SOUTHWEST JIAOTONG UNIVERSITY · UNIVERSITY OF LEEDS
西南交通大学 – 利兹学院
SWJTU-LEEDS JOINT SCHOOL

Parking Robot Based on 3D LiDAR

XJEL3875 Individual Engineering project

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CONTENTS

01

Background & Motivation

Development of Automated Driving,

Problems and significance, literature review and objectives

Automated Driving Development

Mar. 2018

First Self-driving Road Test

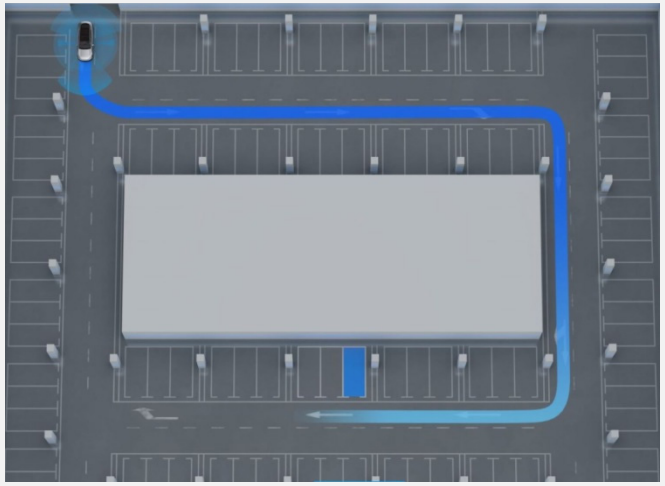
- Level 2 AV is already on the ground
- Mostly based on the computer vision

Source: https://www.gigabyte.com/jp/Article/constructing-the-brain-of-a-self-driving-car

Jun. 2021

First Automatic Parking Release

- To reduce the parking time
- To ensure the parking safety
- ……

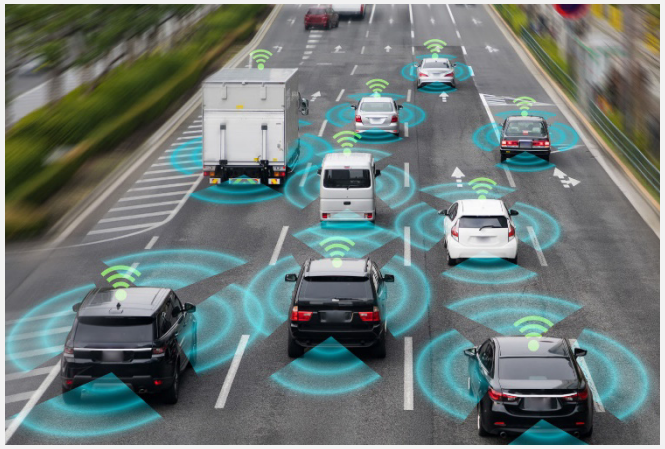


Source: https://www.pingwest.com/a/243965

Early 2025

IoT–based L4 Self-driving

- Hybrid solution of 3D LiDAR and camera
- Driver attention is not required for safety
- Fully automatic control of the terminal
- ……



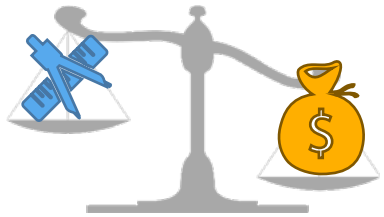
Source: https://www.walleniuswilhelmsen.com/insights/the-future-of-mobility-whats-the-road-ahead-for-self-driving-vehicles

Problems & Significance

1

2D or 3D LiDAR?

- High-definition 3D LiDAR is very expensive (>$15k) but can provide multi-dimensional information without depth camera and supercomputing platforms.
- Normal 2D LiDAR is cheap (~$0.5k) but other sensors are needed to work in cooperation, and 2D LiDAR only plays a supporting role.



2

No Remote Control?

- The existing automatic parking system can only be controlled by the car display.
- However, by remote control, driver gets off the car at the entrance of parking lot; or the car goes to the designated place to pick the driver.
- This saves up to 107 hours a year according to INRIX.

Literature Review

	2016	2017	2018	2019	2020	2021
Cartographer	Developed by Google. Still in maintenance.					
	Very fast but standard prevision. **Error accumulation**. Not easy to modify the code.					
LOAM		Developed by Dr. Zhang Ji at CMU.				
		Low speed but able to **auto optimization**.				
LeGO-LOAM			Developed by Dr. Shan Tixiao at MIT.			
			Improved speed and accuracy of LOAM. Middle speed. **Not suitable for navigation**.			
LIO-SAM				Developed by Dr. Shan Tixiao at MIT.		
				Add IMU & GPS for **high precision and efficiency**. **IMU data is not easy to be configured**.		

Objectives

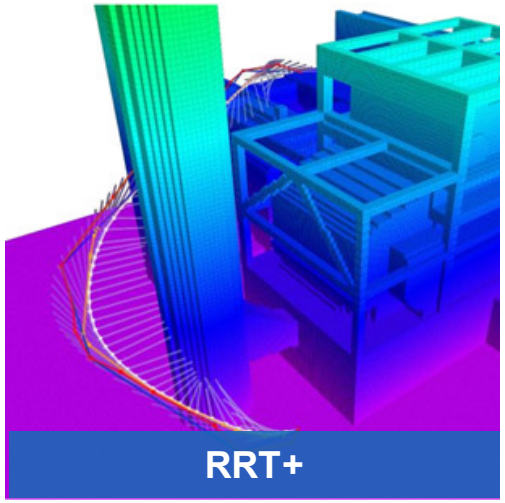
To save **MONEY** and **TIME**!

Simultaneous Localization and Mapping +

Inexpensive 3D LiDAR still has a satisfied precision and accuracy with improved method (IMU).

Source: https://geoawesomeness.com/velodyne-500-lidar/

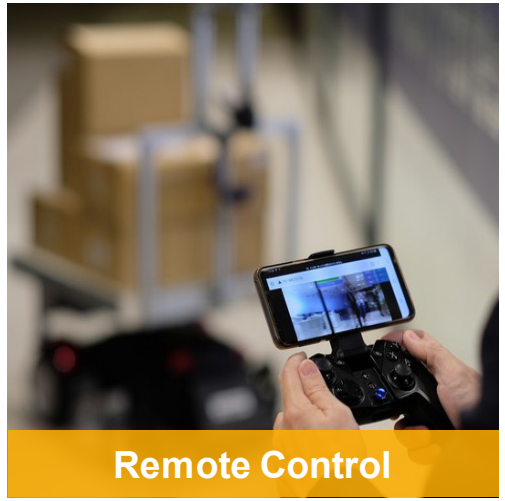
Running in Simulation Environment



Rapid Random-explore Tree +

Real-time and dynamic fast navigation added height info detection for 3D Navi.

Source: https://onlinelibrary.wiley.com/doi/10.1002/rob.21863



Client-Server-Vehicle Arch. Able to control and have visualizations through smartphone.

Source: https://re-how.net/all/1150145

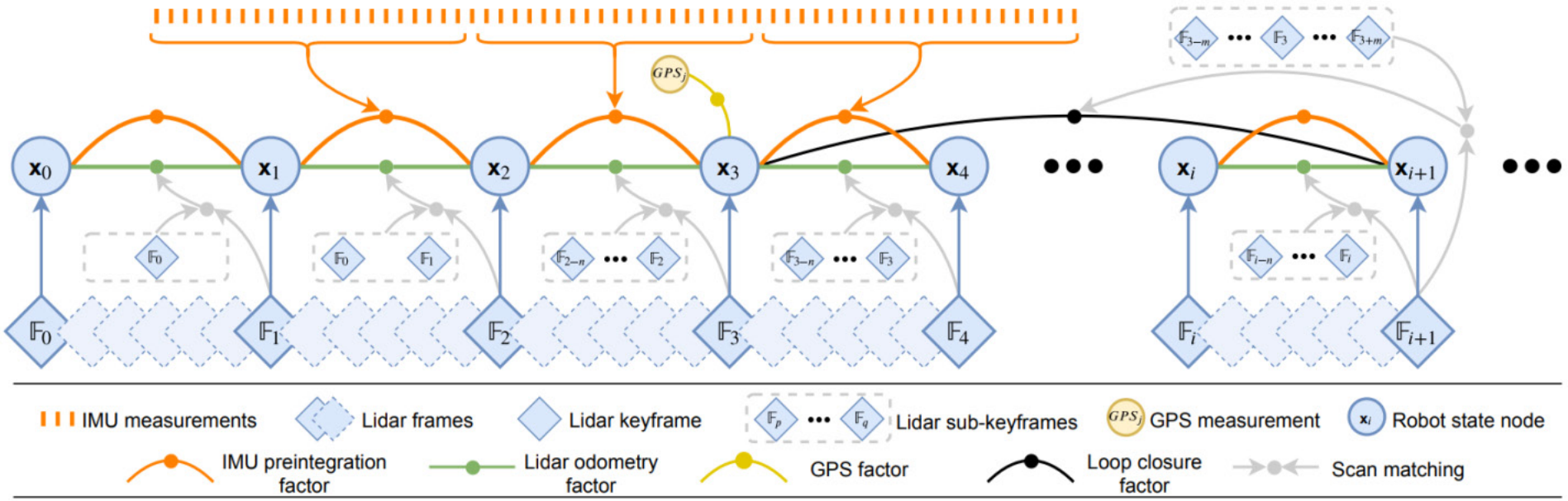
02

Method & Improvement

SLAM+; SLAM+ Performance;

RRT+; Speed Bumps & Arch Gates Recognition

SLAM+: Added IMU for Better Map Building



Added:
Inertial Measurement Unit

Pre-integration Factor

$$\mathrm{v}_{t+\Delta t} = \mathrm{v}_t + \mathrm{g}\Delta t + \mathrm{R}_t(\hat{\mathrm{a}}_t - \mathrm{b}_t^{\mathrm{a}} - \mathrm{n}_t^{\mathrm{a}})\Delta t$$

$$\mathrm{p}_{t+\Delta t} = \mathrm{p}_t + \mathrm{v}_t\Delta t + \frac{1}{2}\mathrm{g}\Delta t^2 + \frac{1}{2}\mathrm{R}_t(\hat{\mathrm{a}}_t - \mathrm{b}_t^{\mathrm{a}} - \mathrm{n}_t^{\mathrm{a}})\Delta t^2$$

$$\mathrm{R}_{t+\Delta t} = \mathrm{R}_t \exp\big((\hat{\omega}_t - \mathrm{b}_t^{\omega} + \mathrm{n}_t^{\omega})\Delta t\big)$$

$$\Delta \mathrm{v}_{ij} = \mathrm{R}_i^{\mathrm{T}}\big(\mathrm{v}_j - \mathrm{v}_i - \mathrm{g}\Delta t_{ij}\big)$$

$$\Delta \mathrm{p}_{ij} = \mathrm{R}_i^{\mathrm{T}}\left(\mathrm{p}_j - \mathrm{p}_i - \mathrm{v}_i\Delta t_{ij} - \frac{1}{2}g\Delta t_{ij}^2\right)$$

$$\Delta \mathrm{R}_{ij} = \mathrm{R}_i^{\mathrm{T}}\,\mathrm{R}_j.$$

SLAM+ Performance

2D vs. 3D LiDAR

2D LiDAR identified the tree as a tiny dot.

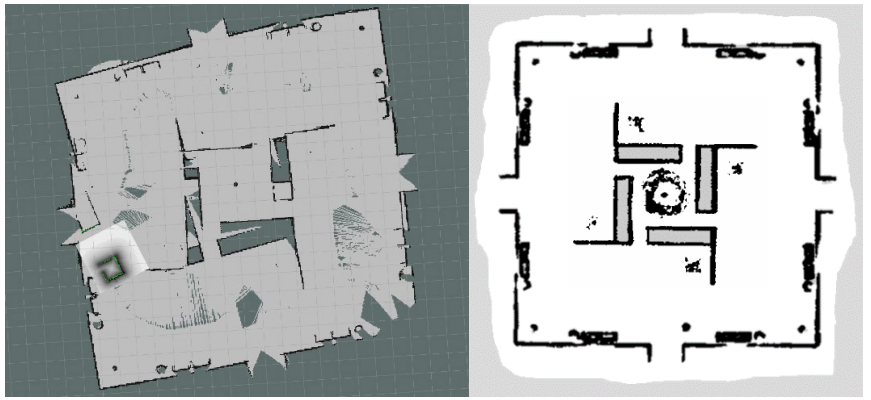
3D LiDAR correctly restored the leaves and branches.

Left: Real-world scene. Middle: Cartographer result. Right: SLAM+ result.

Cartographer vs. SLAM+

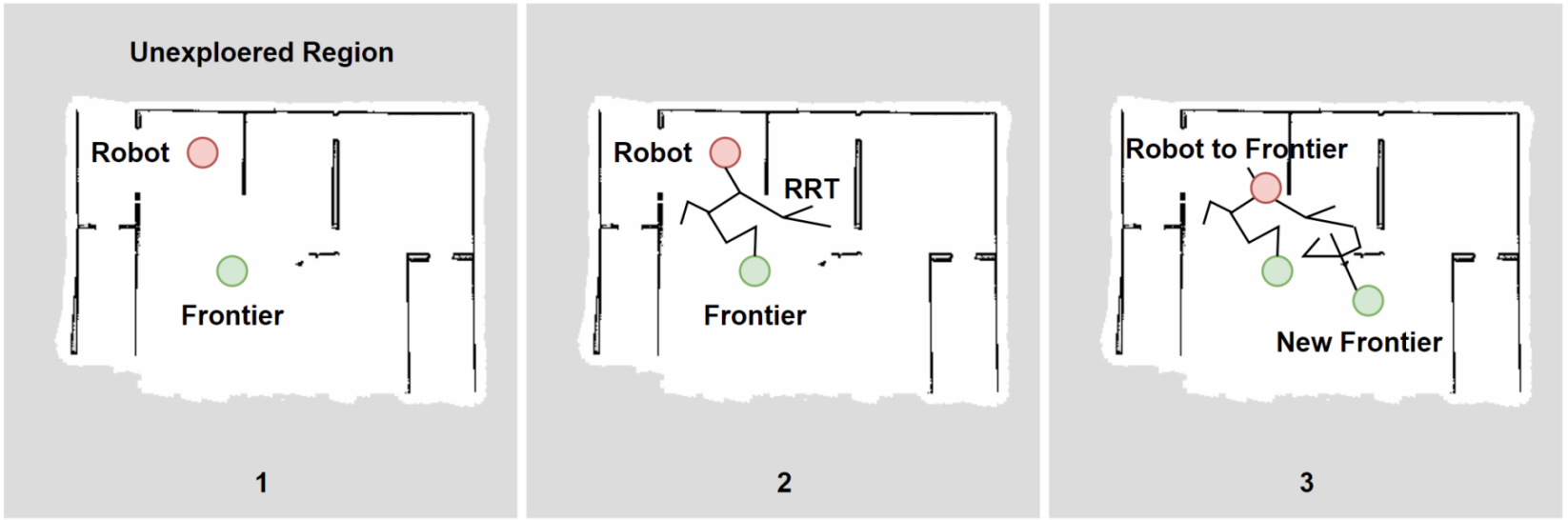
Cartographer had distorted walls.

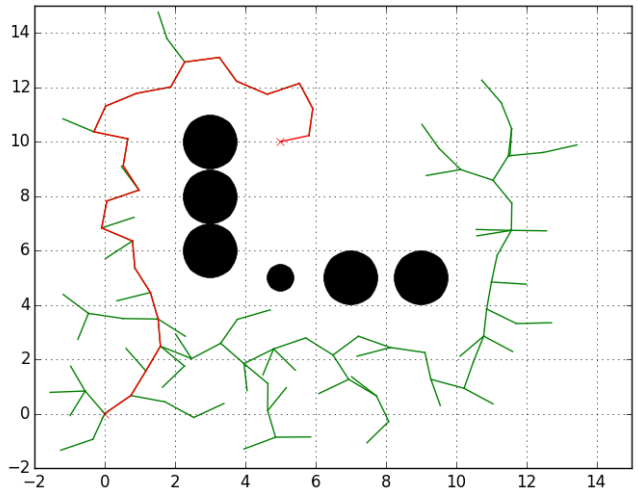
SLAM+ kept precision and scale well.



Left: Cartographer map building process. The map cannot used for navigation. Right: SLAM+ whole map result.

RRT+: An Improved 3D Navigation





Source: https://myenigma.hatenablog.com/entry/2016/03/23/092002

Added Detection for floating PCDs on the path

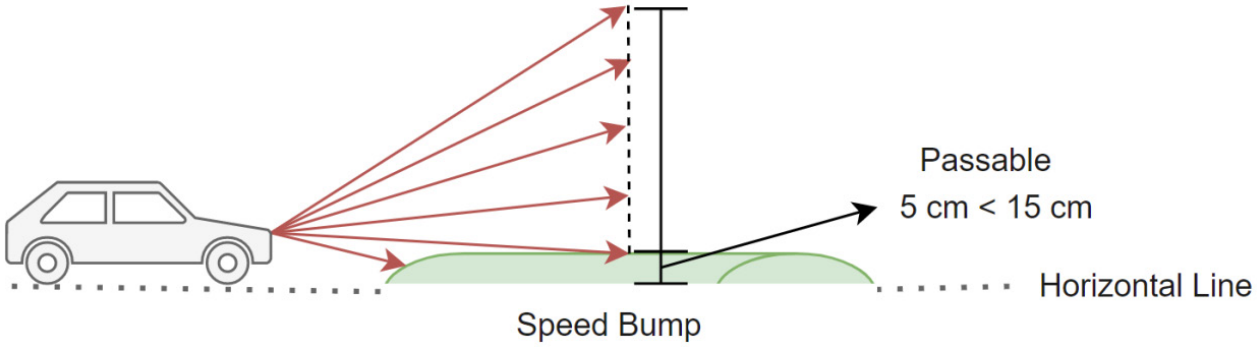
Rapidly-exploring Random Tree

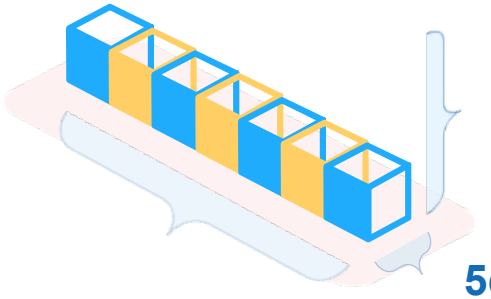
In RRT's path checking functions, they only check the new front points' X and Y positions. By adding the **Z-axis PCD-free check**, the robot can detect real-time dynamic obstacles.

Similarly, by checking the established rules, **Speed Bumps** and **Limited Height Gates** are recognized.

Speed Bump & Arch Gate Recognition

Speed Bump Recognition



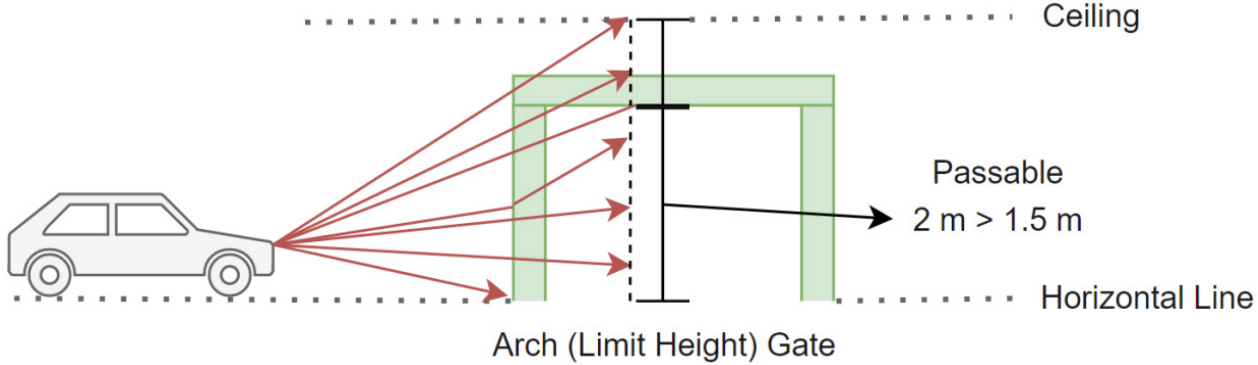


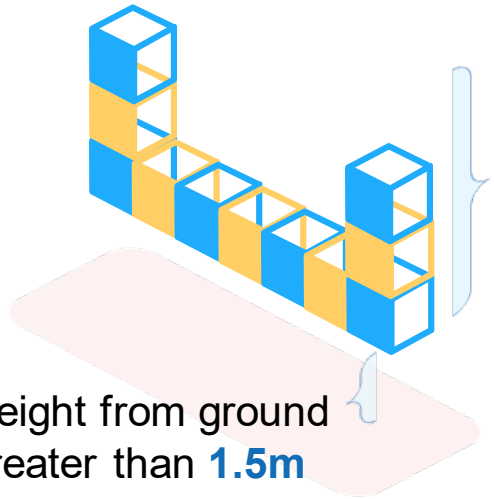
At most **15cm** height

At least **7 cubes** in a row

5cm cube in Gazebo

Arch Gate Recognition





Don't care about height from top

Height from ground greater than **1.5m**

03

System Architecture

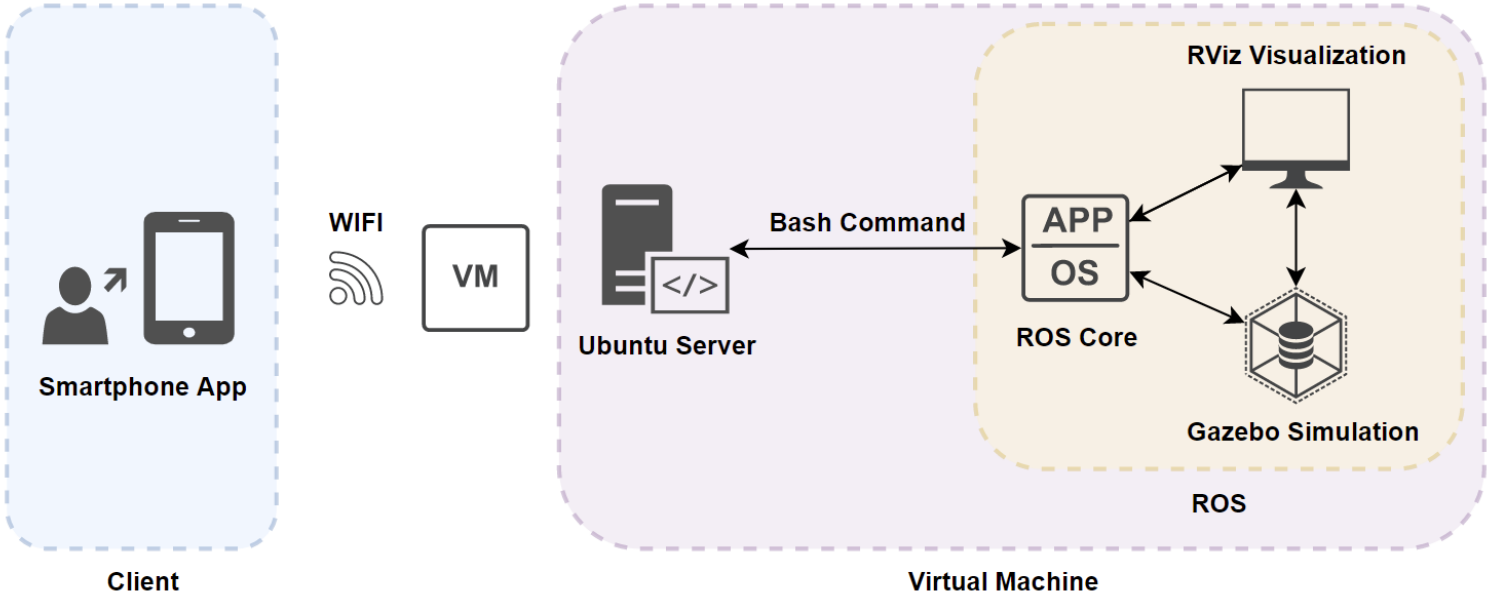
Architecture; Gazebo Setup;
Simulations and Octomap; Protocols; Server; App.

Client-Server-Vehicle (ROS) Architecture

Client

- Smartphone Android App through which data is sent and received.

- **Control**
- **Visualization**



Simulation

- Two scenarios in Gazebo, Low-price 3D LiDAR simulation

- **Vehicle Simulation**
- **LiDAR Verification**

Server

- Ubuntu Server Written in Kotlin to execute commands from cellphone and send data.

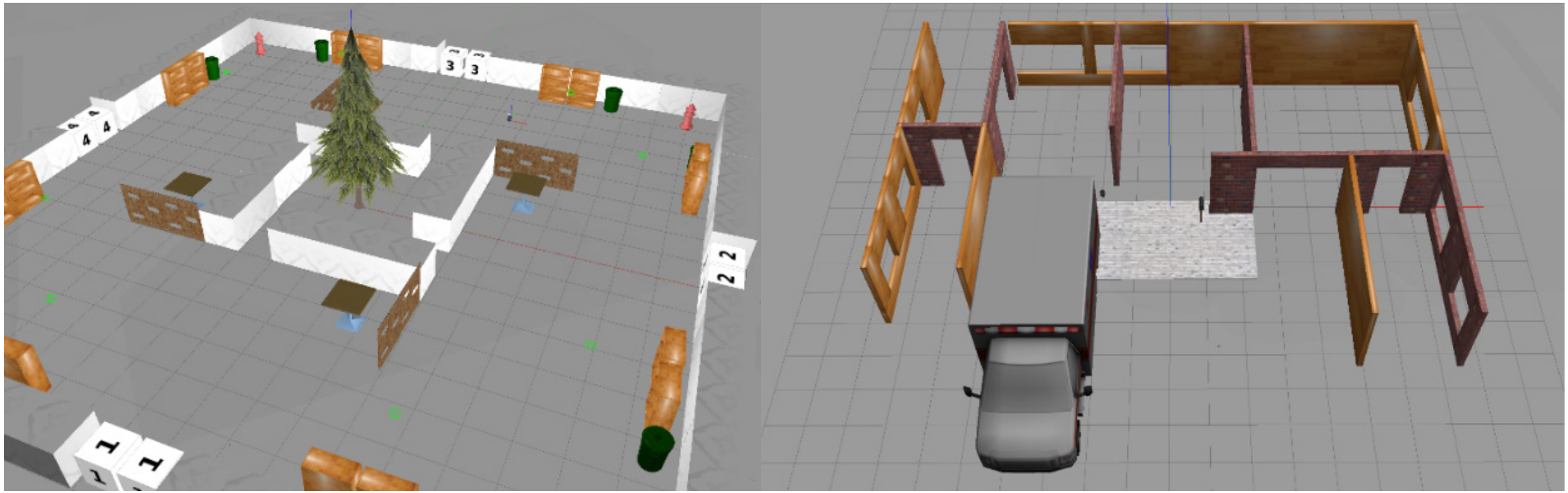
- **Connection**
- **Data Resolving**

Visualization

- Octomap Visualization of Point Cloud Data, Path and Obstacles Display

- **Octomap View**
- **Information View**

ROS – Gazebo Setup



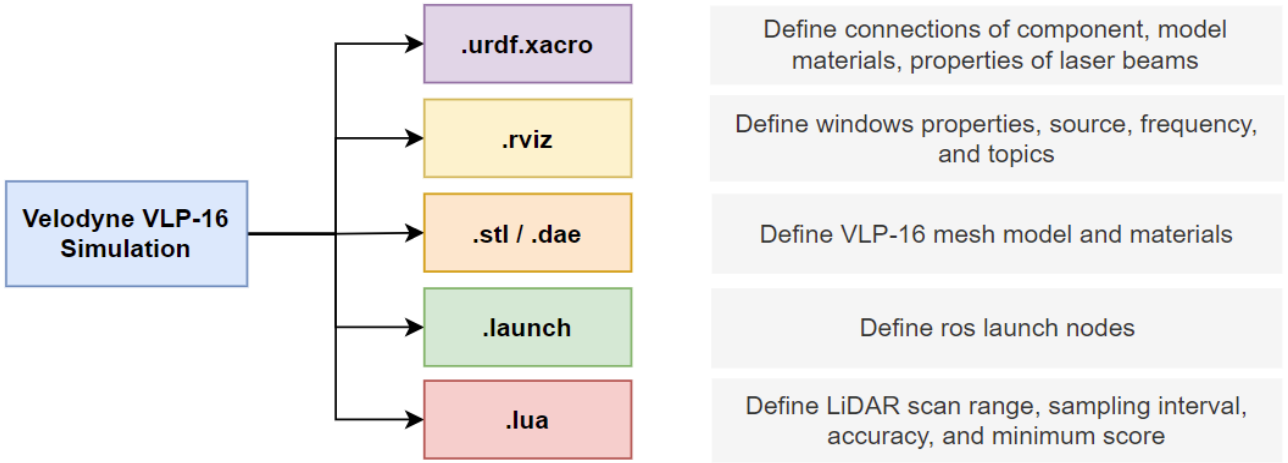
Real-time Obstacle Detection

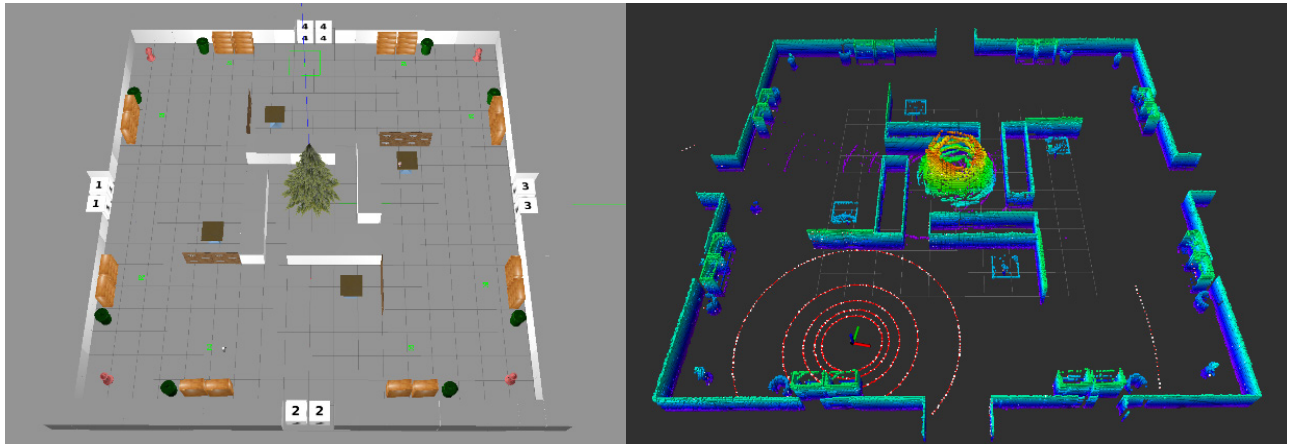
3D Dynamic Path Planning

Speed Bumps & Arch Gates Recognition

ROS – LiDAR Simulation & Octomap

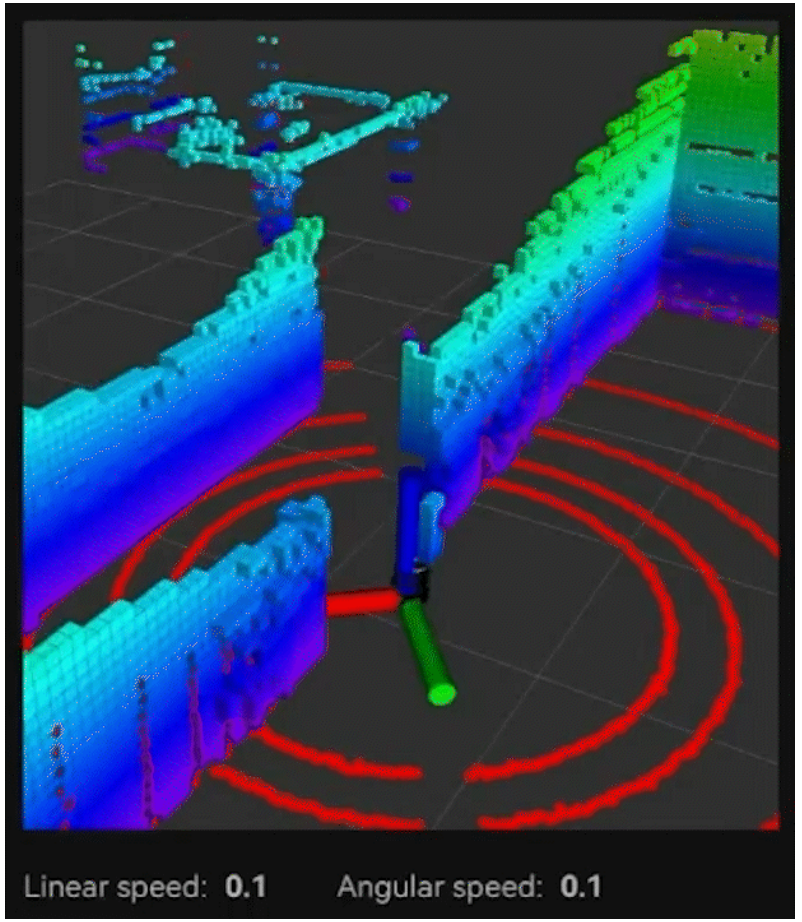
Velodyne LiDAR Simulation





Left: Real-world scene. Right: Map building result.

Result Visualization (Octomap)



Middleware – Server & Protocols

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Fix Instruction

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Data Instruction

n	[	5	m	...

Image & Video Instruction

Inst.	E.g.	Sender	Type	Data	Explanations
X***	x16490 8728…	Client	Test delay	Standard timestamp (longlong)	Test the two-way connection delay
C000	c000	Client	Start core	NAN	Start Gazebo and RViz simulations
P***	pae:[se !45a…	Server	Preview	Image (bitmap)	Send screenshot of image in bit streams
T***	t22$7	Server	Robot info	Linear $ Angular velocity (int$int)	Send current linear and angular velocity
.....					

Instruction & Bash Mapping

Inst.	Bash Command	Explanation

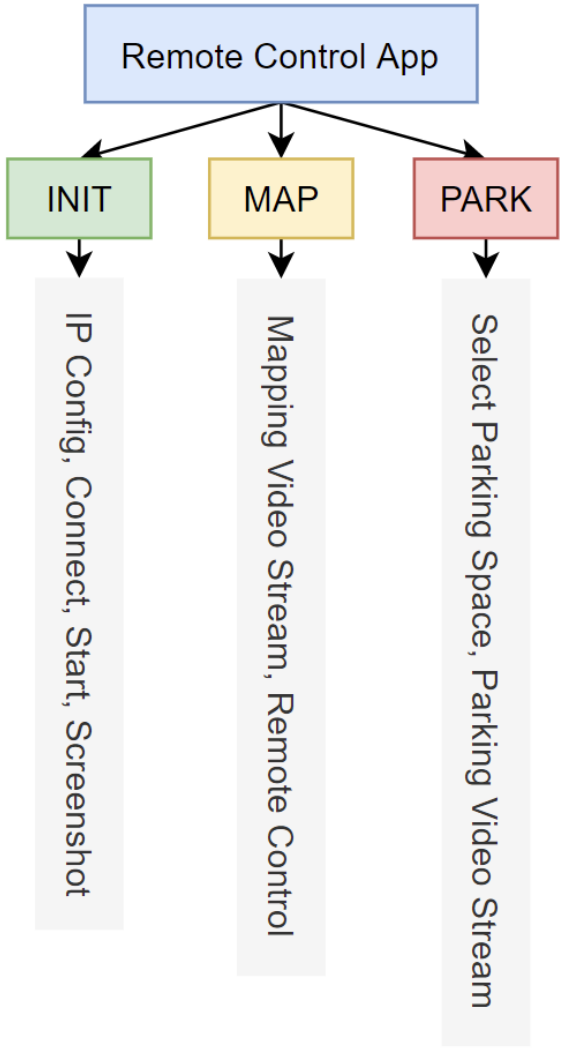
C000	`#!/usr/bin/env bash # omitted below`
	`Source ~/velodyne_ws/devel/setup.bash`
	`roslaunch velodyne_slam_simulation gazebo_turtlebot3.launch`
		Start Gazebo and RViz

P000	`wmctrl -a Gazebo`
	`scrot -b -z -o -q 75 'gazebo_rviz_preview.jpg'`
	`mogrify -resize 50% gazebo_rviz_preview.jpg`
		Take screenshots or video

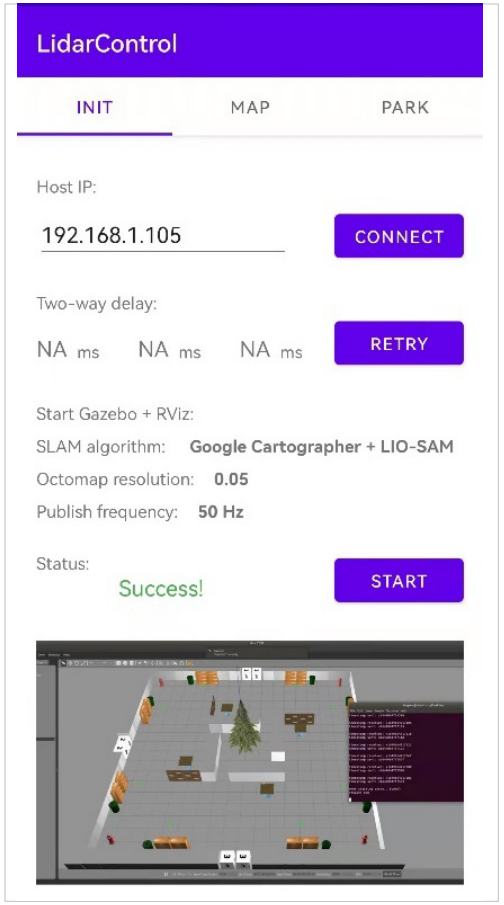
T*	`source ~/.profile`
	`target_term -run 1 roslaunch turtlebot3_teleop turtlebot3_teleop_key.launch`
	`target_term -run 1 $1`
		Input control instructions in specific command line

.....		

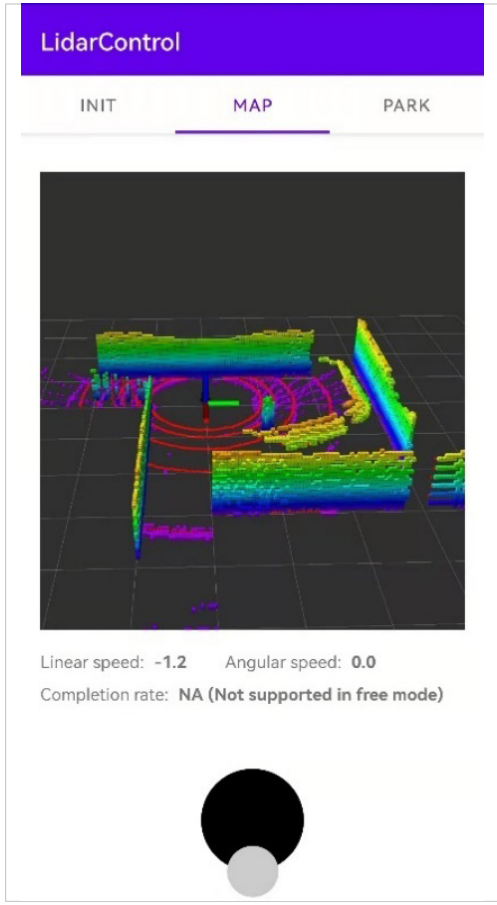
Client – Android App Design



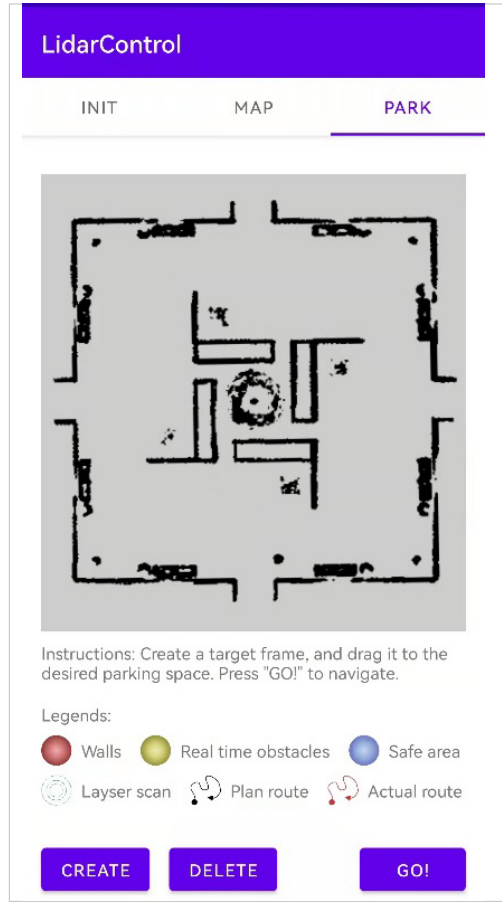
Initial Page



Mapping Page



Parking Page



04

Result Conclusion

Requirements;

Scenario 1: Outdoor Parking Lot; Scenario 2; Conclusion

Prerequisites & Dependencies

Software Versions

Item	Platform / Software	Version
Virtual Machine	VMware® Workstation 16 Pro	16.2.2 build-19200509
Virtual Computer	Ubuntu	18.04.6 LTS
	ROS	Melodic 1.15.8

Hardware Properties

Device	Hardware	Specification
Host Computer	CPU: Intel® Core™ i7-11800H	Cores: 8, Processors: 16
	RAM: Ramaxel Technology 32GB	Type: DDR4, 3200MHz
	Graphics Card: RTX 3080 Laptop	Video Memory: 16GB

Ubuntu Dependencies

Core (up to date version):

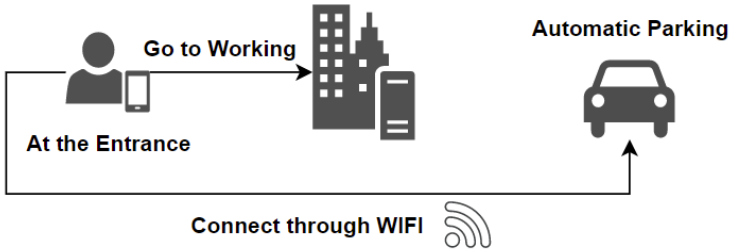
- ros-melodic-desktop-full
- gazebo
- ros-melodic-gazebo-ros-pkgs
- ros-melodic-navigation
- cartographer
- libgtsam-dev
- kotlin

External Tool:

- wmctrl
- scrot
- mogrify
- xdotool

Scenario 1: Outdoor Parking Lot

Outdoor scenario

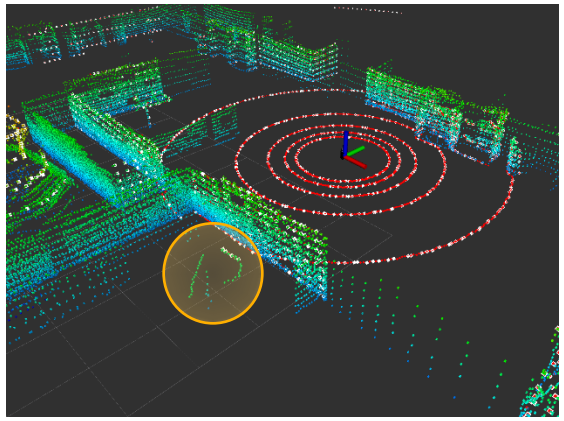


Difficulties

- A tree with complex details
  -> Map Building
- Narrow and dense paths
  -> Navi Planner Performance
- Small obstacles, e.g., tables, fenders, fire hydrants, trash cans
  -> Obstacles Avoidance

Scenario 1: Outdoor Parking Lot

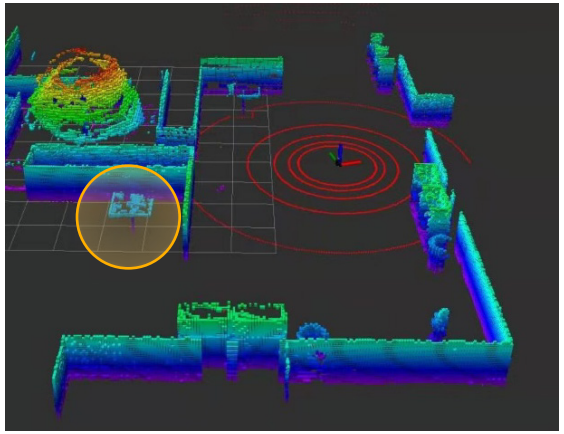
Visualization of Mapping and Navigation



Cartographer

Poor Table Recognition

The walls are sparse, and misaligned. The OGM map generated by map building result cannot be used to navigation.

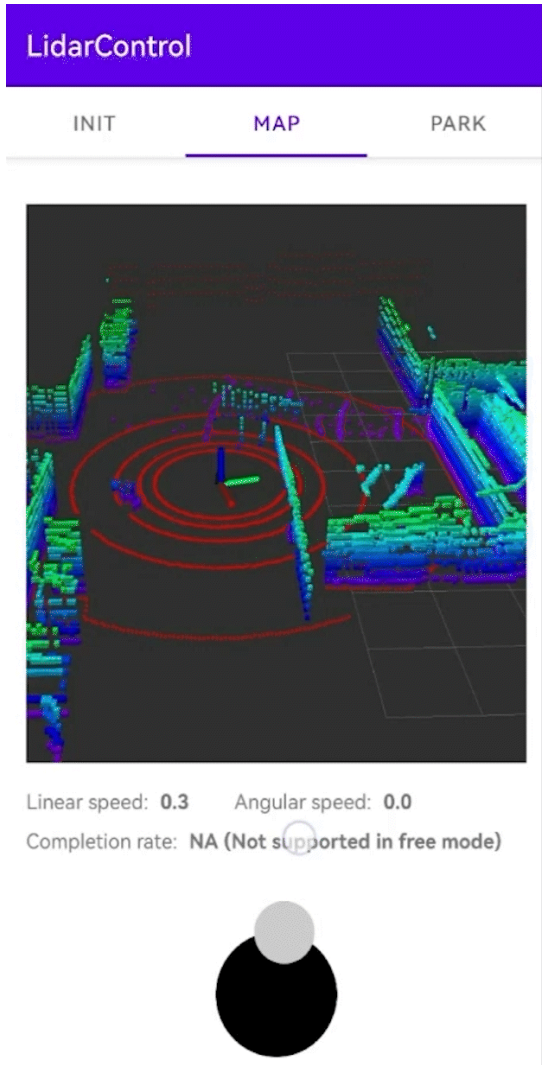


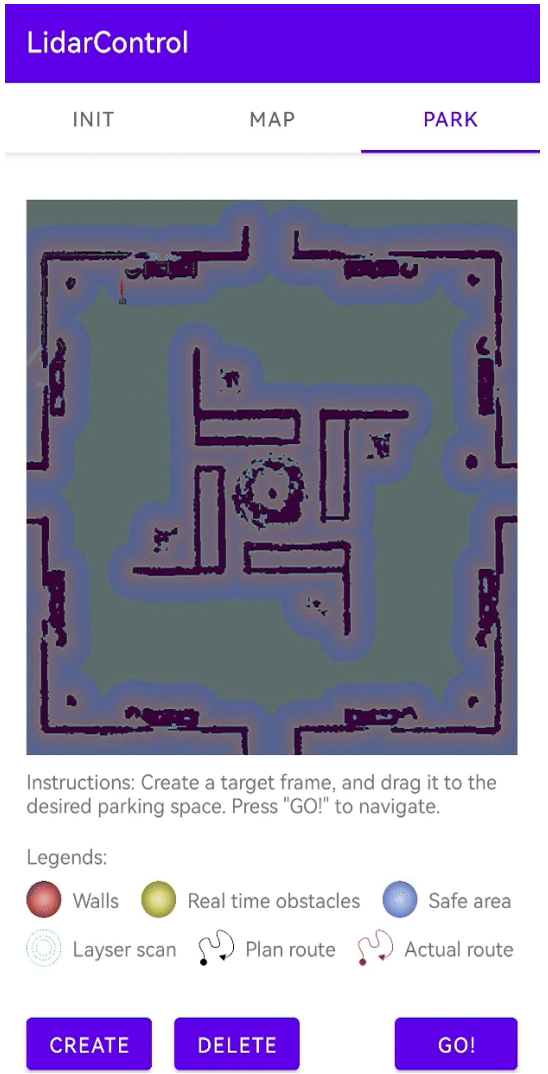
SLAM+

Precise Object Detection

The shape of tables are well restored. All walls and other obstacles have dense point cloud data. The whole result is clean and fine.

Top: Cartographer, Bottom: SLAM+

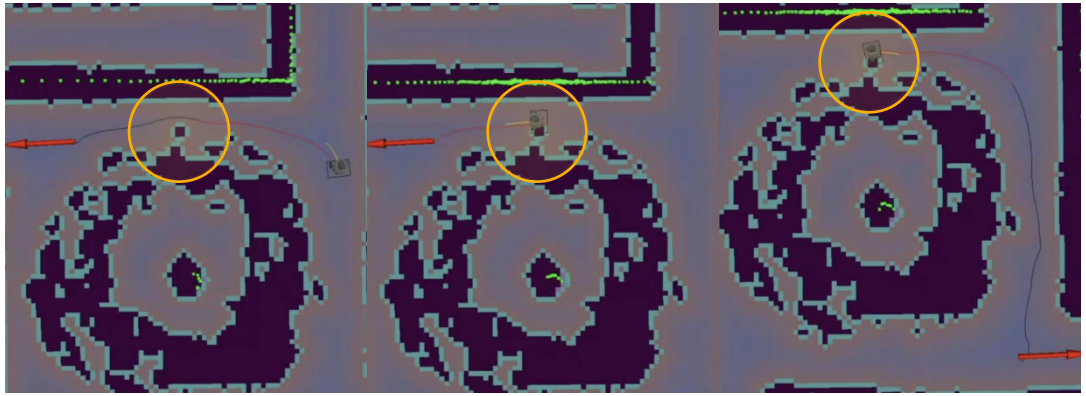




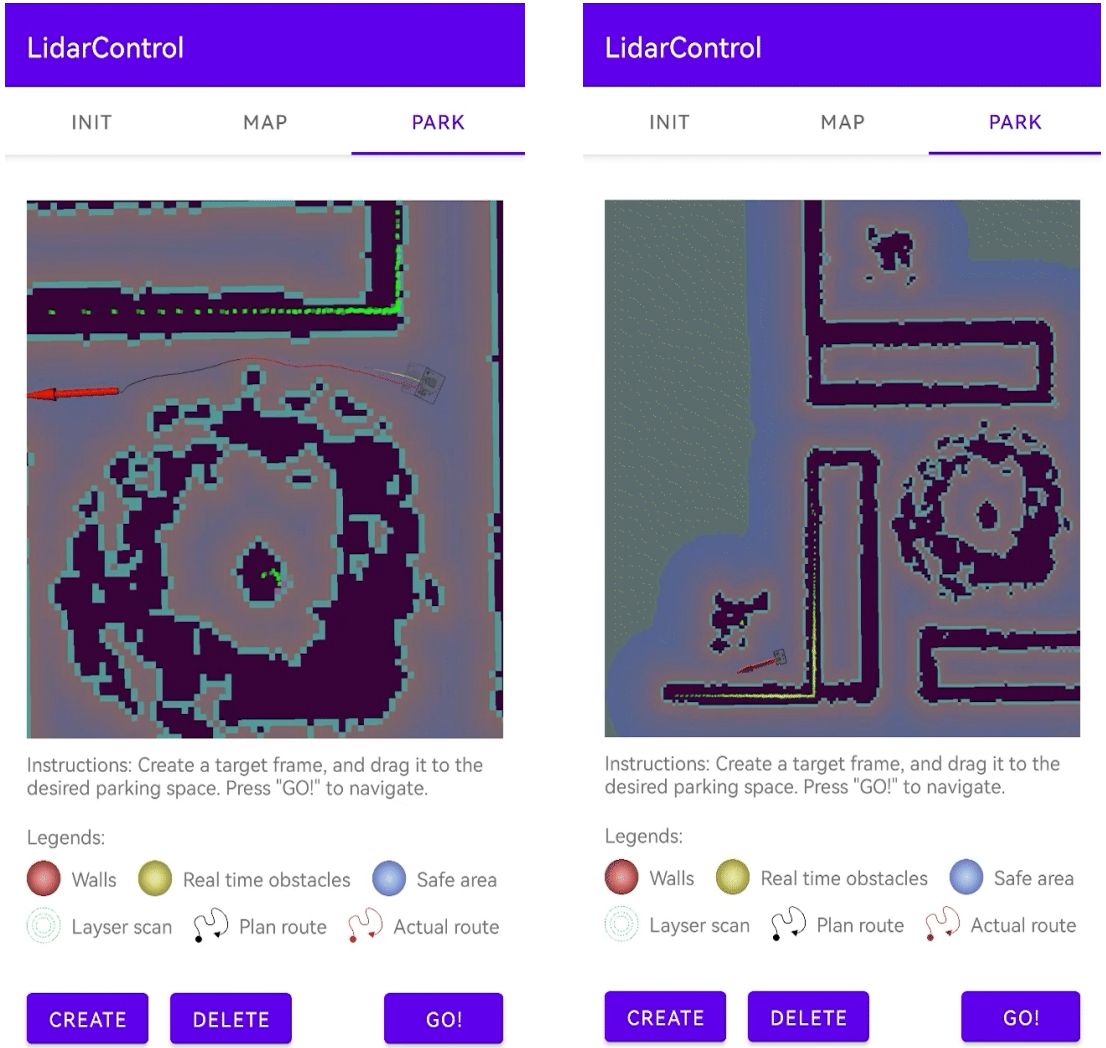
Left: Mapping, Right: Navigation

Scenario 1: Outdoor Parking Lot

Real-time Dynamic Planning

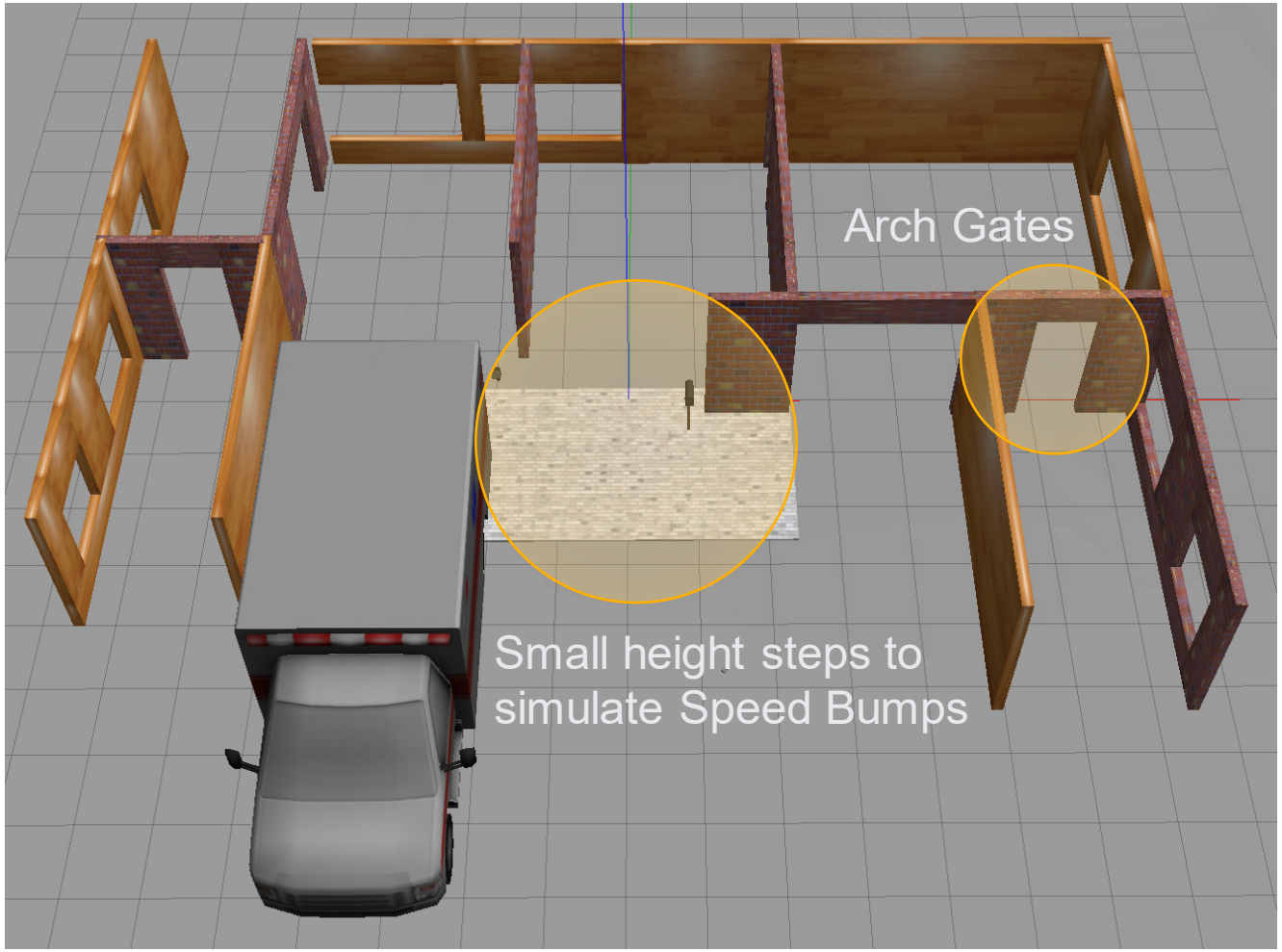


Top: Real-time object detection, Bottom: Dynamic planning

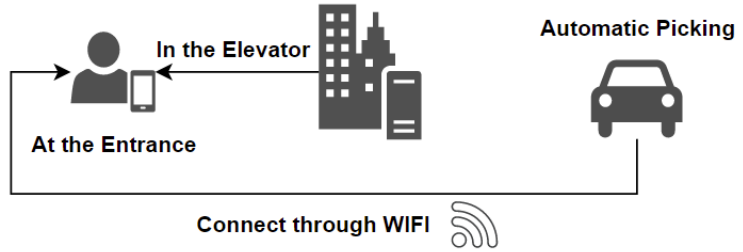


Left & Right: Dynamic planning preview

Scenario 2: Indoor Parking Lot



Indoor scenario

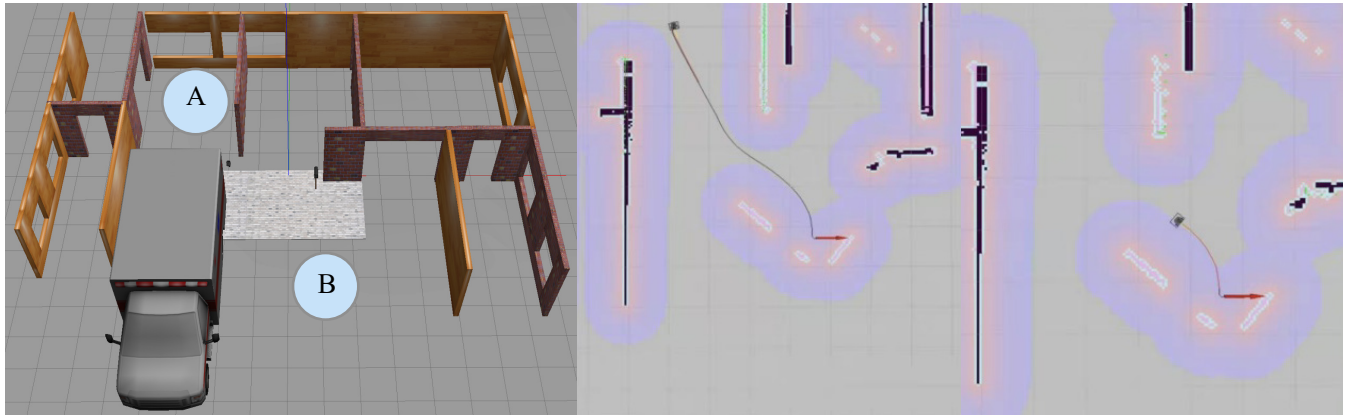


Difficulties

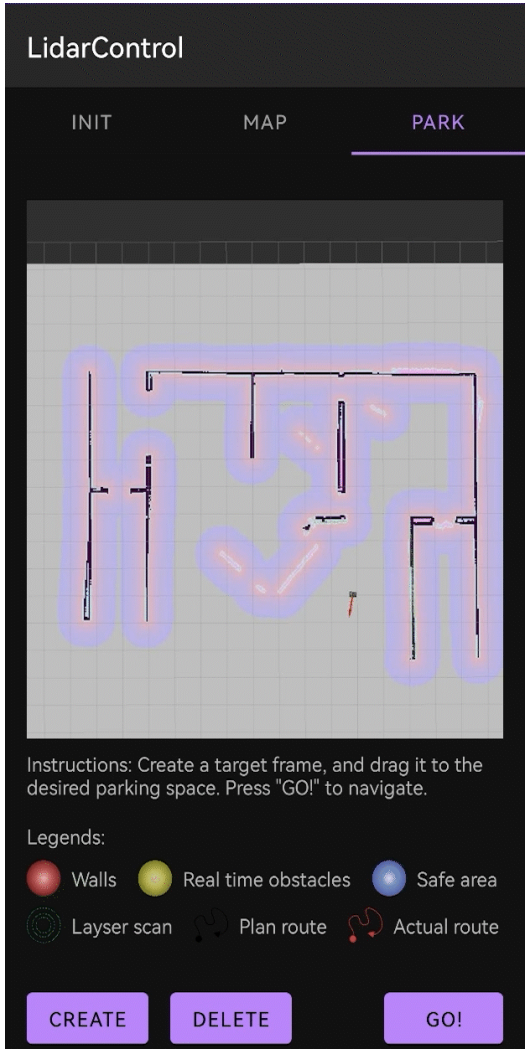
- Multiple paths
  -> Optimal Path Test
- Speed Bumps (white steps)
  -> Speed Bumps Passable
- Limited-height Gates
  -> Arch Gates Passable &
  Hang-over Objects Detection

Scenario 2: Indoor Parking Lot

Speed Bumps Passable

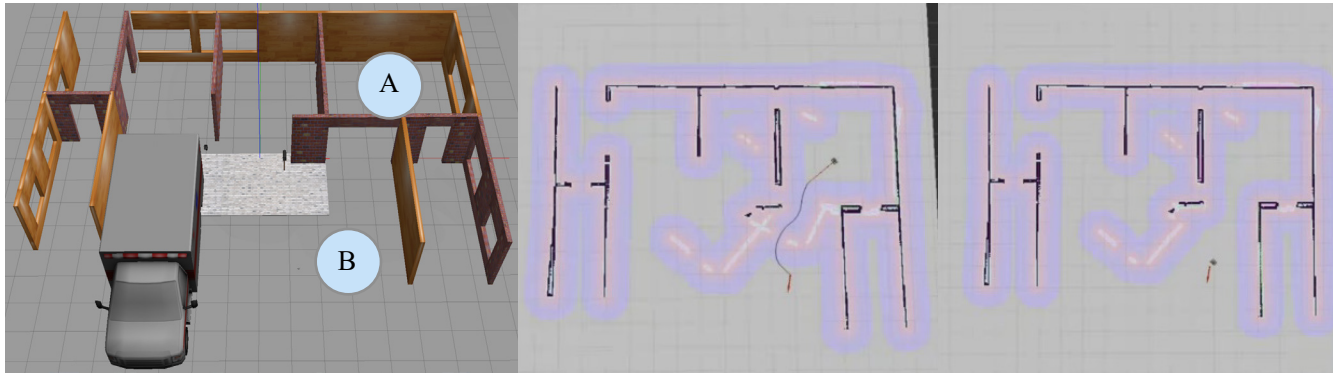


Top: Speed bumps simulation. Bottom: Speed bump passable test

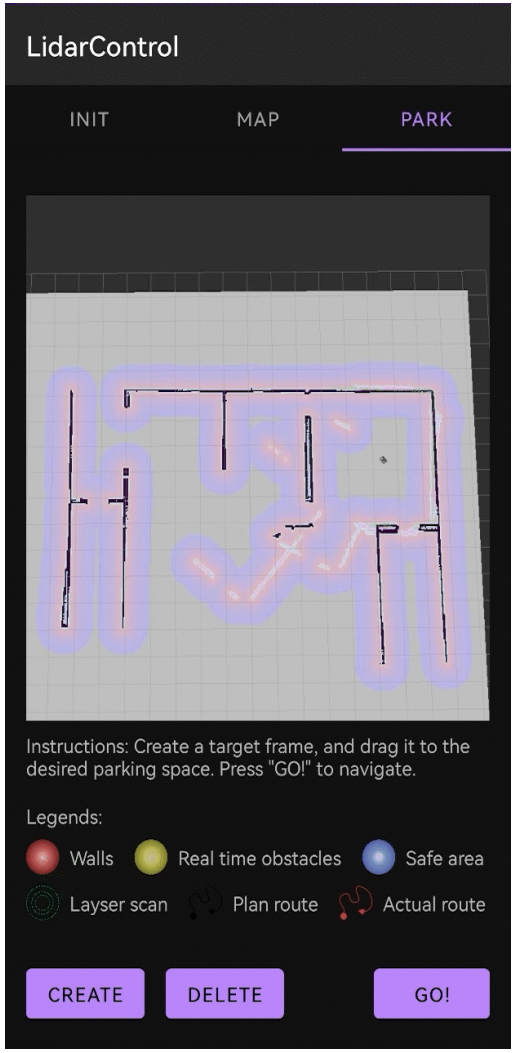


Scenario 2: Indoor Parking Lot

Limited Height Gates Passable



Top: Limited-height gates simulation. Bottom: Limited-height gates passable test



Conclusion – Analysis

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西南交通大学 – 利兹学院
SWJTU-LEEDS JOINT SCHOOL

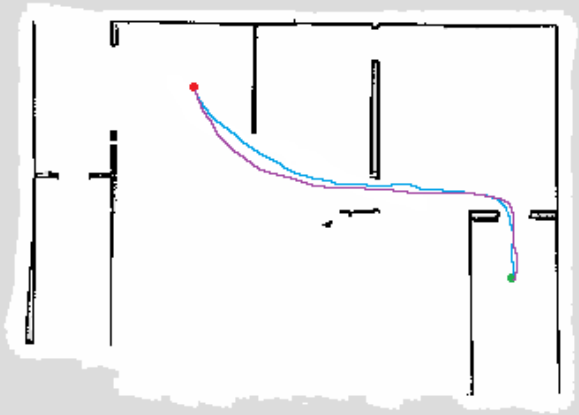
Mapping Time

Algorithm	Scenario 1: Outdoor (s)	Scenario 2: Indoor (s)
Cartographer	487	239
SLAM+	566	258

Navigation Performance

Algorithm	Simple Path Navi. Time	Complex Path Navi. Time	Far Dest. Navi. Time	Far Dest. Calc. Time	Dest. in Obstacles
Global (ROS build-in)	11.25	26.34	45.48	0.69	Report failure
Carrot	10.97	Failed	Failed	NAN	Approach point
DStar	26.77	Failed	Failed	NAN	Calculate, and report failure
RAStar	12.06	17.93	48.63	0.05	Report failure
RRT+	12.48	19.65	44.34	0.28	Trapped in loop

Path Comparison



Red Point: Start; Green Point: End; Blue Path: RRT+; Purple Path: ROS build-in.

Shorter and smoother path in complex environment

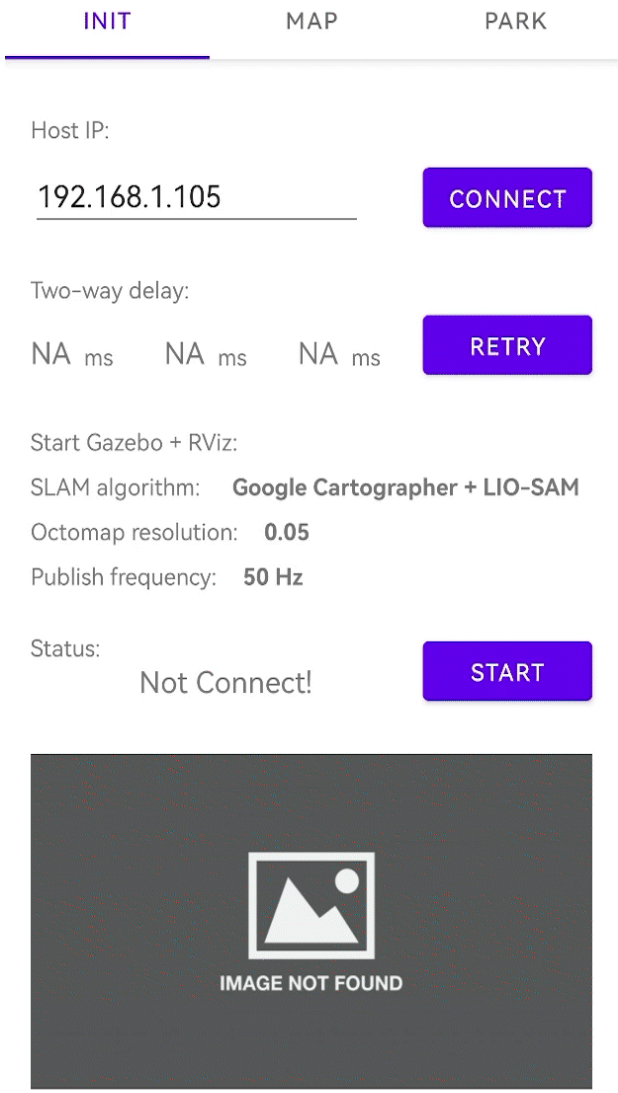
Conclusion & Future Work

My Work

- Scenarios built up, VLP-16 3D LiDAR simulation
- SLAM+: Improved 3D map building and visualization
- RRT+: Optimized 3D real-time dynamic navigation
- Ubuntu server, Android control application

Pros. & Cons.

- **Remote control and visualization via App**
- **Fine map building with inexpensive 3D LiDAR**
- **Real-time dynamic 3D navigation**
- **Not employed due to hardware shortage**
- **Low video streaming efficiency; limited LAN range.**



Thanks for Watching!

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ROS – Octomap Visualization


```
<node pkg="octomap_server" type="octomap_server_node" name="octomap_server">
   // Define the resolution of a cube (Velodyne point). Too high results in low speed.
   <param name="resolution" value="0.05" />
   // Frame defined in rviz file. Odom for 3D visualization and map for 2D.
   <param name="frame_id" type="string" value="odom" />
   // Define the maximum detection range of the sensor. See LiDAR manual.
   <param name="sensor_model/max_range" value="8.0" />
   // Does not show the ground.
   <param name="filter_ground" value="true" />
   // Cast point cloud data into Velodyne points
   <remap from="cloud_in" to="/velodyne_points" />
</node>
```

RRT – Height Judgement


```
// ObstacleFree returns 1:free space, -1:unkown (frontier region), and 0:obstacle
// Add support for 3d checking
Char checking = ObstacleFree(x_nearest, x_new, z_nearest, z_new, mapData);
    if (checking == -1) {
        // Obtain points from each frame
        exploration_goal.header.stamp = ros::Time(0);
        exploration_goal.header.frame_id = mapData.header.frame_id;
        exploration_goal.point.x = x_new[0];
        exploration_goal.point.y = x_new[1];
        // Original code: exploration_goal.point.z = 0, add z-level obstacles checking
        exploration_goal.point.z = z_new[0];
        p.x = x_new[0];
        p.y = x_new[1];
        p.z = z_new[0];
        points.points.push_back(p);
        pub.publish(points);
        // Each time recalculate the path
        targetspub.publish(exploration_goal);
        points.points.clear();
        V.clear();
        ......
        x_new[0] = transform.getOrigin().x();
        x_new[1] = transform.getOrigin().y();
        z_new[0] = transform.getOrigin().z();
        V.push_back(x_new);
        line.points.clear();
    } else if (checking == 1){
      V.push_back(x_new);
      p.x = x_new[0];
      p.y = x_new[1];
      p.z = y_new[0]
      line.points.push_back(p);
      p.x = x_nearest[0];
      p.y = x_nearest[1];
      p.z = z_nearest[0];
      line.points.push_back(p);
    }
pub.publish(line);
```

ROS – Launch File


```
<launch>
  <!-- Arguments -->
  <arg name="model" default="$(env TURTLEBOT3_MODEL)" doc="model type [burger, waffle,
waffle_pi]"/>
  <arg name="map_file" default="$HOME/map.yaml"/>
  <arg name="open_rviz" default="true"/>
  <arg name="move_forward_only" default="false"/>

  <!-- Turtlebot3 -->
  <include file="$(find turtlebot3_bringup)/launch/turtlebot3_remote.launch">
    <arg name="model" value="$(arg model)" />
  </include>

  <!-- Map server -->
  <node pkg="map_server" name="map_server" type="map_server" args="$(arg map_file)"/>
```

ROS – Launch File Continued


```
  <!-- AMCL -->
  <include file="$(find turtlebot3_navigation)/launch/amcl.launch"/>

  <!-- move_base -->
  <include file="$(find turtlebot3_navigation)/launch/move_base.launch">
    <arg name="model" value="$(arg model)" />
    <arg name="move_forward_only" value="$(arg move_forward_only)"/>
  </include>

  <!-- rviz -->
  <group if="$(arg open_rviz)">
    <node pkg="rviz" type="rviz" name="rviz3" required="true"
          args="-d $(find turtlebot3_navigation)/rviz/turtlebot3_navigation.rviz"/>
  </group>
</launch>
```

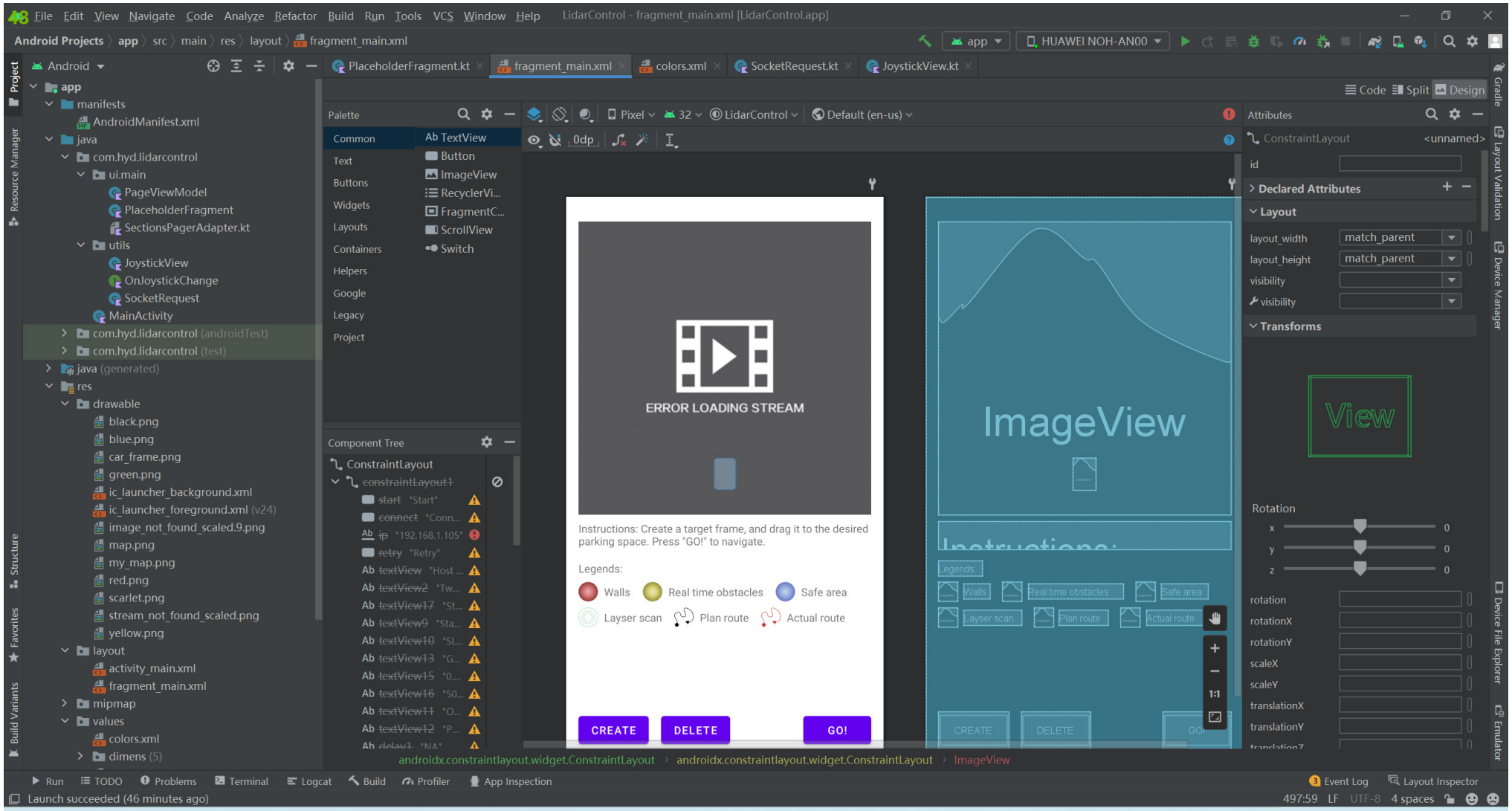
Middleware – Web Socket


```
// From main()
Thread { server1() }.start()
......
fun server1() {
   // Accept the connection on port 7230
   val server = ServerSocket(7230)
   val client = server.accept()
   while (true) {
      val output = PrintWriter(client.getOutputStream(), true)
      val input = BufferedReader(InputStreamReader(client.inputStream))
      val inputText = input.readLine()
      if (inputText == null || inputText == "") continue
      // Decode instructions by the first character
      when (inputText[0]) {
          'x' -> { ..... }
          'c' -> { ..... }
          ......
```

Middleware – Web Socket Continued


```
private fun socketConnectThread() {
    object : Thread() {
      override fun run() {
        try {
        // Obtain the IP address from user input, and specify the port
        listerSocket = Socket(ip.text.toString(), uPORT1)
        val output = PrintWriter(listerSocket!!.getOutputStream(), true)
        val input = BufferedReader(InputStreamReader(listerSocket!!.inputStream))
        // Keep sending data if the connection is not closed, and the data is not null
        while (!closeSocket) {
          if (textBufferWrite1 != "") {
            when (streamType) {
              // socket connection test
              0 -> {
                try {
                  // Read data from the server
                  textBufferRead1 = input.readLine()
                  if (textBufferRead1 != "") {
                    // If read non-null data, then decode data
                    decodeMessage(textBufferRead1)
                  }
                } catch (e: Exception) { ..... }
              }
                // start cores, and streaming preview images
                1, 2 -> { ..... }
                else -> { ..... }
                .....
```

Client – Android App



Client – Android App