Stacks and Toolchains

Module Information [RSE2107A Systems Engineering Project 1]

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Application to our project

Overview of Assignment

Project Goal:
Design an arena inspired by the Hedge Maze at Changi Canopy Park, and develop a ROS 1-based autonomous robot that can navigate both our arena and those created by other teams.

Objectives:

- Apply the Systems Approach (SEBoK 5 Steps) to guide design and decision-making
- Integrate sensors and motor control using ROS 1
- Ensure the robot adapts to other Changi-themed arenas

Current status:

- Arena layout drafted
- Ros 1 setup and initial testing underway
- Robot hardware received

Assignment Contents

1. Project Scope

- Develop a robot using ROS 1 using Lidar and controller on Ubuntu
- Maze navigation challenge under real-world constraints
- Must be able to operate and navigate in our arena and others

2. Arena Planning

- Chosen theme: Hedge Maze from Canopy Park
- Planning key features: branching paths, dead ends, possible inclines, narrow paths
- Constraints: 300mm max height, tight corners, sensor range limitations

Assignment Contents

3. Robot System

- ROS 1 used for real-time control, obstacle detection, and node-based architecture
- Key components: sensors (e.g., Lidar), motors, controller
- Progress: ROS node setup, sensor-motor testing underway

4. SEBoK Systems Approach

- Project structured using the SEBoK 5-step model
- All work documented and aligned with engineering methodology

Mapping of SEBoK steps to our Project

Step 1 - Identifying and Understanding Problems and Opportunities:

Maze + control challenge defined

Step 2 - Synthesizing Possible Solutions:

Maze layout concepts explored, ROS 1 system structure planned

Step 3 - Analysis and selection between Alternative solutions:

Final layout + materials chosen; ROS 1 stack selected

Step 4 - Implementing and Proving a Solution:

Built arena + integrated ROS nodes for teleop and LiDAR

Step 5 - Deploying, Using and Sustaining Systems to Solve Problem:

Reusability across arenas, including documentation and GitHub packaging

Our Project Context

NSoI:

- The LIMO robot and its onboard ROS-1 based tech stack (LiDAR sensing, teleop, path planning)
- Changi-inspired arena our team designed and built

WSoI:

- Other teams arena where our LIMO might navigate in
- The competition environmental constraints, including university guidelines, evaluation criteria, and cross-arena navigation requirements.
- External constraints such as budget limits, arena dimension standards, and common simulation environments

System Context Types

Product System:

- Our integrated system of physical hardware (arena + LIMO) and software (ROS1).
- To be delivered with expected capabilities such as obstacle avoidance, remote navigation, etc

Service System:

- Enables a human-robot interaction service (remote control/navigation)
- ROS nodes enables real time control and feedback for users
- The LIMO must be able to navigate safely under user command

Enterprise System:

- The university module (RSE2107A) defines project goals, constraints, tools and evaluation

Step 1 - Identifying and Understanding Problems and Opportunities

Problem Exploration

Key stakeholders and viewpoints:

- Professors
  - Ensures arenas are realistic and within the constraints
  - LIMO navigation capabilities and performance
  - Applying systems engineering principles

- Students developers (us)
  - Must build arena and robot logic under technical constraints and criteria

- Other teams
  - Expecting fair and testable arena

Problem Exploration

Some potential problems:

- Arena not within dimensions or budget
- Lack of Changi theme clarity
- Poor system integration
- Lack of ROS1 experience
- Tight deadlines and multiple evaluation criteria
- Navigation failures in new arenas
- Misaligned obstacle assumptions
- Arena may be too complex to navigate about

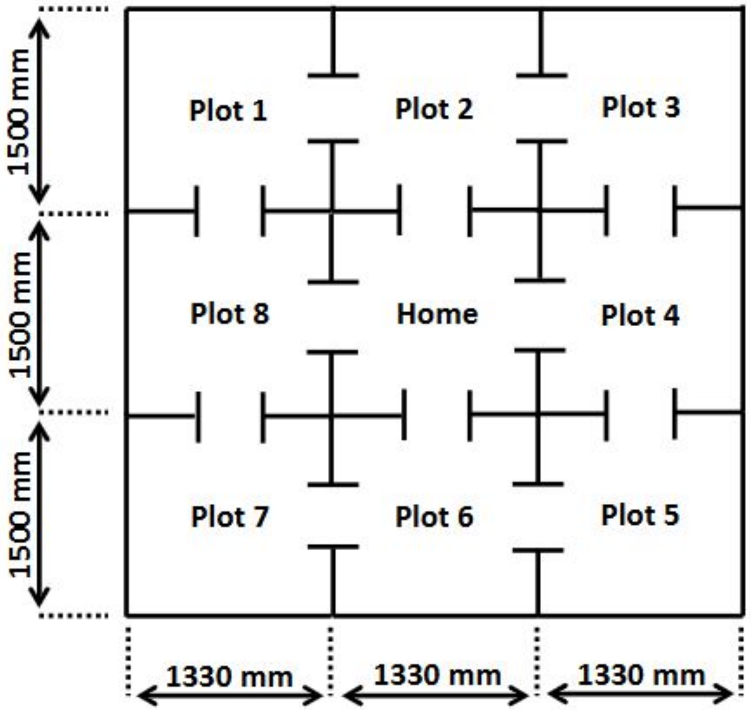
Problem Identification

Problem statement:

The challenge is to design an arena that satisfies fixed dimensional and functional criteria while ensuring our LIMO Robot is capable of navigating and autonomously maneuver to the goal of our arena and other teams.

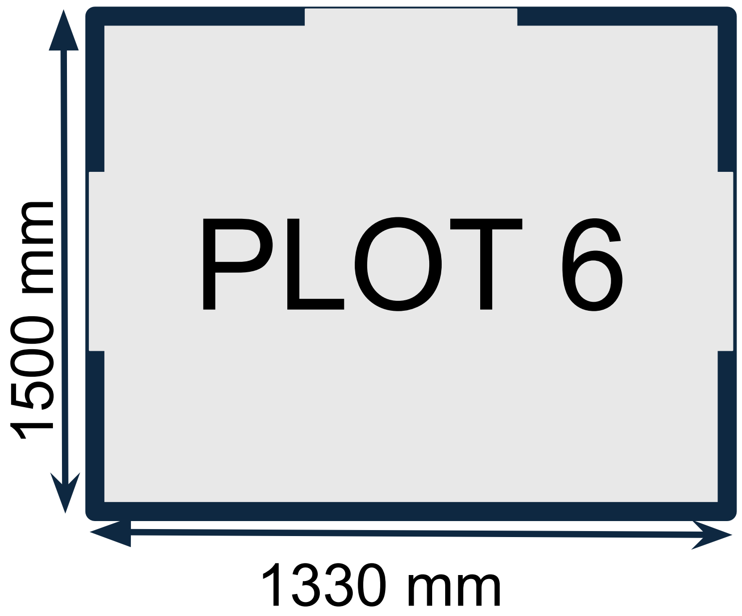
This must be achieved under tight resource and space constraints while supporting reliable navigation from the home plot to all other teams plot

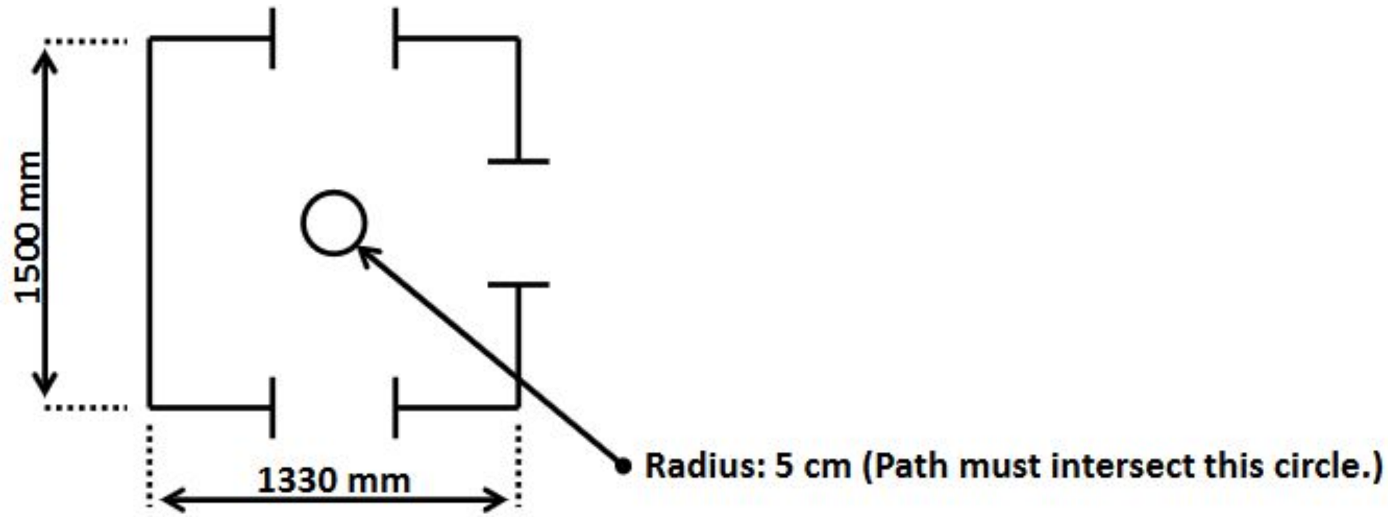
The solution must account for the technical, collaborative and evaluative expectation of all stakeholders involved



Arena constraints:

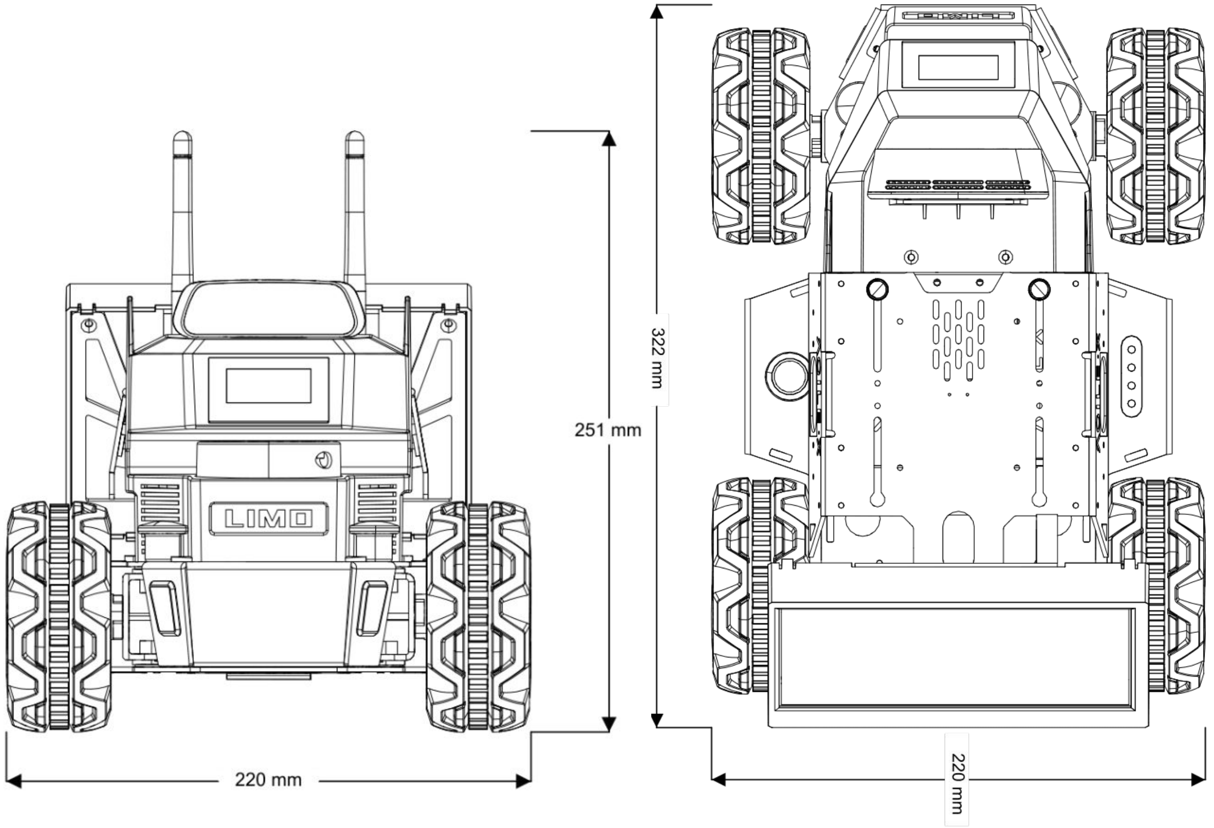
- Arena per maze (1330mm x 1500mm)
- Only Plot 6 and Canopy Park is under group design
- Cannot make multiple levels
- $600 budget





Robot constraints:

- Limo Robot Size (220mm by 322mm)
- Lidar Height (140mm)



Problem Context

Aim of the SoI: Design an arena inspired by the Hedge Maze at Changi Canopy Park, and develop a ROS 1-based autonomous robot that can navigate both our arena and those created by other teams.

Objective of Wider SoI: integrate autonomous navigation using ROS1, where Limo robot can operate reliably across diverse plot designed arena.

Objective of the System: To develop ROS1 autonomous robot capable of mapping, planning and navigating through both familiar and unfamiliar environment without human intervention.

Problem Context

Other conditions:

maintaining consistent localization accuracy, minimize map drift, work under various lighting and surface conditions, complete navigation from start to goal point.

Navigating multiple Arenas with all the same dimensions of 1.33m x 1.5m.

Limited budget of materials.

Step 2 - Synthesizing Possible Solutions

Problem or opportunity context

Problem: Ensuring reliable robot performance in complex spaces with maze-like features, transitions, and interactions across multiple teams' arenas.

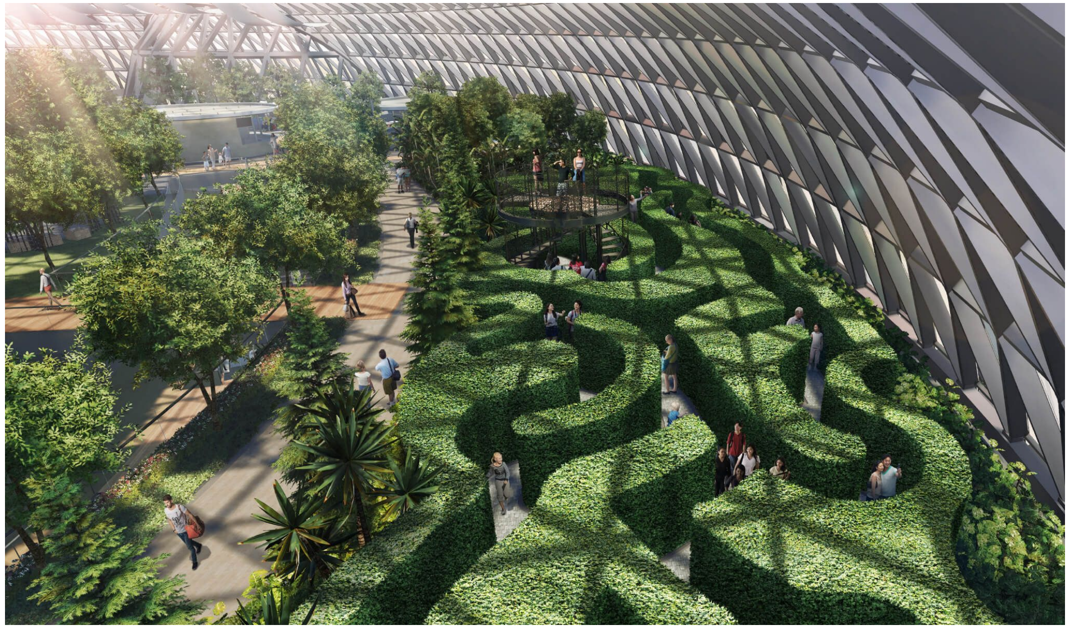
Opportunity: Design an arena that allows robust testing of autonomous navigation strategies in a controlled yet realistic environment.

Constraints:

- Arena size fixed at 1330mm x 1500mm
- Limited time, cost, and robot capabilities
- Shared environment with other teams
- Real-time navigation, obstacle avoidance, and landmark detection required

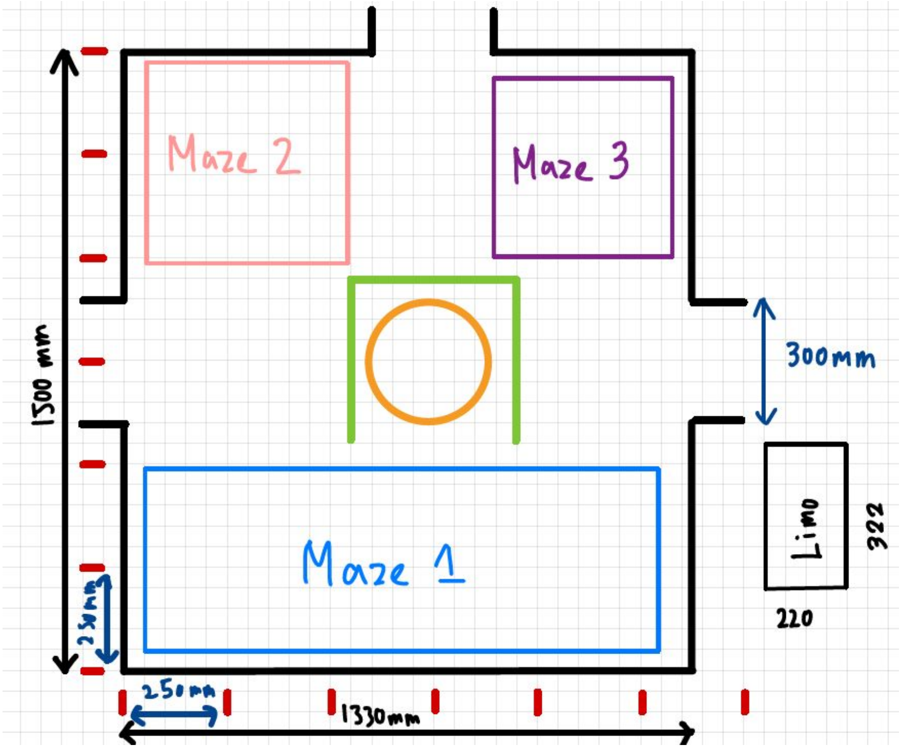
Our Goal

Synthesize an optimal design that balances challenge, feasibility and systems performs and enables a robot to navigate a custom-built arena inspired by Jewel Changi Airport's Canopy Park and Mastercard Canopy Bridge.



Identification of the Boundary of the System

- The arena boundary is fixed at 1500 mm x 1330 mm.
- The arena space includes mazes 1-3, a goal the robot must reach (indicate by yellow circle) and entry/exit
- The system also includes the LIMO robot which must fully operate within this boundary
- External system boundaries are defined by interfaces with neighboring team arenas.



Identification of the Functions of the System

- Navigate through complex layouts (exploration & pathfinding)
- Avoid static and dynamic obstacles
- Transition between zones or out of arena
- Maintain autonomous operation without external commands
- Integrate SLAM, path planning and obstacle avoidance behaviors

Navigation Method

- Wall-Following (Follows wall until Goal is found)
- Lidar obstacle avoidance (Drives toward goal, avoids obstacle)
- Waypoint Following (Uses fixed coordinated or recorded path)
- RTAB-MAP + ROS Navigation (Build map and use global planning)

Identification of the Elements of the System

- Physical
  - Maze walls
  - Arena platform
  - LIMO robot

- Conceptual
  - Navigation logic
  - Arena layout design

- Processes
  - ROS1 based on real time control, mapping, localization and navigation
  - Trial iterations and simulation validation

- Enabling systems
  - RViz/Gazebo simulators
  - GitHub
  - NoMachine

Division of System elements

The arena is divided into:

- Maze 1-3 (open spaces/ obstacle avoidance areas)
- Transition zones (exit and entrance)
- Middle point (Goal)

LIMO Robot navigation stack in divided into:

- Path Planning (Global Planner and Local Planner)
- Control (/cmd_vel)
- Perception (2D LiDAR, IMU)

Grouping of System Elements

Sub-systems

- The 3 zones and central goal point
- Navigation submodules (Global Planner and Local Planner)
- Hardware modules (Lidar, IMU, motor, battery)
- Software Group: ROS1 nodes (SLAM, AMCL, move_base)

Together these form the SOI that interacts with external arenas and the environment

Identification of the Interactions among System Elements

Technical Interface:

- RTAB-Map provides SLAM data which feeds into AMCL or navigation stack for localization.
- DWA planner uses sensor data and map to adjust velocity.

External Interface:

- Our robot must adapt to different arenas built by other teams
- Lighting changes and floor textures may affect camera or visual SLAM performance

Step 3 - Analysis and selection between Alternative solutions

Purpose of Solution analysis

Core Purpose

1. Access different arena layouts, material a the obstacle configurations based on navigation feasibility, cost and project timeline.

2. Analyze trade-off between visual appeal and sensor detectability.

3. Choose the arena that best satisfies limo robot navigation and mapping requirements, stakeholder expectations and practical constraint such as budget and competition time

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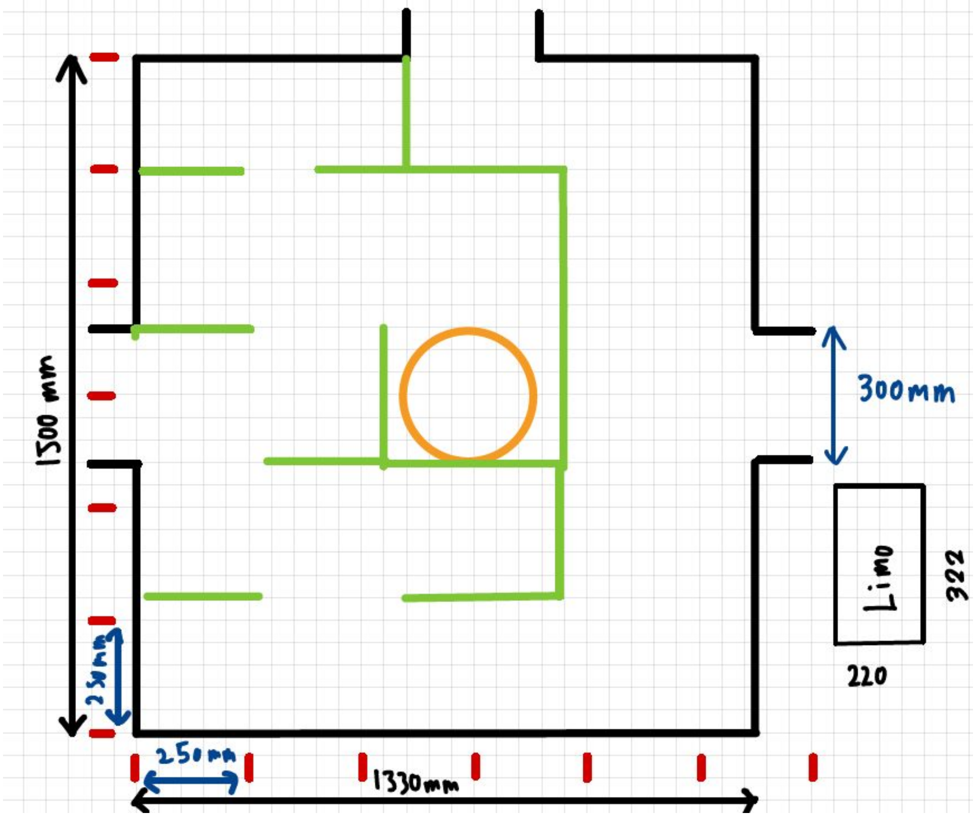
System analysis

Evaluation multiple solution components using defined metrics based on stakeholder needs and project goals:

- Arena design: Navigation clarity, aesthetic value, build complexity, Changi theme clarity
- SLAM options: Mapping accuracy, hardware compatibility, compute load
- Drive Modes: Maneuverability, terrain handling, energy consumption
- Planners: Path efficiency, obstacle avoidance behavior, recover strategies

To narrow down the feasible configurations for further evaluations

Arena Design Options



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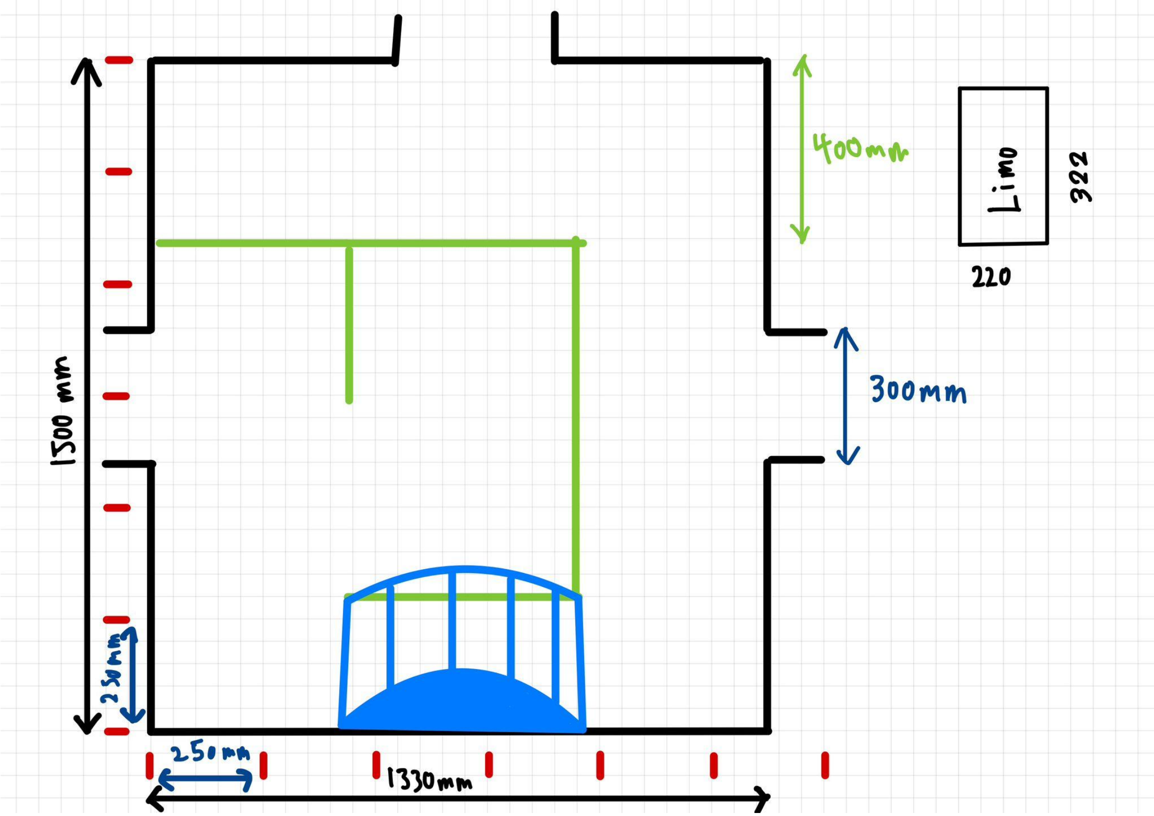

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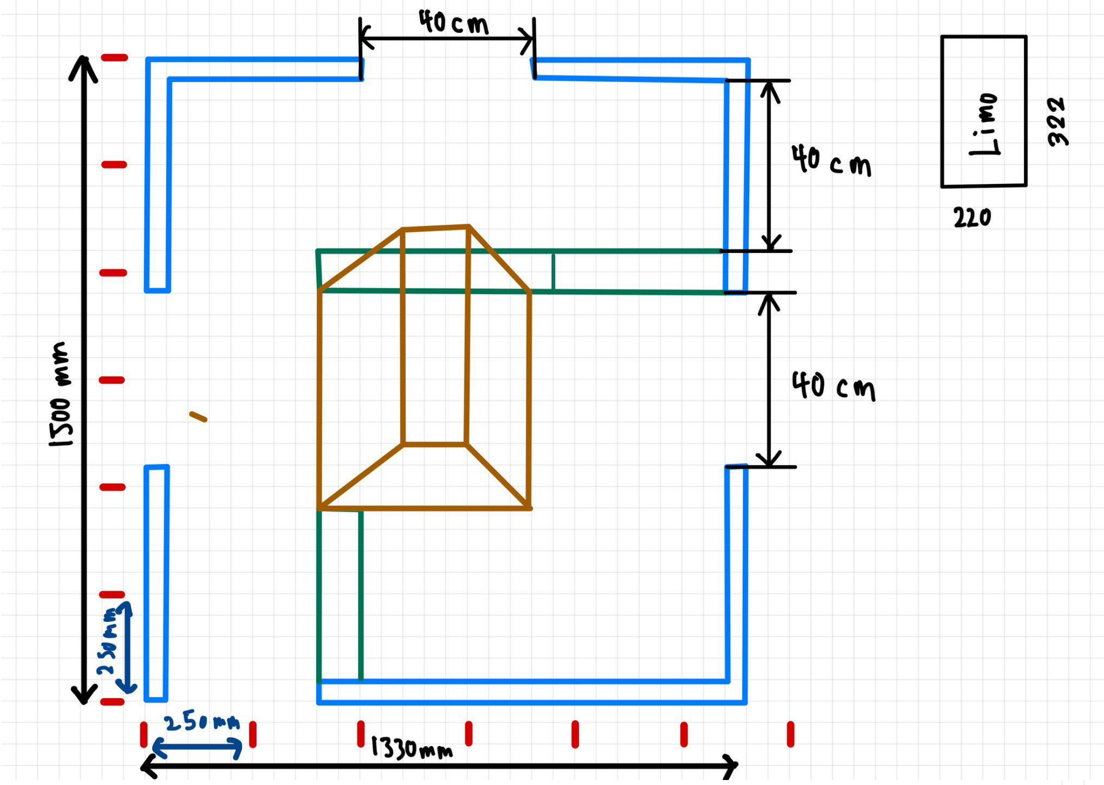
Arena Design Options



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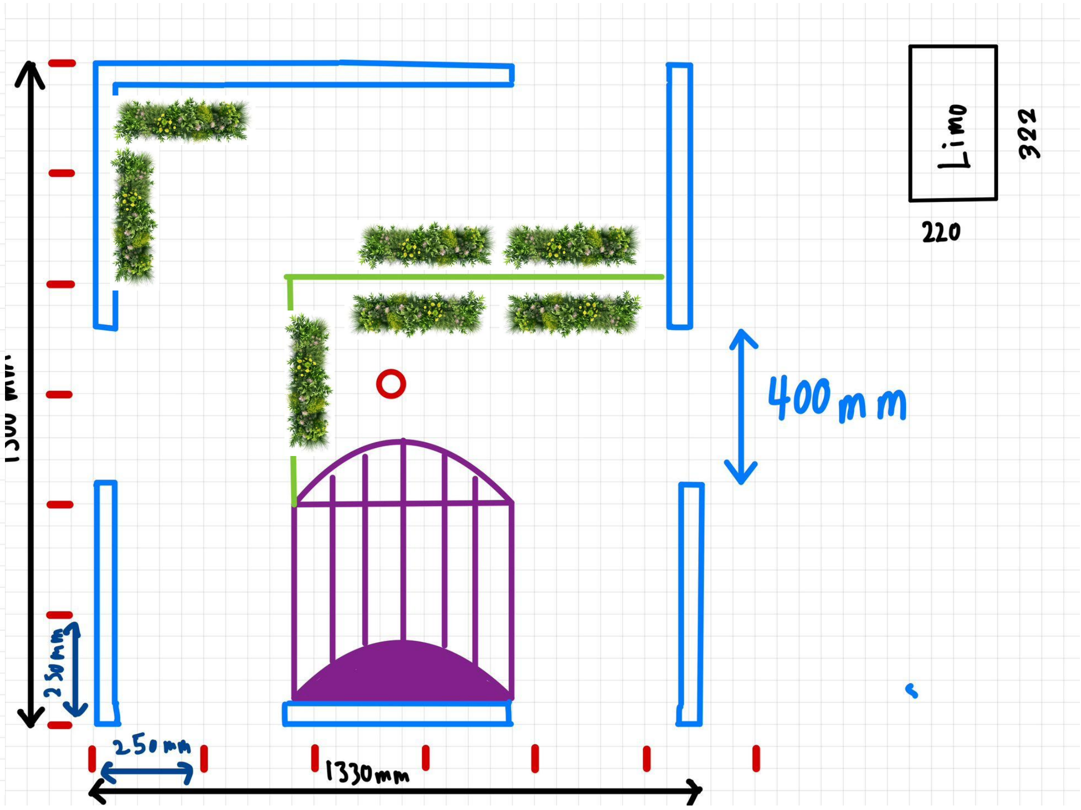

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MATERIALS PLANNING

- Base (Foam Board)
- Arena Boundary (Foam)
- Bridge (Corrugated Board and Foam)
- Hedge Maze (Corrugated Board and Artificial Grass)

Trade Off Studies for Arena

Arena Design 1:

- Narrow passages
- High chance of collision or the robot getting stuck
- Goal point placed in a complex dead-end zone

Arena Design 2:

- Reduced complexity
- Moderate navigation success rate
- Still contains tight corners

Arena Design 3:

- Goal is in a non-dead-end zone
- Low navigation risk
- Ideal for smoother movement and recovery

Arena Design 4:

- High obstacle density with bushes and narrow gaps
- Challenging for path planning and recovery
- Goal surrounded by multiple elements

Trade Off Studies for Arena

Arena Option	Key Features	Advantages	Disadvantages / Risks	Final Decision
Arena Design 1	Narrow corridors, multiple 90° turns	Tests robot turning and navigation accuracy	High risk of getting stuck in corners or dead ends	✘ Rejected
Arena Design 2	Open space with few wide pathways	Easier path planning and fewer obstacles	Less challenge for obstacle avoidance capabilities	✘ Rejected
Arena Design 3	Structured layout with clear pathways and centrally placed obstacles	Least risk of getting stuck; goal point not in a dead end	Moderate challenge; not highly complex for advanced planning	✓ Chosen
Arena Design 4	Mixed layout with narrow passages and scattered vertical/horizontal obstacles	Good test of maneuverability and obstacle avoidance	High complexity; increased chance of local planner failure	✘ Rejected

Trade-Off Criteria for Arena

- Risk of robot getting stuck
- Accessibility of the goal location
- Ease of path recovery
- Complexity for navigation algorithms
- Suitability for multi-arena navigation testing

SLAM Options

SLAM options

- ➢ Gmapping (2D LIDAR + Odom):
  - ○ Lightweight, simple
- ➢ Cartographer (2D LIDAR + Odom + IMU):
  - ○ Better accuracy, more sensors
- ➢ Rtabmap (2D Lidar + Depth Camera + Odom + IMU):
  - ○ High-quality 3D mapping but heavier computation

Selection factors

- Map quality vs CPU Load
- Robot sensor compatibility
- Real time performance needs

SLAM Options Trade-Off

Options	**Map Quality**	**Sensor Requirement**	**CPU Load**	**Final Decision**
Gmapping	Light	2D LIDAR + Odom	Low	✘ Rejected, low accuracy
Cartographer	Meduim	2D LIDAR + Odom + IMU	Medium	✘ Rejected, moderate performance
Rtabmap	High (3D)	2D Lidar + Depth Camera + Odom + IMU	High	✓ Chosen, best quality, suits complex environment

Navigation Options

Global planner

- **Dijkstra**: Guaranteed shortest path but slower (explores all nodes equally)
- **A***: Faster than Dijkstra (uses heuristics), more efficient in complex arenas

Selection factor: Path optimality vs computation time in obstacle heavy layouts

Local planner

- **DWAPlanner**: Velocity based, better for reactive navigation, handles dynamic obstacles well
- **TeblocalPlanner**: Time optimal, plans for flexible paths, better at tight spaces, but heavier CPU load

Selection factors: Path smoothness, ability navigate tight corners, execution stability

Navigation Options Trade-Off

Global Planner				
Option	**Path Optimality**	**Computation Time**	**Arena Suitability**	**Final Decision**
Dijkstra	Guaranteed optimal path	High (explores all nodes)	Better for maze like, obstacle rich layout	✓ Chosen, ensures safe, complete coverage despite being slower
A*	Near-optimal	Faster (Heuristics)	Good in simpler, open layout	✘ Rejected, risk of missing paths in complex arena

Navigation Options Trade-Off

Local Planner				
Option	**Navigation Reactivity**	**CPU Load**	**Tight Space Handling**	**Final Decision**
DWAPlanner	High (Velocity based)	Low	Good	✓ Chosen, balances responsiveness with lower computation, reliable for dynamic environments
TeblocalPlanner	High (Time optimal)	High	Better in tight spaces	✘ Rejected, too cpu-intensive for real-time navigation needs in current hardware setup

Drive Mode Options

Trade off study
Ackermann—turn with radius (Cannot rotate in place or move sideways)
Mecanum—able to Move Sideways (Less grip on uneven terrain)
4WD—Turn in place (Cannot move sideways)

Ackermann Mode
A geometry designed to solve the problem of wheels on the inside and outside of a turn needing to trace out circles of different radii in the steering of vehicles.

Track Mode
It has good off-road performance and can climb 40° slopes and small steps

Mecanum Wheel Mode
The omni-directional motion equipment based on Mecanum wheel technology can realize forward, lateral, oblique, rotation and combinations of motion modes.

Four-Wheel Differential Mode
Four-wheel drive, which can realize on the spot auto-rotation, but it will cause serious tire wear; please do not auto-rotate on the spot for a long time

Drive Mode Options Trade-Off

Mobility Mode	Turning Capability	Sideways Movement	Terrain Performance	Drawbacks	Final Decision
Ackermann Mode	Turns with radius	No	Designed for roads, not off-road	Cannot rotate in place or move sideways	✘ Rejected, [ppr maneuverability for indoor obstacle rich environment
Track Mode	Limited turning	No	Good off-road; climbs 40° slopes, small steps	Not highly maneuverable in tight indoor spaces	✓ Chosen, robust terrain handling outweighs indoor turning limitations
Mecanum Wheel Mode	Omni-directional (includes rotation)	Yes	Poor on uneven terrain	Less grip, lower traction	✘ Rejected, poor terrain performance not suitable for uneven arena surfaces
4-Wheel Differential Mode	Can rotate in place	No	Handles rugged surfaces	Causes tire wear when auto-rotating too long	✘ Rejected, risk of mechanical wear and instability during long auto-rotations

Effectiveness analysis

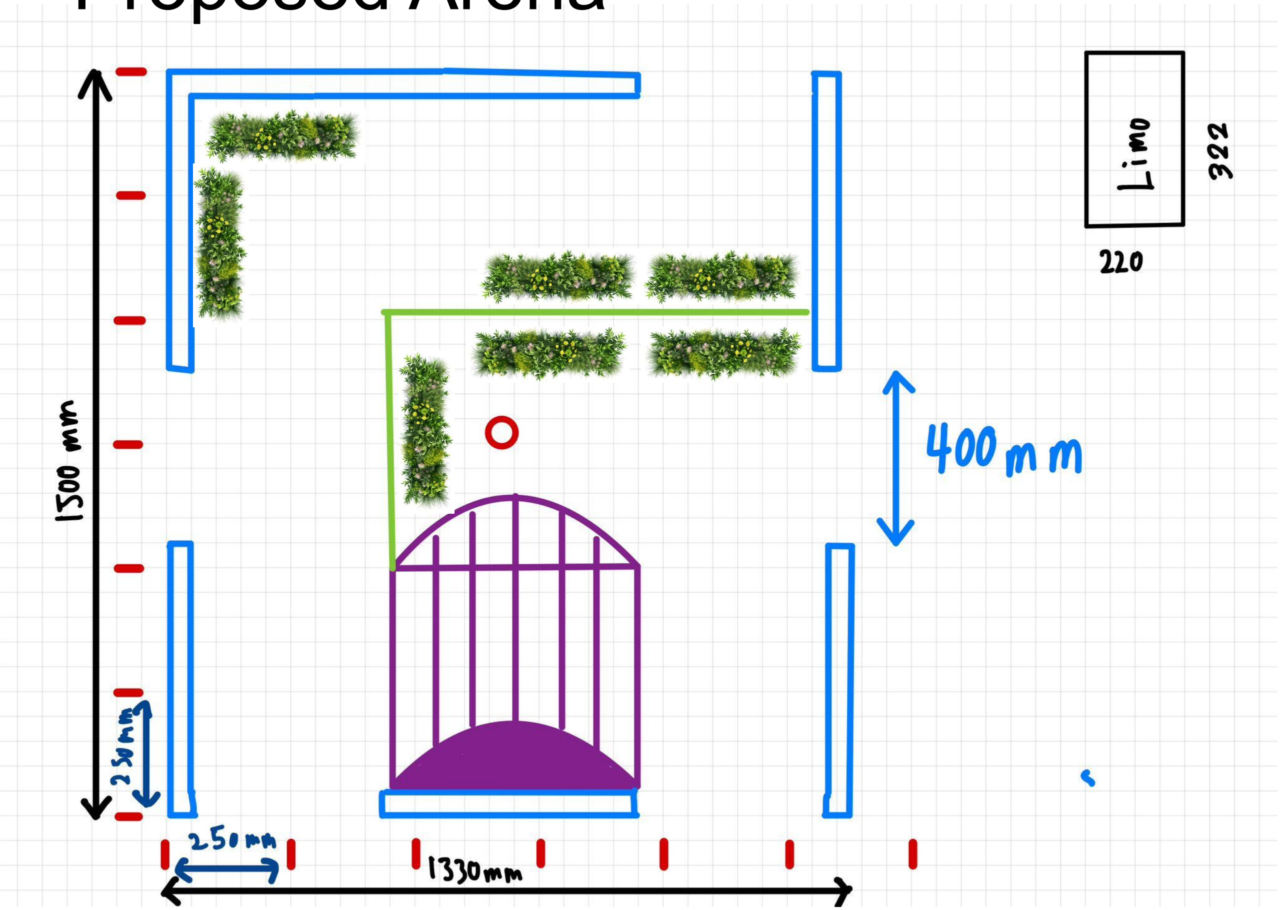
Evaluate the synthesized arena design and ensure chosen arena effectively fulfilled.

- functional requirements:
  - Robot able to autonomously navigate from start to goal with minimal errors
  - Robot can accurately detect and avoid obstacles
  - Robot able to localize and map accurately
  - Robot capable of recovering autonomously when a navigable path cannot be identified.

- and non-functional requirements.
  - Aesthetics must reflect a visually recognizable Changi Airport theme
  - Arena to be stable and free of hazards
  - Materials used and layouts are maintainable and safe for repeated demonstrations
  - arena surface provide consistent traction for all drive type
  - arena should be modular for easy configuration
  - design shall be reproducible across multiple plot
  - Multiple exit or entry points
  - Different terrains
  - able to build the arena within the given budget and time.

Chosen options

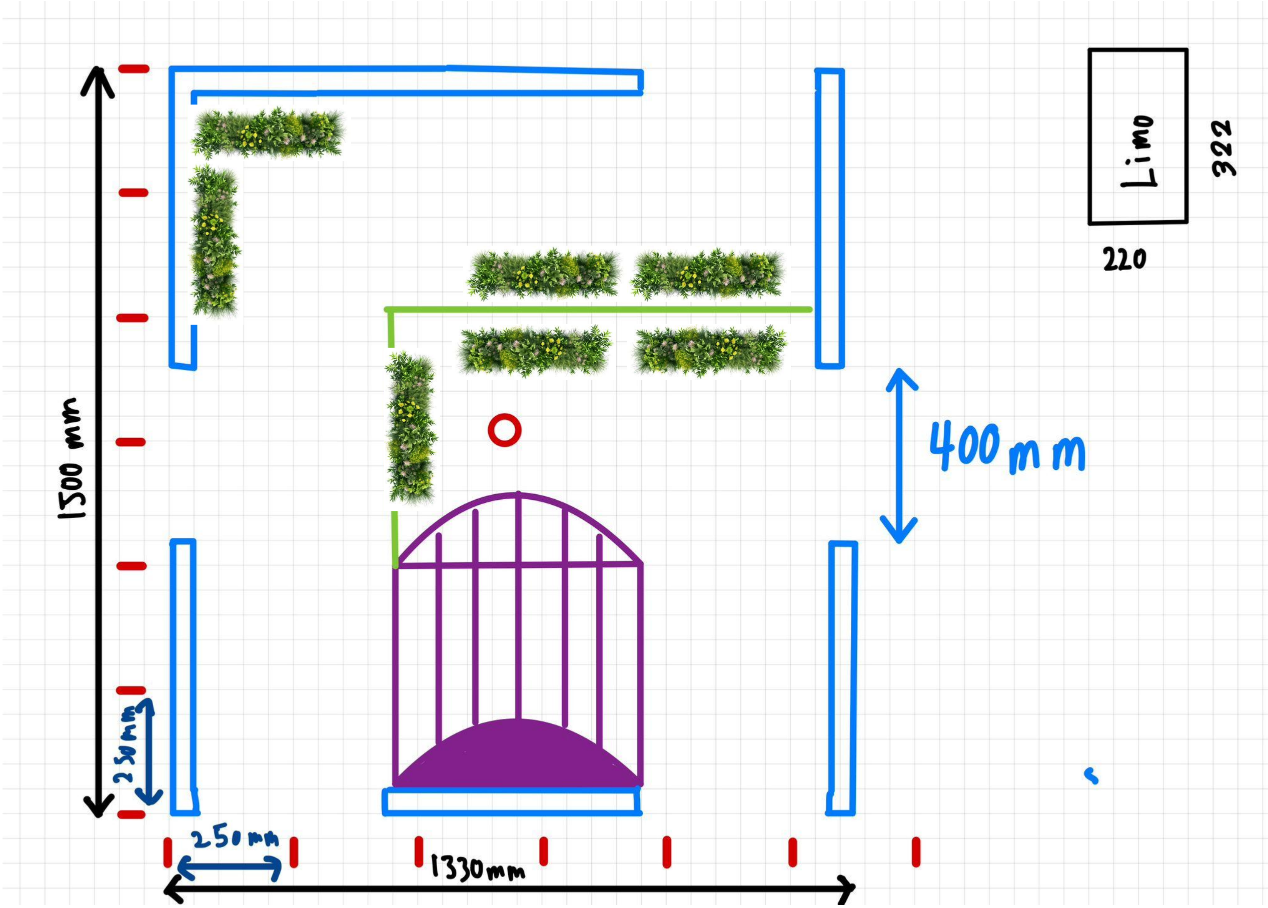
Proposed Arena

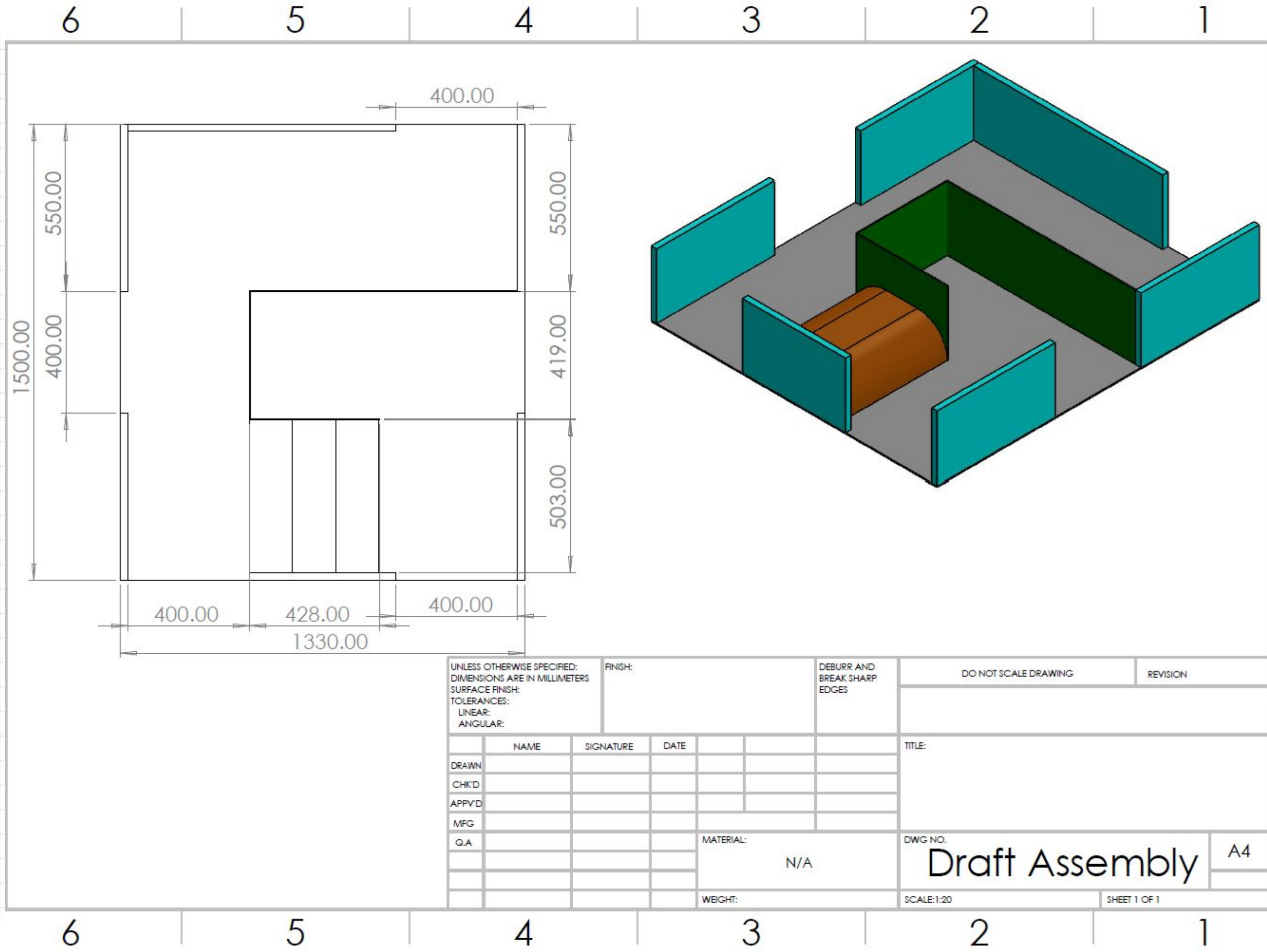


SLAM Options: RTAB-Map
Global Planner: Dijkstra
Local Planner: DWAPlanner
Robot drive mode: Track Mode

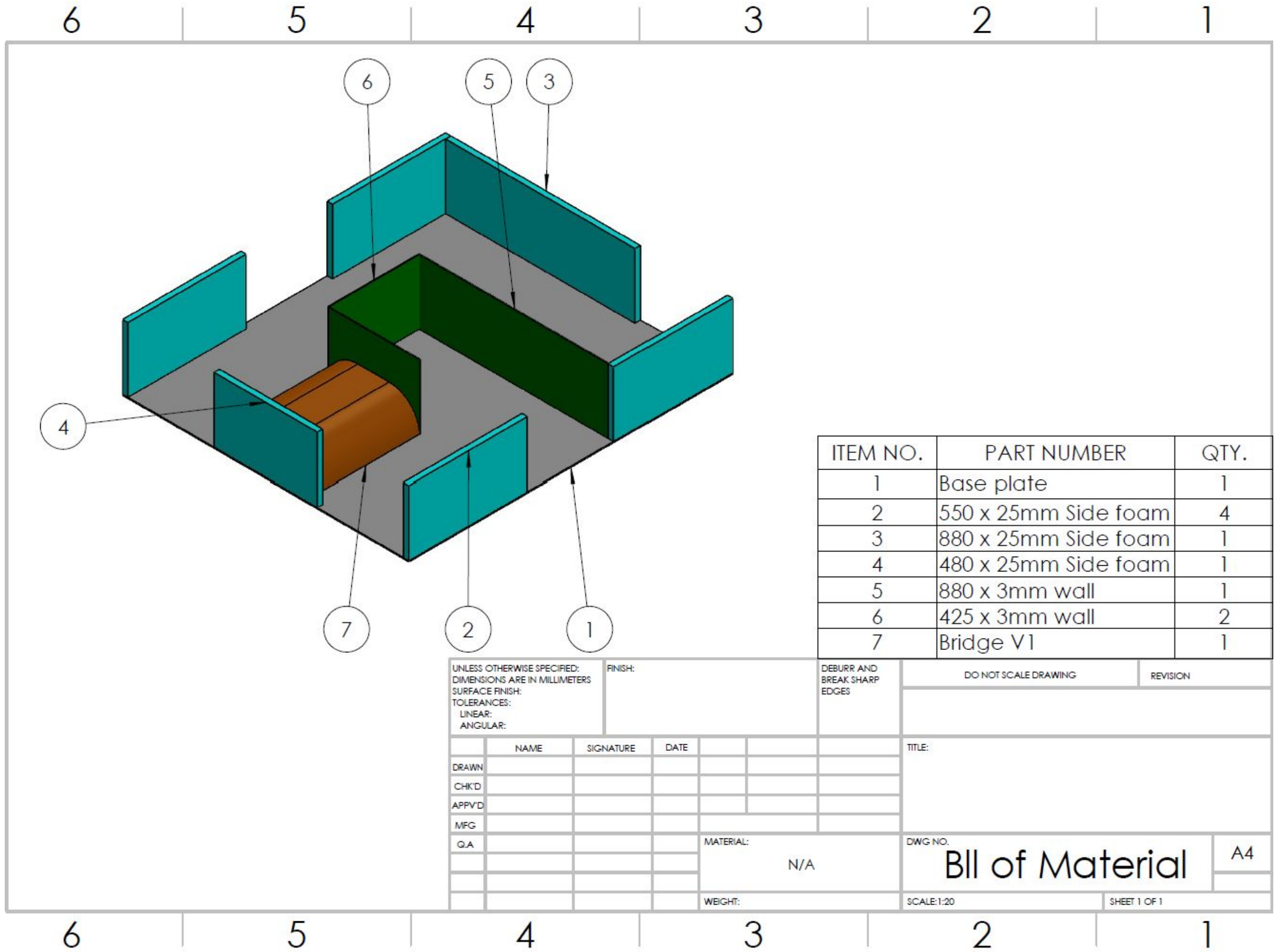
Step 4 - Implementing and Proving a Solution

Proposed Arena



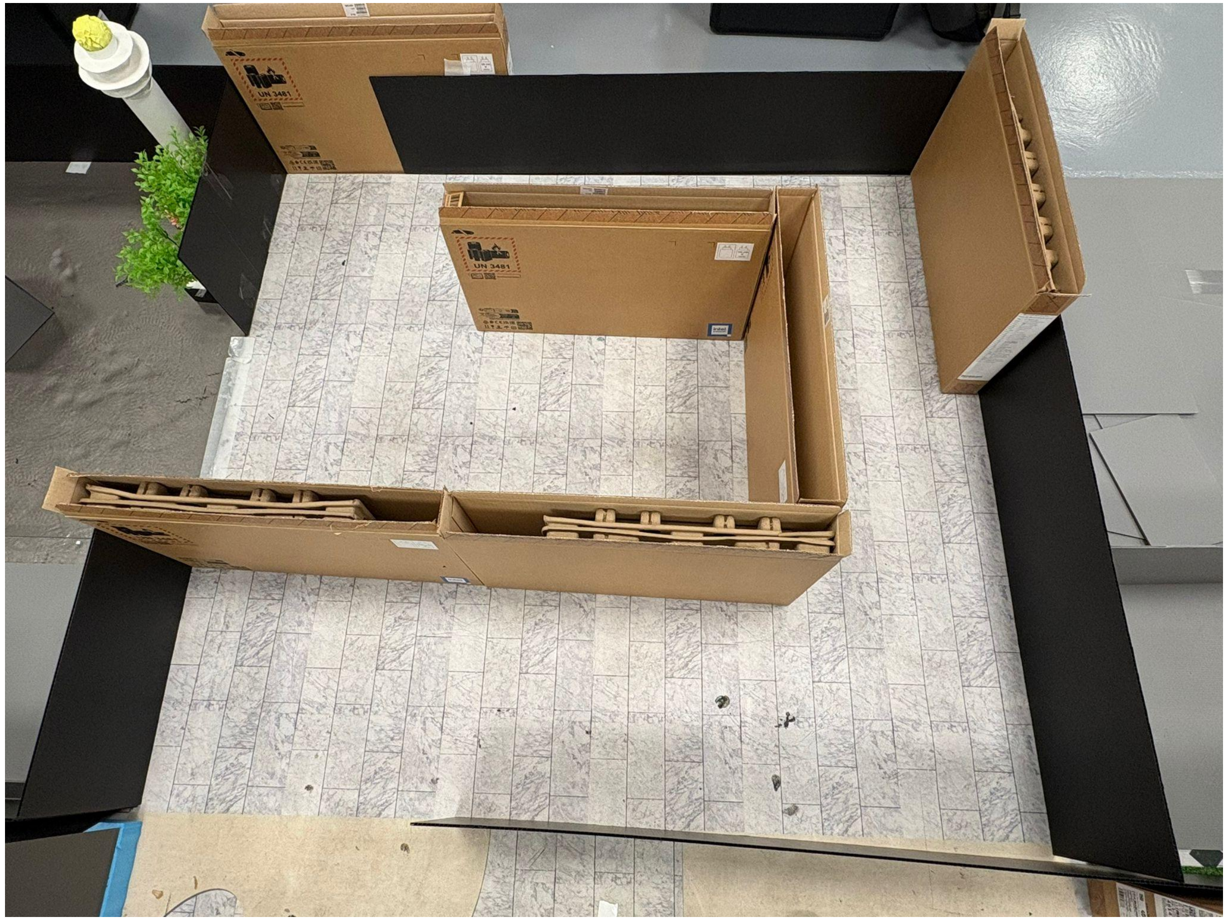


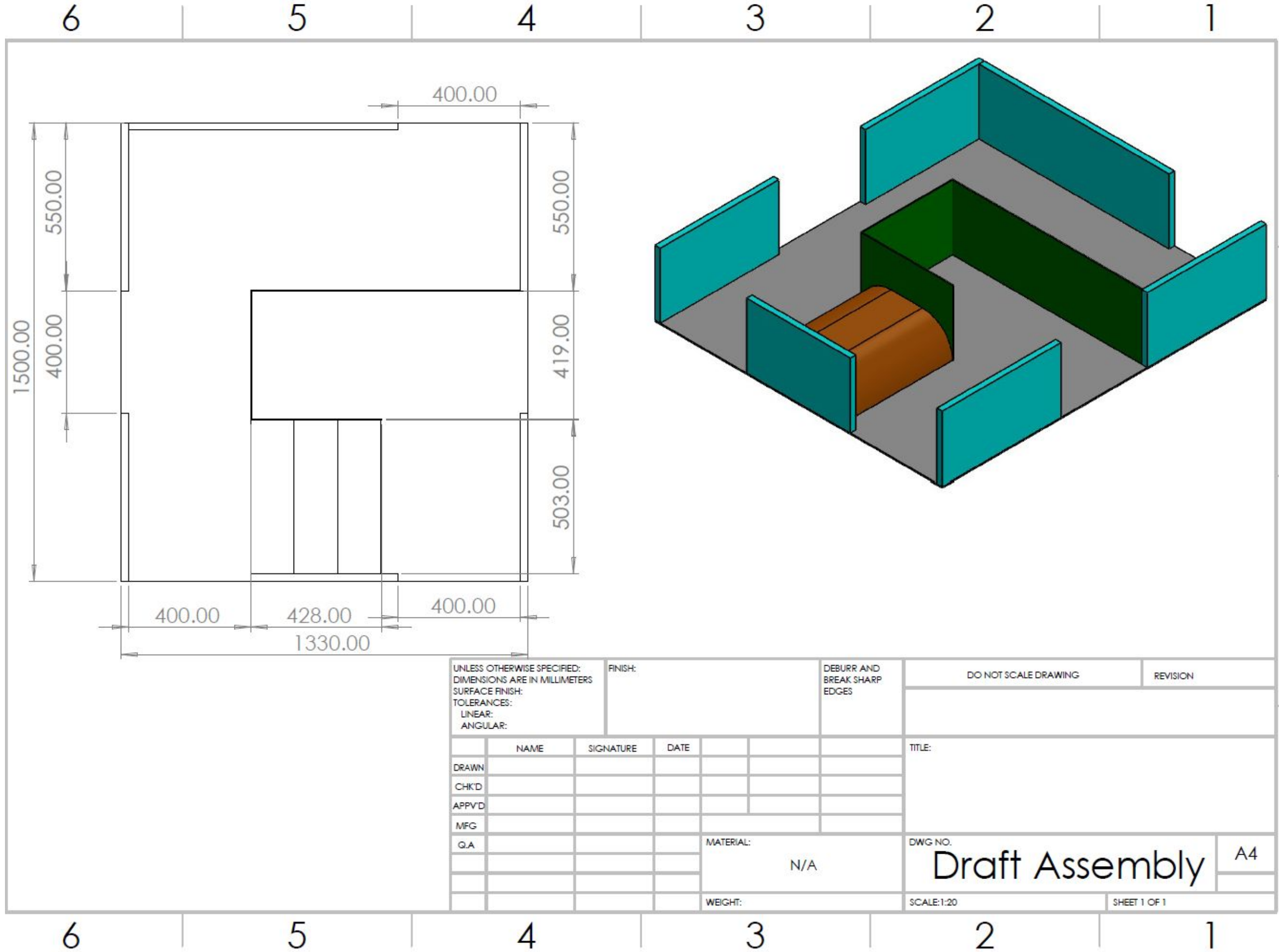
Bill Of Materials



ITEM NO.	PART NUMBER	QTY.
1	Base plate	1
2	550 x 25mm Side foam	4
3	880 x 25mm Side foam	1
4	480 x 25mm Side foam	1
5	880 x 3mm wall	1
6	425 x 3mm wall	2
7	Bridge V1	1

Arena Layout Prototype





Verification

Arena Design Verification:
✓ All dimensions fit the proposed arena size (1330X1500mm)
✓ Floor texture provides sufficient grip (not slippery or uneven)
✓ Entry/exit paths allow the LIMO robot to go through clearly
✘ Robot can navigate smoothly through arena

Robot Verification
✓ Robot can localize and complete the route autonomously
✓ LIDAR provides accurate data for SLAM mapping
✓ Robot can detect obstacles and stop to avoid collision
✓ SLAM builds consistent and complete occupancy grid map
✘ Robot default recovery behaviour able to function at tight spaces and dead ends

Verification

Issue Identified

The initial proposed layout had tight turns that robot could not handle smoothly.

What we did:

- Tested the robot in prototype arena
- Modified layout, adding smoother navigation paths

Verification passed:

✓ Robot successfully navigates from start to goal autonomously without collision

✓ Recovery behavior works when blocked

Verification

Issue Identified

Default recovery behaviour failed when the LIMO reach a dead end with tight spaces

What we did:

- Created custom node for reverse and retrace logic

Verification passed:

✓ Robot can now recover from traps and dead ends

✓ Navigation continues autonomously without manual reset

Validation

Arena Design Validation:

✓ The arena complies with the cost limitation of $600

✘ The arena is visually recognizable as a Changi's Canopy Park

Arena Fairness Validation

✓ Arena boundaries and checkpoints were clearly defined

✓ Start and end points followed the competition requirements

✘ Unclear if LIMO could complete the route in our arena

✘ No confirmation that the arena is competition ready

Validation

Issue Identified

The initial arena lacked strong thematic clarity and did not clearly reflect Changi Airport's Canopy Park aesthetic

What we did:

- Incorporated recognizable features:
  - Canopy Bridge
  - Manulife Sky Nets - Walking
  - Discovery Slides
  - Petal Garden
- Compared to reference photos from actual Canopy Park

Validation Passed:

✓ Stakeholders confirmed theme is recognizable and appropriate

✓ Aesthetics align with original expectations

Validation

Issue Identified

It was unclear if LIMO could complete the route in our arena and no confirmation that the arena is competition ready

What we did:

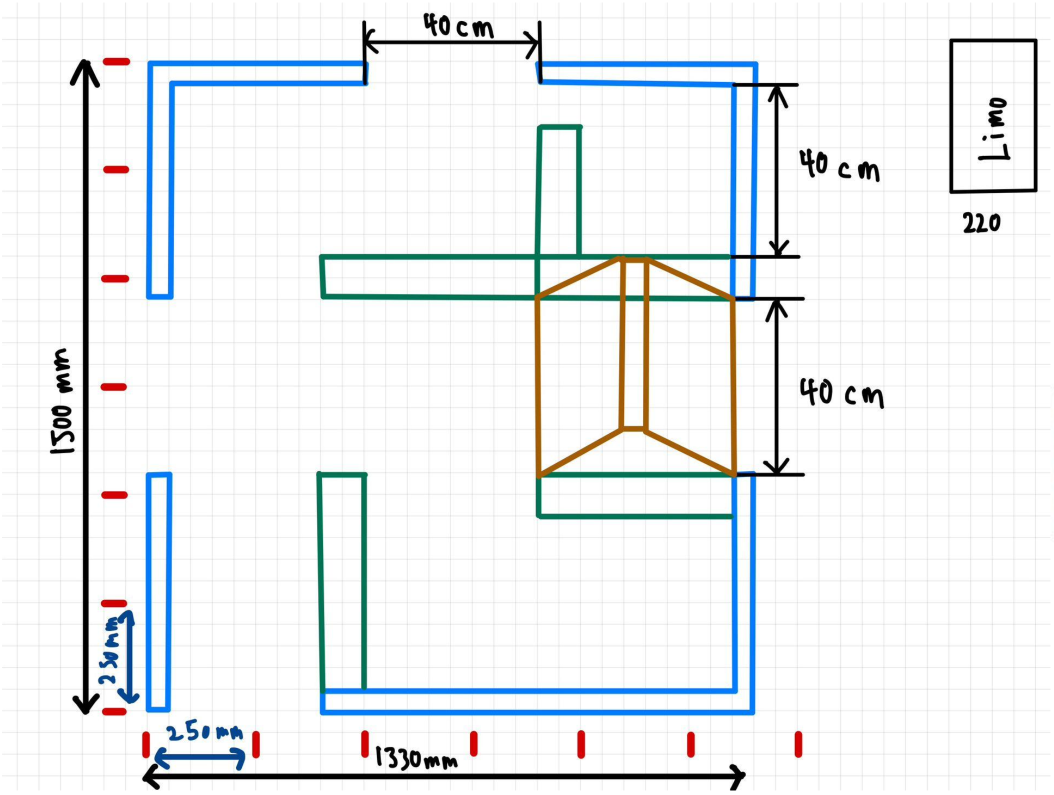
- Conducted reasonability test by running our own LIMO robot through the full arena
- Checked for unnecessary collision, dead-ends, or ambiguous paths
- Observed behavior under tight turns and bridge crossing

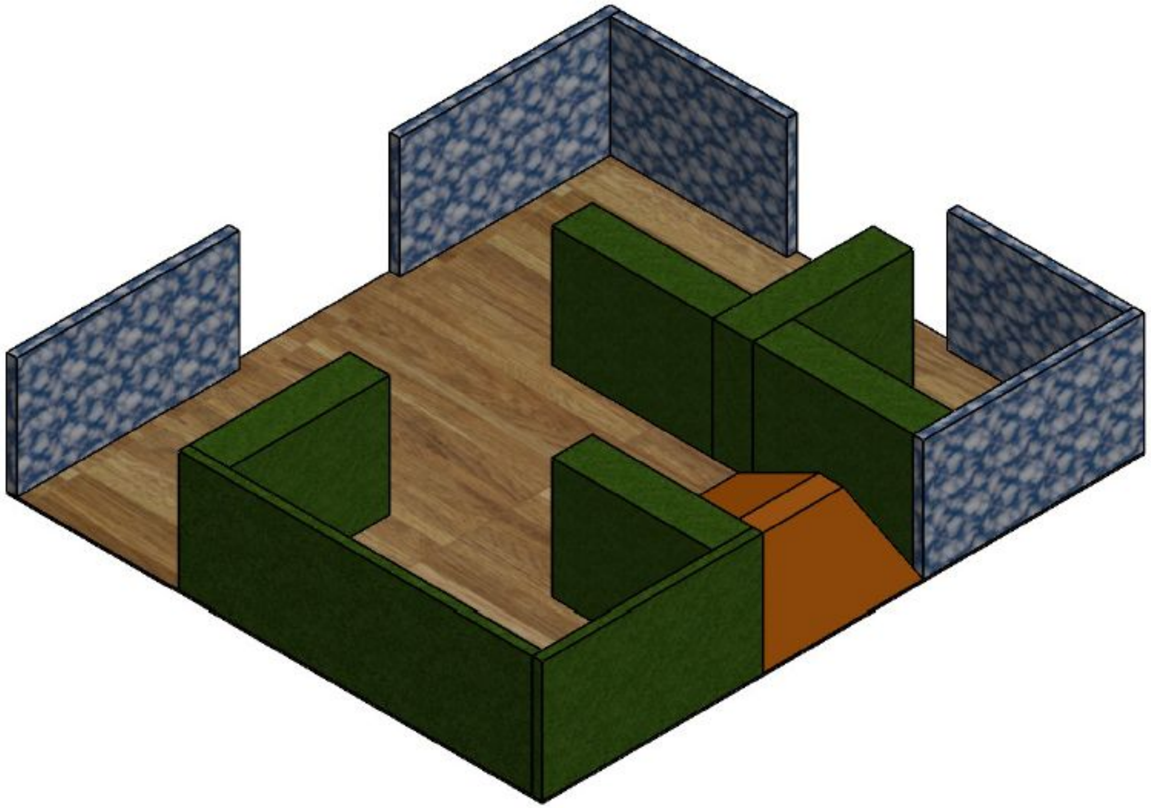
Validation Passed:

✓ Robot successfully completed route from start to end

✓ Stakeholder accepted test run as evidence of arena fairness and readiness

Final Arena





Final Arena

Step 5 - Deploying, Using and Sustaining Systems to Solve Problem

Deployment - Preparing the Arena and Robot

- Since the arena was built on the competition site there was no need to move it
- Initial layout adjusted during pre-development testing:
  - Tight turns fount to hinder robot navigation
  - Curves widened and obstacles repositioned for better pathing
  - Safe entry and exit points for robot
- Robot and arena interoperability verified through internal testing
- Checked that deployment would not introduce new system risks such as steep corners

Using - Operating the System

1. Planned for emergent properties

We Identified possible issues that could arise from robot navigation during arena design

- Designed wider path to avoid navigation failures from sharp turns
- Adjusted obstacle placement to prevent SLAM data dropouts
- Factored in sensor visibility to support robust localization

2. Handling unexpected issues during use

During testing and usage, we encountered unforeseen problems

- Even after recovery behavior robot cannot find a new path after it gets stuck
- Adjusted the arena layout and navigation parameters for stability
- Made minor prop reposition to improve object avoidance

3. Established Emergency Handling procedures

We implemented contingency plans to deal with in-run failures

- Operator standby protocol for manual robot reset if stuck
- Ensure arena allows Human access without disturbing layout
- Clear criteria for retry attempts in testing and final demonstration

Sustainment - System Maintenance and Viability

- Arena :
  - Reinforce corners and joints
  - Using robust materials
  - Designing arena in sections for easier reconfiguration and repairability
  - Regular inspection of the arena after every test run

- Robot
  - Follow manufacturer guidelines for charging and discharging to extend battery lifespan
  - Maintain a version controlled repository for navigation stack parameters and RTAB-Map parameters
  - Backup map data and robot configurations

Disposal

- Software Archiving: The ROS configuration files, launch files, and custom scripts (C++/Python) were backed up and stored in a version-controlled repository (e.g., Git) for future reference or reuse.

- Hardware Handling: The LIMO robot were returned to the lab inventory or reassigned for future student or research projects.

- Arena Teardown: The custom-built arena was dismantled, and reusable materials were recovered or recycled where possible.

Individual Q&A

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