Real-Time Localization and Mapping in Mobile Robots

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GEAR Guided Engineering Apprenticeship in Research

INTRODUCTION

- The purpose of the project is to implement real-time simultaneous localization and mapping algorithms in Turtlebots to demonstrate 2-D mapping capabilities

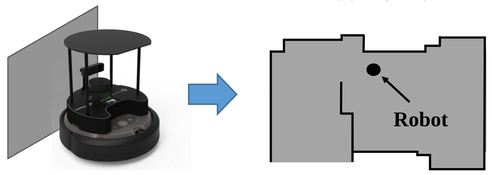


Figure 1: 2D Map Model of MURO Lab from top-down

Our Mobile Robot: TurtleBot 4

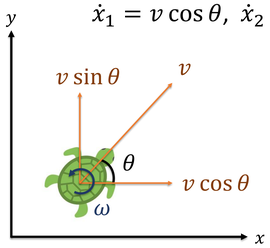
- The TurtleBot 4 is a mobile educational/research robot with advanced computing power, equipped with a multitude of sensors for data collection and modern mobility/control applications
- Operates wirelessly through network connection with a personal computer using ROS and Linux

Figure 2: Image of TurtleBot 4 with visible iRobot® Create® 3 mobile base, Raspberry Pi 4 display using ROS 2, 2D LiDAR, and OAK-D stereo camera

Unicycle Model Dynamics

- Movement of the TurtleBot is modelled through unicycle dynamics, a path-dependent state system
- Given a 2D plane with x-y coordinates, the equations of motion are given by:

$$\dot{x}_1 = v\cos\theta,\ \dot{x}_2 = v\sin\theta,\ \dot{\theta} = \omega$$



Heading: (x, y, θ)
v – linear input velocity
ω – angular input velocity

Figure 3: Model of unicycle dynamics on a 2D x-y plane

Controls

- TurtleBot 4 controls used in the project was a simple open-loop control system
- Wireless control via ROS Keyboard Teleoperation package, displayed on Linux command-line interface

u i o
j k l
m , .

Figure 4: Keyboard keys for moving around the TurtleBot

METHODOLOGY

Light Detection and Ranging (LiDAR) Data

- LiDAR operates on time of flight (TOF) principle
- LiDAR message obtained via /scan topic:
  - I. Ranges [m]: [0.15 (min) – 12 (max)]
  - II. Angles [rad]: angle_increment (0.5 degrees)
  - III. Timestamp and Header
- Data point of observed obstacle calculated by:

$$x = d\cos\theta \qquad y = d\sin\theta \qquad z = 1$$

- Data points are in LiDAR (sensor) frame and need to be transformed in order to obtain a static map

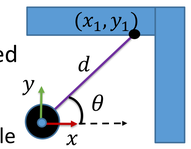


Figure 5: LiDAR model hitting an obstacle

Iterative Closest Point (ICP) Correction

- Iterative Closest Point (ICP) Algorithm
  - I. Compares current dataset to previous dataset

Association: point-to-point correspondence

Transformation: $\tilde{T} = \underset{T}{argmin}\frac{1}{N}\sum_i^N \|\boldsymbol{t_i} - \boldsymbol{Ts_i}\|^2$

Error Evaluation: $\boldsymbol{e} = \frac{1}{N}\sum_i^N \|\boldsymbol{t_i} - \boldsymbol{Rs_i} + \boldsymbol{t}\|^2$

N – # of points **R** – rotation matrix **t** – translation
$\boldsymbol{t_i}$ – target points $\boldsymbol{s_i}$ – source points

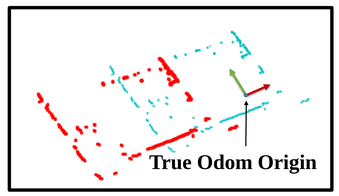


Figure 7: Comparison of transformed data without ICP (red) versus with ICP (blue)

Odometry-Based Localization

- Odometry message obtained via /odom topic:
  - I. Position [m]
  - II. Orientation [quaternions]
- Estimation of robot's change in position and orientation over time based on motion sensors

$$\vec{\boldsymbol{p}}_{\boldsymbol{odom}} = \boldsymbol{R_z} \times \vec{\boldsymbol{p}}_{\boldsymbol{sensor}} + \boldsymbol{d}$$

- Wheel encoder induced drift

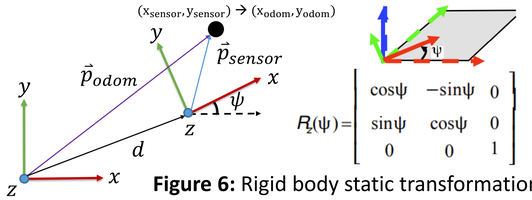


Figure 6: Rigid body static transformation

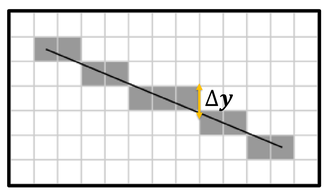
Occupancy Grid Mapping

- Discretization of map space into elements with calculated occupancy probability estimation

$$\boldsymbol{p(m_i|\, z, x) \rightarrow 0: free} \quad \boldsymbol{p(m_i|\, z, x) \rightarrow 0.5: unknown}$$
$$\boldsymbol{p(m_i|\, z, x) \rightarrow 1: occupied}$$

p – occupancy probability $\boldsymbol{m_i}$ – occupancy cell
z – sensor measurements **x** – position of robot

- Bresenham's Line Drawing Algorithm
  - I. Declares free space on occupancy grid map



Decision parameter: $\boldsymbol{\phi_{k+1} = \phi_k + 2\Delta y}$

Figure 8: Bresenham's line algorithm for LiDAR data

IMPLEMENTATION

- Iterative data transfer from TurtleBot to written mapping algorithm via ROS publishers and subscribers

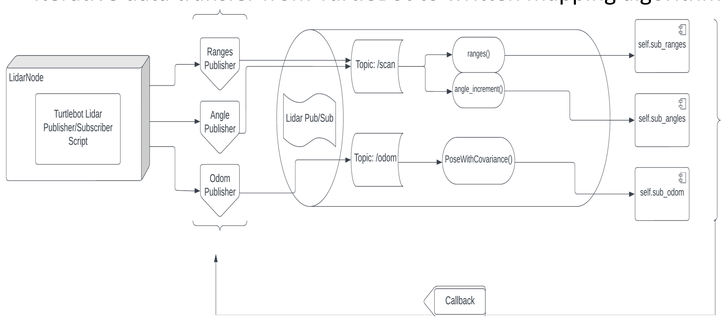


Figure 9: Flowchart documenting real-time mapping procedure

Publisher: Sends data from node to topic
- I. TurtleBot (topic: /odom)
- II. LiDAR (topic: /scan)

Subscriber: Receives data from a topic
- I. Written Mapping Algorithm

RESULTS

- Final maps obtained using mapping algorithm

Figure 10: Raw LiDAR scan data map of MURO Lab

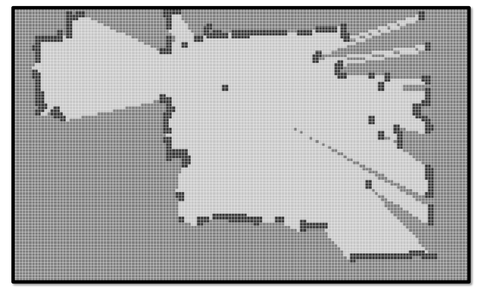


Figure 11: Occupancy Grid Map of MURO Lab

CONCLUSIONS

- Wrote algorithm that reads TurtleBot 4 sensor data and creates a resulting map of environment
- Integrated ROS topic publisher and subscriber to perform localization and mapping in real-time
- Future Work:
  - I. Extend to Multi-Robotic Network
  - II. Extend to Quadcopter collaboration
  - III. Incorporate MarvelMind Beacon localization

REFERENCES

[1] A. Kramer (2019). LIDAR Odometry with ICP. Bot Blog. http://andrewjkramer.net/lidar-odometry-with-icp/

[2] A. Sakai, D. Ingram, J. Dinius, K. Chawla, A. Raffin, A. Paques (2018). PythonRobotics: a Python code collection of robotics algorithms. https://doi.org/10.48550/arXiv.1808.10703

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