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BACHELOR THESIS

Development of a Virtual interactive Laboratory Testbench for Socially-Aware Robot Navigation

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thws
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Declaration of Authorship

I, Prince Sakariya, declare that this thesis titled, "Development of a Virtual interactive Laboratory Testbench for Socially-Aware Robot Navigation" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
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Signed:

Date:

"Thanks to my solid academic training, today I can write hundreds of words on virtually any topic without possessing a shred of information, which is how I got a good job in journalism."

Dave Barry

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Abstract

Faculty of Electrical and Mechanical Engineering
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B.Eng. Mechatronics

Development of a Virtual interactive Laboratory Testbench for Socially-Aware Robot Navigation

by Prince Sakariya

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too…

Acknowledgements

The acknowledgments and the people to thank go here, don’t forget to include your project advisor…

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List of Abbreviations

LAH	**L**ist **A**bbreviations **H**ere
WSF	**W**hat (it) **S**tands **F**or

Physical Constants

Speed of Light $c_0 = 2.997\,924\,58 \times 10^{8}\,\mathrm{m\,s^{-1}}$ (exact)

List of Symbols

a	distance	m
P	power	W ($J\,s^{-1}$)
ω	angular frequency	rad

For/Dedicated to/To my…

Chapter 1

Introduction

1.1 Background and Motivation

As robots increasingly operate in human-populated environments such as hospitals, shopping malls, and homes, traditional navigation approaches focused solely on collision avoidance and path optimization have proven insufficient. Socially-aware navigation represents a critical advancement that extends beyond obstacle avoidance to incorporate human comfort, cultural norms, and implicit social conventions. This evolution is essential for robots to gain acceptance in shared human spaces. Social navigation is inherently interdisciplinary, bridging robotics, social psychology, cultural anthropology, and human-computer interaction. At its core lies the concept of proxemics—the study of human use of space and its cultural variations—first introduced by anthropologist Edward T. Hall in 1966. Hall's delineation of intimate, personal, social, and public interaction zones provides a fundamental framework for robot navigation in human environments, as respecting these invisible boundaries is crucial for social acceptance. The development of socially-aware mobile robots faces several significant challenges:

- *Complexity of Social Rules* - Human spatial behavior is governed by implicit, context-dependent rules that vary across cultures and situations. These rules are typically learned intuitively by humans but must be explicitly encoded for robots.
- *Experimentation Challenges* - Real-world testing with humans is resource-intensive, potentially risky during early development stages, and difficult to reproduce consistently across different research groups.
- *Interdisciplinary Knowledge Requirements* - Developing effective social navigation systems demands expertise across multiple domains, creating both research and educational barriers.
- *Technical Implementation Hurdles* - Integrating social awareness into existing navigation frameworks requires sophisticated software architecture and computational efficiency to maintain real-time performance.

Recent advances in social robotics have produced numerous platforms and approaches for addressing these challenges (Kästner et al., 2021, Pérez-Higueras et al., 2023, Savva et al., 2019). However, these innovations often remain siloed within research laboratories, with limited accessibility for educational purposes. This accessibility gap represents a significant obstacle for preparing the next generation of roboticists to develop socially-aware systems.

1.2 Problem Statement

Often times, navigation systems treat humans as mere dynamic obstacles without considering social contexts, leading to behaviors that may be technically efficient but socially inappropriate. This research addresses the gap between technically sound and socially acceptable robot navigation in human-shared spaces.

Despite significant research advances in social navigation, three critical problems persist:

1. *Technical-Social Disconnect* - Most deployed robot navigation systems continue to treat humans as mere dynamic obstacles, disregarding social contexts and norms. This approach leads to behaviors that may be computationally efficient but socially inappropriate or discomforting to humans sharing the space.

2. *Educational Access Barriers* - Existing social navigation implementations typically demand extensive technical expertise and computational resources, making them inaccessible for educational purposes. Students face significant hurdles in learning about and experimenting with social navigation concepts due to complex installation requirements, dependencies, and hardware constraints.

3. *Lack of Standardized Learning Tools* - While several research platforms exist, there is a notable absence of standardized educational tools that demonstrate social navigation concepts in a structured, pedagogically sound manner. This gap impedes effective teaching and learning of this increasingly important aspect of robotics.

This thesis addresses these interconnected problems by developing an accessible, education-focused platform that bridges the gap between advanced social navigation research and practical robotics education.

1.3 Research objectives

This bachelor thesis aims to develop an educational system for teaching and experimenting with social robot navigation concepts. The primary goal is to create a virtual laboratory environment that lowers technical barriers and provides structured learning experiences. Specific objectives include:

1. **Create an accessible virtual testbench** that demonstrates various social navigation concepts without requiring extensive technical setup or specialized hardware. This environment will:
   - Integrate existing open-source social navigation implementations
   - Provide a virtualized environment that runs efficiently on standard student hardware
   - Offer a unified interface for interaction with different navigation approaches

2. **Develop structured educational experiments** that:
   - Demonstrate a variety of off-the-shelf social navigation algorithms
   - Illustrate the effects of different proxemic models and parameter configurations
   - Allow comparison between socially-aware and traditional navigation approaches

- Showcase the impact of environmental context on navigation behavior

3. **Enable hands-on experimentation** through:
   - Real-time costmap parameter modification
   - Customizable evaluation metrics for navigation performance
   - Visualization tools for understanding algorithm decision-making

4. **Create comprehensive educational materials** including:
   - Laboratory exercises with clear learning objectives
   - Documentation explaining theoretical concepts and their implementation
   - Guided exploration activities with progressive complexity

The system is designed primarily for undergraduate and graduate robotics courses, enabling students to develop an intuitive understanding of social navigation principles through direct experimentation before potentially developing their own implementations.

1.4 Scope and Limitations

This thesis focuses on creating an educational platform for social navigation rather than developing novel navigation algorithms or proxemic models. The scope encompasses:

In Scope:

- Integration of existing open-source social navigation implementations
- Development of a virtualized environment for accessible deployment
- Creation of standardized test scenarios for comparative evaluation
- Design of structured educational experiments and supporting materials
- Implementation of visualization tools for algorithm behavior and decision processes
- Extension of existing platforms with missing components required for educational purposes

Out of Scope:

- Development of fundamentally new social navigation algorithms
- Large-scale human studies to validate navigation approaches
- Physical robot implementation and testing
- Cross-platform compatibility beyond the specified virtualization approach
- Comprehensive cultural adaptation of proxemic models

Limitations:

- The system will prioritize educational clarity over computational performance
- Simulated human behaviors will represent simplified models of actual human movement patterns
- The virtualized environment introduces some performance overhead compared to native installation
- The platform targets educational use cases rather than deployment-ready implementations

These scope boundaries ensure the project remains achievable within the constraints of a bachelor thesis while still delivering significant educational value through an accessible platform for teaching social navigation concepts.

Chapter 2

Literature Review

2.1 Social Navigation in Robotics

2.1.1 Definition and Importance

Rios-Martinez, Spalanzani, and Laugier, 2015 gave a compact description of socially-aware navigation: *"Socially-aware navigation is the strategy exhibited by a social robot that identifies and follows social conventions (in terms of management of space) to preserve a comfortable interaction with humans. The resulting behavior is predictable, adaptable, and easily understood by humans."* This definition implies that, from the robot's point of view, humans are no longer perceived only as dynamic obstacles but also as social entities.

The importance of social navigation is paramount for robots (Kruse et al., 2013) intended to operate in human-centric environments such as homes, hospitals, shopping malls, offices, and public spaces. As robots become increasingly integrated into our daily lives, their ability to interact seamlessly and naturally with humans is crucial for their acceptance and widespread adoption. Poor social navigation can lead to discomfort, anxiety, inefficiency, and even safety hazards for humans. Conversely, robots capable of navigating socially appropriately can enhance human productivity, provide assistance in various tasks, and improve overall quality of life. Furthermore, in applications like assistive robotics and healthcare, the ability of a robot to navigate in close proximity to individuals, while maintaining their comfort and safety, is fundamental (Möller et al., 2021).

2.1.2 Key Challenges

Developing robust social navigation capabilities in robots presents several key challenges:

- **Human Behavior Prediction:** Humans are inherently unpredictable. Their motion patterns are influenced by a multitude of factors including their goals, intentions, emotions, social context, and cultural background. Accurately predicting human trajectories and intentions is a significant challenge, requiring sophisticated models that can capture the nuances of human behavior.

- **Social Norms and Etiquette:** Navigating social environments requires adherence to a complex set of implicit social norms and etiquette. These norms can vary across cultures and situations. Robots need to understand and respect these norms, such as maintaining appropriate personal space, avoiding sudden or erratic movements, and yielding to pedestrians in certain situations.

- **Uncertainty and Dynamic Environments:** Human-populated environments are inherently dynamic and uncertain. People may change their direction or speed unexpectedly, form groups, or engage in interactions that affect robot navigation. Robots must be able to perceive and react to these dynamic changes in real-time while maintaining their navigation goals.

- **Computational Complexity:** Implementing sophisticated models for human behavior prediction, social norm understanding, and real-time adaptation can be computationally demanding. Developing efficient algorithms that can run on robot platforms with limited computational resources is a crucial challenge.
- **Evaluation Metrics and Benchmarking:** Defining appropriate metrics to evaluate the social acceptability and effectiveness of robot navigation is challenging. Establishing standardized benchmarks and simulation environments is necessary to facilitate the comparison and progress of different social navigation approaches.

2.2 Proxemics and Human-Robot Interaction

2.2.1 Proxemics Theory

Edward Hall's theory of proxemics Hall et al., 1968 suggests that people will maintain differing degrees of personal distance depending on the social setting and their cultural backgrounds.

- *Intimate space* - the clossest "bubble" of space surrounding a person. Entry into this space is acceptable only for the closest friends and intimates.
- *Social and consultative spaces* - the spaces in which people feel comfortable conducting routine social ineractions with acquaintances as well as strangers.
- *Public space* - the area of space beyond which people will perceive iteractions as impersonal and relatively anonymous.

The main contribution of Hall's Proxemics into path planning consists of providing a framework to build social maps, i.e. dynamic maps in which humans are perceived as obstacles following the definition of Hall's personal space. The work by Henkel et al. Henkel et al., 2014 evaluates different distance strategies by how they affect the human's perception of the robot's likeability, intelligence and submissiveness.

2.2.2 Application in Robotics

Proxemics has been employed in robotics to guide the development of spatially aware path planning. Robots use proxemic principles to maintain comfortable distances from humans, avoid intrusions into personal zones, and adjust their behavior based on environmental context. Several implementations integrate proxemic rules into costmaps and behavior trees to ensure adherence to social comfort zones, increasing user satisfaction and perceived safety. Proxemic-aware navigation also supports differentiated behaviors depending on robot intent — for example, service robots vs. delivery robots — providing richer HRI experiences

2.3 Simulation Platforms for Social Navigation

Helbing et al. Helbing and Molnár, 1995 show that pedestrian motion can be described by a simple social force model for individual pedestrian behavior. The social force model is an essential component in many platforms including Arena-rosnav Kastner et al., 2022, HuNavSim Pérez-Higueras et al., 2023 etc. to simulate the pedestrian movements. The navigation comprises of path planners and costmaps. There are two types of planners - global planner determines a path from the current location to the goal location, and a local planner follows the global path. Costmaps are created using static maps and real-time data from onboard sensors.

Sacco et al. Sacco, Recchiuto, and Mårtensson, 2024 use A* global planner and an MPC, with a detailed cost function to achieve advanced social navigation capabilities with the help of SMPC (Social Model Predictive Control) software stack. They leverage the predicitvity of MPC and the reactivity of SFM, modelling the pedestrian motion.

Chen et al. Chen et al., 2018 presented SA-CADRL (Socially Aware Collision Avoidance with Deep Reinforcement Learning) to explain/induce socially aware behaviors in a RL framework. They generalized to multiagent ($n > 2$) scenarios through developing symmetrical neural network structure, and demonstrated on robotic hardware autonomous navigation at human walking speed in a pedestrian-rich environment.

There exist various other approaches based on traditional algoritms as well as novel Neural Network, Deep Reinforcement Learning etc. In the next section, several simulation platforms, their advantages and disadvantages are described.

2.3.1 Overview of Existing Platforms

This section focuses on capabilities, features, and limitations of each environment for making specific recommendations for implementation purposes.

Habitat-Sim is a flexible, high performance 3D simulator with a focus on embodied AI research including navigation tasks Savva et al., 2019, Szot et al., 2022. It is capable of running thousands of simulations in parallel, with photo-realistic 3D environments from real-world scans, semantic scene understanding and support for multiple sensors (RGB, depth, semantic segmentation). It is however limited by a lack of in-built social navigation features, human motion models can be integrated however it requires some technical understanding of AI and has a steep learning curve.

SEAN 2.0 is specifically designed for social navigation research with emphasis on human behavior modeling Tsoi et al., 2022. It is a high fidelity, extensible, and open-source simulation platform for fair evaluation of social navigation algorithms. Environments correspond to the physical, static elements in a scenario in Unity. *SEAN 2.0* [1] includes warehouss, lab, and outdoor environments from *SEAN 1.0* with annotations for new pedestrian behaviours. It also provides numerous evalutation metrics including path efficiency, path irregularity, completed, totol time etc. It is limited by the simulation backend options as it limited to Unity.

HuNavSim focuses specifically on realistic human navigation behavior modelling Pérez-Higueras et al., 2023. It is a new open-source software library used to simulate human navigation behaviors. The tool, programmed under the new ROS 2 framework, can be employed to control the human agents of different general robotics simulators. It utilizes a Social Costmap Layer (a custom ROS 2 version of the social

[1] https://sean.interactive-machines.com/

navigation layers implemented in ROS 1 [2]) It provides a wide range of metrics for various scenarious, however it is limited by the number of available planners and lacks documentation which makes it a difficult choice for educational applications.

Arena-rosnav is an open-source modular benchmark environment built on ROS that specifically targets socially aware navigation Kästner et al., 2021. It provides support a total of 15 navigation planners (see table: **??**) which include classic, hybrid and learning-based planners. It (Arena Rosnav 3.0)[3] provides support for several both 2D and 3D simulators including Flatland, Rviz, Gazebo, Unity and provides an interface to integrate other simulation softwares, worlds like *Hospital, Canteen, Campus, Factory and Warehouse* are supported in Gazebo and *Hospital, Restaurant School, Japanese Garden and Warehouse* are supported in Unity, additionally users can add or create new worlds. Multiple robots including *tutlebot3-burger, jackal, ridgeback, agvota, tiago, robotino, youbot, turtlebot3_waffle_pi etc.* are supported and users can add more easily. It's limitations however are that it is a little above 50 GB in size and computationally intensive.

2.3.2 Comparison and Suitability for Education

Simulation tools differ in usability, fidelity, extensibility, and educational value:

- **Habitat-Sim** offers high visual fidelity but is difficult for beginners due to limited social behavior modules.
- **SEAN 2.0** provides tailored environments for social navigation and good evaluation metrics, making it suitable for advanced education.
- **HuNavSim** is lightweight and ROS 2 compatible but suffers from poor documentation.
- **Arena-rosnav** is ideal for research and advanced robotics courses, providing a wide range of planners and robot models, but requires high computational resources.

2.4 Summary of Gaps and Research Opportunities

While considerable progress has been made, several gaps persist:

- Lack of universal benchmarks for social navigation evaluation.
- Insufficient modeling of nuanced social behaviors (e.g., group dynamics, cultural norms).
- Limited cross-simulator compatibility.
- High barrier to entry due to complex setups or resource demands.
- Sparse integration between proxemics theory and learning-based planners.

Opportunities exist in developing:

- Lightweight, user-friendly simulation tools for education.
- Integrative frameworks combining proxemics.

[2] https://github.com/robotics-upo/nav2_social_costmap_plugin
[3] https://3.arena-rosnav.org/

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Appendix A

Installation Instructions

This appendix provides instructions for setting up the development environment used in the experiments.

A.1 Virtual Machine Setup

1. Download and install **VirtualBox** from the official website:

   https://www.virtualbox.org/wiki/Downloads

2. Import the provided virtual machine image (`dev.ova`) into VirtualBox. A step-by-step guide for importing `.ova` files can be found here:

   https://chenweixiang.github.io/docs/How_to_Import_and_Export_OVA_Files_in_VirtualBox.pdf

Once the virtual machine is imported, you can launch the pre-configured development environment to reproduce experiments, build the workspace, and run simulations.

A.2 Virtual machine Launch

Once the virtual machine is imported successfully, go ahead and click the **Start** button (See Fig:A.1). This will launch a new virtual box window where the system is running Ubuntu 20.04. The login the details are as follows:

- *User name*: dev
- *Password*: thws

Arena-rosnav and Visual Studio Code are fully installed in this virtaul machine and are can be used now.

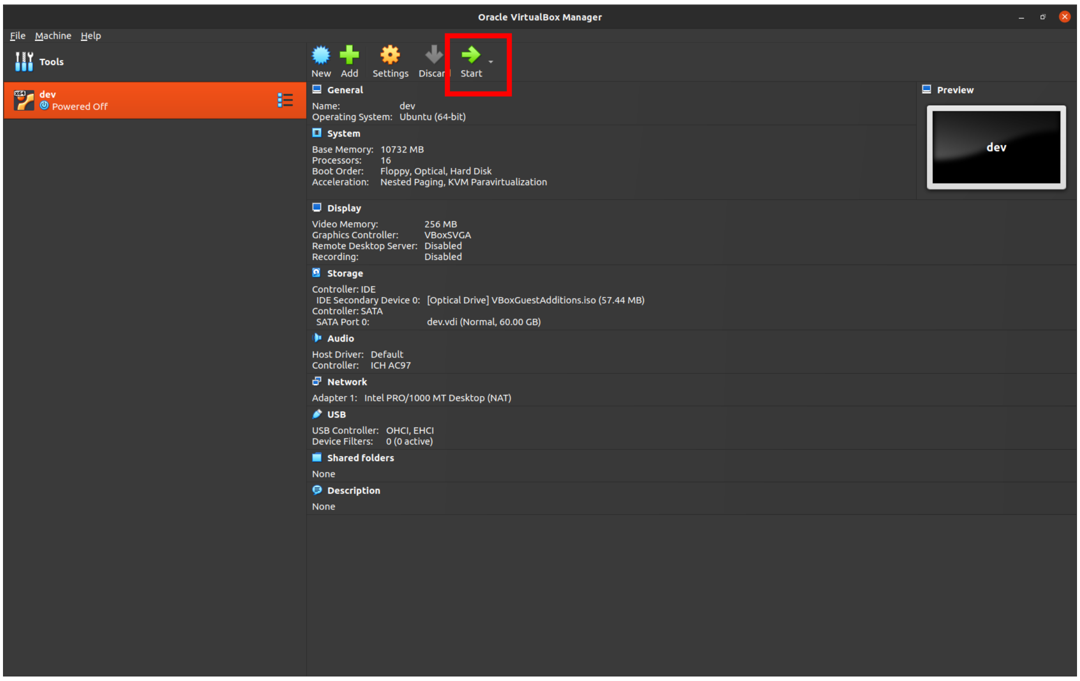

FIGURE A.1: Virtual Box main window

Appendix B

Implementation Details of Social Layer Integration in Arena-Rosnav

This appendix documents the step-by-step procedure for integrating the social navigation layer into the costmap using the Arena-Rosnav simulation framework. The configuration enables socially-aware robot navigation by leveraging proxemic behavior modeling.

B.1 Repository Setup

Step 1: Clone the `people` repository

Clone the `people` repository into the utilities folder:

```
cd ~/arena_ws/src/arena/utils
git clone -b noetic https://github.com/DLu/people.git
```

This repository provides the `people_msgs` message type which must be published on the `/people` topic. For documentation, see: https://docs.ros.org/en/api/people_msgs/html/msg/People.html.

Step 2: Clone the `navigation_layers` repository

Clone the `navigation_layers` repository:

```
cd ~/arena_ws/src/arena/utils/navigation
git clone -b noetic https://github.com/DLu/navigation_layers.git
```

This repository provides the `social_navigation_layers` package, which includes the Proxemic and Passing layers. See documentation: http://wiki.ros.org/social_navigation_layers.

B.2 Publishing `people_msgs` from Pedsim

Step 3: Modify the `pedsim_simulator`

Find the simulator:

```
rospack find pedsim_simulator
```

Modify the following files to publish `people_msgs`:

- `src/simulator.cpp`
- Corresponding header file

Ensure the message is published on the `/people` topic.

B.3 Rebuild Workspace

Step 4: Rebuild with `catkin build`

```
cd ~/arena_ws
catkin build
```

B.4 Costmap Configuration

Step 5: Add Social Layer Plugins

Edit the costmap parameters file for the robot (e.g., Jackal):
`/home/dev/arena_ws/src/arena/simulation-setup/entities/robots/jackal/configs/costmaps/global_costmap_params.yaml`

Add the following plugin:

```
- { name: proxemic_layer, type:
"social_navigation_layers::ProxemicLayer" }
```

Parameters for each layer are configured in: `costmap_common_params.yaml`

B.5 Launching and Runtime Adjustment

Step 6: Launch the Simulation

First, source the workspace and activate the virtual environment if needed:

```
source ~/arena_ws/devel/setup.bash
roslaunch arena_bringup start_arena.launch
```

Step 7: Use `rqt_reconfigure` for Dynamic Parameters

Open a new terminal and run:

```
rosrun rqt_reconfigure rqt_reconfigure
```

This allows for real-time adjustment of social navigation parameters.

Appendix C

Evaluation Pipeline for Arena-Rosnav

This appendix outlines the procedure for evaluating simulation results using the tools provided in the Arena-Rosnav framework.

C.1 Environment Setup

1. Open the Arena workspace in VS Code:

   ```
   cd /home/dev/arena_ws
   code .
   ```

2. Open a new terminal in VS Code: `Ctrl + Shift + ``

3. Activate the poetry environment:

   ```
   cd ~/arena_ws/src/arena/arena-rosnav
   poetry shell
   cd ~/arena_ws/src/arena/evaluation/arena_evaluation/
   scripts
   ```

C.2 Generating Evaluation Metrics

1. Suppose your recorded data is located at:

   ```
   /home/dev/arena_ws/src/arena/evaluation/arena_evaluation
   /data/25-05-03_11-49-11/jackal
   ```

   This directory should contain the following files:

   - `episode.csv`
   - `odom.csv`
   - `params.yaml`
   - `pedsim_agents_data.csv`
   - `scan.csv`
   - `start_goal.csv`

2. Run the following command to compute evaluation metrics (replace path as necessary):

```
python get_metrics /home/dev/arena_ws/src/arena/
evaluation/arena_evaluation/data/25-05-03_11-49-11/
jackal --pedsim
```

3. A new file `metrics.csv` will be generated in the data directory.

C.3 Plotting Evaluation Results

1. Navigate to the `plot_declarations` directory and create a YAML configuration file:

```
cd ~/arena_ws/src/arena/evaluation/arena_evaluation
/plot_declarations
touch eval_teb_2025.yaml
```

2. Copy contents from `sample_schema.yaml` into your new file:

```
cp sample_schema.yaml eval_teb_2025.yaml
```

3. Edit the YAML file to match your evaluation data and desired plots.

4. Generate plots using the following command (adjust path as necessary):

```
python create_plots /home/dev/arena_ws/src/arena
/evaluation/arena_evaluation/plot_declarations/
eval_teb_2025.yaml
```

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