Perception-Based Adaptive Speed Control Framework for Autonomous Mobile Robots

Akbar Taufiqurrahman, Soo Young Shin*

akbartaufiq@kumoh.ac.kr, wdragon@kumoh.ac.kr*

Department of IT Convergence Engineering
Kumoh National Institute of Technology

Abstract

This paper presents a perception-based adaptive speed control framework that enables autonomous mobile robots to adjust their speed based on surrounding environmental complexity, without relying on explicit obstacle semantics or prior maps. Environmental complexity is measured using an Environmental Complexity Score (ECS), computed directly from raw range-based sensor data by evaluating local range variance and measurement density. Based on the ESC, the robot's movement speed is adaptively regulated, resulting in slower speeds in cluttered and unstructured environments, and faster speeds in more structured environments. The proposed framework attempts to mimic how humans behave in unknown environments, namely by adjusting their movement speed to increase caution in making decisions. This method is expected to be applicable to a wide range of autonomous mobile robotic platforms using range-based sensor as the perception system.

Keywords: autonomous mobile robot, adaptive speed control, environmental complexity, unknown environments, range-based sensing.

I. Introduction

Autonomous mobile robots are increasingly deployed in environments with limited or no prior knowledge, such as search and rescue (SAR), disaster response, and emergency inspection scenarios. In such scenarios, the environment is often unstructured, cluttered, or unpredictable [1]. These conditions could increase the complexity of the robot's navigation system and increase the risk of mission failure due to collisions between the robot and obstacles.

Many existing navigation systems regulate robot speed based on explicit obstacle detection, semantic understanding, or predefined environmental assumptions [2]. While such approaches perform well in structured settings, they are often less effective in unknown environments with irregular geometry and unpredictable spatial complexity. In these situations, maintaining aggressive robot speed can increase navigation risk and reduce overall operational robustness.

Inspired by the way humans naturally slow down when entering uncertain or cluttered spaces, this paper proposes a perception-based speed adaptation strategy that adjusts robot speed based on estimated environmental complexity. The estimation is calculated directly from raw range-based sensor data and the speed is accordingly adapted. This method is expected to increases the robustness of autonomous mobile robots navigation system and introduces cautious behavior in unknown environments.

II. Methodology

This chapter discusses how perception data from range-based sensors is used to estimate experimental complexity in autonomous mobile robot operation for robot speed adjustment. It also discusses speed control strategies for achieving smooth speed transitions.

A. Environmental Complexity Estimation

Environmental complexity is estimated directly from raw range-based sensor measurements, such as LiDAR scans. For each incoming scan, the sensing space is divided into fixed windows, in which the local statistics are computed. The first indicator is the range variance, which reflects the consistency of distance measurements within a local region:

$$\sigma_r^2 = \frac{1}{N}\sum_{i=1}^{N}(r_i - \bar{r})^2,$$

where r_i denotes the measured range of the i-th beam, $\bar{r}$ is the mean range within the window, and N is the number of valid measurements. In structured environments such as corridors or open passages, range measurements tend to be smooth and consistent, resulting in low variance. Whereas cluttered or irregular environments produce larger fluctuations in range, leading to higher variance.

To obtain the spatial complexity of the environment, measurement density calculations are utilized. Measurement density is defined as,

$$\rho = \frac{N_{\text{valid}}}{N_{\text{expected}}},$$

where N_{valid} is the number of valid range returns and N_{expected} is the expected number of measurements given the sensor resolution. Higher density values represent the level of environmental clutter, while lower values indicate more open spaces.

B. Environmental Complexity Score

The range variance and measurement density are normalized and combined into a single Environmental Complexity Score (ECS):

$$ECS = w_1 f(\sigma_r^2) + w_2 f(\rho),$$

where w_1 and w_2 are weighting coefficients satisfying $w_1 + w_2 = 1$, and $f(\cdot)$ denotes a normalization function mapping each indicator to the range $[0, 1]$. A higher ECS value indicates a more complex and unstructured environment.

C. Adaptive Speed Control Strategy

The estimated ECS is used to regulate the vehicle's speed through a simple adaptive control law:

$$v = clip(v_{\max}(1 - ECS), v_{\min}, v_{\max}),$$

where $v_{\max}$ and $v_{\min}$ denote the maximum and minimum allowable speeds, respectively.

III. Conclusion

This paper presented a perception-based adaptive speed control framework for autonomous mobile robots operating in unknown environments. By regulating robot speed based on environmental complexity inferred from raw range-based sensor measurements, the proposed approach avoids reliance on explicit obstacle semantics or prior maps. The use of range variance and measurement density enables robots to behave more cautiously in complex environments while maintaining efficiency in simpler regions. Future work will focus on experimental validation and the integration of the proposed framework with higher-level navigation and planning systems.

ACKNOWLEDGMENT

"This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS-2025-00553810, 50%)."

"This research was supported by the MSIT (Ministry of Science and ICT), Korea under the ITRC (Information Technology Research Center) support program (IITP-2025-RS-2023-00259061, 50%) supervised by the IITP (Institute for Information & Communications Technology Planning & Evaluation)."

REFERENCES

[1] X. Zhang, J. Wang, Y. Fang, and J. Yuan, "Multilevel Humanlike Motion Planning for Mobile Robots in Complex Indoor Environments," IEEE Transactions on Automation Science and Engineering, vol. 16, no. 3, pp. 1244–1258, Jul. 2019, doi: https://doi.org/10.1109/tase.2018.2880245.

[2] X. Zhou, J. Zhu, H.-Y. Zhou, C. Xu, and F. Gao, "EGO-Swarm: A Fully Autonomous and Decentralized Quadrotor Swarm System in Cluttered Environments," May 2021, doi: https://doi.org/10.1109/icra48506.2021.9561902.