchers, equipping them with insights to evaluate the effects of varied design interventions and policies on robot-human dynamics. Our quantitative analysis underscores the tangible importance of our findings, suggesting that expanding safety perimeters around robots might decrease collision incidents and optimize pedestrian movement. In sum, this research marks a pivotal advancement in deciphering and shaping robot-human coexistence in urban environments.

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Abbreviations

SADR Sidewalk Autonomous Delivery Robots

PMR Public Mobile Robot

PAM Predictive Avoidance Model

IoT Internet of Things

AI Artificial Intelligence

3D Three-dimensional

GIS Geographic Information System

RSS Responsibility-Sensitive Safety

MAS Multi-Agent Simulation

LiDAR Light Detection and Ranging

BIM Building Information Models

CAD Computer-Aided Design

CPDC Campus Planning, Design, and Construction

CSBO Campus Services & Business Operations

FS Facilities Services

GCP Ground Control Point

GPS Global Positioning System

3D-CAD Three-Dimensional Computer-Aided Design

2D Two-Dimensional

OSM Open Street Map

DTM Digital Terrain Model

API Application Programming Interface

UI User Interface

CSV Comma Separated Values

LOS Level of Service

Chapter 1

Introduction

Urban areas, characterized by their dynamic and densely populated environments, are presently undergoing a transformation due to the integration of technological advancements, especially in the realm of robotics. Public Mobile Robots (PMRs) have become emblematic of this transformation, exemplifying the intersection of technology and urban development. Within the category of PMRs, the Sidewalk Autonomous Delivery Robot (SADR) has emerged as a significant representative, particularly due to its function and interaction within pedestrian precincts. This research's primary aim is to examine SADRs and their operational dynamics within the Keele Campus of York University, Toronto, Canada. This investigation is rooted in the assessment of their functionality, the implications of their presence in public spaces, and the overarching concerns related to safety, efficiency, and the multifaceted nature of human-robot interactions.

The subsequent sections will elucidate the foundational technologies facilitating these

robotic interactions, such as Digital Twin-Based Simulations, and the challenges therein, particularly the complexities associated with GIS Integration. Additionally, the impact of e-commerce on delivery modalities and the consequent rise of SADR in urban settings will be explored. Paramount to this study is an assessment of safety considerations and the implications of introducing these robotic entities into urban ecosystems.

1.1 Background - Robot Inclusive Environments

1.1.1 Digital Twin-Based Simulations

Digital twin models are powerful tools enabling the simulation and analysis of real-world scenarios. These simulations offer vital insights that can enhance efficiency, lower costs, and improve predictive maintenance capabilities. Their transformative potential is particularly evident in the creation of a web-based 3D model of a university campus. This digital replica, exceeding the capabilities of a mere virtual campus tour, could serve as an invaluable asset for campus management, predictive analytics, and smart city planning. The integration of data and AI in the digital twin models marks a promising evolution in urban development strategies.

1.1.2 GIS Integration: A Roadblock and Potential Solution

While digital twin models harbor immense potential, the integration of Geographic Information System (GIS) data with 3D game engines like Unity and Unreal presents considerable

challenges. The unique ecosystem of GIS, replete with complex formats, specific terminologies, and proprietary tools, complicates this integration. This obstacle hampers the creation of effective, realistic digital twin simulations, necessitating the development of advanced methodologies. The exploration of novel approaches could potentially aid in streamlining the integration of GIS data with simulators. While these innovative methodologies may not provide a complete solution, they can progressively enhance the authenticity and effectiveness of digital twin simulations, thus making them more useful for the study and understanding of robot-human dynamics in urban environments

1.1.3 E-commerce Reshaping Delivery

The e-commerce revolution has fundamentally transformed consumer expectations and demand for parcel delivery. This transformation has complicated the last-mile delivery sector, inflating costs. However, the emergence of sidewalk delivery robots offers a promising solution. Their operational ease, cost-effectiveness, and positive environmental impact make them an attractive option for improving freight efficiency [1].

1.1.4 SADR: A Step Towards a Robot Inclusive Environment

This study explores the potential of Sidewalk Autonomous Delivery Robots (SADRs), small autonomous robots designed for operation on pedestrian sidewalks or footpaths. As robots' autonomy and mobility advance, their presence in public spaces and interactions with humans increase. The rise in last-mile delivery robots underscores the need for safe and efficient

human-robot coexistence in urban areas. This urgent need paves the way for comprehensive research into human-robot interaction dynamics, robot mobility improvements, and navigation assistance in pedestrian zones and intersections. Such research aims to create an inclusive environment where humans and robots coexist harmoniously.

1.2 Safety Concerns

The safety of pedestrians is a primary concern when considering the deployment of last-mile delivery sidewalk robots. Existing studies have focused on the interactions between robots and humans on sidewalks and between robots and vehicles at road intersections. However, there is a need to extend this body of research and critically evaluate the safety implications of integrating SADR into the urban fabric. This necessitates the development of simulation tools that can accurately mimic real-world conditions and provide reliable assessments of robot-human interactions and their potential impact on pedestrian safety.

1.3 Problem Statement

The current state of simulation techniques presents a significant gap in accurately modeling robot-human interactions within urban environments, particularly as it pertains to the enhancement of pedestrian safety and the efficiency of robot operations. Despite the potential benefits of robot-human and robot-cityscape interactions, their simulation under near-real-world conditions remains a significant challenge. In response to this critical issue, the focus of

this study is to establish a comprehensive, web-based 3D digital twin simulation framework for the Keele Campus of York University in Toronto, Canada. Through this framework, the study aims to simulate and evaluate various scenarios, thereby improving the operational efficacy of robots and bolstering pedestrian safety within urban environments.

1.4 Purpose and Objectives

The primary objective of this study is to develop a comprehensive digital twin-based simulation framework that studies the interactions between sidewalk delivery robots and pedestrians in urban environments. This framework will not only help in understanding the dynamics of robot-human interactions but will also offer insights into how to optimize these interactions to ensure the safety of pedestrians and the efficient operation of robots. The study also aims to bridge the current research gap regarding the operation of last-mile delivery robots, particularly SADR, in urban areas. The study hopes to contribute significantly to the literature on human-robot interaction and urban planning by focusing on these areas.

1.5 Research Gaps

In the midst of the expanding integration of multi-functional robots into human environments, a vast research gap remains unaddressed. The growing presence of robots in public spaces necessitates a comprehensive understanding and optimization of their operations. However, the existing deterministic algorithms often stumble when faced with uncertainties and mutual

influences characterizing robot-human interactions in urban settings. Furthermore, while the usage of last-mile delivery robots, particularly Sidewalk Autonomous Delivery Robots (SADRs), is on the rise due to the booming parcel delivery market, there is a lack of research exploring the intricacies of their interactions with humans and vehicles in shared spaces. The nuances of pedestrian safety and mobility in crowded urban spaces when navigating alongside these robots have not been sufficiently explored under real-world conditions. These significant gaps in research underline the importance of this thesis.

1.6 Methodology Outline

This study employs an innovative approach to tackle the complexities associated with creating a digital twin simulator, aiming to advance the examination of interactions between sidewalk delivery robots and pedestrians in urban settings. The methodology encompasses the following key steps:

Integration of Geographic Information System Data. The methodology first navigates the challenge of effectively integrating Geographic Information System (GIS) data into game engines such as Unity and Unreal. Through the development of pioneering solutions, the study seeks to create a fully functional, web-based GIS simulator.

Rendering and Steering Behaviours. The next phase entails incorporating steering behaviours into ArcGIS WebScene objects, employing the ThreeSteer library for agent visualization and navigation. A unique solution is devised to bridge communication between ThreeSteer and ArcGIS using feature layers, significantly enhancing the realism and

interactivity of the simulation."

Pedestrian Navigation and Collision Avoidance. The construction of an advanced agent-based model that simulates nuanced pedestrian behaviors and interactions. To further enhance the robustness of the simulations, it integrates the Predictive Avoidance Model (PAM) into the methodology. PAM enhances the capabilities of the Social Forces model by incorporating a predictive aspect, thereby enabling the anticipation of potential collisions and triggering early avoidance maneuvers. Extending the ThreeSteer library with PAM significantly amplifies the collision avoidance capabilities, thereby improving the fidelity of the pedestrian navigation and collision avoidance simulations.

Route Planning and Analysis. To optimize the routing system, the methodology involves applying the ArcGIS Indoors software tool (ArcGIS Indoors is an indoor mapping, space management, and wayfinding tool developed by ESRI). This intricate process includes the refinement of the base pathway polygon into the indoor geodatabase's 'levels' feature class, pruning unnecessary preliminary network pathways, and enhancing the network's efficiency.

Simulation Analysis Tools. Finally, the methodology comprises the development of post-simulation analysis tools. These tools incorporate key metrics such as effort (metabolic energy expenditure), kinetic energy, and events like interpersonal space violations and collisions among agents. This allows for a comprehensive evaluation of interaction dynamics between autonomous entities and pedestrians.

The methodology ultimately results in the creation of a large-scale, high-fidelity digital twin of the York University campus, an ArcGIS-based digital twin model combined with

THREE.js-based agents for realistic simulations, an optimized routing system for efficient navigation, and robust analysis tools for understanding agent performance. Thus, this research provides a solid foundation for future investigations into the integration of autonomous robots into urban environments.

1.7 Contributions

1. Research Ideas and Initiations:

- **Ali Hassan** spearheaded the inception, design, and execution of the research.
- The mentorship and guidance of Professor **Dr. Gunho Sohn** extended from formulating research questions to devising innovative methodologies.
- Professor **Dr. Petros Faloutsos** provided a critical review and suggested innovative avenues for progress.
- **Dr. Muhammad Usman** contributed to the theoretical formulation of the simulation framework and collaborated in shaping the experimental design, thereby strengthening the empirical foundation of the research.
- **Dr. Seungho Yang** played a pivotal role in refining the experiment design, particularly concerning urban planning aspects.

2. Project Management:

- The **Advisory Committee** and collaborators from the **ISSUM Project** provided essential project management, offering continuous feedback, improvement

suggestions, and strategic guidance.

3. Project Funding:

- Financial support and a belief in the vision were provided by the **ISSUM Project**, the **Ontario Research Fund**, York University, and Mitacs Accelerate Fellowship with Esri Canada collaboration.

4. Data Acquisition:

- **Dr. Connie Ko** exhibited meticulous effort in crafting the 3D model of the York University campus, gathering comprehensive data from surveys to lidar information, thereby materializing the conception of the digital twin.

5. Data Processing:

- **Michael Luubert** assisted in processing various GIS data layers, including land use information.
- Additionally, **Dr. Connie Ko** played a crucial role in refining and processing data related to the 3D model of the campus, ensuring its seamless integration with the research objectives.

6. Providing In-house Software, Libraries, and Equipment:

- **Esri Canada** offered technical support and infrastructure.
- **Michael Luubert** provided solutions pertaining to ArcGIS, optimizing the implementation and usage of APIs.

7. Developing Systems:

- **Dr. Muhammad Usman** implemented the foundational system for the project template as a proof of concept.
- **Michael Luubert** was instrumental in implementing route analysis using ArcGIS indoor.
- **Melissa Keremer** contributed to the enhancement of the TwinWalk framework and the integration of the Predictive Avoidance Model (PAM).
- Furthermore, **Melissa Keremer** executed and processed critical metrics, unveiling profound insights into agents' navigational behaviors and patterns.

8. Research Innovations:

- Professor **Dr. Gunho Sohn** provided guidance to align the research with broader academic and industry objectives.
- Professor **Dr. Petros Faloutsos** offered invaluable insights on simulation and visualizations, thereby enhancing the interaction metrics.
- **Dr. Brent Hall** and **Dr. Jon Salter** contributed expert domain knowledge, ensuring the research's practical relevance and effective implementation.

9. Writing:

- **Ali Hassan** took the lead in composing the thesis.

- Professor **Dr. Gunho Sohn**, Professor **Dr. Petros Faloutsos**, **Dr. Muhammad Usman** and other contributors provided feedback on the manuscript.

1.8 Thesis Structure

This thesis seeks to establish an advanced simulation framework to scrutinize interactions between sidewalk delivery robots and pedestrians in urban environments. It focuses on assessing pedestrian safety and the operational efficiency of robots within shared spaces. The remainder of this thesis is structured into the following chapters:

- **Chapter 2 - Literature Review:** This chapter presents a thorough literature review, providing context to the role of simulation and digital twins in the evolving landscape of autonomous robots. It also delves into pedestrian navigation methodologies and the potential and challenges of SADR.
- **Chapter 3 - Constructing a Digital Twin of the Campus:** This chapter outlines the process of developing a digital twin of the York University campus, discussing methods of structuring building models, terrain and land use modeling, and incorporation of street furniture and other objects.
- **Chapter 4 - Methodology:** This chapter introduces the developed methodology, dubbed TwinWalk, a multi-agent digital twin simulation system. It also discusses various aspects such as scenario configuration, modeling of sidewalk delivery robots, route planning, and simulation statistics.

- **Chapter 5 - Performance Evaluation of Web-based Digital Twin Model and Simulator:** This chapter focuses on the experimental validation of the reliability, efficiency, and scalability of our web-based digital twin model and simulator, particularly emphasizing its performance dynamics.
- **Chapter 6 - Experiment Design and Results:** This chapter presents the design of experiments performed using the developed simulation framework. It offers a comprehensive analysis of the results obtained, focusing on metrics such as proximity violations, collisions, flow density, and robot efficiency.
- **Chapter 7 - Conclusion:** This final chapter summarizes the thesis's achievements and contributions to the field of integrating autonomous robots into urban environments. It also suggests future research directions based on the findings.

This structured approach offers a comprehensive exploration of each research stage, contributing significantly to the integration of autonomous robots into urban environments.

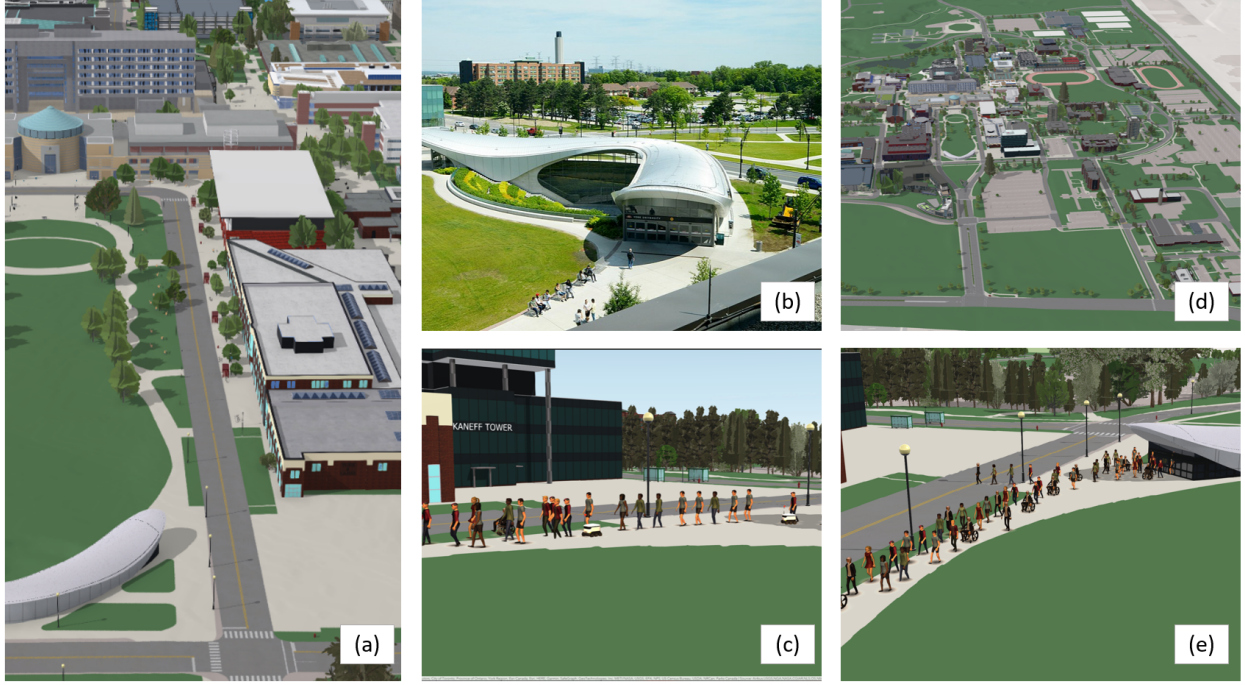


Figure 1.1: Comparison of York University's Keele Campus and its Digital Twin: (a) Overview of Keele Digital Twin Campus; (b) The university Subway Station; (c) Experiment area on the digital twin; (d)-(e) Simulated agents navigating around the Subway Station.

1.9 Publications

- **Hassan, Ali**; Usman, Muhammad; Kremer, Melissa; Yang, Seungho; Faloutsos, Petros; Sohn, Gunho; "Digital Twins: Simulating Robot-Human Sidewalk Interactions", *International 3DGeoInfo Conference 2023, Springer LNGB&C series*, (Accepted)
- Yang, Seungho; Usman, Muhammad; **Hassan, Ali**; Faloutsos, Petros; Haworth, Brandon; Sohn, Gunho; "Responsive Urban Planning to Improve Pedestrian Physical

Distancing in Pandemic Using Urban Digital Twin", *Sustainable Cities and Society*, 97,

(In review)

Chapter 2

Literature Review

This chapter comprehensively reviews the literature surrounding Sidewalk Autonomous Delivery Robots (SADRs), their technological advancements, associated challenges, and their interaction with urban environments.

In the era of rapid technological progress, traditional food and parcel delivery methods are being reconsidered due to the escalating demand for efficiency and sustainability. The innovation of last-mile technologies has emerged in response to these needs, creating novel approaches for delivery solutions that could potentially revolutionize urban transportation systems [2]. Particularly, Sidewalk Autonomous Delivery Robots (SADRs) stand out as a suitable alternative for meeting the needs of tech-savvy consumers [1]. These automated delivery solutions leverage modern technologies to transport goods autonomously, improving delivery efficiency, reducing traffic congestion, and minimizing ecological impacts [3, 4]. The market for mobile robots (including trucks and drones) in logistics, delivery, and warehousing is

expected to reach an impressive \$83 billion and \$334 billion in 2032 and 2042, respectively[5]. However, despite offering several promising benefits, SADRs also raise concerns around congestion and obstruction on sidewalks and the potential risk of accidents [6, 7].

2.1 Evaluating Urban SADRs with Digital Twinning

To address the potential hazards associated with the deployment of SADRs in urban spaces, it is crucial to assess their performance and safety measures thoroughly. Simulation and digital twin technologies have become instrumental tools in this regard, allowing researchers to emulate real-world scenarios within controlled virtual environments [8, 9]. By simulating various interactions and responses of the robots, potential risks and issues can be identified and mitigated before actual deployment [10]. Furthermore, digital twin technology, a tool of growing popularity in urban planning, is also finding its place in the evaluation of SADRs. This technology creates a virtual representation of a city or an urban space, linking it with real-world data to enable real-time monitoring, analysis, and prediction of various scenarios [11, 12]. Consequently, the use of digital twins can provide researchers with a dynamic simulation environment where they can monitor and predict the impact of different interventions in real-time, thus improving urban planning and management [13, 14].

2.2 Pedestrian Simulation

In the context of pedestrian environments, Multi-Agent Simulation (MAS) has emerged as an effective method for representing human interactions and movements within virtual environments [15, 16]. Various pedestrian navigation and collision avoidance methods have been developed and integrated into these simulations, enabling them to capture human-like movement and responses [17, 18, 19, 20, 21]. Notably, the application of MAS in the research of SADR has opened up opportunities to explore different navigational strategies that allow the robots to navigate sidewalks safely while adhering to pedestrian regulations [22, 23]. Recent studies have proposed novel navigation models that consider social relationships and human factors, enabling the robots to mimic human decision-making in complex environments [24, 25, 26, 27, 28, 29, 30].

2.3 SADR: Potential and Challenges

SADR, designed to autonomously transport packages by navigating sidewalks, represent a promising solution to last-mile delivery challenges [31]. The underpinning of their operation lies in sophisticated sensors, cameras, and navigation systems that assist them in detecting and circumventing obstacles in their path [32, 33, 34, 35, 36]. Yet, the complexity of urban environments and human interactions pose substantial challenges to their successful implementation. These challenges include but are not limited to, pedestrian safety, robot navigation, social acceptance, legal and regulatory issues, and data privacy [37, 38]. The

potential of SADR in transforming the last-mile delivery process is contingent upon their ability to seamlessly coexist with pedestrians and other sidewalk users. Therefore, extensive research and rigorous testing are required to ensure their safe and efficient operation in diverse urban conditions. With continuous advancements in autonomous technology and urban planning, SADR could become an integral part of the urban transportation ecosystem, bringing transformative changes to the delivery industry [31].

2.3.1 Harnessing Simulations for Autonomous Advancements

Simulations are paramount in advancing autonomous driving research, offering a nexus between theory and real-world application. Their value is multi-faceted: they provide a safer environment to gauge vehicle performance, ensure economic viability, and facilitate the standardization of safety measures. A standout example is the Responsibility-Sensitive Safety (RSS) model proposed by Shalev-Shwartz and his team [39]. This model delineates the essential safety benchmarks every autonomous vehicle should uphold, highlighting the industry’s move towards standardized safety assurance.

Additionally, the financial constraints of real-world testing are addressed through simulations. As Rong and his team[40] aptly emphasize, simulators, like the LGSVL Simulator, grant researchers a realistic, yet virtual, platform for rigorous algorithm testing. This circumvents the substantial costs associated with tangible vehicle assets.

Moreover, the broader impact of autonomous vehicles on our roads, such as enhanced road capacity and improved traffic flow, as presented by Liu et al. [41], is best assessed in

simulated environments. These insights are critical for understanding the transformative potential of autonomous technology. Venturing into cooperative autonomous driving, Cui et al. [42] showcased the integration of robotics and network simulators, paving the way for studying how autonomous vehicles might collaboratively navigate. Such platforms allow for an in-depth assessment of cooperative driving algorithms, considering intricate variables like vehicle dynamics and inter-vehicle communication.

Transcending the realm of road vehicles, the methodologies and insights derived from these simulations hold significant implications for other autonomous entities. For instance, simulations are pivotal for understanding and optimizing sidewalk delivery robots. These virtual studies can illuminate their interactions with pedestrians, ensuring both safety and efficiency as they become integral to urban ecosystems.

2.4 SADR Simulation

This section provides an overview of the various studies conducted on Sidewalk Autonomous Delivery Robots (SADRs) and their navigation methods, highlighting the diverse range of approaches and techniques explored in the literature. Table 2.1 presents a concise summary of these studies.

Morales et al.[32] emphasized the potential of SADRs in alleviating traffic congestion, highlighting the importance of these robots in navigating pedestrian areas while adhering to pedestrian laws and regulations. This research underscores the significance of legal and regulatory compliance in the operation of autonomous vehicles. In a similar vein, Kümmerle

et al.[34] investigated SADR equipped with sensors and cameras. Their research focused on the use of these technologies for autonomous navigation, underlining the importance of advanced sensory equipment in achieving successful, independent robot navigation. Wen et al.[24] delved into the application of Velodyne-16 LiDAR technology for situational awareness in SADR. The study demonstrated the viability of LiDAR-based obstacle detection as a critical component of autonomous navigation, furthering our understanding of sensor technologies in the field. Sorokin et al.[25] explored the concept of quadrupedal robots for sidewalk navigation, a deviation from the conventional design of SADR. The study emphasized the use of onboard sensors, a route plan, and a two-staged learning framework for effective navigation, showcasing the potential versatility of autonomous robot designs and control schemes. In another study, Wen et al.[26] proposed a vision-based sidewalk navigation algorithm for SADR. Their research explored navigation through sidewalk segmentation, costmap generation, and motion planning, suggesting a new way for SADR to understand and navigate complex urban environments. Yu et al.[27] focused on emulating pedestrian social behaviour in SADR. The study proposed novel navigation strategies, including group surfing, curb-following, and human-aware collision avoidance, pointing out the importance of human-like behaviour in the social acceptance and successful integration of SADR. Nguyen et al.[28] explored robotic wheelchairs in crossing situations, employing side-by-side navigation that considers the social relationship and the walking behaviour of humans. This research extended the application of human-like behaviour in autonomous navigation beyond SADR, highlighting its relevance in other assistive technologies. Lastly, Shiomi et al.[43] focused

on humanoid torsos with a human-like collision avoidance system. Their study, though not explicitly on SADR, provides insights applicable to the broader field of autonomous robots. The research emphasized the design of collision avoidance systems using the Social Force Model, particularly suitable for pedestrian environments like shopping malls, suggesting potential methods for SADR to interact safely with human pedestrians. The diverse range of research topics and navigation methods highlighted in this section underscores the breadth and depth of ongoing work in the field of SADR. As technology continues to advance, it is likely that these methods will continue to evolve, further expanding the capabilities and potential of SADR.

SADR predominantly function on sidewalks, complying with pedestrian regulations to transport packages autonomously, presenting a novel solution to address last-mile delivery challenges [31]. As shown in Table 2.1, various studies have explored different aspects of autonomous robots and their navigation methods. These studies encompass a diverse range of robot types, including SADR, quadrupedal robots, humanoid torsos, and robotic wheelchairs. The navigation methods employed in these studies vary from adhering to pedestrian laws [32], utilizing sensors and cameras [34], and employing LiDAR-based obstacle detection [24], to incorporating human-like collision avoidance and pedestrian social behaviour emulation [27]. Notably, Nguyen et al. [28] focused on robotic wheelchairs, considering the social relationship and walking behaviour of humans during side-by-side navigation. A recent study demonstrated a framework for IndoorSim-to-OutdoorReal transfer for navigation, further supporting the potential of autonomous robots to navigate robustly novel environments and

obstacles [30].

Study	Short Description	Type	Navigation Method
Morales et al.(2009)[32]	Explores traffic congestion alleviation	SADRs	Navigating pedestrian areas while adhering to pedestrian laws and regulations
Kümmerle et al.(2015)[34]	Equipped with sensors and cameras	SADRs	Autonomous navigation using sensors and cameras
Wen et al.(2022)[24]	Velodyne-16 LiDAR for situational awareness	SADRs	LiDAR-based obstacle detection
Sorokin et al.(2022)[25]	Quadrupedal robot for sidewalk navigation	Quadrupedal Robots	Uses onboard sensors, a route plan, and a two-staged learning framework
Wen et al.(2022) [26]	Vision-based sidewalk navigation algorithm	SADRs	Navigation through sidewalk segmentation, costmap generation, and motion planning
Yu et al.(2019)[27]	Pedestrian social behaviour emulation	SADRs	Group surfing, curb-following, human-aware collision avoidance
Nguyen et al.(2018)[28]	Robotic wheelchairs in crossing situations	Robotic wheelchairs	side-by-side navigation considering the social relationship and walking behaviour of humans
Shiomi et al.(2014)[43]	Human-like collision avoidance	Humanoid torso	collision avoidance system using the Social Force Model designed for shopping malls and similar pedestrian environments

Table 2.1: Research on autonomous robots and their navigation methods

2.5 Conclusion: The Future of SADR_s

The escalating interest and ongoing research in the field of SADR_s are highlighted in this comprehensive review. Their potential to revolutionize the last-mile delivery system becomes apparent in light of their capacity to reduce congestion in urban traffic and to provide an efficient and cost-effective method of delivering goods. The diverse applications of these autonomous technologies extend into numerous sectors, including retail, hospitality, healthcare, and beyond.

The discussed studies reveal the integration of an array of autonomous navigation methods and systems into these robots, manifesting the versatility and sophistication of these machines. Incorporating an array of systems such as sensors, cameras, LiDAR, two-stage learning frameworks, pedestrian behaviour emulation, and complex algorithms for sidewalk segmentation, costmap generation, and motion planning, these robots ensure safety, efficiency, and reliability as they navigate pedestrian environments. Adherence to laws and regulations, along with the capacity to interact seamlessly with pedestrians and other sidewalk users, is a testament to these innovations.

In the design, testing, and performance assessment of these robots, the critical role of simulations and digital twins cannot be overstated. These tools provide a platform for detailed analysis and evaluation of the robots' capabilities and potential risks in a controlled environment prior to real-world deployment. In addition, the role of multi-agent simulations in representing human interactions within the environment and aiding in the development of

effective and safe pedestrian navigation techniques is significant.

Despite the clear potential and benefits of SADR, the challenges they pose, such as sidewalk congestion and collision risks, remain a major concern. It is incumbent upon researchers, developers, and urban planners to continuously devise strategies to mitigate these risks and to enhance the harmonious integration of SADR into urban spaces.

This review aims to inspire and stimulate future research and development in this promising and rapidly evolving field. We have made significant strides in the development of SADR and their navigation methods, yet there remains a vast expanse of unexplored terrain. Through continued innovation, collaboration, and rigorous testing, we are poised to unlock the even greater potential of SADR in revolutionizing last-mile delivery and transforming the urban transportation ecosystem.

Chapter 3

Building the Digital Twin of York University

In today's world of advanced modeling and simulation, the terms "virtual model" and "digital twin" are often used interchangeably, leading to misconceptions about their true nature and capabilities. While they both serve as digital imitations of real-world entities or systems, the depth of their integration and their overall utility differ significantly.

A digital twin is essentially a virtual representation of a physical asset, activated through data and simulators [44]. Its strength lies in real-time prediction, optimization, monitoring, control, and decision-making enhancement. As proposed by Sundby et al. [45], the capabilities of a digital twin can be segmented into various levels, ranging from a basic standalone entity (0) to achieving full autonomy (5). This spectrum includes gradations such as descriptive (1), diagnostic (2), predictive (3), and prescriptive (4).

Building on this, web-based digital twin simulators play a pivotal role. With their capacity to integrate a plethora of data sources like geospatial data, they offer invaluable insights into physical and environmental aspects of locations [46]. By harnessing the power of GIS data, these simulators craft immersive virtual realities that mirror real-world conditions down to the minutest detail, making them especially apt for intricate studies, such as understanding the dynamics between sidewalk delivery robots and pedestrians [37].

On the other side of the spectrum, a virtual model typically captures a specific facet or moment from the real world and remains static, devoid of the dynamism offered by continuous data updates. A prime illustration of this dynamic representation is the digital twin model of York University’s Keele campus (Figure 3.1). Far from being just a static visual, it’s a living model that continually integrates updates from diverse data sources such as land-use changes, GIS data, building entrances and exits, and even minute details like accessibility markings. This holistic integration facilitates a two-way interaction, where simulations of the digital twin can provide insights into the real-world campus scenario. The intricate depth of this integration clearly outpaces the capabilities of a conventional virtual model, positioning the digital twin as an indispensable tool for forecasting and making informed decisions about the campus’s future.

3.1 Structuring Building Models

The York University campus features a variety of 90+ buildings, dedicated to diverse functionalities such as teaching, administrative operations, student residences, and additional

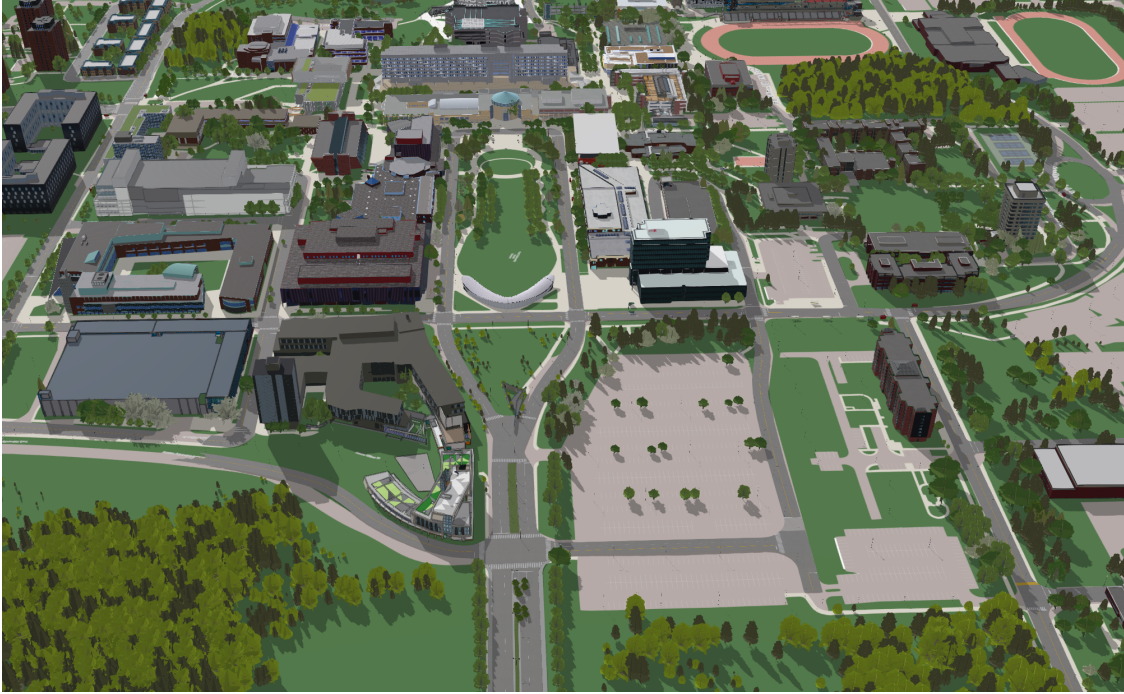


Figure 3.1: Snapshot of York University Campus 3D Digital Twin

facilities like restaurants and parking areas. Four types of models were employed to construct these building models: Building Information Models (BIM), 2D-Computer Aided Design (CAD) floor plans, 3D-CAD floor plans, and SketchUp building exterior models.

3.1.1 BIM Models

Our dataset comprises eleven distinct Building Information Models (BIM), all presented in Revit (.rvt) format. Five of these models provide detailed interior structures, while the remaining six encapsulate comprehensive exterior designs.

Figure 3.2 delineates a characteristic interior and exterior dataset. Figure 3.2(a) illustrates the internal architectural complexity and the inherent functional layout of Farquharson Life

Sciences. Figure 3.2(b) integrates georeferencing techniques with BIM to offer a georeferenced depiction of The Bergeron Centre, juxtaposed with ESRI imagery.

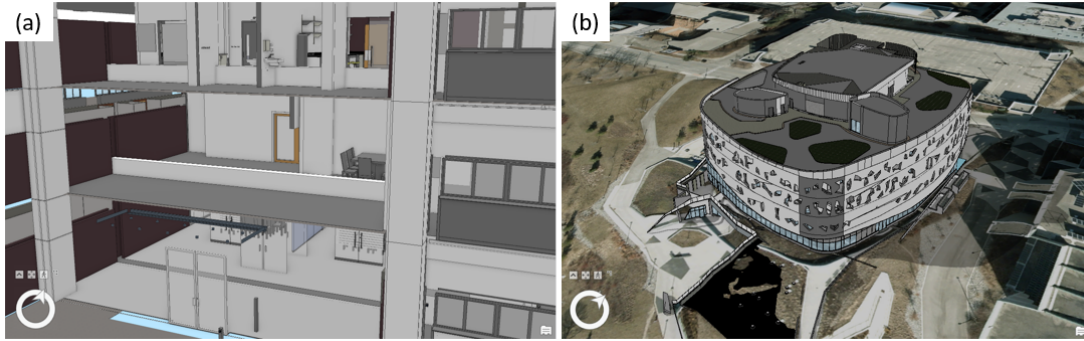


Figure 3.2: An example of BIM model. (a) is an example of an interior model for Farquharson Life Sciences and (b) is an example of the exterior model for Bergeron Centre on ESRI Imagery

Each of the eleven BIMs has been georeferenced according to global coordinates, enabling their positioning within a global spatial framework. This process enhances their applicability in diverse fields like urban planning, disaster management, and architectural studies. It is crucial to mention that besides georeferencing, no further modifications or alterations were made to the original BIM data.

York University's Campus Planning, Design, and Construction (CPDC), a vital part of the Facilities Services (FS) Department, generously provided comprehensive BIM models. FS/CPDC is responsible for maintaining the architectural integrity of the campus. Under their supervision, the BIM models were enhanced and archived in the AutoDesk Revit [47] format. A meticulous process was followed to isolate interior and exterior building features

for incorporation into the respective models. The resulting dataset presents a detailed digital representation of the buildings, fostering innovative architectural studies and further research.

3.1.2 2D-CAD Floor Plans

The extensive dataset encompasses 84 buildings, each represented via two-dimensional (2D) floor plans in the .dwg format. Notably, 29 of these have undergone meticulous georeferencing using world coordinates, thus providing a global spatial context. The remaining 55 models maintain their original formats, devoid of global spatial location. An example of an original, un-georeferenced floor plan for the Lassonde Building’s first floor is delineated in Figure 3.3(a).

Each Computer-Aided Design (CAD) file encapsulates detailed architectural features, including walls, windows, doors, and designated room numbers. In the summer of 2020, these 2D-CAD floor plans were subjected to a comprehensive georeferencing process. Figure 3.3(b) exemplifies this process, revealing a georeferenced floor plan overlaid onto base map imagery.

To georeference these buildings, ground control points (GCPs), topographic basemaps, and aerial imagery from the ArcGIS Pro software were utilized. An Affine transformation, a linear mapping method preserving points, straight lines, and planes, was implemented to attain the requisite spatial accuracy. Simultaneously, root mean square errors were meticulously documented to facilitate future evaluations and ensure optimal spatial accuracy.

GCPs data were archived in .wld files, which can be accessed via a text editor. Additionally, room annotations, including room numbers, were extracted from each georeferenced building

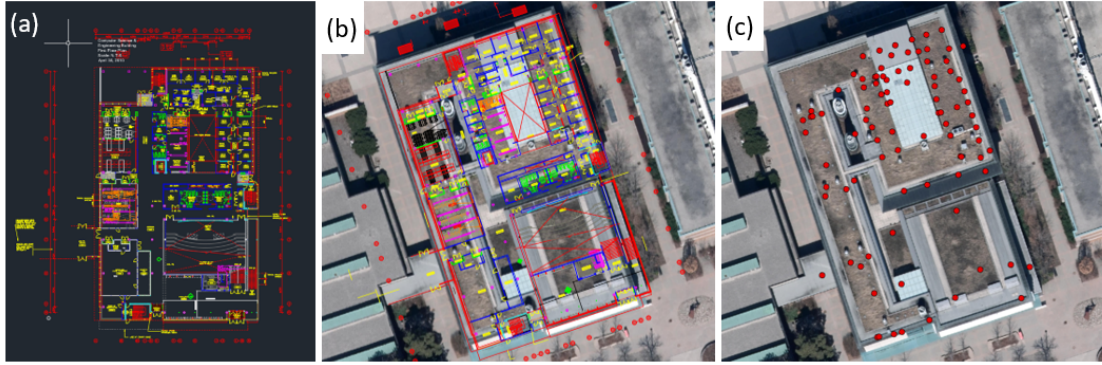


Figure 3.3: Illustration of 2D CAD floor plans: (a) original un-georeferenced floor plan for the first floor of Lassonde Building, (b) georeferenced floor plan overlay on basemap imagery, and (c) georeferenced room annotation GIS layer.

and saved as a 2D point layer, thereby enabling efficient navigation and referencing within the building, as depicted in Figure 3.3(c). This rigorous procedure yields a robust, georeferenced dataset with augmented usability for a plethora of applications in planning and architectural research.

3.1.3 3D-CAD Models

As detailed in Section 3.1.2, the dataset includes 2D CAD floor plans for 84 buildings. For 75 of these buildings, a process was instigated to extrapolate the wall layers—depicted as lines in 2D—into a three-dimensional format. To create this representation, walls were extruded to a uniform height of 3 meters, while floors, crafted based on each 2D floor plan’s outer boundaries, were assigned a consistent thickness of 0.3 meters. Notably, ceilings were deliberately excluded from the model to facilitate unobstructed top-down visualization.

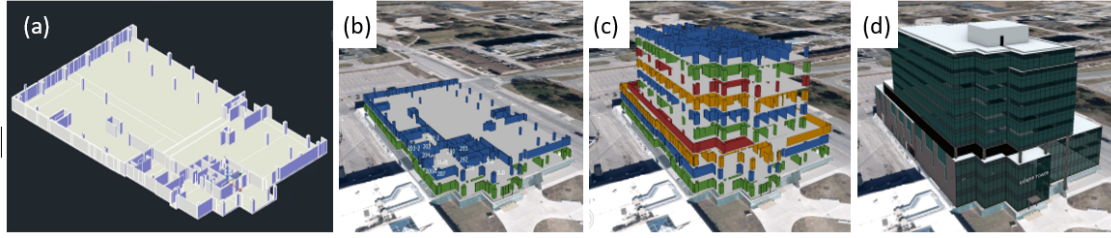


Figure 3.4: Illustration of 3D CAD models: (a) un-georeferenced second floor of Kaneff Tower, (b) georeferenced floor plan with room annotation overlay on basemap imagery, (c) stacked 3D floor plans based on LiDAR information, and (d) SketchUp model.

Currently, the building models, inclusive of the 3D floor plans, are reliant on a LiDAR dataset acquired in 2018 to determine building heights. Each floor’s height is calculated by dividing the total building height—obtained from the LiDAR dataset—by the number of floors within the building.

3D floor layers and extruded 3D walls were effectively produced for a total of 84 structures, as showcased by the second floor of the Kaneff Tower in Figure 3.4(a). Among these, 29 have been georeferenced and supplemented with room annotations to expand their functional potential. Using LiDAR data, height attributes were designated to the building models, enabling a vertical arrangement of all floor plans, as illustrated in Figure 3.4(c). Figure 3.4(d) presents an interactive architectural representation via a SketchUp model of the Kaneff Tower.

3.1.4 Sketup and Blender Models

As specified in Section 3.1.1, six buildings within the dataset have been supplemented with detailed Building Information Model (BIM) exterior models. To furnish a more thorough representation, exteriors for an additional 33 buildings were constructed using SketchUp¹, and 34 buildings utilized Blender software². These exterior models were georeferenced according to world coordinates, providing a global spatial context.

The creation of these models began with the extraction of building footprints from the Open Street Map (OSM)[48], which were then extruded to form a rudimentary three-dimensional shape. Further architectural details such as roofs, windows, doors, and columns were meticulously incorporated into the extruded footprint. This process was enhanced with supplementary data sourced from Google Street View, Google Earth, and on-site photographic references, thereby ensuring the architectural accuracy of the models.

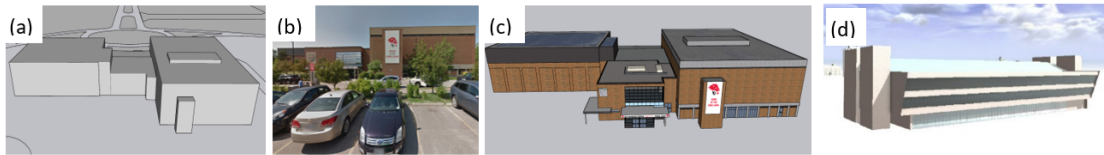


Figure 3.5: Illustration of SketchUp model creation process: (a) extruded OSM downloaded data, (b) Google street-view of the same building, and (c) final Sketchup model, (d) final Blender model.

Once finished, the geometric models were georeferenced to global coordinates, which

¹<https://www.sketchup.com/>

²<https://www.blender.org/>

allowed for their use as outlines for the 3D walls and floors that were constructed, as described in Section 3.1.3. An example of such a model is illustrated in Figure 3.4(d).

Figures 3.5(a) and 3.5(b) demonstrate the process leading to the final SketchUp model, displayed in Figure 3.5(c). Figure 3.5(a) showcases the initial extruded footprint derived from OSM, and Figure 3.5(b) presents the Google Street View of the same structure, which functioned as supplementary data. These stages culminate in the completed SketchUp model, represented in Figure 3.5(c), which embodies the Tait McKenzie Physical Education Centre.

Figure 3.5(d) draws attention to an example of a Blender model, emphasizing the variance between modeling techniques utilized by different software. This step-by-step approach in developing detailed 3D building models signifies a dedication to architectural accuracy, beneficial for a wide range of applications such as urban planning and architectural studies

3.2 Terrain and Land Use

Understanding the physical characteristics of an environment is pivotal for the creation of any comprehensive 3D model. Terrain and land use of an area not only shape its visual representation but also its functionality and the interactions of objects within that space. Both factors are of utmost importance for urban planning, architectural design, environmental studies, and, in our context, enhancing the realism and accuracy of 3D simulations. This section provides an in-depth look at terrain representation and land use categorization, discussing the methods used and the challenges faced. By capturing the nuances of the terrain and categorizing the purpose of each land parcel, we aim to ensure that the simulated

environment mirrors the real world with high fidelity.

3.2.1 Terrain

The underlying bedrock of any comprehensive 3D model lies in its Digital Terrain Model (DTM), as it enhances the model’s realism by accounting for geographical undulations and accurate altitude representations. Coupled with land use information, the DTM plays a vital role in facilitating realistic and accurate simulations of dynamic objects such as pedestrians, primarily by defining appropriate movement paths.

LiDAR data served as the primary source of terrain information for this project. The ground LiDAR points were extracted from the dataset and subjected to a semi-automatic classification process. The resulting dataset was then rasterized with a resolution of 0.5m x 0.5m, thereby effectively capturing terrain details. Nonetheless, this classification process was not without its challenges.

Specifically, three main problems occurred during the classification process. Firstly, non-ground points such as those representing trees were at times incorrectly classified as ground points, leading to a spiked representation in the terrain. Secondly, genuine ground points in certain areas were missed during the classification process, resulting in sinks or depressions post-interpolation. Lastly, a lack of ground points in regions representing building footprints often led to interpolation errors.

A two-fold approach was adopted to address these terrain inaccuracies involving a minimum focal operation followed by a maximum focal operation, with the same kernel size employed

for both. Through experimental iterations using kernel sizes of 3, 5, 7, 9, and 11 pixels, a kernel size of 5 pixels was chosen based on visual inspection.

Further refinement was introduced in the original DTM to accommodate building footprints. The interpolated DTM elevation within each building footprint was replaced with a constant value, allowing the building model to rest on a flat surface. In the case of a building located on sloped terrain, the calculated elevation was manually adjusted to align with the physical terrain's construction. After this rigorous process, the DTM was subjected to a detailed visual inspection, and minor adjustments were made manually to specific areas.

3.2.2 Landuses

The land use data for this project, represented in GIS 2D layers, was obtained from Campus Planning, Design & Construction (CPDC). Within the context of this study, 'land use' is a term denoting the specific use of a particular area of land, which is crucial for defining objects of simulation in the respective simulation tasks

The project's database consists of three main land use categories: 1) Driving roads, 2) Parking lots, and 3) Sidewalks. Each category has unique attributes such as ownership, length, and street name for driving roads; type, name, and the number of parking spaces for parking lots; and construction material and ownership information for sidewalks.

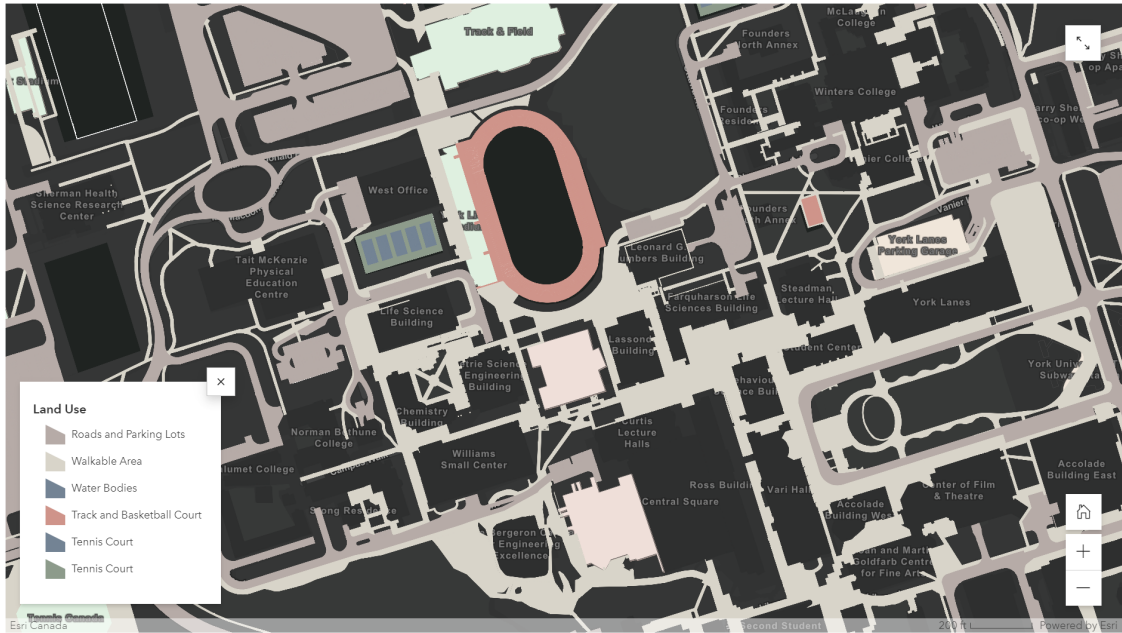


Figure 3.6: Land use dataset for driving road, parking, and sidewalks

Figure 3.6 provides a visual representation of the aforementioned data, showcasing the GIS datasets for parking lots, driving roads, and sidewalks. This layered data structure aids in establishing a comprehensive understanding of the land use pattern in the study area, thereby facilitating more accurate and practical simulation tasks.

The development of the campus roadways in the 3D model entailed a multi-step process, beginning with the importation of road centerlines from Toronto Open Data and roadways from the master CAD file into CityEngine. Following importation, the road lines underwent cleaning and simplification via CityEngine’s curve tools and were adjusted to align with the terrain surface. To reflect real-life road widths, the road shape geometry was modified accordingly. The CityEngine Complete Streets generative rule was subsequently applied to these road shapes, facilitating the revision and creation of detailed road markings, such as

centrelines, parking spaces, bike lanes, and crosswalks.

A 3D mesh, generated within CityEngine, was exported to the Web Scene as a scene layer. However, issues pertaining to inadequate terrain alignment for the interactive model necessitated a solution via scripting. A Python script was utilized to capture raster tiles of the textured street mesh in ArcGIS Pro, which yielded hundreds of tiles. These tiles were then stitched together to drape the final, accurate mesh tile layer over the terrain in the web scene.

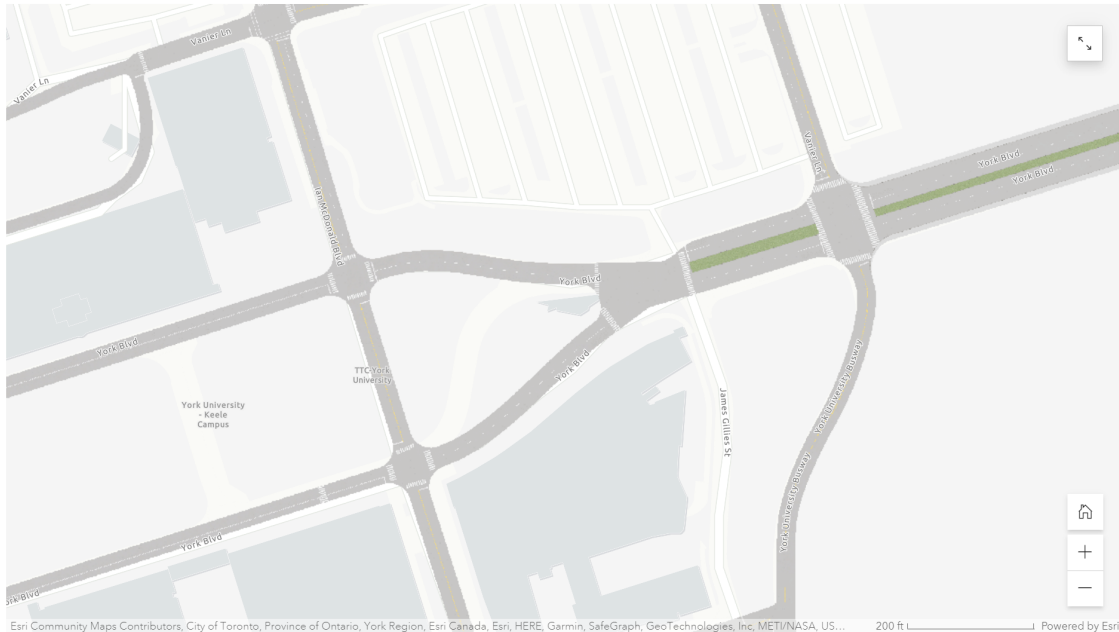


Figure 3.7: York Campus roads draped over the terrain

3.3 Trees Street Furniture

The dataset incorporates 3D models of various street furniture elements, including 1) Trees, 2) Light Poles, 3) Bus Stations, 4) Bins (Concrete bins, tri-bins, clothing donation bins), 5)

Fire Hydrants, 6) Benches, 7) Bike Cages and Bike Racks, 8) Blue Light Emergency Phones, and 9) Wheeltrans signs.

3.3.1 Trees

The campus landscape is punctuated by an impressive collection of 5079 trees, comprising 54 distinct genera. Employing handheld GPS devices, surveyors recorded critical attributes of each tree, including species, diameter at breast height, tree height, crown diameter, and notes indicating health conditions. However, the integrity of tree locations was partially compromised due to GPS errors. In order to rectify these discrepancies, we adopted a robust approach to validating and aligning the center locations of trees. By synchronizing LiDAR data and Google Maps aerial imagery, we managed to refine the location accuracy of the trees.

The ESRI symbols catalog [49] served as the source for 3D tree models, which were assigned based on the tree genera recorded in the field survey data. For trees that didn't have corresponding 3D models, a generic approach was adopted wherein unmatched coniferous trees were assigned pine models, and unmatched deciduous trees were assigned maple models. The 3D tree models were not oriented in any particular direction.

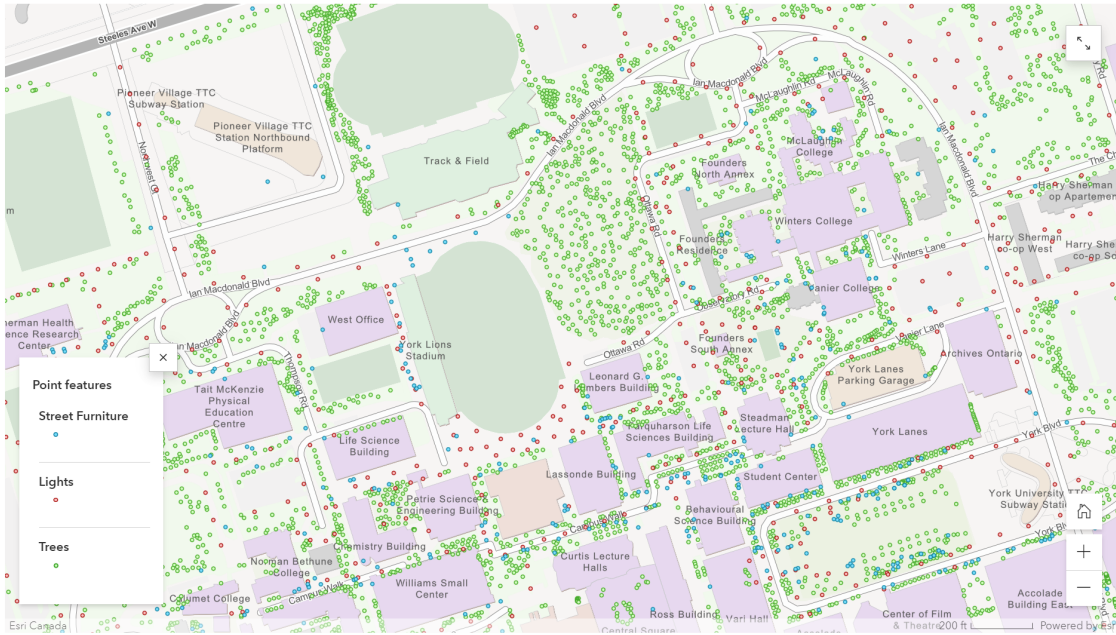


Figure 3.8: Point Feature (trees, lighting fixtures, street furniture) locations across the Campus.

3.3.2 Light Poles

A total of 930 light poles, spanning 17 distinct types, are documented within the university campus, as indicated in Figure 3.9. While these light poles' locations were recorded as a 2D GIS layer in 2018, the dataset did not include the height and orientation of each pole. This data deficit was addressed in 2021 when these details were integrated into a 3D model of the campus. Emphasis was placed on incorporating the orientation of the light poles (Types 3, 4, 5, 8, 9, 13, 14, 15, 16) to guarantee their illumination was directed appropriately, for instance, towards sidewalks. The model's height was approximated visually and is expounded in Table 3. Nine 3D light models represent the 17 types of light poles; hence, multiple light poles with

comparable appearances were grouped together under the same 3D model.



Figure 3.9: Different type of light poles

3.3.3 Bus Transit Shelters

The university campus hosts eight distinct types of bus transit shelters, categorized according to their respective transit operators. These include 1) Toronto Transit Commission Bus, 2) Go Transit, 3) Village Shuttle, 4) York Region Transit YRT, 5) Wheel-Trans-TTC, 6) Bus Rapid Transit (BRT) VIVA, 7) Brampton Transit, and 8) Glendon Shuttle. The Village Shuttles and Glendon Shuttles are managed by the university, while the remaining are public transit operations. Data pertaining to these shelters was recorded as a 2D GIS layer. Consequently, when transitioning to a 3D model for these bus transit shelters, the orientation information was included to ensure their correct positioning along the sidewalk. At present, the model does not feature individualized bus transit shelter models for each category; instead, it utilizes the default bus transit shelter models provided by ESRI symbols.

3.3.4 Street Furniture

The university campus is equipped with a variety of street furniture, classified into five key categories: bins, fire hydrants, benches, bicycle storage facilities (racks and cages), and blue light emergency phones. Three types of bins are cataloged in the dataset: concrete garbage bins, tri bins (garbage bins with multiple openings for sorting waste), and clothing donation bins. Orientation data has been appended to the 3D models of the concrete garbage bins and clothing donation bins to ensure alignment with the walkways. No such orientation data, however, has been applied to the clothing donation bins.

The dataset also includes 149 fire hydrants, which are incorporated into the 3D campus model without any added orientation. A total of 218 benches are cataloged across the campus, subdivided into four types: concrete, donated, metal, and wood. A single wood 3D bench model, sourced from ESRI symbols [49], represents the concrete, donated, and wood benches. A 3D metal bench model, procured from Sketchup Warehouse, represents the metal benches. Orientation information is incorporated for all bench types to ensure correct positioning; they are oriented to face the streets or, in the case of circular groupings, towards the center.

Regarding bicycle storage, the campus houses two bike cages and 62 bike racks. Both are represented in the 3D campus model using a 3D bike rack model sourced from ESRI symbols [49], with added orientation information for appropriate placement along roads or sidewalks.

Finally, the campus hosts 49 blue light emergency phones, represented in the 3D model by a standard phone booth model. These models do not include any added orientation information.

The high-level workflow of the complete process is presented in Figure 3.10, traversing from the diverse input data sources through to the visualization of feature layers on Esri's ArcGIS Online cloud. This comprehensive process leverages the robust capabilities of Esri's ArcGIS Pro and CityEngine software to manage and transform the data.

Specifically, the input data, highlighted in yellow, undergoes rigorous processing using the ArcGIS Pro and CityEngine software, indicated in blue. This results in the creation of feature layers, represented in orange, which are subsequently published to Esri's ArcGIS Online cloud. These feature layers are utilized to construct a web scene for enhanced visualization.

In addition to the conventional processing stages, an auxiliary geoprocessing step was necessitated. Executed via a Python script in ArcGIS Pro, this step entailed the conversion of the 3D road mesh exported from CityEngine into a tiled image layer. The objective of this conversion was to achieve better alignment of the road mesh with the ground, by draping it on the terrain. This pivotal step, illustrated at the bottom of the workflow diagram, provides a vital enhancement to the terrain alignment, contributing to the overall accuracy and realism of the generated digital twin model.

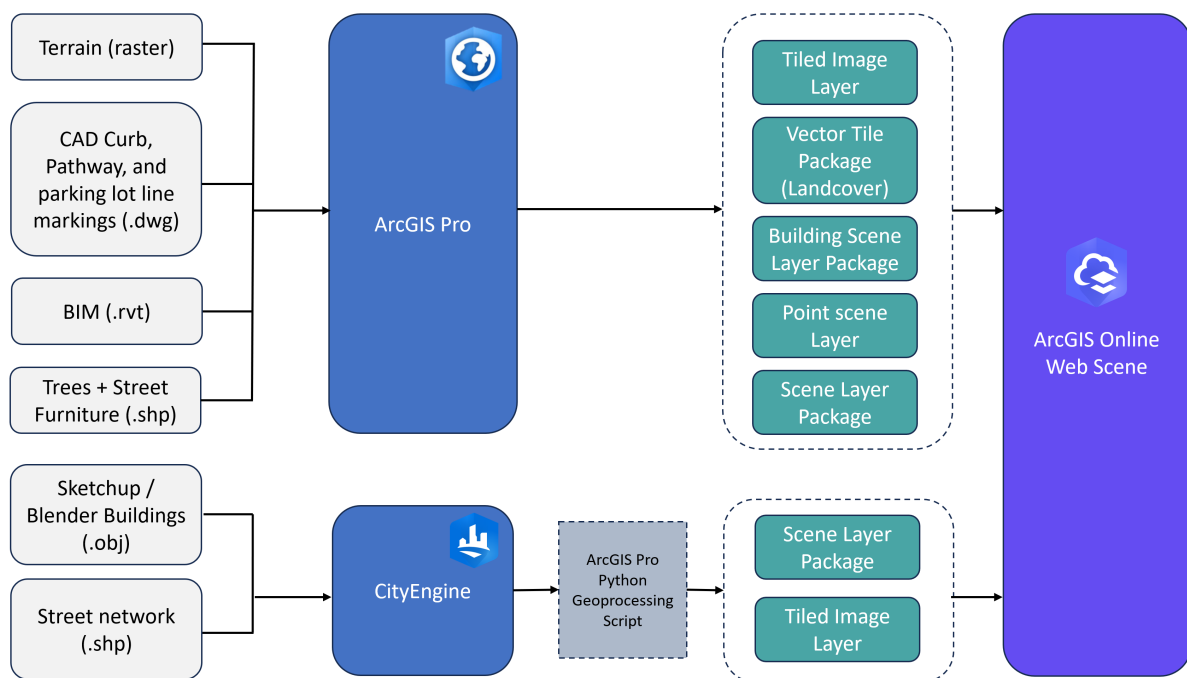


Figure 3.10: ArcGIS online WebScene publishing workflow

Chapter 4

Methodology

In this study, agent-based modeling is utilized using a Multi-Agent System (MAS) to demonstrate the behaviour of pedestrians and sidewalk robots through evidence-based planning and learning. The simulations are conducted on the digital twin of the York University Keele Campus, located in Toronto, Canada. The digital twin of the campus is built and hosted using Esri's ArcGIS technology [50], providing a highly detailed and accurate 3D map of the campus, including roads, sidewalks, and street furniture. Various experiments are designed to collect sufficient data for performing sensitivity analyses, focusing on pedestrians' safety and comfort and robots' efficiency. The agent-based movement of pedestrians and their collision avoidance behaviour reveal crowd intelligence as a group, enabling situational awareness and obstacle avoidance for both robots and pedestrians as they navigate safely from their origins to their destinations. More details about experiments and analysis are added in the relevant section below.

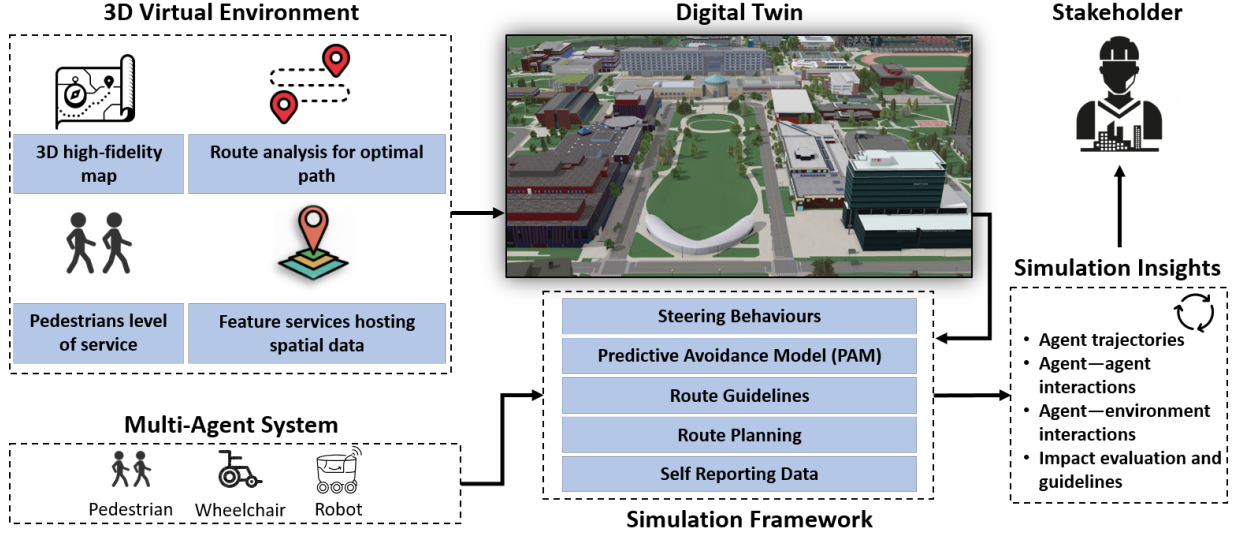


Figure 4.1: An overview of the proposed framework, illustrating the essential elements and operations in a digital twin-based simulator for pedestrians and sidewalk delivery robots.

4.1 TwinWalk: A Multi-Agent Digital Twin Simulation System

In urban planning and smart cities, understanding and improving pedestrian and robot interactions is of pivotal importance. Our study leverages a detailed digital twin of York University’s Keele Campus, created using Esri’s ArcGIS technology, to simulate these interactions with the help of the TwinWalk simulation system.

The digital twin-based sidewalk simulator incorporates core functions that enable the simulation of human-human, human-robot, and robot-robot interactions in a realistic and complex environment. A high-fidelity university campus map, including terrain, trees, green

spaces, parking lots, sports facilities, and buildings, represents this environment. Agents, consisting of pedestrians and sidewalk robots, navigate through the campus using the sidewalks and following routing paths offered by ArcGIS route analysis API. The resulting data from these interactions are analyzed to study emergent behaviour in human-robot interactions and identify ways to improve safety, efficiency, and comfort for sidewalk users.

As shown in figure 4.1, a combination of various tools and frameworks are employed to build the sidewalk simulations, with the foundation being a detailed 3D model consisting of GIS feature layers for trees, lighting, street furniture model locations, accurately modeled 3D buildings and sidewalks hosted on ArcGIS, and a point layer for all building entrances and exits. The agent-based modeling and intelligence are achieved by implementing multiple steering behaviours, such as follow, avoid, and seek, required for efficient navigation. These steering behaviours are based on Craig Reynold’s research and are customized to suit the specific needs of the simulation [51].

The rendering of the simulation is achieved via the utilization of THREE.js [52], a versatile, cross-browser JavaScript library and API. Its primary function is to facilitate the creation and rendering of animated 3D computer graphics within a web browser environment, leveraging the capabilities of WebGL for this purpose. For incorporating steering behaviours within the simulation, we have employed ThreeSteer [53], an adept library based on THREE.js, explicitly designed to address such requirements.

While the ThreeSteer library has proved to be a substantial foundation for implementing steering behaviours, certain limitations are observed in its interaction with ArcGIS WebScene

objects. In this study, our application involves the use of a 3D model of our campus, which is hosted on the ArcGIS platform. It's important to clarify that these observed limitations are not due to any inherent shortcomings within the platforms themselves, but rather, they stem from differing operational paradigms of the ThreeSteer and ArcGIS platforms.

To navigate these challenges, we have adopted a novel approach, which capitalizes on the ability to create a communication channel between ThreeSteer agents and ArcGIS. This approach harnesses the capabilities of feature layers hosted on ArcGIS Online, which serve as a conduit for this communication. Our methodology involves querying these feature layers to extract critical information, such as the position and dimensions of the objects within the 3D model. The extracted data is then used to create bounding boxes with the aid of the ThreeSteer library as shown in figure 4.2. These bounding boxes serve a dual purpose: they not only encapsulate the key information about each object, but they also serve as the nexus for interaction between the WebScene and the steering agents.

Our innovative strategy provides a robust solution to the observed compatibility issues between ThreeSteer and ArcGIS. This approach paves the way for the efficacious execution of steering behaviours in the context of our 3D model environment. The essence of this strategy lies in the integration of these distinct components into a coherent system, thereby enhancing the overall functionality of both platforms. This process not only builds a robust and versatile foundation but also encourages future advancements.

This methodology effectively mitigates the challenges associated with direct interactions between the two platforms, enabling a synergistic integration. This harmonious relationship



Figure 4.2: Visualization of Street Furniture Position Points: ArcGIS Hosted Layer Display-
ing Critical Information Including Position, Dimensions, and Size (a), and Corresponding
Bounding Boxes Created through Querying the Hosted Layer (b).

significantly augments user interactivity, leading to a more immersive and fluid simulation experience. This integrative approach, in turn, bolsters the realism of the web-based GIS simulation.

The proposed approach is a manifestation of creative problem-solving capabilities in the realm of web-based GIS simulation. It provides a paradigm that merges the functional strengths of both ThreeSteer and ArcGIS, thus showcasing the potential of innovative thinking in overcoming interoperability limitations. This unique strategy sets a benchmark for future endeavors aimed at integrating disparate technology platforms to achieve harmonious coexistence and improved functionality.

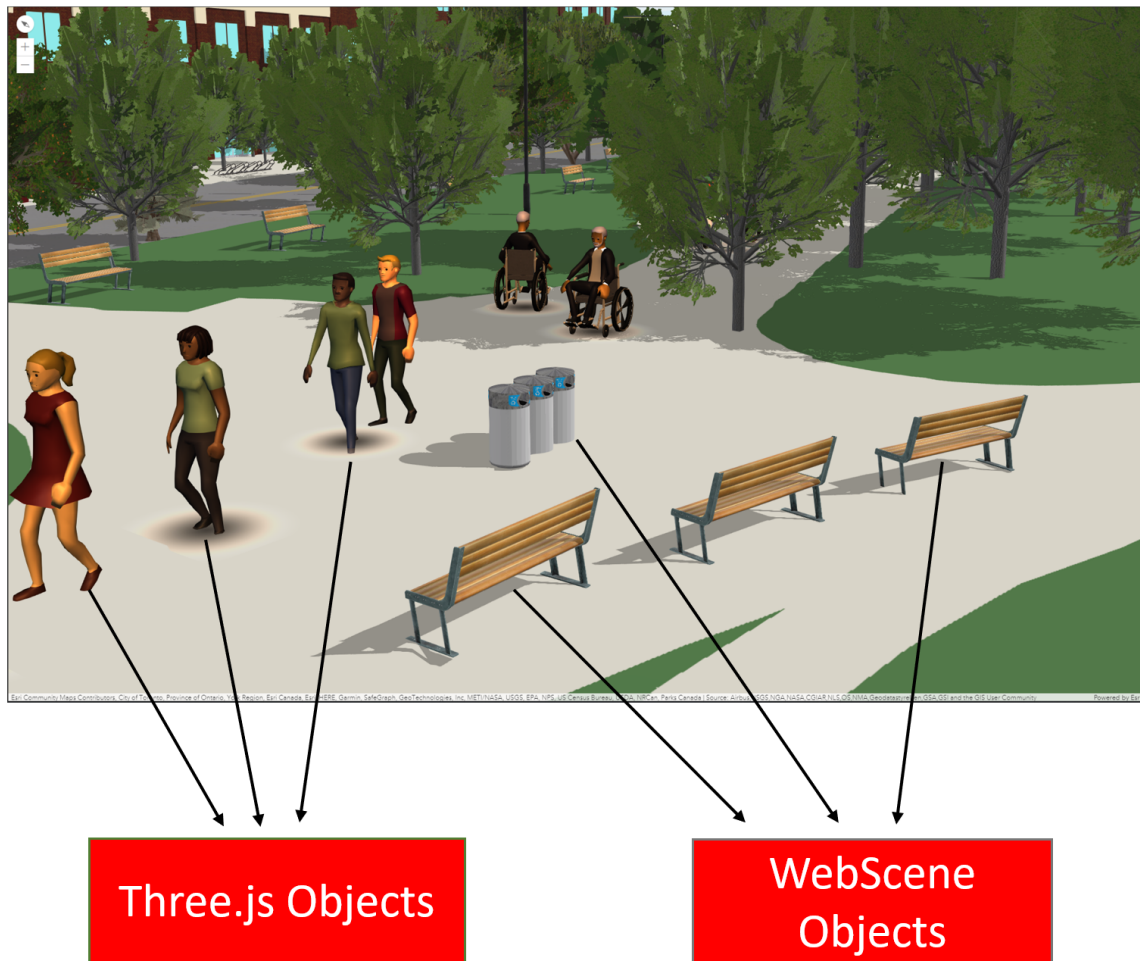


Figure 4.3: Three-Dimensional Rendering of Objects Using ArcGIS Online WebScene Integrated with Three.js for Enhanced Visualization.

4.1.1 Simulation Cycle

The simulation cycle is a four-step process that begins with defining the goal and hypothesis of the expected results, see Figure 4.4. This initial step is critical in determining the purpose and direction of the simulation, as it sets the tone for the entire process. The next step

involves setting up the scenario, which includes determining the intensity of agents to simulate along with their origin and destination locations. This step requires careful consideration of the specific variables involved and should be tailored to the desired outcome of the simulation. Once the scenario has been set up, the simulation can be run and analyzed both visually and quantitatively. This step is crucial in determining the accuracy of the simulation and identifying any potential flaws in the design or execution. Finally, the data-driven feedback obtained from the simulation can be visualized, and sensitivity analysis can be performed. This step involves reviewing the results of the simulation and analyzing how changes to certain variables may affect the overall outcome. Overall, the simulation cycle is an iterative process that allows researchers to test hypotheses and gain insights into complex systems.

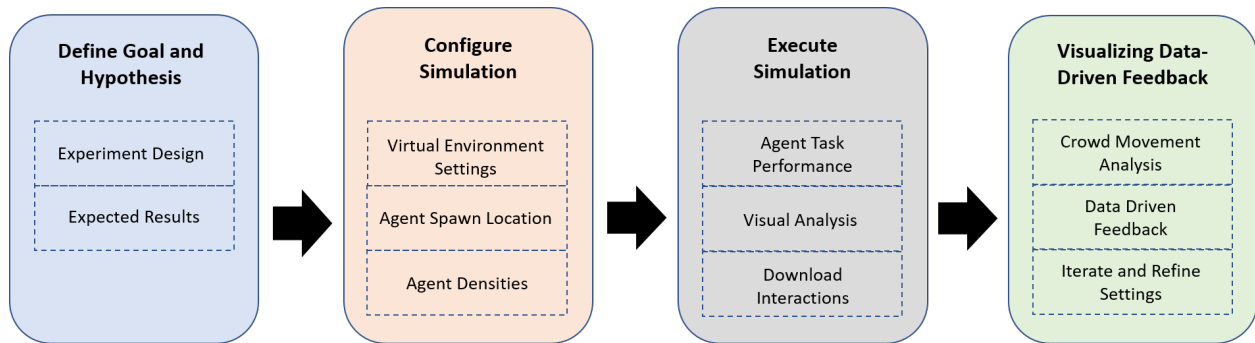


Figure 4.4: Steps of simulation cycle: Define the goal, set scenario, run & analyze, visualize feedback.

4.1.2 SADR Simulation: Utilizing the Starship Model

After careful analysis of multiple sidewalk delivery robots, we selected Starship,³ as the basis for our robot model. Starship's small self-driving vehicles, which weigh less than 35kg and are designed to operate on sidewalks at a maximum speed of 6 km/h, are capable of delivering goods locally within 15-30 minutes and within a radius of up to 5 km. Starship delivery robots have already been successfully tested in Tallinn by Volt, an online food ordering service, and Domino's pizza delivery services, where they were used as "personal delivery devices." As a global leader in autonomous delivery, Starship has driven over 10,000,000 kilometers and completed 4,000,000 deliveries across Europe and America [54]. Therefore, we believe that using the Starship model as the basis for our simulation tool will enable us to accurately capture the capabilities and limitations of current sidewalk delivery robot technology.

4.1.3 Optimal Path and Route Planning

Optimal paths are integral to routing applications, as they guarantee the selection of the most efficient and effective routes. Navigation and pathfinding are vital components of many simulation tools, such as Unity and Unreal Engine, which offer built-in services for these purposes. We employed Esri's ArcGIS Indoors software tools to determine the best paths for routing applications. While ArcGIS Indoors tools are primarily designed for creating indoor navigation networks, they can also be effectively utilized with sidewalk polygons representing

³<https://www.starship.xyz/>

building hallways to constrain the network lattice. To establish a precise and efficient routing system, the base pathway polygon was imported into the levels feature class of the indoor geodatabase, enabling the generation of a graph map for the base pathway. In the summer of 2022, entrance and exit point data were gathered to eliminate unnecessary preliminary network pathways for routing between selected locations, ensuring that only the required pathways were incorporated into the routing network. Further refinement and simplification of the thinned network were performed using a scripted geoprocessing tool in ArcGIS Pro (Figure 4.5), streamlining the routing process and enhancing the system's overall accuracy. By using these sophisticated tools and techniques, the routing system was optimized to deliver the most efficient and effective routes for pedestrians and sidewalk robots navigating the campus.

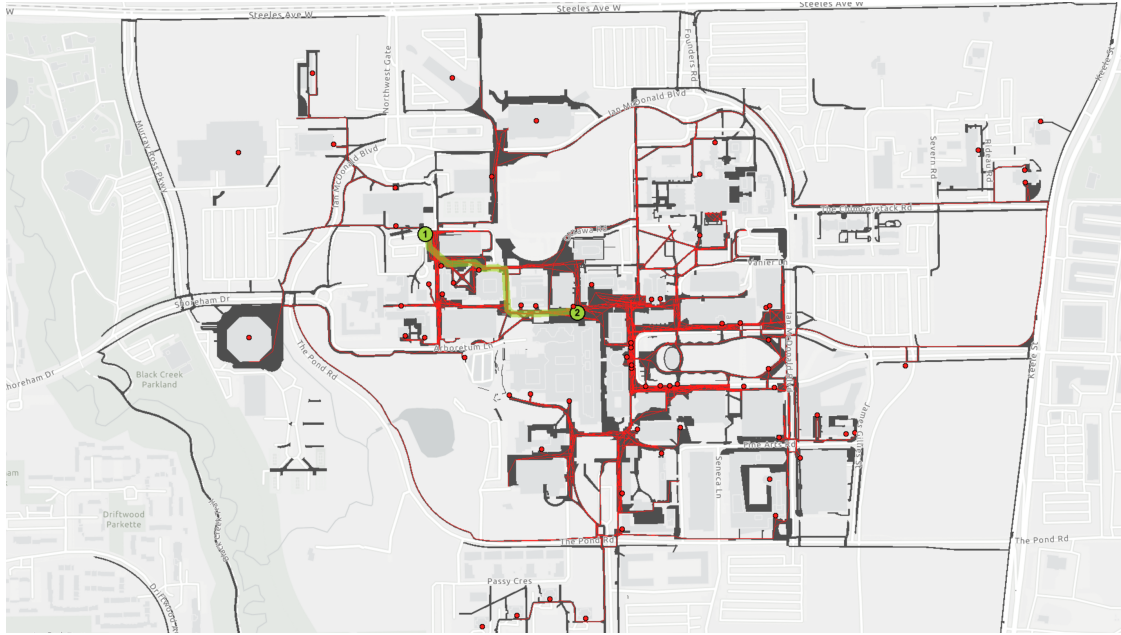


Figure 4.5: Navigation Analysis Network Graph: Green-highlighted shortest path connects the starting point (1) to the destination (2), illustrating efficient routing.

4.1.4 Interactive Simulator: User Interface Design

Utilizing the ArcGIS Online platform, the web-based virtual model of the campus offers smooth interaction via the ArcGIS JavaScript API. Any computer equipped with adequate processing and graphics capabilities can access this system through a browser, thus negating the need for additional software. The simulator efficiently handles critical spatial data like entrances, exits, street furniture, and land-use details, drawing and scrutinizing this information directly from ArcGIS Online through the same JavaScript API.

The underlying technical complexities are hidden from the user, creating a streamlined and intuitive user experience. Upon entry, users encounter a landing page showcasing a York

University virtual model. This display is accompanied by a user interface (UI) that allows for various scenario configurations, as seen in Figure 4.6.

The UI provides options for adjusting both pedestrian and interacting agent parameters. Users can access Route Control for selecting starting and ending points and Directional Control for determining uni- or bidirectional movement between these points.

In addition, the UI offers agent spawning control parameters. These include the choice of uniform or random agent spawning, the ability to determine the number of pedestrian and robot agents, the interval between spawns, and an option to implement social distancing measures. This robust control suite allows users to create scenarios tailored to their needs.

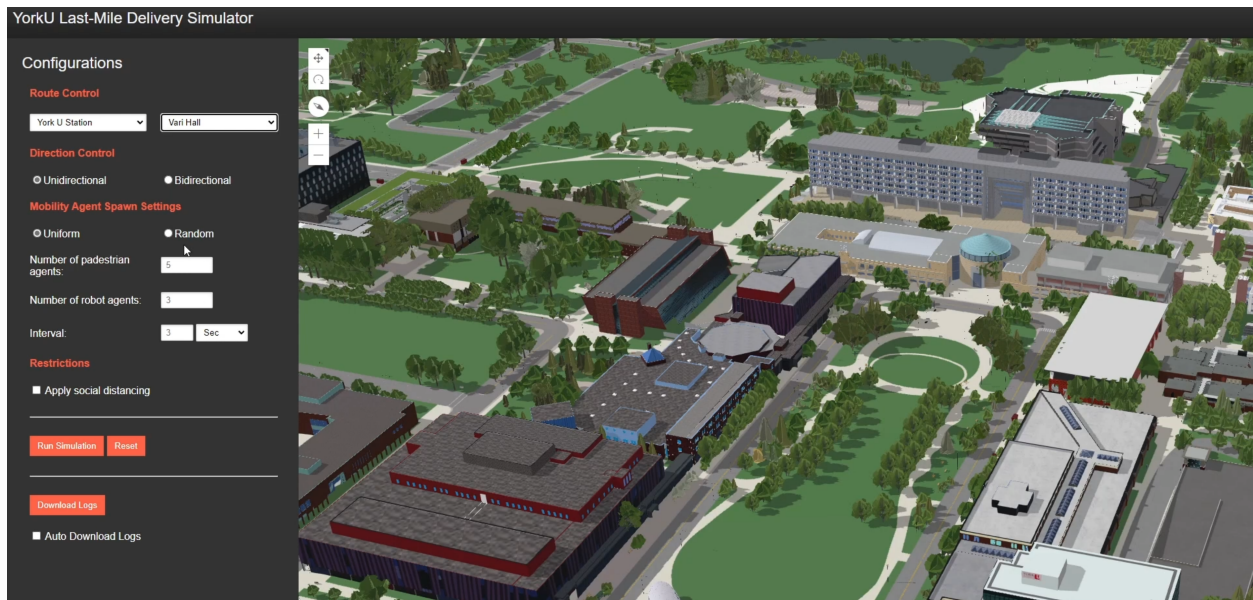


Figure 4.6: The user interface (UI) of the web-based last-mile simulation platform, designed for conducting comprehensive campus-wide scenario analyses within a virtual representation of York University.

4.2 Pedestrian and SADR Simulations

The study of pedestrian navigation and collision avoidance techniques has evolved significantly over recent decades, giving rise to a diverse range of methods that simulate varying aspects of human-like movements [55, 17]. These methods consider both pedestrians and robots as self-propelled entities operating within a continuous space. In our investigation, microscopic models form the foundation for simulating the intricate dynamics of pedestrian motion.

In our navigation approaches, pedestrians, wheelchair users, and robots are regarded as self-propelled entities traversing a continuous space. We utilized microscopic models as the basis for simulating pedestrian dynamics, which includes people walking and using motorized wheelchairs. We employed agent-based modeling for these groups to better capture the intricacies of their interactions and individual behaviours in navigating sidewalks. This approach allows for a more accurate representation of their individual behaviours and decision-making processes, which is critical for developing effective and socially compliant navigation strategies in shared environments. In particular, we modeled motorized wheelchair users as a part of our efforts to account for the full spectrum of entities that might be encountered in an urban sidewalk setting, ensuring that our simulations are inclusive of accessibility needs. Wheelchair users are an essential part of the pedestrian landscape and their inclusion is crucial for creating a realistic and comprehensive model of sidewalk dynamics.

By modeling individual pedestrian and wheelchair movements, we can derive macroscopic descriptions of pedestrian flow, the design of pedestrian facilities, and the examination of

theoretical issues, such as determining the safe proximity between robots, pedestrians, and wheelchair users or establishing appropriate robot movement speed [56, 57]. This approach provides a holistic view of the interactions and dynamics on shared sidewalks, accounting for the varied behaviours and movements of pedestrians, wheelchair users, and robots as shown in figure 4.7.



Figure 4.7: Last Mile Delivery Robot Simulation Tool: (a) and (b) show diverse mobility agents, including robots, pedestrians, and wheelchair users, seamlessly progressing to their destinations. In (c), agents adhere to the path created by the route analysis API.

4.2.1 Pedestrian Simulation

One of the pioneering microscopic simulation models, known as Boids [51], simulated flocking behaviours in birds or fish using three fundamental rules: alignment, separation, and cohesion.

Successive models evolved from this basis, including force-based models such as Social Forces [58], which directed agents towards their goals and maintained safe inter-agent distances through the use of attractive and repulsive forces.

This mechanism was further refined by introducing a predictive aspect, enabling agents to initiate avoidance maneuvers proactively in anticipation of potential collisions. The Predictive Avoidance Model (PAM) [17] is an example of such a model. It employs a piecewise predictive function based on relative velocities between agents to forecast potential future collisions within a defined time window. Demonstrated to effectively model diverse human behaviours, including distracted pedestrians [59], PAM is the simulation algorithm employed in our work.

4.2.2 SADR Simulation

Sidewalk Autonomous Delivery Robots (SADRs) present an innovative response to the challenges of last-mile delivery. Operating primarily on sidewalks, SADRs autonomously transport packages while abiding by pedestrian regulations, thereby offering a solution that reduces vehicular traffic and congestion [31, 32, 33]. These robots, equipped with state-of-the-art sensors, cameras, and navigation systems [34], proficiently detect and evade obstacles, such as pedestrians, cyclists, pets, and other sidewalk users. They operate in accordance with established pedestrian laws and regulations, without necessitating human intervention [35, 36].

Supporting the integration of pedestrian navigation models for SADR sidewalk navigation, Shiomi et al. [43] developed a human-like collision avoidance system for mobile robots.

This system, based on the Social Force Model from human science literature, was explicitly designed for pedestrian environments such as shopping malls. The proposed system, subjected to real-world field trials, showcased increased comfort for pedestrians and safer navigation, outperforming traditional collision-free methods due to its alignment with pedestrian behaviour in crowded situations.

To support further the idea of using pedestrian navigation regulations and models for robot navigation on sidewalks, Shiomi et al. [43] developed a human-like collision avoidance system for mobile robots by applying a pedestrian model from human science literature, specifically the Social Force Model designed for shopping malls and similar pedestrian environments. The proposed system was tested through 2-hour field trials in real-world settings and demonstrated not only increased comfort for pedestrians but also safer navigation compared to traditional collision-free methods, as it better aligns with the behaviour of pedestrians in crowded situations. Based on the literature review and the promising results mentioned above, we used the PAM for our robot simulations to ensure effective and safe navigation in pedestrian environments.

4.2.3 Post-Simulation Analysis: Evaluation Metrics and Insights

While visualization provides a valuable means of assessing the dynamics of a system in simulation, it is frequently more beneficial to explore the performance and interactions of systems post-simulation. This analysis often utilizes data generated during the simulation process. With this goal in mind, we have incorporated several metrics into our model that

are conducive to post-simulation analysis.

These metrics, self-generated by the participating entities, are logged and can be downloaded in a CSV format. The logged data include pertinent details such as the geographical position of agents (latitude and longitude), exerted effort, kinetic energy, path length, and total time spent by each agent.

The 'effort' metric quantifies the energy expended by each agent to navigate the sidewalk. This metric factors in mass, velocity, and time. In parallel, the 'kinetic energy' provides a measure of the energy of motion for all entities, including both humans and autonomous agents. This is calculated considering their instantaneous kinetic energy and the duration of their interaction.

An essential part of our evaluation metrics includes critical incidents like personal space violations (infringements of the 2m distancing guideline) as shown in figure 4.8 and collision points. A 'personal space violation' occurs whenever the 2m radius around an individual is breached by either another pedestrian or an autonomous entity. These violations serve as a valuable measure of comfort level and adherence to social norms. On the other hand, 'collision points' track any physical contact between entities, signifying a potential safety risk.

In addition to these, we monitor the 'overall flow' of pedestrians and autonomous entities on the sidewalk. This metric gives an insight into the efficiency of navigation, measuring the ease and speed at which all entities traverse the sidewalk without significant disruptions to one another.

Through the interpretation of these metrics, we aim to optimize the coexistence of

autonomous entities and pedestrians. The comprehensive understanding garnered from this evaluation assists in refining the navigation algorithms of autonomous entities, suggesting improvements in sidewalk management, and enhancing safety measures. It ensures fluid navigation and minimal disruptions, facilitating a harmonious coexistence.

This systematic analysis underpins our endeavor to understand the dynamics of integrating autonomous entities into pedestrian spaces, identify potential areas of improvement, and ensure efficient, comfortable, and safe cohabitation. Our clear explanation of each metric and variable aims to illuminate the objectives and rationale behind our simulation experiments.

- social Space of Agent A
- social Space of Agent B
- Proximity Violation

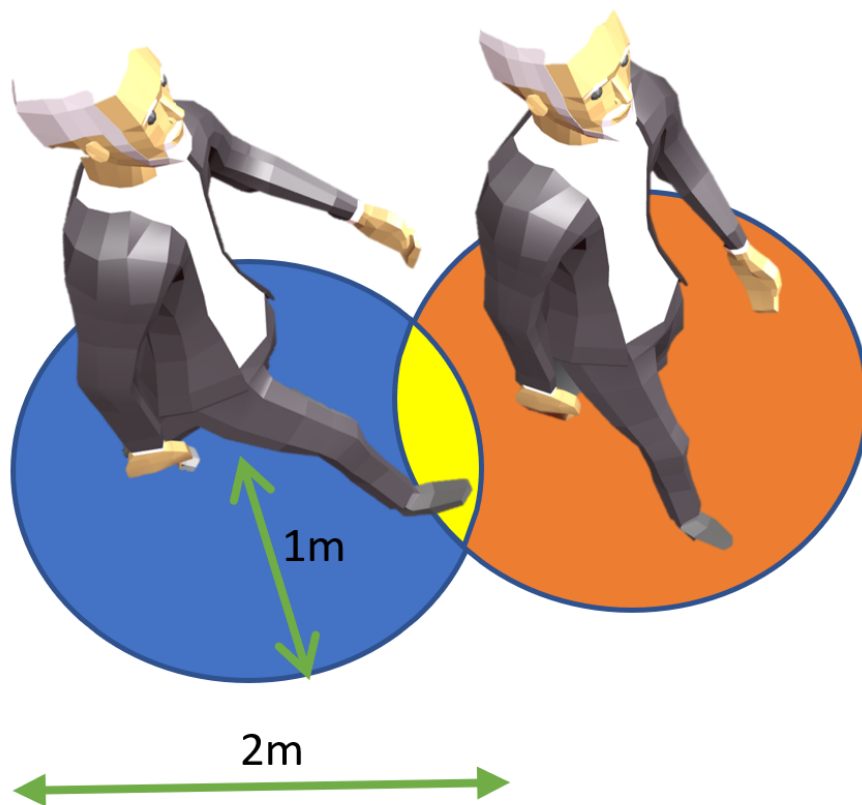


Figure 4.8: An illustration of an agent's social space and its violation.

Chapter 5

Performance Evaluation of Web-based Digital Twin Model and Simulator

This chapter focuses on the experimental validation of the reliability, efficiency, and scalability of our web-based digital twin model and simulator, particularly emphasizing its performance dynamics. We have conducted a comprehensive series of tests, assessing various facets of performance to provide an in-depth evaluation of the system's strengths and potential weaknesses.

The performance analysis, conducted on a robust system with an AMD Ryzen 9 5900X 12-Core Processor, an RTX 3090 graphics card, and 64GB of RAM, offered crucial insights into the system's capability to accurately mirror real-world scenarios, identify prospective bottlenecks, and suggest improvements to elevate the system's overall performance. It further enabled a comparative evaluation of our model's efficiency with similar digital twin models

and simulators, on the basis of assessed performance metrics.

We evaluated two distinct versions of the campus digital twin models. The first, an exhaustive model, rigorously replicates all physical aspects of the campus such as structures, roads, sidewalks, and green spaces. In contrast, the second version is a simplified model, strategically excluding certain visual elements, like trees, to diminish model complexity and more effectively manage computational demands. Regardless of these visual modifications, it's worth noting that both versions possess uniformly comprehensive underlying scene awareness data, imperative for the simulation of agents.



Figure 5.1: Comparative Visualization of Digital Twin Campus Models. (a) The full-featured model displays a detailed representation of all physical features, and (b) The optimized model demonstrates a simplified version with selective visual elements, still retaining comprehensive scene awareness data crucial for agent simulation.

In order to scrutinize the system’s performance, key factors such as system stress, agent mobility, routing efficiency, and computing efficiency were investigated under varying conditions and levels of system loads. Stress performance involved the system undergoing escalating workloads to measure responsiveness and reliability under high-stress conditions. A diverse array of scenarios were simulated to examine how the system’s performance would adapt to amplified complexity.

A critical element in our analysis was the evaluation of agent mobility, which revolved around examining the movements of robots and pedestrians within our simulated environment. By closely monitoring their trajectories, speeds, and inter-agent interactions, we could gather insights into the simulator’s capacity for replicating real-world mobility patterns and supporting dynamic interactions among different types of agents.

Two contrasting experiments, each involving different numbers of mobility agents, were conducted to discern valuable insights about the scalability and efficiency of our simulator. The first experiment, involving a single robot and pedestrian, recorded an average total effort of 1668.50 Joules, kinetic energy of 0.47 Joules, and path length of 467.48 meters. Comparatively, the second experiment, featuring thirty mobility agents, displayed a modest increase in total effort to 1726.11 Joules, while kinetic energy slightly decreased to 0.39 Joules and path length marginally increased to 468.56 meters. The higher flow rate in the second experiment suggests increased interactions and congestion within the system, which is a realistic representation of crowded scenarios, further confirming the robustness of our digital twin model and simulator.

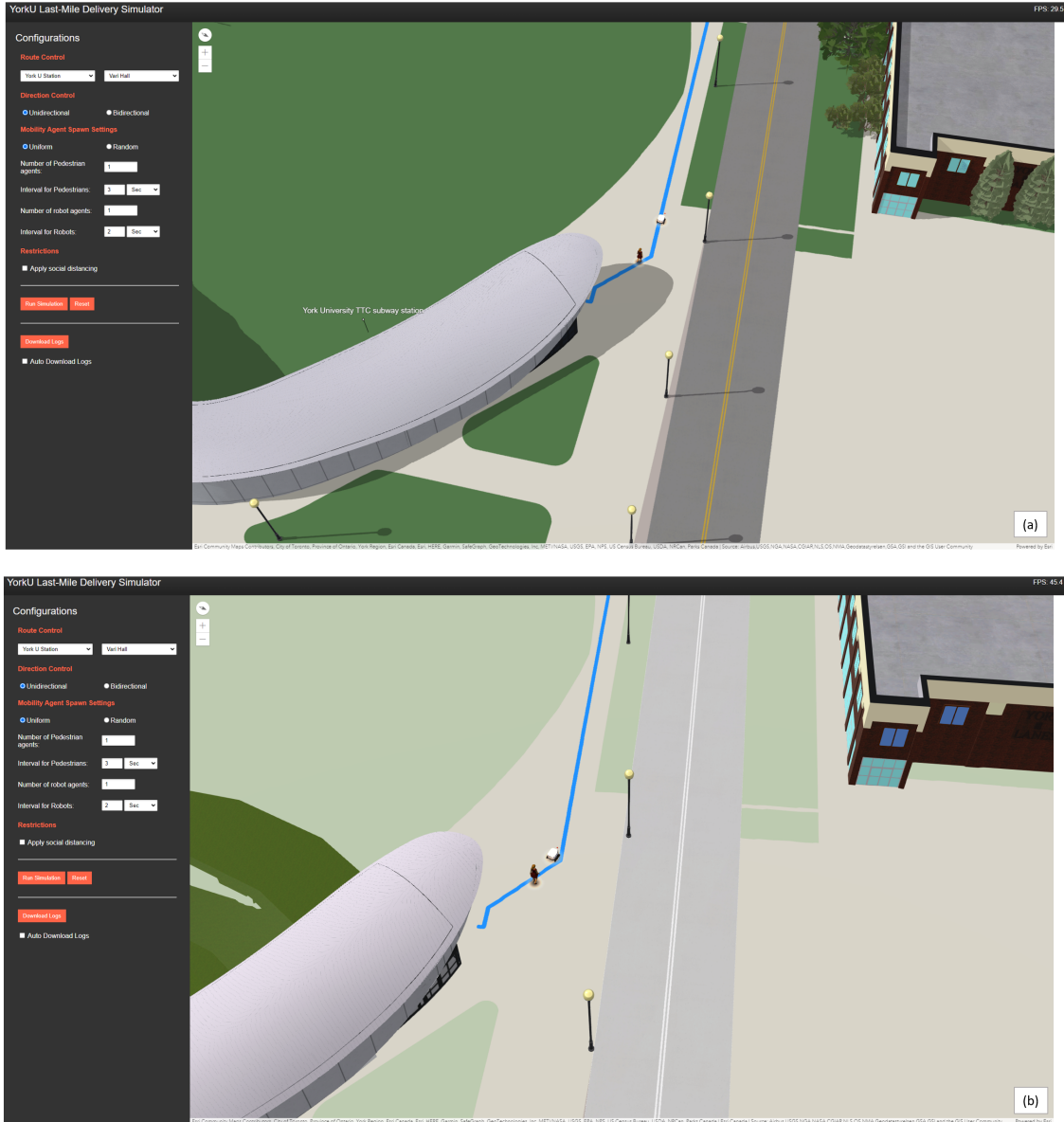


Figure 5.2: Performance Analysis of the Comprehensive and Simplified Digital Twin Models. The comprehensive model, with its high level of detail, maintains a frame rate of 30 FPS. The simplified model, which trades some visual detail for efficiency, achieves a higher frame rate of 45 FPS.

An important metric in our evaluation was routing efficiency, evaluated by analyzing the

paths taken by the delivery robots to their destinations, taking into account factors such as total distance covered, time taken, and route alterations due to interactions with pedestrians. Despite a reduction in frames per second (fps) impacting the visual fluidity of the simulation, it did not compromise the accuracy of interaction logging or the mobility of our agents, affirming the simulator’s stability under varying conditions.

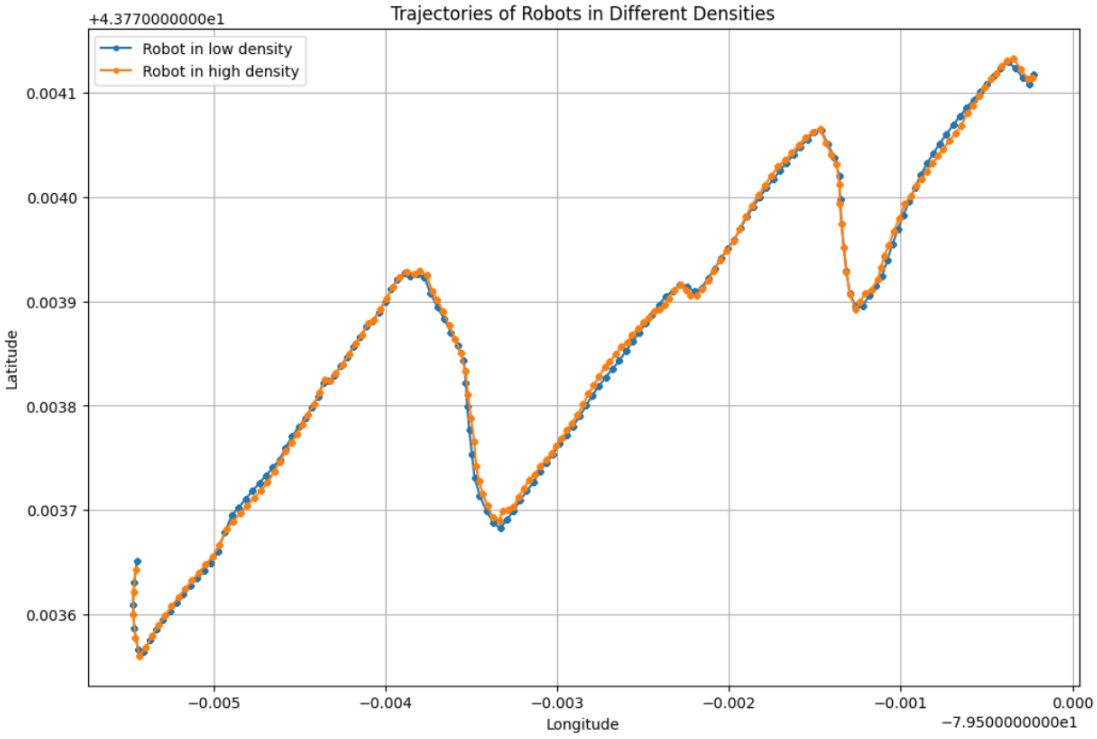


Figure 5.3: Robot Trajectories Under Varied Mobility Scenarios. The trajectories of two sidewalk robots operating under low-mobility (represented in blue) and high-mobility (represented in orange) scenarios. Remarkably, despite lower frames per second in the high-mobility scenario, both robots adhere to an efficient path, underscoring the simulator’s ability to sustain agent performance amidst varying densities.

The findings of these experiments provide substantial insights into the performance of our digital twin model and simulator. There is a positive correlation between the number of agents in the system and the overall computational load, however, the simulator maintained a steady frame rate despite increased stress levels, validating its capacity to handle complex scenarios without significant performance degradation.

In conclusion, our performance evaluation has been instrumental in understanding the model and simulator's feasibility and efficiency. It unequivocally showcased the system's capability to manage increased complexity, and its potential to simulate a broad range of real-world scenarios. Future work will concentrate on optimizing the system's performance based on these findings and enhancing the range of scenarios it can accurately replicate.

Chapter 6

Experiment Design and Results

This chapter presents our comprehensive experimental framework and the results derived from our study. The primary aim of the study is to scrutinize the dynamics between pedestrians and autonomous sidewalk delivery robots. Leveraging an advanced agent-based modeling approach, we mirror the complexity of urban settings by simulating encounters between pedestrians, wheelchair users, and autonomous delivery robots on sidewalks.

The chapter is divided into two main sections. The first section explores the design of our experiment, which is executed in three distinct phases. Each phase unravels new facets of the dynamics on shared sidewalks. The second section showcases the findings from each experimental phase, leading to a more profound understanding of the interplay between pedestrians and autonomous robots on sidewalks.

6.1 Experiment Design

Our experimental design unfolds over three phases - "Service Model Reconfiguration", "Interplay of Density Variations", and "Navigational Complexity Assessment", each contributing to a deeper understanding of shared sidewalk dynamics.

The initial phase, "Service Model Reconfiguration", involves refining Fruin's Level of Service (LOS) model. We expand its traditional focus on pedestrian densities to account for the emerging presence of sidewalk delivery robots. This enables us to scrutinize the potential implications of robot density on pedestrian movement and flow dynamics.

The second phase, "Interplay of Density Variations", keeps the LOS constant, while manipulating the densities of pedestrians and robots. This part of the experiment investigates the variations in interactions and dynamics on sidewalks that result from different densities of pedestrians and robots. This analysis provides a comprehensive view of shared sidewalk complexities in an anticipated future characterized by the widespread presence of autonomous sidewalk delivery robots.

The final phase, "Navigational Complexity Assessment", deepens our exploration by introducing varying LOS levels, multiple origin-destination combinations, and two-way traffic on sidewalks. This phase tests the impact of these variables on the overall functionality of the sidewalk ecosystem.

We utilize a controlled, multi-faceted approach using agent-based modeling, simulation, and digital twin frameworks to assess the safety and behavior of pedestrian interactions

with autonomous sidewalk delivery robots. Our models represent each entity— pedestrians, wheelchair users, and delivery robots—with realistic attributes and behaviors. This experiment’s structure, involving distinct phases with varying agent densities and a randomized introduction of agents, contributes to the realism and applicability of our study.

6.2 Phase 1: Service Model Reconfiguration

As urban environments evolve, the impact of emerging technologies on pedestrian walkways and sidewalks must be considered. The traditional Fruin’s Level of Service (LOS) model [60] as shown in Table 6.1 focuses on pedestrian density but does not account for the growing presence of sidewalk delivery robots. To address this, we propose a modified LOS model that considers both pedestrian and robot densities, providing a more accurate representation of dynamic interactions and space requirements on shared sidewalks.

Fruin’s LOS	Walkway (ped/m ²)	Stairs (ped/m ²)	Queue (C)
A	< 0.31	< 0.54	< 0.83
B	0.31–0.43	0.54–0.72	0.83–1.08
C	0.43–0.72	0.72–1.08	1.08–1.54
D	0.72–1.08	1.08–1.54	1.54–3.57
E	1.08–2.17	1.54–2.70	3.57–5.26
F	> 2.17	> 2.70	> 5.26

Table 6.1: Fruin’s level of service hierarchy [60]

In the evolving landscape of urban design, as robotic presence in pedestrian zones becomes increasingly prevalent, it is essential to understand the nuances of their integration. Given

the specified physical dimensions of the robots: 27.4"(69.7cm) in length, 22.4"(56.9cm) in width, and 22.5"(57.1cm) in height⁴, their spatial occupation is undeniable. Such robots, by virtue of their size and operational areas, have the potential to significantly influence pedestrian flow and density. This scenario underscores the imperative need to re-evaluate and refine Level of Service (LOS) standards to ensure the harmonious coexistence of humans and robots in pedestrian zones.

In response to the challenges previously highlighted, we propose a mathematical model tailored to quantify the adjusted pedestrian density, symbolized by D'_p . The formal representation of this model is as follows:

$$D'_p = D_p - (D_r \times \frac{A_r}{A_p}) \quad (6.1)$$

Where:

- D_p represents the intrinsic pedestrian density.
- D_r denotes the robot density within the given area.
- A_p signifies the average spatial footprint of a pedestrian.
- A_r indicates the mean area occupied by a robot.

The essence of this model is to adjust the pedestrian density, accounting for the equivalent spatial consumption of robots, as if they were pedestrians.

For a practical understanding, consider the example where A_p is 0.5 m^2 for pedestrians and A_r is 0.396 m^2 for robots. This framework offers a means to calibrate densities in

⁴<https://starshipdeliveries.com/industry/>

diverse pedestrian scenarios. This approach facilitates a deeper insight into robot-pedestrian interactions, thereby enabling judicious adjustments to LOS standards in areas characterized by both pedestrian and robot movement.

This research endeavors to recalibrate Fruin’s LOS model, tailoring it to contexts where pedestrians and autonomous sidewalk delivery robots coexist. Through this refined model, we elucidate a series of experimental scenarios comprising various pedestrian and robot densities. This foundational work sets the stage for subsequent empirical data collection and analysis, furthering the understanding and optimization of these proposed densities.

1. **Traditional Fruin’s LOS:** It classifies walkway densities based purely on the number of pedestrians per square meter (ped/m^2). For instance, LOS A represents very low-density pedestrian traffic, while LOS D indicates a more crowded scenario.
2. **Adjusted LOS with Robots:** Given the addition of sidewalk robots, we’ve incorporated two density levels for the robots – ‘low’ and ‘high’. The new labels are:
 - **A+:** LOS A pedestrian density with a low-density of robots.
 - **A++:** LOS A pedestrian density but with a high density of robots.
 - **D+:** LOS D pedestrian density combined with a low robot density.
 - **D++:** LOS D pedestrian density coupled with a high robot presence.

These new labels can be referred to in Table 6.2.

The "+" and "++" suffixes intuitively represent the increasing robot densities. Specifically,

a single "+" denotes scenarios with fewer robots, while "++" symbolizes areas with a higher robot presence.

This adjusted LOS model provides a nuanced understanding of the shared sidewalk space dynamics. It highlights how the introduction of robots impacts pedestrian flow and helps urban planners and policymakers make informed decisions concerning shared walkways amidst the rise of autonomous delivery systems.

Scenario Code	Adjusted LOS	Description	Adjusted Densities (ped/m ² and robots/m ²)
S1	A	Low-density pedestrian traffic	< 0.31 pedestrians
S2	D	High-density pedestrian traffic	1.08 - 0.72 pedestrians
S3	A+	Low-density pedestrian with low-density robots	0.24 - 0.28 pedestrians, 0.04 - 0.06 robots
S4	D+	High-density pedestrian with low-density robots	1.065 - 0.675 pedestrians, 0.04 - 0.06 robots
S5	A++	Low-density pedestrian with high-density robots	0.21 - 0.24 pedestrians, 0.1 - 0.13 robots
S6	D++	High-density pedestrian with high-density robots	1.005 - 0.57 pedestrians, 0.1 - 0.13 robots

Table 6.2: Scenarios for Adjusted LOS Incorporating Pedestrian and Robot Densities.

In the scenarios presented in Table 6.2, the term 'pedestrian' encompasses not just individuals on foot but also those using wheelchairs. This broader definition of pedestrian traffic is instrumental in capturing a realistic and holistic picture of urban sidewalk dynamics. Recognizing the diversity of users in real-world pedestrian environments, our study inten-

tionally integrates wheelchair users as an integral component of the pedestrian group. For every ten pedestrians encountered in our simulation, one was a wheelchair user, reflecting a randomness factor of 1:9. Such a configuration ensures that our model is more representative of actual pedestrian conditions, where the term 'pedestrian' is not limited to those on foot. By incorporating both foot pedestrians and wheelchair users, alongside robots, the study offers a comprehensive analysis of shared sidewalk spaces, aiming to inform urban planning in an era increasingly marked by the coexistence of humans and autonomous machines.

Eliminating cognitive memory from the agent-based models in this study ensures consistent agent behaviours and decision-making processes, allowing for the isolation of the effects of varying pedestrian, wheelchair user, and robot densities on interactions and navigation patterns. This design choice prevents the introduction of confounding variables related to learning or adaptation, offering a controlled environment for assessing the impact of experimental conditions on agent behaviour and system performance. The study contributes to a deeper understanding of pedestrian interactions with autonomous sidewalk delivery robots under diverse densities and paves the way for future exploration of more complex adaptive behaviours and their potential implications for safety and efficiency in real-world scenarios.

Two discrete research zones were selected to scrutinize the influence of varying pedestrian and robot densities on sidewalk dynamics. As shown in figure 6.1, the first study area (a) is located between the university's Subway Station and the Lassonde Building, a bustling location with high pedestrian traffic and diverse demographics, ensuring a representative

sample of the general population. The second study area (b) extends from Seneca at York to the Ignat Kaneff Building, another prominent location on campus with a significant pedestrian influx. These two study areas aim to capture the diversity of pedestrian behaviour and effectively evaluate the performance of the proposed scenarios under different conditions.

Data on individual agents and the system as a whole were gathered during each experimental scenario, including self-reported metrics such as position, speed, effort, kinetic energy, path length, and collision information. These data were collected at regular intervals and stored in a CSV file format for further analysis.

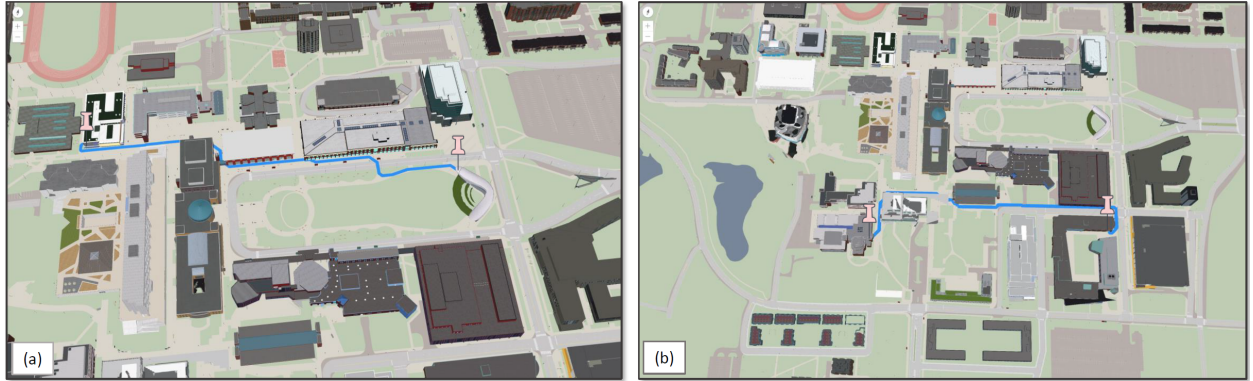


Figure 6.1: Two study areas showcase pedestrian and robot routes, with walkway paths emphasized in blue, connecting origin and destination.

6.2.1 Results

Our study investigates pedestrian and sidewalk robot interactions using agent-based modeling, focusing on metrics such as effort, kinetic energy, path length, and total time taken for each agent. Effort measures the energy expended by the agents to navigate the sidewalk, taking

into account factors such as mass, velocity, and time. Kinetic energy quantifies the energy of motion for both pedestrians and robots, considering their instantaneous kinetic energy and the duration of the interaction.

These metrics aim to evaluate the efficiency, comfort, and safety of the coexistence of sidewalk robots and pedestrians on sidewalks. The choice of a 2m proximity violation is informed by recent research emphasizing the importance of maintaining such a distance for public health [61]. The study on the Social Distancing Index (SDI) illustrates that maintaining a 2m safe distance, especially in populated environments like retail stores, has proven effective in minimizing distance-based violations, thereby suggesting its potential effectiveness in other dynamic environments, such as sidewalks [61]. Considering the global emphasis on social distancing due to concerns like COVID-19, a 2m benchmark provides a relevant and informed standard to evaluate the safe coexistence of pedestrians and sidewalk robots. The overarching goal is to understand and optimize the integration of these robots into pedestrian realms, ensuring that both entities navigate smoothly and with minimal disruptions.

Proximity Violations and Collisions

We analyzed data (Figure 6.2) collected from 12 different scenarios (i.e., repeating 6 scenarios from Table 6.2 for the two study areas as shown in Figure 6.1), involving collisions and proximity violations among pedestrians, wheelchair users, and robots. The cumulative spawn count for all entities reached 698, consisting of 469 pedestrians, 186 robots, and 43 wheelchair

users. There were a total of 475 collisions, with the majority involving robot-to-pedestrian interactions (47.6%), followed by pedestrian-to-pedestrian interactions (38.5%) and wheelchair users involved in 13.9% of the collisions. On the other hand, there were 40,674 recorded proximity violations, with pedestrian-to-pedestrian interactions being the most prevalent (70.0%). Robot-to-pedestrian violations accounted for 25.7% of the incidents, while wheelchair users were involved in a smaller percentage of proximity violations, constituting 4.3% of the total.



Figure 6.2: Comparative analysis of collisions (TOP) and proximity violations (BOTTOM): bar graphs depicting the prevalence and distribution of incidents among pedestrian, wheelchair user, and robot agent pairs.

To understand better the overall share of each agent type in causing violations and collisions as per their population across all scenarios, we adjusted the above percentage calculations of proximity violations and collisions based on their spawn count. While pedestrians had the

highest average of proximity violations (60.7), they experienced the fewest collisions (0.39 per pedestrian). Conversely, robots and wheelchair users had lower proximity violation averages but higher collision rates, with 1.2 collisions per robot and 1.5 per wheelchair user. The observed differences in proximity violations and collision rates among pedestrians, robots, and wheelchair users could also be attributed to factors such as the average moving speed and personal space occupied by robots on sidewalks. With their higher average speeds, robots may have a more challenging time adjusting to sudden changes in their environment or anticipating other agents' movements. This difficulty in adapting could result in increased proximity violations and collisions. Table 6.3 shows a snapshot of data collected for the given scenarios from the two study areas. Our findings suggest that urban planners and other stakeholders should take into consideration the time of day (e.g., rush hours, after office hours, weekends, etc.) and population density (i.e., Level of Service) of sidewalks when permitting robots on the shared spaces. By accounting for these factors, stakeholders can identify optimal times and routes for robots to operate, minimizing congestion and ensuring a safer coexistence with pedestrians and wheelchair users. This could involve implementing dedicated robot lanes, restricting robot usage, minimizing robot population density during peak hours, or mandating lower speed limits for robots in crowded areas.

Scenario	Pedestrians Count	Robots Count	Study Area (a)		Study Area (b)	
			Proximity	Collisions	Proximity	Collisions
S1	30	0	P-P: 923 P-W: 27 W-P: 96	0	P-P: 960 P-W: 51 W-P: 96	0
S2	75	0	P-P: 4456 P-W: 247 W-P: 254	P-P: 11 P-W: 2 W-P: 1 W-W: 3	P-P: 4782 P-W: 172 W-P: 187	P-P: 28 P-W: 7 W-P: 6
S3	18	8	P-P: 508 P-R: 70 P-W: 6 R-P: 222 R-W: 52 W-P: 31 W-R: 4	P-P: 3 R-W: 1	P-P: 293 P-R: 36 P-W: 16 R-P: 129 R-R: 9 R-W: 96 W-P: 118 W-R: 12	P-R: 4 R-P: 2 R-W: 6 W-R: 2
S4	60	12	P-P: 3647 P-R: 350 P-W: 76 R-P: 1029 R-R: 38 R-W: 17 W-P: 85 W-R: 7	P-P: 3 P-R: 7 R-P: 7 R-W: 1	P-P: 3965 P-R: 215 P-W: 82 R-P: 680 R-R: 87 R-W: 67 W-P: 197 W-R: 12	P-P: 18 P-R: 8 P-W: 7 R-P: 9 R-R: 9 R-W: 4 W-P: 1 W-R: 2 W-W: 2
S5	18	38	P-P: 419 P-R: 272 P-W: 5 R-P: 837 R-R: 898 R-W: 56 W-P: 7 W-R: 15	P-P: 2 P-R: 3 R-P: 5 R-R: 8 W-R: 1	P-P: 250 P-R: 213 P-W: 39 R-P: 790 R-R: 674 R-W: 90 W-P: 41 W-R: 28	P-R: 6 R-P: 3 R-R: 13 R-W: 12 W-R: 3
S6	55	35	P-P: 2816 P-R: 962 P-W: 97 R-P: 2014 R-R: 940 R-W: 96 W-P: 158 W-R: 53	P-P: 10 P-R: 18 P-W: 2 R-P: 32 R-R: 19 R-W: 13 W-P: 2 W-R: 7	P-P: 2705 P-R: 631 P-W: 212 R-P: 1588 R-R: 672 R-W: 145 W-P: 334 W-R: 67	P-P: 15 P-R: 26 P-W: 7 R-P: 28 R-R: 24 R-W: 36 W-P: 9 W-R: 20 W-W: 9

Table 6.3: Proximity violations and collisions between different agents for the two study areas as shown in Figure 6.1. (P=Pedestrian, R=Robot, W=Wheelchair)

Flow Density

Flow density is a crucial metric for assessing the movement and dynamics of pedestrians and sidewalk robots on sidewalks. To determine flow density, we consider both spatial and temporal dimensions. Spatially, we evaluate a circular region with a radius of 2 meters, approximating an area of 12.57 square meters. Temporally, our analysis frames a 2-second window. For each agent (whether pedestrian or robot) in our dataset, we identify how many other agents are within this 2-meter radius and 2-second time frame, giving us a measurement reflecting the number of agents present within this specified spatiotemporal boundary.

It represents the concentration of agents in a given area and time interval, capturing the ease with which they can coexist and navigate the sidewalk. The observed differences in the average minimum distances between pedestrians and robots play a significant role in shaping the density flow patterns in the respective scenarios. The average minimum distance between robots and pedestrians is 0.599m, which is substantially larger than the 0.333m average minimum distance between pedestrians. This increased separation between robots and pedestrians suggests that robots maintain a greater buffer zone in their surroundings, contributing to a more evenly distributed density flow. This characteristic is particularly evident in scenarios with a higher proportion of robots, where the larger average minimum distances help to create a more dispersed flow and reduce congestion.

In contrast, the smaller average minimum distance between pedestrians indicates that individuals tend to maintain closer proximity to one another during violations than the robots. Consequently, scenarios with a higher number of pedestrians exhibit denser flows, as the closer

interactions lead to a more compact and concentrated distribution of individuals. Figure 6.3 illustrates the difference in flow density, (a) depicting a scenario with only pedestrians (S1), while (b) showcasing a scenario featuring both pedestrians and robots (S3).

The findings suggest that, contrary to some reports [62], robots may not inherently contribute to sidewalk congestion, potentially allowing for smoother co-existence with pedestrians. Hence, urban planners could consider incorporating robots sharing sidewalks as a design decision when designing shared urban spaces, provided they carefully account for the number of robots in the overall crowd density. This approach suggests a potential for smooth coexistence and navigation for both pedestrians and robots, contributing to a more harmonious and efficient urban environment.

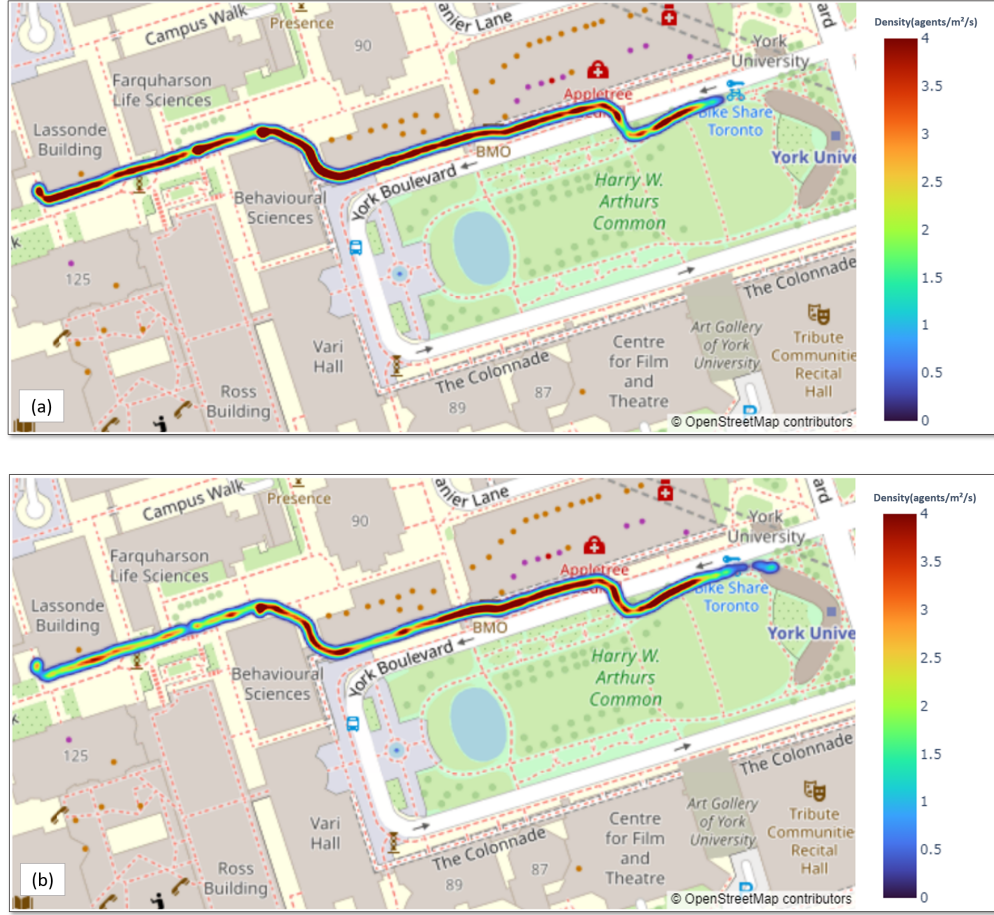


Figure 6.3: Comparative analysis of flow density between two distinct scenarios: (a) scenario S1 representing low-density pedestrian traffic and (b) scenario S3 featuring comparable low-density pedestrian traffic but with an added low-density of robots.

To further comprehend the diverse implications of agent compositions on sidewalk dynamics, it is imperative to extend our analysis beyond the isolated cases of S1 and S3. By exploring the spectrum of flow densities across all experimental scenarios, we can gain a holistic understanding of the unique challenges and interactions introduced by varied pedestrian and robot densities.

For a more comprehensive perspective, we analyzed the flow densities of all six scenarios, ranging from Seneca to the Ignatt Kanff building. Each scenario has its distinct composition of pedestrians and robots, thus presenting varied flow patterns, interactions, and challenges.

These six scenarios provide an in-depth insight into the potential real-world implications of mixed-agent sidewalks, from low-density robot-only scenarios to those dominated by pedestrian traffic. By understanding the dynamics across these diverse configurations, urban planners and policymakers can make more informed decisions on integrating robots into urban landscapes. Figure A.7 presents flow density maps encompassing all scenarios within study area 2. For an in-depth analysis of flow density in study area 1, consult Appendix A.1.

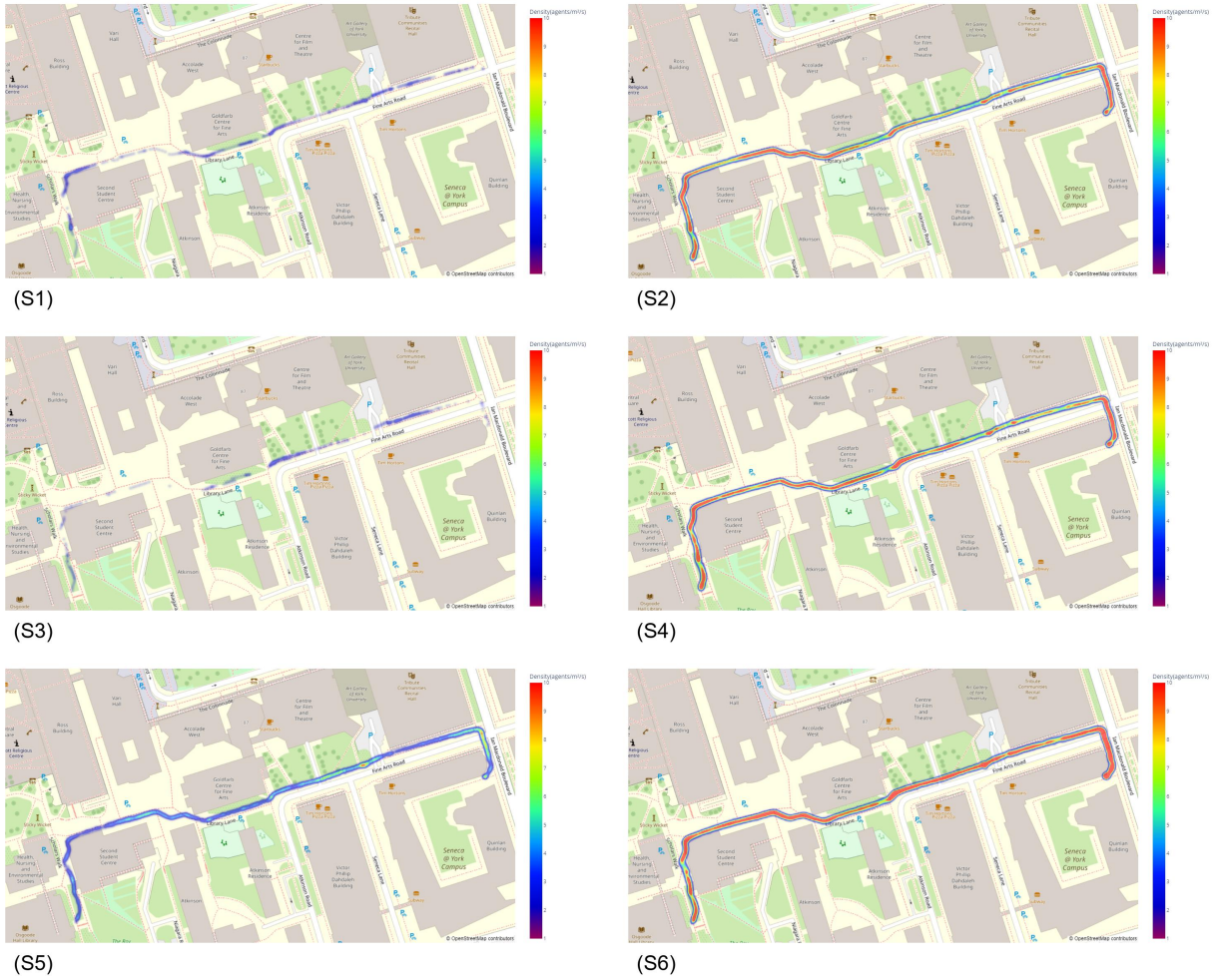


Figure 6.4: Flow density analysis for all six scenarios between Seneca to Ignatt Kanff building.

The graphic showcases the variations in flow dynamics based on different agent compositions, offering insights into how pedestrian-robot interactions mold the sidewalk environment.

Robot Efficiency

In scenario S4, we evaluated the trajectories of a pedestrian and a robot, each traveling from the same origin to the same destination over a given period. The evaluation was aimed

at understanding the overall efficiency of navigation, focusing particularly on the robot's performance in its role of delivering parcels. While the term 'efficiency' might suggest a simple difference in travel speed, in the context of our study, it encompasses several other aspects of navigation. This includes the ability of the robot to effectively plan its route, make real-time decisions, adapt to environmental conditions, and avoid collisions, all of which collectively contribute to the completion of the task without unnecessary delays or interruptions.

The trajectories, recorded in terms of latitude and longitude, allowed us to compute the total distance traveled and the total time taken by each agent. The pedestrian covered a total distance of 0.46 km, whereas the robot traveled slightly further, covering 0.47 km. However, the robot completed the trajectory in a shorter time span of 462.41 seconds (approximately 7.71 minutes), compared to the pedestrian who required 581.46 seconds (approximately 9.69 minutes). These findings highlight not just the differences in speed, but more importantly, the effectiveness of the robot's navigation system in enhancing its efficiency in a shared environment. The robot's capabilities for advanced collision avoidance and real-time decision-making played a key role in this context.

Figure A.8 provides a visual representation of the trajectories of both the pedestrian and the robot, following the same route to the same destination. From the observed data, we noticed that the robot's trajectories displayed wider turns compared to the pedestrian, suggesting that the robot maintained a greater interpersonal distance, especially in denser areas such as turns. This behaviour, which is in stark contrast to pedestrians who tend to move in closer proximity to other agents, is a critical aspect of the robot's design, enabling it to

maintain a larger buffer zone for safety and efficiency. This capability ultimately contributes to the robot's superior performance in shared sidewalk environments. Therefore, it is clear that the robot's efficiency is a product of not just its speed, but also these added components that ensure safe, effective, and unobstructed sidewalk navigation.

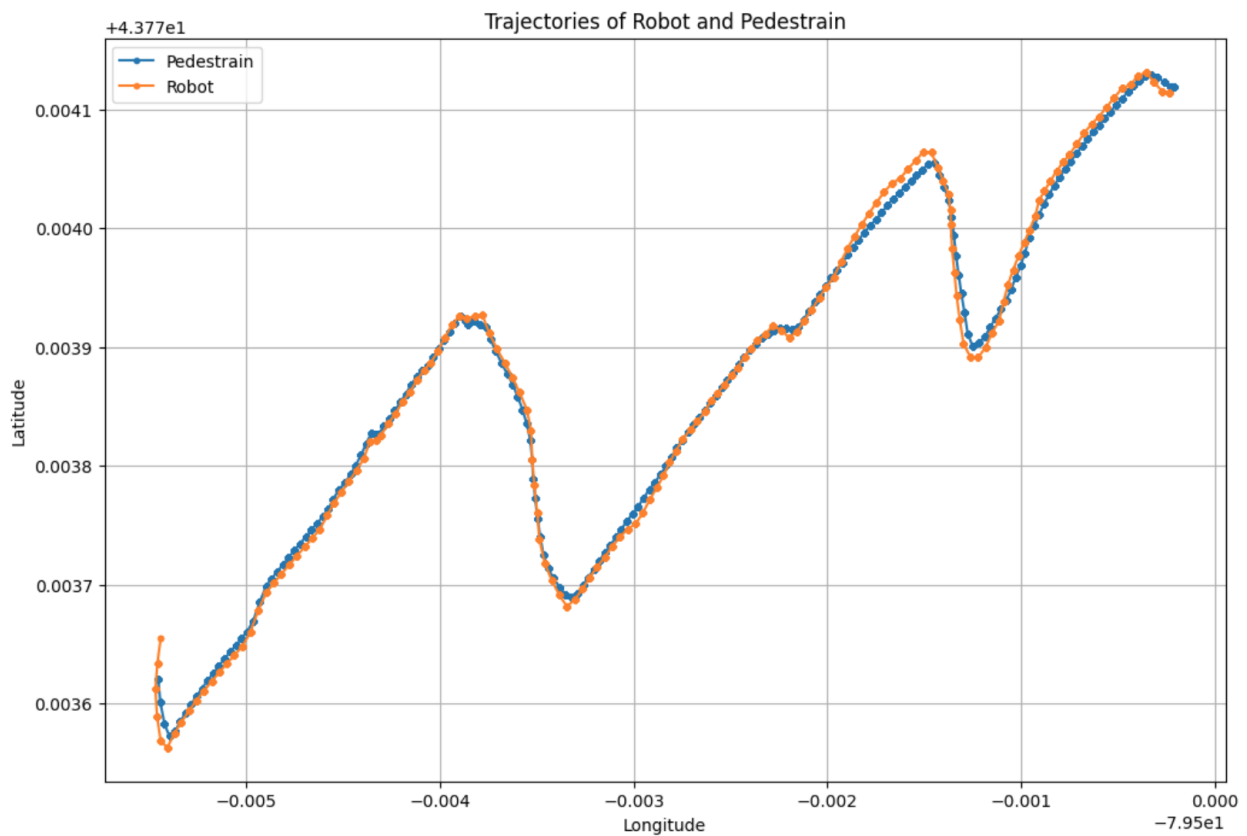


Figure 6.5: Trajectories of a pedestrian and a robot following the same route to reach the same destination.

6.3 Phase 2: Interplay of Density Variations

In the second phase of the experiment, we involved deeper into the dynamics of shared sidewalks under a fixed LOS but with varying densities of pedestrians and robots. This approach is undertaken to assess the impact of diverse agent compositions on the overall sidewalk ecosystem.

Firstly, we investigate scenarios with only pedestrian agents and separately, only robot agents, to establish independent baseline behaviours for each type of entity. The pedestrians-only model examines traditional pedestrian dynamics, while the robot-only model provides insights into how a fleet of autonomous delivery robots would operate in isolation on sidewalks.

Building upon these baselines, we then introduce a mixed-model scenario, where the density of pedestrian agents remains at the baseline level and robots are incrementally added. This experiment enables us to examine how the introduction of robots influences baseline pedestrian dynamics and pedestrian flows.

Further, we scrutinize two distinct scenarios under the fixed LOS density: a more pedestrians-centric density and a robot-centric density. The pedestrians-centric scenario is characterized by a higher density of pedestrians relative to robots, representing a common contemporary urban setting. In contrast, the robot-centric scenario represents a potential future situation with a higher ratio of robots to pedestrians, offering insights into how shared sidewalks might function in a more robot-dominant environment.

Finally, we test an equal-density scenario where the numbers of pedestrians and robots are

equivalent, aiming to study the dynamics that emerge when both entities share the sidewalk space equally.

The findings from this second phase of the experiment not only highlight the effects of varying densities of robots and pedestrians on shared sidewalks but also help to understand and anticipate the challenges that might arise as autonomous sidewalk delivery robots become more prevalent in urban settings.

Scenario Number	Scenario Name	Description	Pedestrian Count	Robot Count
S1	Pedestrian Only (Baseline)	Scenario only involves pedestrians on the sidewalk. No robots are included.	80	0
S2	Robot Only (Baseline)	Scenario only involves robots on the sidewalk. No pedestrians are included.	0	80
S3	Pedestrian-centric Density	Scenario involves more pedestrians than robots on the sidewalk, with fixed LOS densities.	60	20
S4	Robot-centric Density	Scenario involves more robots than pedestrians on the sidewalk, with fixed LOS densities.	20	60
S5	Equal Density	Scenario involves an equal number of pedestrians and robots on the sidewalk, with fixed LOS densities.	40	40
S6	Incremented Robots	Scenario involves pedestrians at base-line numbers and an increasing number of robots over time.	70	10

Table 6.4: The scenario configurations used in phase 2 of the experiment, show both the count for pedestrians and robots.

Following a meticulous evaluation of numerous potential origin-destination pairs, we identified the route from York University Subway station to the Scott Library building as the

most appropriate study area for the second phase of our experiment. This choice, illustrated in Figure 6.6, provides an array of navigation options through diverse sections of the university, thereby encapsulating a wide range of possible encounters between pedestrians and robots. Moreover, this route includes a variety of turns, further contributing to the realism of our experimental scenarios. This complexity allows us to better understand the intricacies and subtleties of pedestrian-robot interactions in lifelike urban environments.

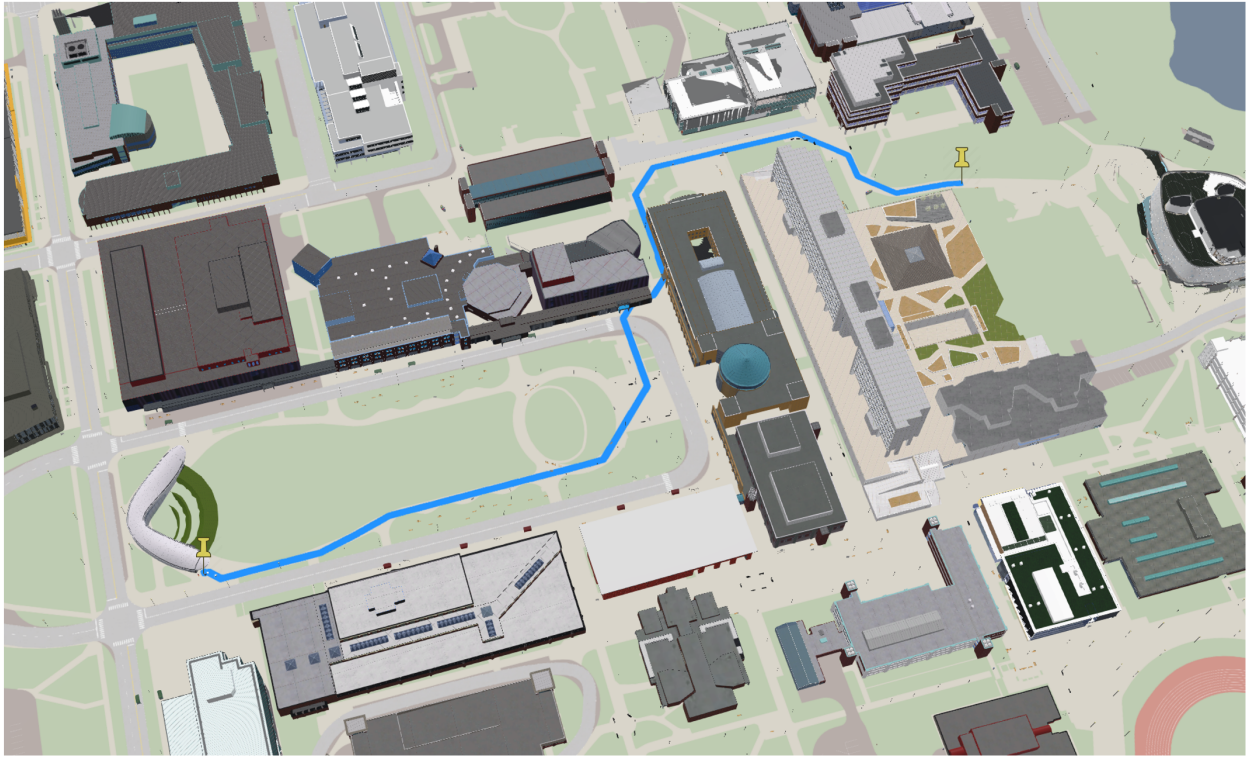


Figure 6.6: Phase 2 study route, capturing the intricate path from York University Subway station to Scott Library, chosen for its real-world complexity and varied pedestrian-robot interaction scenarios.

In the phase 2 experiment results as shown in Table 6.5, there is a striking disparity

between the "Pedestrians Only (Baseline)" and "Robot Only (Baseline)" scenarios. For the "Pedestrians Only (Baseline)" scenario, we recorded 14 total collisions and 4627 proximity violations. However, this dramatically reduced to zero collisions and just 9 violations in the "Robot Only (Baseline)" scenario, despite the same number of entities on the path.

This notable difference reveals a higher propensity for pedestrian entities to engage in collisions and violations as compared to robotic entities when navigating the path individually. Specifically, in the pedestrian-only scenario, all of the collisions and violations were intraspecific, highlighting the challenges in pedestrian-pedestrian interactions on the walkway. Notably, pedestrians were involved in the vast majority of violations (96.11%), with wheelchair users accounting for a smaller proportion.

Contrastingly, the robot-only scenario demonstrated an extremely low level of violations, and no collisions occurred at all. This reveals a stark contrast between the pedestrian and robot entities' navigation capabilities and interactions. It suggests that the robots, presumably operating under programmed rules and sensors, can maintain sufficient distance from each other to avoid both collisions and violations.

Consequently, these results indicate that pedestrian entities, in this experimental setup, are more prone to collisions and violations than robots when navigating the path individually. This stresses the importance of developing sophisticated, human-like navigation algorithms for autonomous entities to enable them to better interact with pedestrian users and reduce collisions and proximity violations in real-world environments. For a detailed examination of flow density and movement trajectories, please refer to Appendix A.2.

Scenario Number	Scenario Name	Pedestrian Count	Robot Count	Collisions (Type and Count)	Violations (Type and Count)
S1	Pedestrian Only (Baseline)	80	0	P-P: 8 P-W: 2 W-P: 4	P-P: 4447 P-W: 58 W-P: 122
S2	Robot Only (Baseline)	0	80	None	Total: 9
S3	Pedestrian-centric Density	60	20	P-P: 6 P-R: 4 R-P: 14 R-R: 5 R-W: 11 W-P: 7 W-R: 1 W-W: 7	P-P: 2591 P-R: 442 P-W: 133 R-P: 1162 R-R: 112 R-W: 75 W-P: 217 W-R: 20
S4	Robot-centric Density	20	60	P-R: 6 P-W: 2 R-P: 5 R-R: 35 R-W: 25 W-P: 4 W-R: 12	P-P: 206 P-R: 367 P-W: 28 R-P: 1118 R-R: 924 R-W: 165 W-P: 87 W-R: 74
S5	Equal Density	40	40	P-P: 5 P-R: 19 P-W: 1 R-P: 31 R-R: 51 R-W: 36 W-R: 13	P-P: 1294 P-R: 648 P-W: 60 R-P: 1590 R-R: 842 R-W: 157 W-P: 92 W-R: 63
S6	Incremented Robots	70	10	P-P: 7 P-R: 7 P-W: 5 R-P: 13 R-W: 5 W-P: 12 W-R: 1	P-P: 3107 P-R: 218 P-W: 205 R-P: 661 R-R: 9 R-W: 46 W-P: 321 W-R: 13

Table 6.5: Breakdown of collisions and violations for each scenario in the phase 2 experiment.

(P=Pedestrian, R=Robot, W=Wheelchair)

6.4 Phase 3: Navigational Complexity Assessment

Continuing from Phase 2, the third phase further investigates the dynamics of shared sidewalks under varying LOS. This phase probes into the intricacies of diverse densities of pedestrians and robots, focusing on different agent spawn configurations. The overarching aim is to discern the effect of these varied agent compositions and configurations on the overall functionality of the sidewalk ecosystem.

In this phase, two distinct experiments were conceived: E1 and E2. While E1 deploys a two-way routing system, distributing agent counts uniformly across both traffic directions, E2 takes on a more intricate approach by integrating multiple origin-destination (OD) pairs and allocating agent counts across multiple pathways.

6.4.1 E1 - Two-Way Traffic Dynamics

In our endeavor to determine suitable geographical locations for E1, the pathway from the York University Subway station to the Scott Library building came forth as an optimal choice. Intriguingly, this location resonates with the study area of Phase 2, as depicted in Figure 6.6. The decision to harmonize the choice of location across the two phases wasn't incidental but deliberate. This alignment not only reinforces the experimental continuity but also furnishes an unparalleled platform to contrast the dynamics of one-way against two-way traffic.

Table 6.6 presents the scenario configurations for E1 of phase 3 of the experiment. It includes both the count and density of pedestrians and robots, representing one side of traffic

only.

Scenario Number	Scenario Name	Description	Pedestrian Count	Robot Count
S1	Pedestrian Only (Baseline)	Scenario only involves pedestrians on the sidewalk. No robots are included.	40	0
S2	Robot Only (Baseline)	Scenario only involves robots on the sidewalk. No pedestrians are included.	0	40
S3	Pedestrian-centric Density	Scenario involves more pedestrians than robots on the sidewalk, with fixed LOS densities.	30	10
S4	Robot-centric Density	Scenario involves more robots than pedestrians on the sidewalk, with fixed LOS densities.	10	30
S5	Equal Density	Scenario involves an equal number of pedestrians and robots on the sidewalk, with fixed LOS densities.	20	20
S6	Incremented Robots	Scenario involves pedestrians at base-line numbers and an increasing number of robots over time.	35	05

Table 6.6: The scenario configurations for E1 of phase 3 of the experiment, show both the count for pedestrians and robots. Note: The counts represent one side of traffic only.

The results from E1 of the third phase of the experiment shed light on the effects of varying densities of robots and humans, as well as their spawn intervals, on shared sidewalks. This phase provides valuable insights into potential challenges and interaction dynamics that might emerge as autonomous sidewalk delivery robots become increasingly common in urban environments.

The E1 results are displayed in Table 6.7. These outcomes depict a varied occurrence of collisions and proximity violations across the different scenarios. Such a detailed breakdown

helps discern the intricate dynamics between the different agents, providing valuable pointers on potential problems and solutions for environments where sidewalks are shared.

In the "Pedestrian Only" scenario of E1, there were 42 collisions and 4353 violations. The "Robot Only" scenario documented 48 collisions and 1085 violations. In the "Incremented Robots" scenario, the numbers stood at 95 collisions and 4354 violations. The "Pedestrian-centric Density" and "Robot-centric Density" scenarios recorded 122 and 193 collisions, along with 4177 and 3051 violations, respectively. Meanwhile, the "Equal Density" scenario witnessed a spike with 289 collisions and 4534 violations.

Scenario Number	Scenario Name	Pedestrian Count	Robot Count	Collisions (Type and Count)	Violations (Type and Count)
S1	Pedestrian Only (Baseline)	80	0	P-P: 12, P-W: 10, W-P: 15, W-W: 5	P-P: 3600, P-W: 249, W-P: 504
S2	Robot Only (Baseline)	0	80	48	1085
S3	Pedestrian-centric Density	60	20	P-P: 11, P-R: 18, P-W: 7, R-P: 18, R-R: 21, R-W: 26, W-P: 8, W-R: 9, W-W: 4	P-P: 2139, P-R: 400, P-W: 164, R-P: 859, R-R: 165, R-W: 133, W-P: 270, W-R: 47
S4	Robot-centric Density	20	60	P-R: 15, R-P: 16, R-R: 129, R-W: 20, W-P: 3, W-R: 8	P-P: 324, P-R: 378, P-W: 17, R-P: 921, R-R: 1261, R-W: 68, W-P: 44, W-R: 2738
S5	Equal Density	40	40	P-P: 10, P-R: 50, P-W: 8, R-P: 62, R-R: 114, R-W: 29, W-P: 5, W-R: 11	P-P: 1244, P-R: 707, P-W: 77, R-P: 1415, R-R: 758, R-W: 132, W-P: 154, W-R: 47
S6	Incremented Robots	70	10	P-P: 33, P-R: 14, P-W: 12, R-P: 11, R-R: 21, R-W: 9, W-P: 14, W-R: 2	P-P: 3091, P-R: 248, P-W: 164, R-P: 562, R-R: 11, R-W: 44, W-P: 219, W-R: 15

Table 6.7: E1 experiment results showing the number of collisions and 2m violations for each scenario. (P=Pedestrian, R=Robot, W=Wheelchair)

6.4.2 E2 - Multi-Origin Pathways

In the domain of urban mobility, the synergy between robots and pedestrians within shared spaces is crucial. This becomes even more pronounced in environments characterized by multiple origins and destinations, mirroring the hustle and bustle of urban centers. Addressing this, the E2 segment of Phase 3 sought to dig deeper into such intricate scenarios. By adopting two distinct origin-destination (OD) pairs — namely, the pathway from the Scott Library Building to Seneca at York, and the connection between Vari Hall and Bergeron — we endeavored to simulate real-world complexities.

Far from being arbitrary, the selection of these routes was strategic. Each was laden with navigation challenges and peppered with numerous turns, forming a mosaic of potential encounters. These conditions set the stage for multifaceted interactions between agents, offering invaluable insights into shared sidewalk dynamics. The paths chosen for this pivotal segment of the study were:

1. Scott Library Building to Seneca at York.
2. Vari Hall to Bergeron.

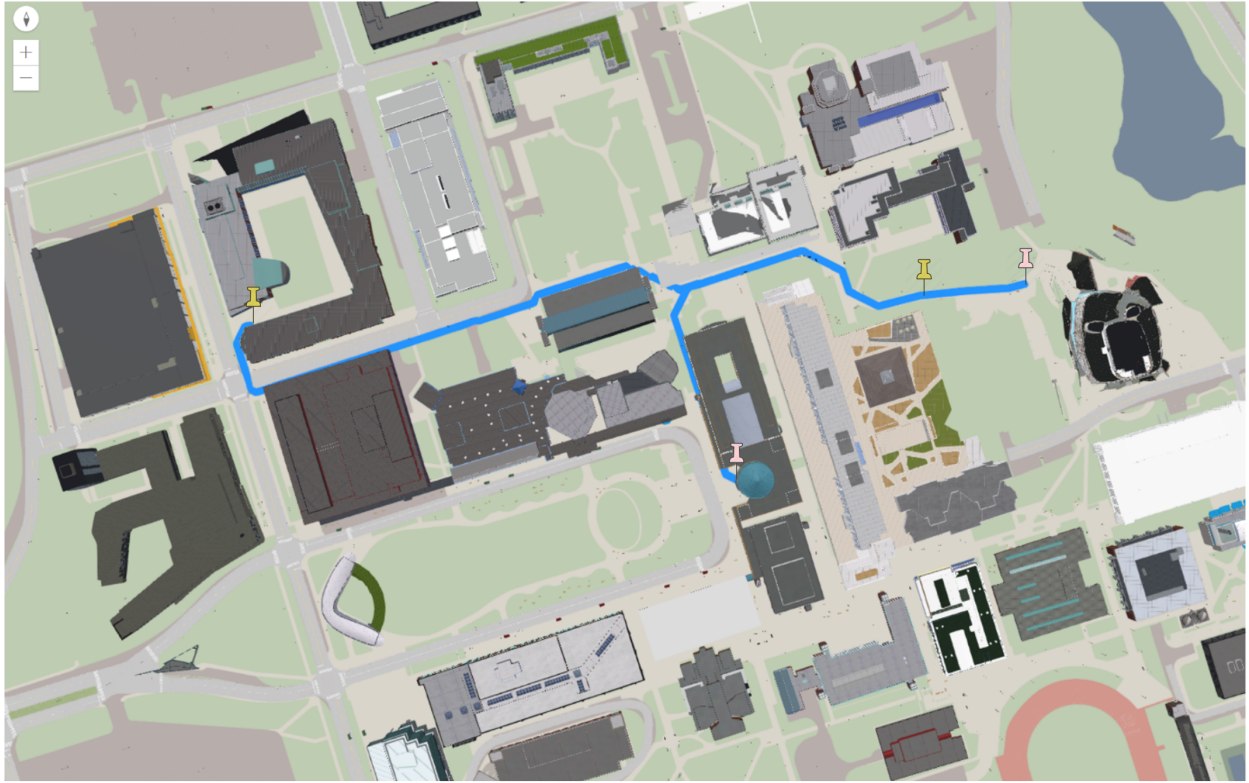


Figure 6.7: Detailed routes from Phase 3 E2, illustrating the pathways from Scott Library to Seneca at York, and Vari Hall to Bergeron. These intricately designed routes were specifically chosen to encapsulate complex agent interactions, typifying real-world shared sidewalk dynamics.

These diverse scenarios, from pedestrian-dominant to robot-dominant situations, offer insights into the challenges and solutions for future urban planning involving mixed mobility. Specific configurations for each scenario can be found in Table 6.8. It’s essential to highlight that spawn counts were equally distributed between the two Origin-Destination pairings.

Scenario Number	Scenario Name	Description	Pedestrian Count	Robot Count
S1	Pedestrian Only (Baseline)	Scenario only involves pedestrians on the sidewalk. No robots are included.	80	0
S2	Robot Only (Baseline)	Scenario only involves robots on the sidewalk. No pedestrians are included.	0	80
S3	Pedestrian-centric Density	Scenario involves more pedestrians than robots on the sidewalk, with fixed LOS densities.	70	10
S4	Robot-centric Density	Scenario involves more robots than pedestrians on the sidewalk, with fixed LOS densities.	20	60
S5	Equal Density	Scenario involves an equal number of pedestrians and robots on the sidewalk, with fixed LOS densities.	40	40
S6	Incremented Robots	Scenario involves pedestrians at base-line numbers and an increasing number of robots over time.	70	10

Table 6.8: The scenario configurations for E2 of phase 3 of the experiment, show both the count for pedestrians and robots. Note: Spawn counts are split between two Origin-Destination.

In the third phase, the E2 results offered a more in-depth exploration into the dynamics of shared sidewalk environments, revealing trends consistent with the observations made in Phase 2 and E1. The Pedestrian Only (Baseline) scenario, primarily characterized by pedestrian activity, resulted in 50 collisions and 3625 violations. In contrast, when sidewalks were dominated by robots in the Robot Only (Baseline) scenario, there were 77 collisions accompanied by 889 violations. The introduction of robots at a gradually increasing rate in the Incremented Robots scenario led to a notable 104 collisions and 3506 violations. When the focus was shifted to scenarios with specific density configurations, the Pedestrian-

centric Density scenario, where pedestrians were more prevalent than robots, documented 111 collisions and 4213 violations. Meanwhile, the Robot-centric Density scenario, where robots were in the majority, witnessed 149 collisions and 2756 violations. Interestingly, the Equal Density scenario, designed to have a balanced number of robots and pedestrians, recorded the highest figures with 152 collisions and 3704 violations. These findings, detailed in Table 6.9, emphasize the complex interaction dynamics in shared spaces and underscore the importance of creating strategies that ensure harmonious human-robot coexistence on sidewalks.

Scenario Number	Scenario Name	Pedestrian Count	Robot Count	Collisions (Type and Count)	Violations (Type and Count)
S1	Pedestrian Only (Baseline)	80	0	P-P: 16, P-W: 13, W-P: 19, W-W: 2	P-P: 3229, P-W: 157, W-P: 239
S2	Robot Only (Baseline)	0	80	Total: 77	Total: 889
S3	Pedestrian-centric Density	60	20	P-P: 11, P-R: 23, P-W: 7, R-P: 22, R-R: 13, R-W: 14, W-P: 6, W-R: 14, W-W: 1	P-P: 2392, P-R: 401, P-W: 103, R-P: 989, R-R: 50, R-W: 75, W-P: 179, W-R: 24
S4	Robot-centric Density	20	60	P-R: 25, R-P: 21, R-R: 87, R-W: 6, W-P: 2, W-R: 4	P-P: 309, P-R: 429, P-W: 4, R-P: 1076, R-R: 842, R-W: 61, W-P: 8, W-R: 2738
S5	Equal Density	40	40	P-P: 7, P-R: 22, P-W: 5, R-P: 34, R-R: 52, R-W: 14, W-P: 4, W-R: 14	P-P: 916, P-R: 592, P-W: 52, R-P: 1469, R-R: 543, R-W: 79, W-P: 37, W-R: 16
S6	Incremented Robots	70	10	P-P: 31, P-R: 13, P-W: 8, R-P: 13, R-R: 6, R-W: 15, W-P: 5, W-R: 6, W-W: 7	P-P: 2426, P-R: 204, P-W: 145, R-P: 462, R-R: 7, R-W: 68, W-P: 180, W-R: 14

Table 6.9: E2 experiment results showing the number of collisions and 2m violations for each scenario. (P=Pedestrian, R=Robot, W=Wheelchair)

The completion of this phase of the experiment highlights a clear increase in collisions and violations upon introducing robots into shared sidewalk environments. This observation underlines how the presence of robots substantially alters the dynamics of sidewalk interactions, leading to more complex and potentially hazardous scenarios. This escalation is particularly pronounced in situations involving high robot densities, where the number of collisions and violations sees a significant upswing.

Experiments E1 and E2 demonstrated this trend distinctly. Scenarios with equal densities of humans and robots consistently showed the highest number of collisions and violations. Conversely, scenarios with only humans or robots registered substantially fewer incidents, underscoring the increased complexity when different types of agents share the same space. For a detailed examination of flow density and movement trajectories, please refer to Appendix A.3.

6.5 Summary

Our extensive study analyzed the interactions between pedestrians, robots, and wheelchair users in shared spaces, focusing on violations and collisions in relation to their population across various scenarios. This involved three experimental phases which revealed significant trends in violation and collision behaviors under varying conditions.

The first phase established a critical baseline, focusing on the impact of density and the presence of robots in two distinct study areas. Findings indicated that when no robots were present, violations increased proportionally with pedestrian density but resulted in minimal

collisions. The introduction of robots, particularly in higher densities, led to a substantial increase in violations and collisions, highlighting the challenges of interaction in environments shared with robots.

In the second phase, the scenarios were diversified to include a range of situations involving pedestrian and robot density. These findings suggested that high robot densities complicate not just pedestrian-robot, but also robot-robot interactions, necessitating improved navigation and communication protocols for robots.

The third phase further analyzed these interactions through two experiments, which reaffirmed that as the number of robots increased in comparison to pedestrians, violations, and collisions escalated accordingly. It was especially evident in scenarios with equal pedestrian and robot density where the highest count of collisions between robots was recorded.

Throughout our research, pedestrians displayed the highest average violations, despite having the lowest collision count. On the other hand, both robots and wheelchair users demonstrated fewer average violations, but their collision rates were significantly higher. These variations can be attributed to factors such as the average speed and the spatial footprint of the different agents, with robots facing challenges due to their superior speeds and their inability to predict sudden changes or movements from other agents. Our findings emphasize the need for urban planners and other stakeholders to consider various factors when incorporating robots into shared spaces. The time of the day and the population density of sidewalks are critical considerations that can help in determining suitable times and routes for robot operations. This could involve creating dedicated lanes for robots, restricting robot

usage, minimizing robot population during peak hours, or setting lower speed limits for robots in areas with high pedestrian concentration.

In conclusion, our findings shed light on the complexities of interactions between pedestrians and robots in shared spaces. The increased density of robots not only heightens violations and collisions with pedestrians but also between robots. This underlines the importance of advanced strategies, such as improved communication protocols and predictive navigation algorithms, for safer, more efficient cohabitation in robot-inclusive societies.

Chapter 7

Conclusion

The integration of sidewalk delivery robots into urban environments necessitates a comprehensive understanding of their interactions with pedestrians. This thesis embarked on a detailed exploration using agent-based modeling to simulate these interactions, aiming to foster harmonious cohabitation in urban spaces.

7.1 Building the Digital Twin

The endeavor to construct a refined digital twin environment was both nuanced and revelatory. Central to this undertaking was the creation of a sprawling campus-scale digital twin, reflecting the multifaceted dimensions and subtleties of urban settings. Rather than being a basic 3D visualization, this model was a sophisticated digital mirror of real-world intricacies. Integral to this development was the utilization of GIS data. With GIS as our foundation, we seamlessly integrated topographical, infrastructural, and environmental information, ensuring

that our digital twin was not only aesthetically faithful but also contextually aligned with real-world data. The depth and granularity of this GIS-infused data guaranteed meticulous representation of every avenue, walkway, structure, and open area. This comprehensive digital twin served as an intricate backdrop for the research, enabling intricate simulations and examinations of interactions among robots, pedestrians, and wheelchair users.

7.2 Simulation Framework

TwinWalk, our proprietary simulation framework, was instrumental in bringing the digital twin to life. Acting as the nerve center of our simulations, TwinWalk enabled the modeling of intricate interactions between various agents within the digital twin’s environment. The Predictive Avoidance Model (PAM), as a part of this framework, facilitated the detailed modeling and simulation of both robot and human movements. By adopting an agent-based modeling approach, TwinWalk allowed for the simulation of many scenarios. From simple interactions on less crowded pathways to complex dynamics in high-density areas, TwinWalk’s capabilities were exhaustive. The framework also ensured the seamless integration of real-world data, such as GIS, which enhanced the realism and accuracy of each simulation scenario. The symbiotic relationship between the digital twin and TwinWalk facilitated a detailed examination of real-world challenges, yielding nuanced and implementable findings.

7.3 Experiments and Results Summary

The design of the experiments was rooted in the aim of creating a comprehensive understanding of interactions between robots, pedestrians, and wheelchair users within the urban environment. Utilizing the extensive digital twin and the capabilities of the TwinWalk framework, the experiments were crafted to simulate a myriad of real-world scenarios. These ranged from simple, low-density interactions to more intricate, high-density dynamics. The scale of the experiments was expansive. Spanning three extensive phases, each experiment phase incorporated diverse agent densities and configurations, thereby ensuring a holistic portrayal of potential interactions. This expansive scale, combined with the granularity of the digital twin and the sophistication of TwinWalk, ensured that the experiments were not just large in number but also rich in detail.

Building on this foundation, the results of the simulation-based experiments were both enlightening and actionable. These experiments generated critical insights that will prove invaluable for formulating regulations governing SADRs in urban locales. The rich dataset harvested from these simulations, with metrics encompassing pedestrian collisions, proximity violations, and traffic flow, provides a deep reservoir of knowledge for decision-makers. This information will empower authorities to delineate optimal SADR deployment areas, demarcate zones necessitating heightened caution, and craft strategies ensuring robot safety and efficiency.

However, the interpretation of our findings mandates a nuanced lens. Despite sidewalk

robots maintaining an impressive safety margin, they displayed an elevated rate of proximity violations, especially towards pedestrians, and an increased incidence of collisions. These events were more pronounced in high-density areas and scenarios with a higher robot-to-human ratio. Such revelations stress the importance of further research to fathom these dynamics and create risk-mitigating strategies.

Additionally, the data accentuated the role of robot densities in modulating the frequency and nature of both proximity violations and collisions. These insights underscore the necessity for refined robot navigation and communication protocols in areas teeming with activity. Such findings also emphasize the importance of considering elements like peak traffic hours and sidewalk LOS in the issuance of operational permits for sidewalk robots.

Based on these insights, it is suggested that urban planners might consider formulating strategies to outline more effective robot operating schedules and routes with the intention of alleviating congestion and bolstering safety. Potential tactics could include the creation of dedicated robot lanes, limiting robot operations during high-traffic periods, or introducing speed restrictions in densely populated zones.

7.4 Next Steps for Research

The conclusions drawn from this investigation underscore the intricate challenges associated with deploying sidewalk robots within urban environments. It would be prudent for subsequent research to concentrate on identified trends, notably humans' tendencies for proximity infringements and the potential escalation in accidents due to robots. Ensuring alignment

with ISO standards currently in the drafting stage is imperative. Modifying our simulator to evaluate adherence to these standards prior to the real-world deployment of robots could offer invaluable perspectives for industry stakeholders.

To encapsulate, this study highlights the importance of rigorous planning, continuous research, and the formulation of progressive strategies to facilitate the smooth assimilation of robots into urban contexts. Giving precedence to improved robot communication protocols and anticipatory navigation algorithms will be crucial to forge a cohesive and efficient urban milieu.

Appendix A

Experiment Results

The appendix presented herein offers an in-depth visual exploration of both the trajectory and flow density analyses conducted during the research. These analyses are central to unraveling the complex dynamics of pedestrian-robot interactions across diverse urban scenarios. The appendix is systematically divided into sections, each dedicated to a specific aspect: flow density across different study areas and phases, and the movement trajectories of robots and pedestrians.

For flow density, each figure illuminates the variations across six distinct scenarios, highlighting the impact of different agent compositions on the sidewalk environment. Such visualizations are invaluable in showcasing how pedestrian-robot interactions can influence and shape urban spaces.

Separately, the trajectory images trace the paths of robots and pedestrians, offering a detailed view of movement patterns and interactions over time. These trajectories provide

insights into navigational choices, potential conflict zones, and areas of harmonious coexistence.

A.1 Flow Density: Phase 1, Study Area 1

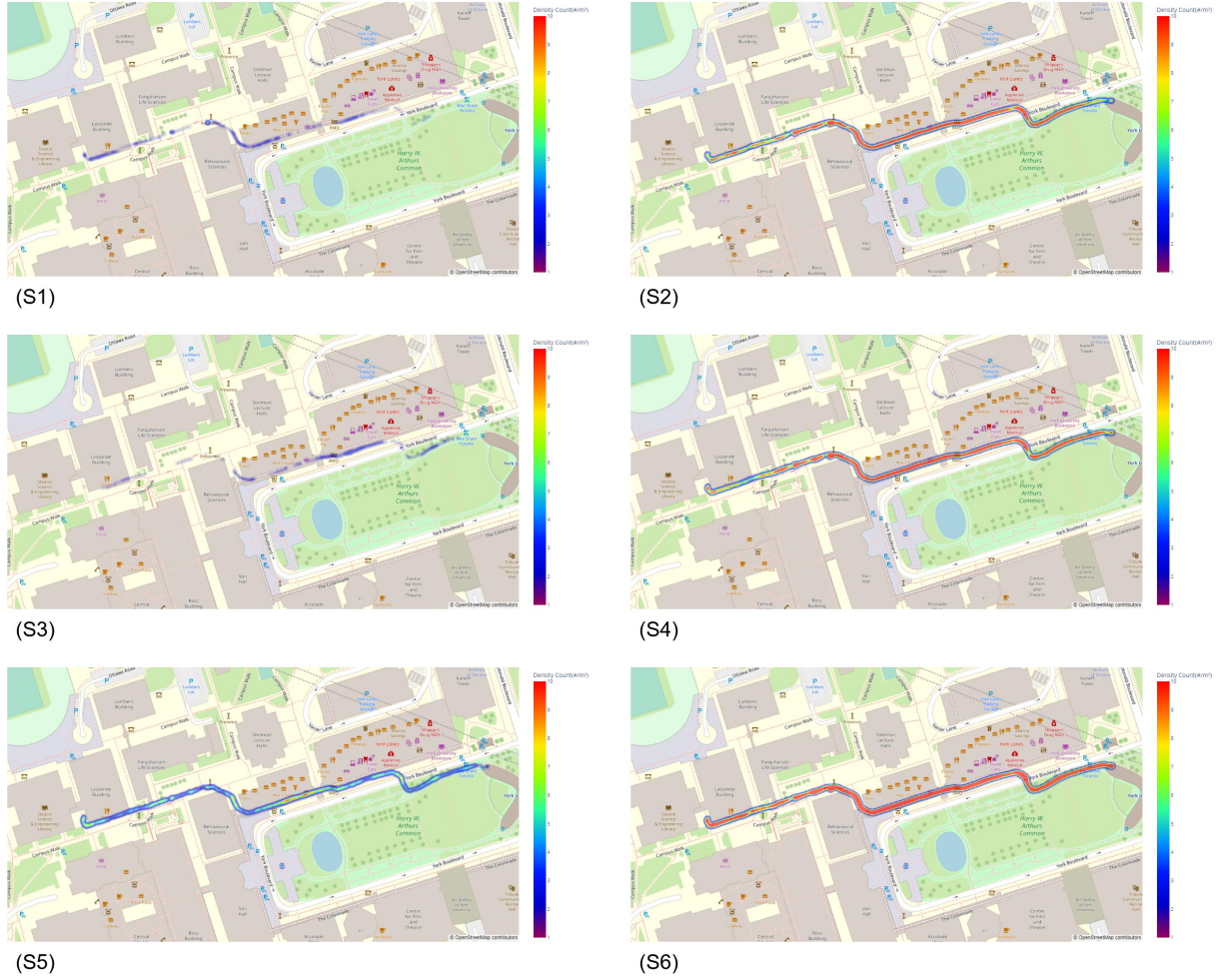


Figure A.1: Flow density depiction for six scenarios on the route between Subway Station and Lassonde Building. The graphic illustrates how varying agent compositions influence flow patterns and the subsequent interactions between pedestrians and robots.

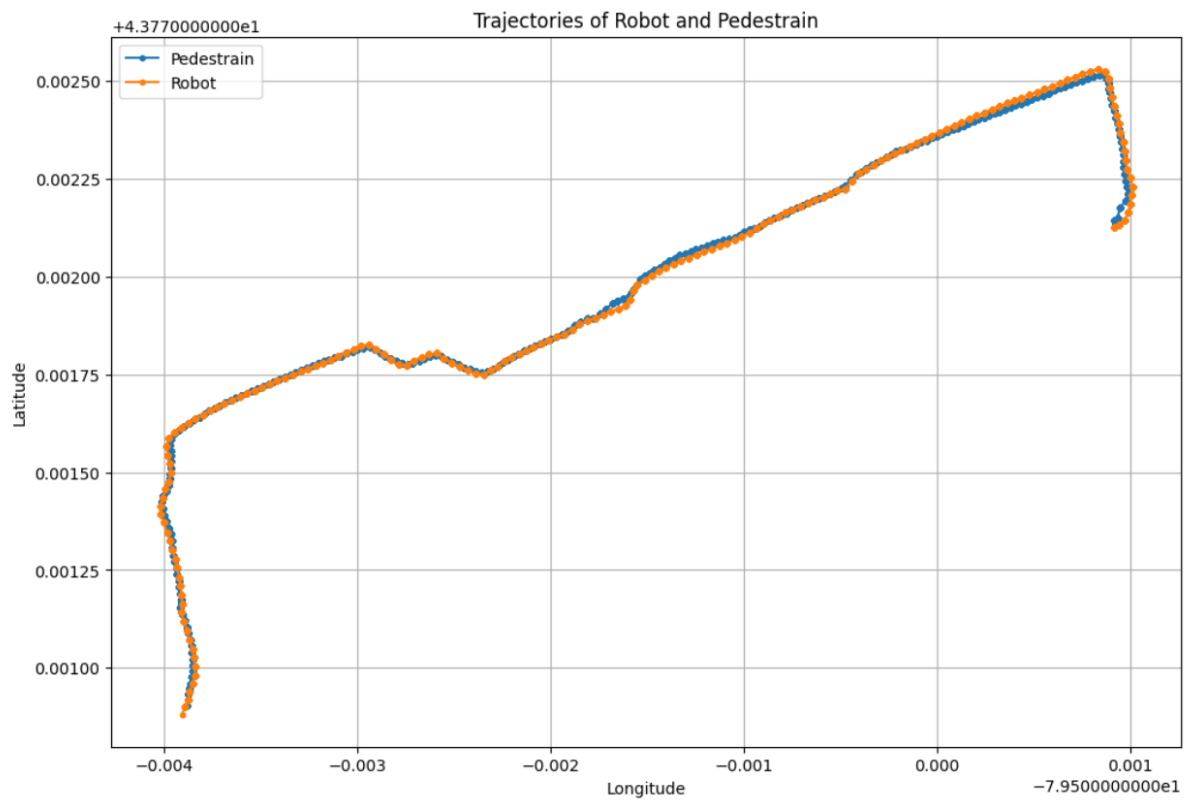


Figure A.2: Trajectories of a pedestrian and a robot following the same route to reach the same destination in study area 2.

A.2 Flow Density: Phase 2

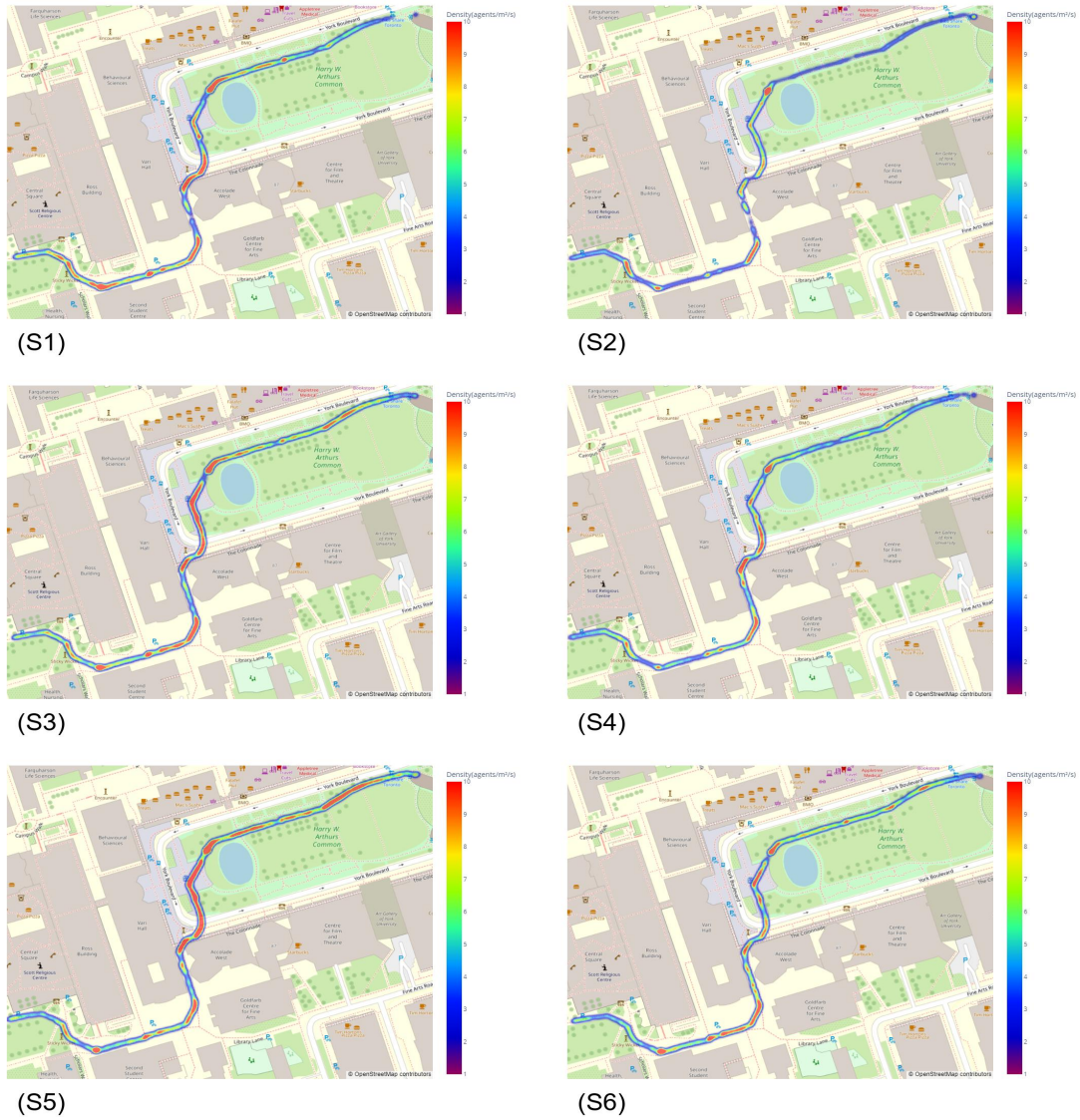


Figure A.3: A comparative density analysis of six scenarios on the pedestrian pathway from the Subway Station to the Scott Library building. This visualization highlights the changing dynamics of the sidewalk environment influenced by robot integration.

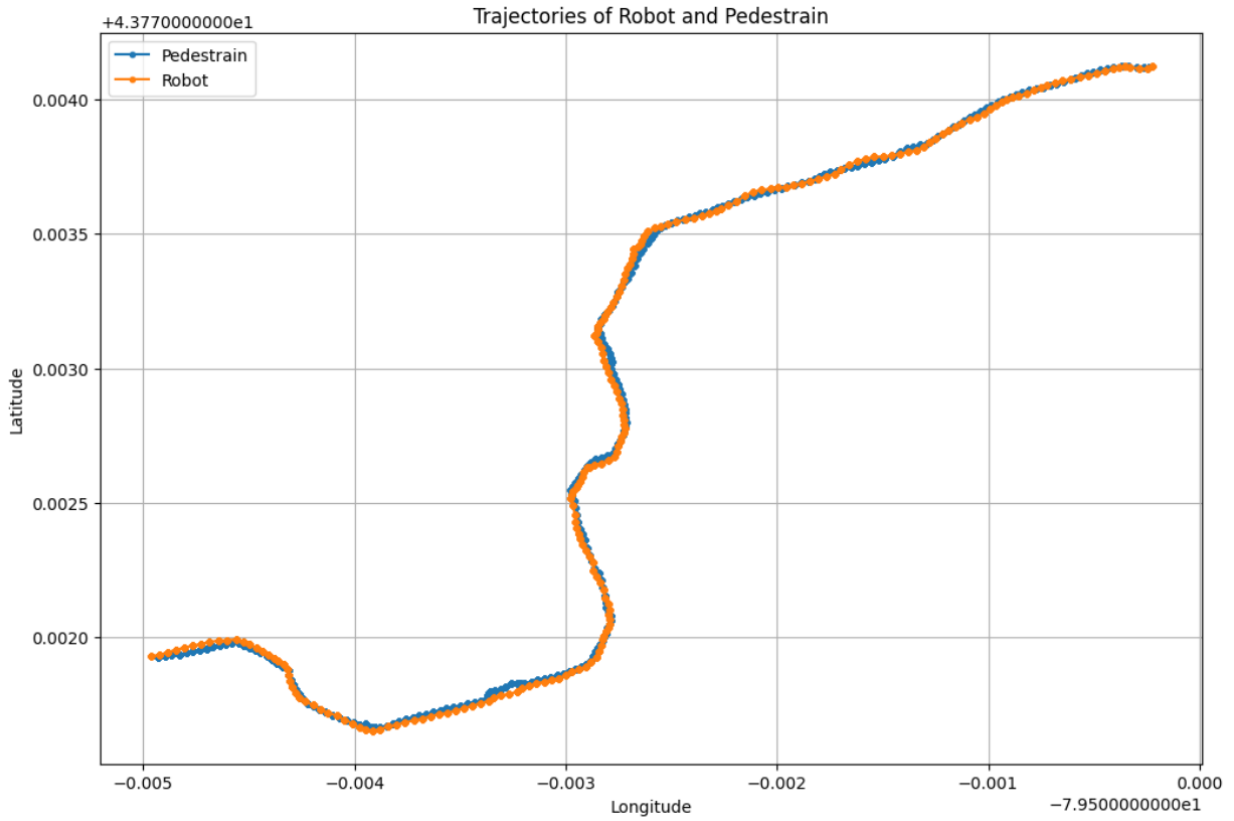


Figure A.4: Trajectories of a pedestrian and a robot following the same route to reach the same destination during Phase 2.

A.3 Flow Density: Phase 3

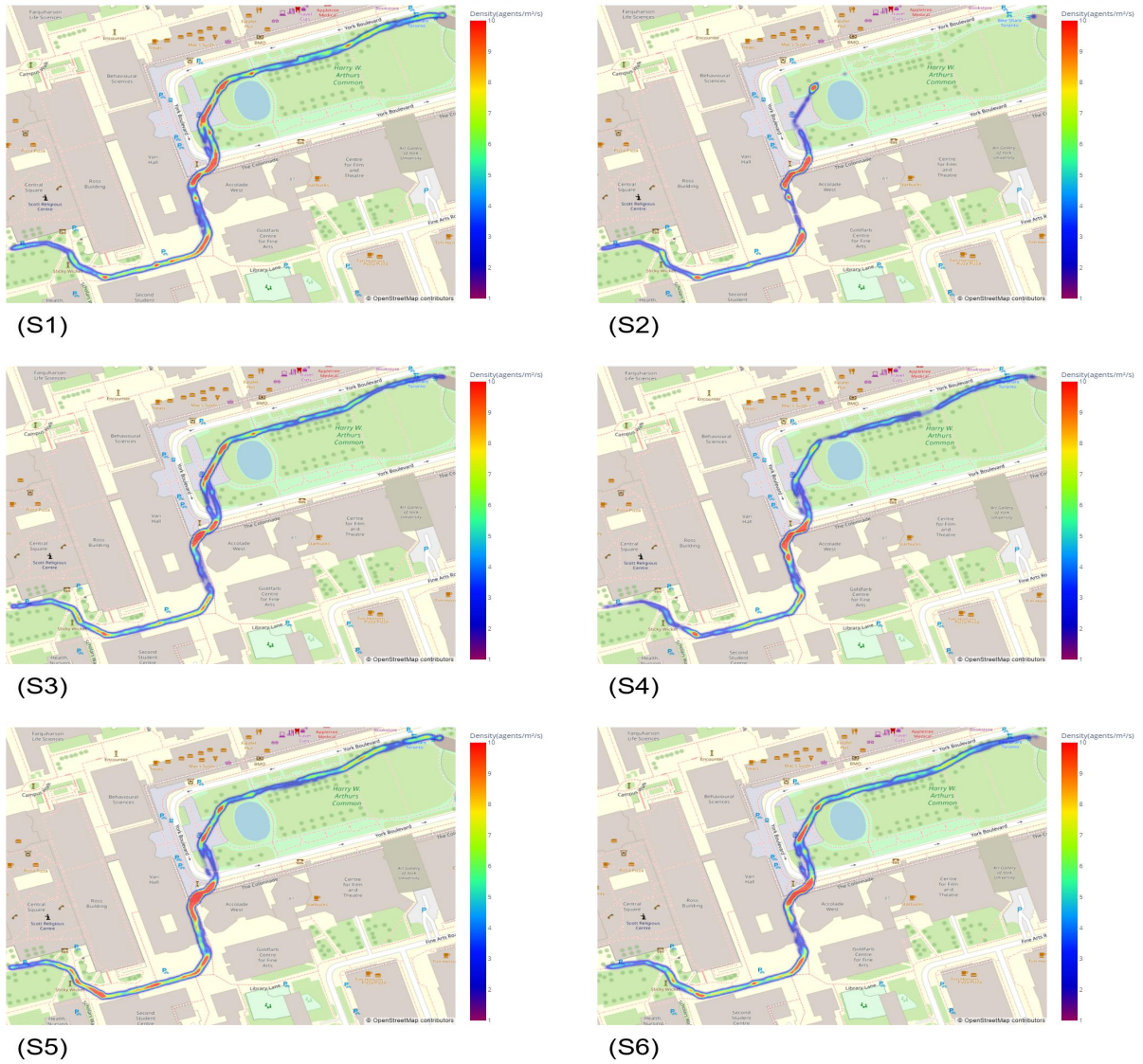


Figure A.5: Analysis of flow density across six scenarios between Subway Station and Scott Library building, emphasizing the effects of two-way pedestrian traffic on robot navigation.

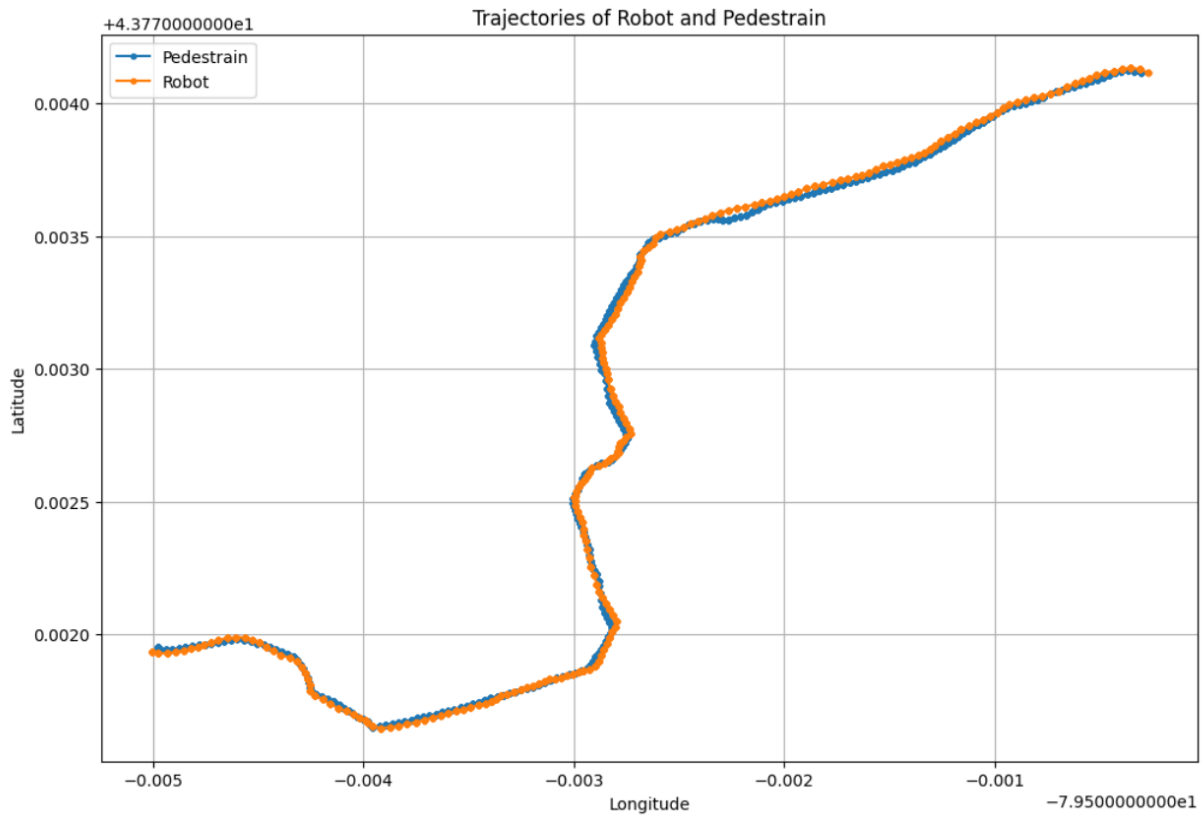
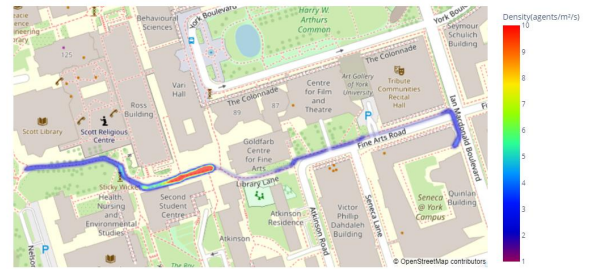


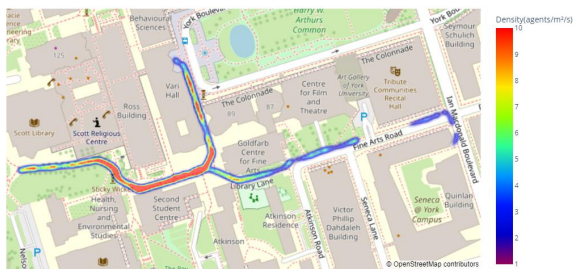
Figure A.6: Trajectories of a pedestrian and a robot following the same route to reach the same destination during Phase 3, E1.



(S1)



(S2)



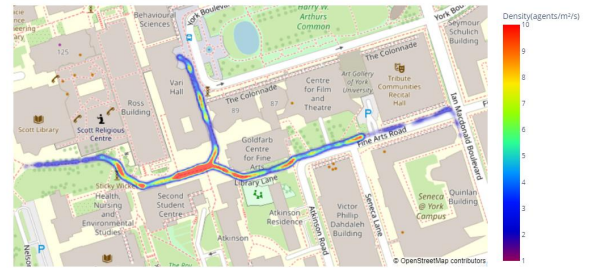
(S3)



(S4)



(S5)



(S6)

Figure A.7: Flow density visualization for scenarios spanning the route from Scott Library Building to Seneca at York, capturing the interplay between pedestrians and robots near Vari Hall and Bergeron.

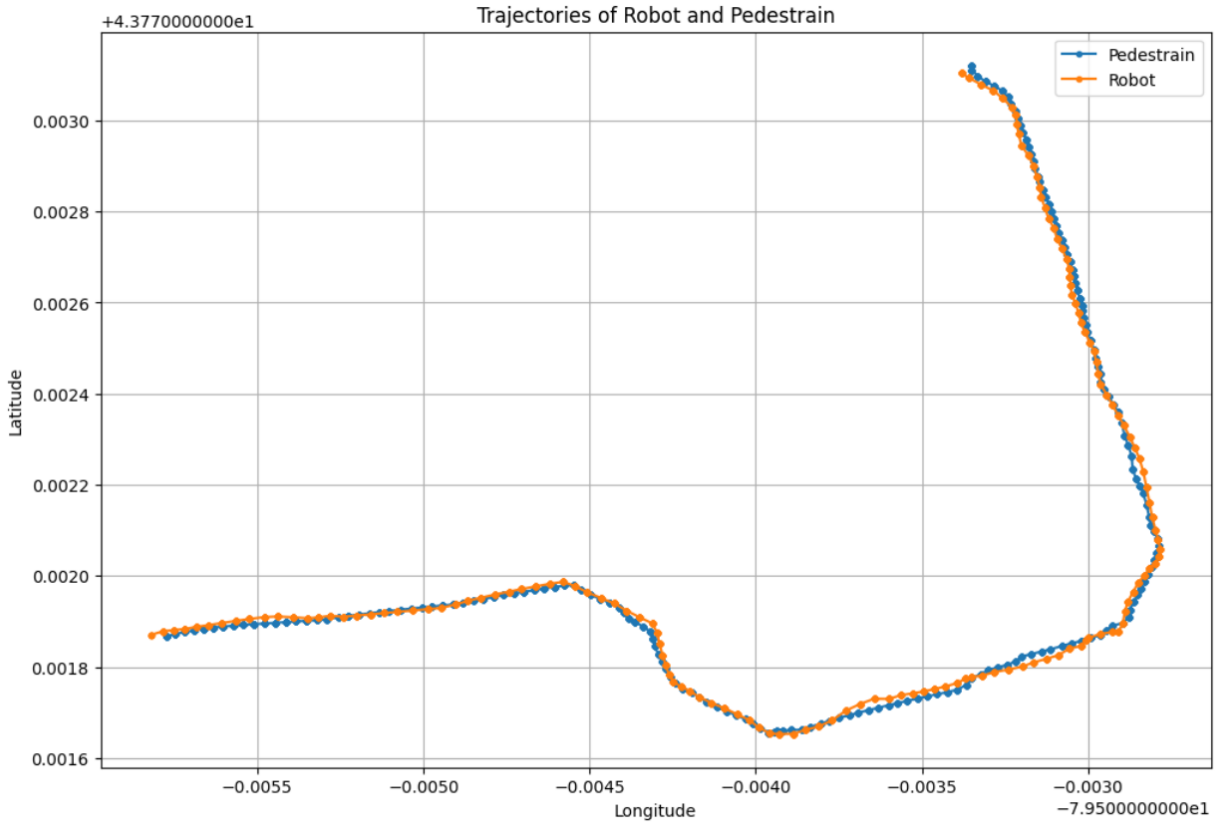


Figure A.8: Trajectories of a pedestrian and a robot following the same route to reach the same destination during Phase 3, E2.

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