IMPLEMENTATION OF AN AUTONOMOUS WHEELCHAIR: MECHATRONIC DESIGN AND SLAM NAVIGATION

Chun-Ju Wu[1], Yu-Cheng Kuo[1,2], and Chung-Hsien Kuo[1,2]

[1]Department of Electrical Engineering,
National Taiwan University of Science and Technology, Taipei, Taiwan
[2]Center for Cyber-physical System Innovation,
National Taiwan University of Science and Technology, Taipei, Taiwan

ABSTRACT

This paper presents an autonomous robotic wheelchair navigation system (ARWNS). The proposed ARWNS provides the functions of indoor map construction, wheelchair localization, path planning, obstacle avoidance navigation. A front LiDar was utilized in this paper to create the indoor map, to localize the wheelchair itself, as well as to identify the front obstacles. Hector simultaneous localization and mapping (SLAM) open source codes of the Robot Operating System (ROS) were applied in this paper to realize a LiDar-based map construction and localization system. The rapidly-exploring random tree (RRT) approach was further applied in terms of the SLAM-based map information to dynamically plan a feasible path to reach the destination. Furthermore, the autonomous navigation system was proposed by utilizing artificial potential field (APF) approach so that the robotic wheelchair is capable of following the planned path to reach the destination without any collision with obstacle. Finally, a lab-made robotic wheelchair controller was implemented based on the aforementioned approaches for experimental validation in terms of different obstacle arrangements.

KEYWORDS

Mobile robot navigation, Simultaneous Localization and Mapping, Rapidly-exploring Random Tree, Artificial Potential Field

1. INTRODUCTION

According to a study of wheelchair users in the United States, as many as 40% of users are unable to effectively control the wheelchair due to symptoms such as cognitive impairment, visual impairment, and spasticity [1]. Robotic wheelchair is an extension of autonomous mobile robots that provides an autonomous driving paradigm for handicapped wheelchair users. Many successful robotic wheelchair projects provided promising solutions to improve the quality of life (QoL) and convenience of maneuverability of wheelchairs.

2. RELATED WORK

Wang et al. [2] presented the development of an autonomous robotic wheelchair navigation system in the environment with slope way. An optimal trajectory considering searching efficiency was proposed via adopting an adaptive weighting Gaussian Mixture Model (GMM) based sampling strategy. In addition, Wang et al. [3] presented a self-supervised drivable area and road anomaly segmentation approach robotic wheelchairs by utilizing the RGB-D camera data. The RGB-D data-based semantic segmentation neural networks were applying to get predicted labels. In addition, self-supervised approach exhibits more robust and accurate results.

Path planning is an essential problem of autonomous mobile robots. In recent years, LiDar-based simultaneous localization and mapping (SLAM) techniques [4] were widely used for the map construction and robot localization. The uses of the robot operation system (ROS) increases the robustness and efficiency of developing the mobile robot SLAM system. For a successful navigation needs a feasible path route plan to the navigation, and the robotic wheelchair can track the planned path to reach the destination. Zhou et al. [5] presented an autonomous robot navigation system, and the proposed navigation system utilized the Dijkstra algorithm to find the shortest path. In addition, the laser range finder data were processed to establish a visibility map in term of the iterative closest point (ICP) algorithm.

For the navigation system studies, Zhu et al. [6] presented an improved wall-following approach. The proposed method is capable of escaping from local minimum in artificial potential field based path planning results. Meanwhile, Wang et al. [7] demonstrated an object-based path planning approach in terms of using grids-potential fields for intelligent robot. At the same time, Mihailidis et al. [8] developed an intelligent powered wheelchair to enable mobility of cognitively impaired older adults, and the proposed control system is capable of performing anti-collision system. Mario et al. [9] In order to assist wheelchair users to move more easily and safely. They combined ultrasonic sensing and fuzzy logic, an obstacle avoidance controller implemented in a field programmable gate array for an electric wheelchair. Various obstacle tests were performed and the controller performance was evaluated. The system can make 46.16 decisions per second and can navigate in narrow areas to reduce the possibility of collisions. For the same purpose. Jiangbo et al. [10] combined RGP camera, infrared camera, 4 ultrasonic sensors, laser LiDAR and personal computer to form a real-time low-cost smart wheelchair shared control system. Based on intelligent sensor network and sensor priority control algorithm, its system can detect obstacles of different dangerous levels, issue alarms and calculate safe paths. After the simulation scenario test, the result shows that the system is reliable and effective.

Meanwhile, Njah Malek et al. [11] Designed a smart wheelchair that can detect obstacles and navigate using ultrasound and infrared. Indushekhar Prasad Singh et al. [12] Only the commercial RGB-D camera and car odometer have been used to realize positioning and obstacle avoidance navigation functions. Amira Elkodama. [13] In-depth discussion on the design, manufacture and testing of intelligent obstacle avoidance wheelchairs, which can combine joysticks and voice-driven wheelchairs. After testing, users can reach their destination with minimal instructions. Eun Yi Kim et al. [14] developed a smart wheelchair system suitable for the elderly and the disabled, which combines vision and eight ultrasonic sensors to detect obstacles and identify outdoor places, and generate paths to avoid collisions with obstacles. After the experiments, the proposed system can identify different types of outdoor places with 98.3% accuracy, and the path accuracy of avoiding obstacles can reach 92.0%. Amiel Hartman et al. [15] Developed an intelligent wheelchair system with hardware description language integration, and used a camera combined with a scanner optical distance sensor to avoid obstacles, and can detect terrain obstacles in urban scenes. Shun Niijima et al. [16] focused on the development of autonomous navigation for electric wheelchairs in large urban areas, proposing a 6-DoF pose localization switching reference 3D map and a two-step path planning framework. The experimental results on the street showed that the system can last for 133 minutes. Realize 8.8KM autonomous navigation within. Anny Wee-Kiat et al. [17] try to reduce the mental burden of the brain signal to control the wheelchair, propose an autonomous wheelchair that uses steady-state visual evoked potential based brain computer interfaces to achieve the objective. Reduce the mental burden of users by means of autonomous navigation. Ananda Sankar Kundu et al. [18] applied the inertial measurement unit (IMU) and myoelectric units as wearable sensors, extracted seven common gestures through shape based feature extraction and Dendogram Support Vector Machine (DSVM), and mapped them command to control the wheelchair. It has been experimentally tested that it can have a longitude of 90.5% when operating the wheelchair. Yang Yu et al. [19] proposed an asynchronous control paradigm based on sequential motor imagery (sMI), which can enrich the control commands of a motor imagery-based brain-computer interface. After a feasibility test, it navigates along a predetermined route. The success rate was 94.2%, which confirmed the effectiveness of the proposed system.

In this paper, an autonomous robotic wheelchair navigation system is presented, and this navigation system combines the rapidly-exploring random tree for path planning. Based on the planned path, the artificial potential field is further applied to reach the destination as well as avoiding obstacles. The organization of this paper is as follows. Section II elaborates the methods of this paper, including powered wheelchair mechatronic design, rapidly-exploring random tree and artificial potential field. Section III presents the experiments and discussions. Finally, conclusion and future works are summarized in Section IV.

3. METHODS

3.1. Powered Wheelchair Mechatronic Design

In this paper, an economical manual aluminum wheelchair with the model of SM-100.3 from Karma Co. Ltd. was used for the installation of adds-on electric components to make it possible to be controlled via microcontrollers. The DC motors were mounted on the wheel axial flanges so that the wheels may drive via DC motors. Fig. 1 shows the CAD of the adds-on modules of the proposed robotic wheelchair, including two 24V/ 350W DC motors, a HOKUYO UST-20LX LiDar and a control box containing a battery set and a Arduino microcontroller for generating DC motors' pulse width modulation (PWM) commands via converting the motion commands to inverse kinematics angular velocities.

Figure 1. CAD of the adds-on modules of the proposed robotic wheelchair

The overall control framework of the proposed robotic wheelchair navigation system is shown in Fig. 2. The host computer of the navigation system is a PC-based controller. An Intel NUC running Linux operation system and robot operation system (ROS) collects the 40 Hz LiDar information for SLAM. In this paper, Hector SLAM open source codes were used in this study to create the map and to localize the wheelchair itself. Because the ROS Hector SLAM open source codes is a convenient tool to realize SLAM, this paper will not describe the technical details of Hector SLAM. The interested readers may get more Hector SLAM information from [3].

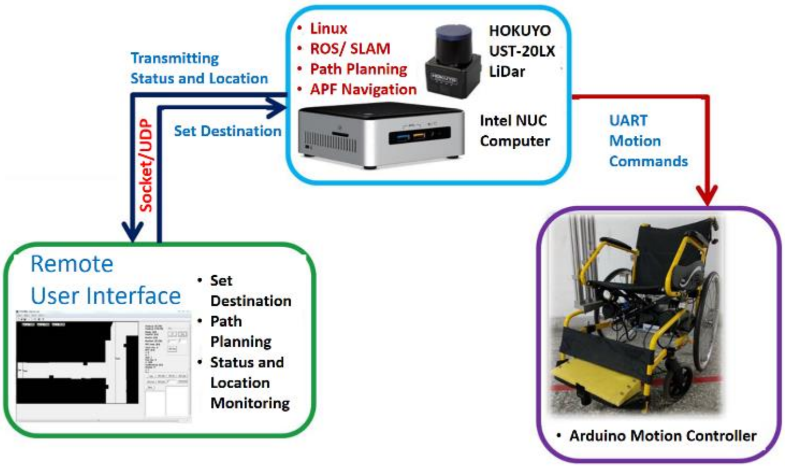

Figure 2. Control system framework of robotic wheelchair navigation system

An example of a map created via Hector SLAM in our campus EE building basement environment is shown in Fig. 3. This environment was used for one of validation environments in this paper. The green line indicates the recorded trajectory of the robotic wheelchair during manual drive control. In addition, the current wheelchair heading can also be investigated. In addition to Hector SLAM, the core approaches of rapidly-exploring random tree (RRT) path planning and artificial potential field (APF) navigation system are also implemented in the PC-based navigation controller. The RRT and APF will be introduced in the following sections.

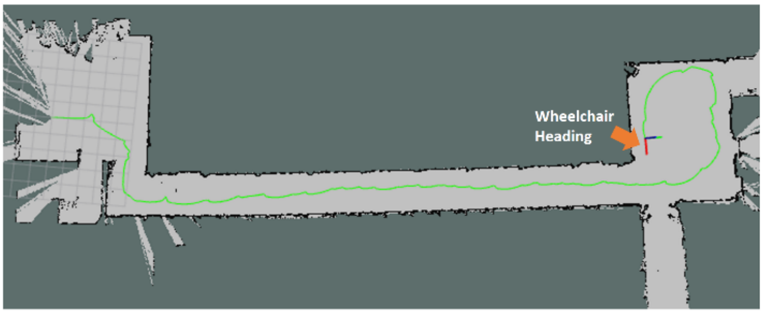

Figure 3. The map constructed via Hector SALM in our campus building

The proposed robotic wheelchair was desired to be controlled, dispatched and monitored through a wireless network (i.e., wifi). Hence, a remote graphical user interface (GUI) that was coded via Microsoft Visual Studio Integrated development Environment (IDE) with C++ programming language was presented. The remote GUI connected to the ROS navigation controller via user datagram protocol (UDP) socket. A dual way communication was realized via remotely setting destination as well as remotely collecting the status, location and planned path for monitoring.

3.2. Rapidly-exploring Random Tree (RRT)

Rapidly-exploring random tree (RRT) is an algorithm to discover a feasible path of a start-to-goal pair in a known map environment. By randomly creating space-filling trees, the goal node would be possible to be reached through the randomly connected trees. Hence, the RRT is available to find a feasible path from the start location to the destination (i.e., goal) location via avoiding all known obstacles and walls in the SLAM map. Fig. 4 is a simple illustration of describing the tree growing of RRT. In this figure, 4 selected steps including the start and goal steps and two intermediate steps by following the step numbers of “1” to “4”.

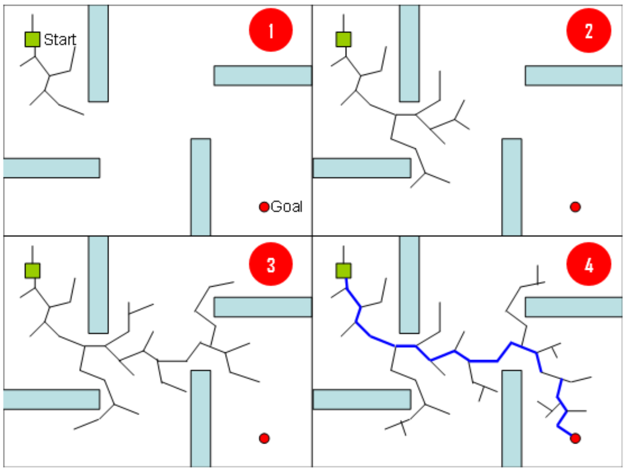

Figure 4. Simple illustration of describing the tree growing of RRT

The pseudo code of a typical RRT is shown in Table I. It is noted that P_{init} indicates the initial position; P_{rand} indicates the randomly generated node position; P_{near} indicates the nearest neighboring node to P_{rand}; P_{new} indicates the newly updated node via evaluating the distance ($\triangle d$); N indicates the iteration; T indicates the nodes in the tree.

Table 1. Pseudo Code of Basic RRT

Basic RRT (P_{init}, N, $\triangle$d)	
1	T.init(P_{init});
2	for n = 1 to N
3	$P_{rand} \leftarrow$ RANDOM ();
4	$P_{near} \leftarrow$ NEAREST_NEIGHBOR(P_{rand} , T);
5	$P_{new} \leftarrow$ NEW (P_{near} , $\triangle$d);
6	T.add_vertex(P_{new});
7	T.add_edge(P_{new});
8	Return T

According to the step 4 in Fig. 4, the RRT path is a piece-wise continuous path. A piece-wise continuous path is not feasible for the robot to follow. Hence, a convex reduction process is further applied. The convex reduction process is shown in Fig. 5. The blue circles are obstacles on the map. The black line segments are trees generated from the searching iterations. The path formed through the connected blue line segments is a piece-wise continuous RRT path. The path formed via the connected red line segments is the convex reduction path. It is clear that only two convex points are required in this situation. The final path should not cross any obstacles on the map.

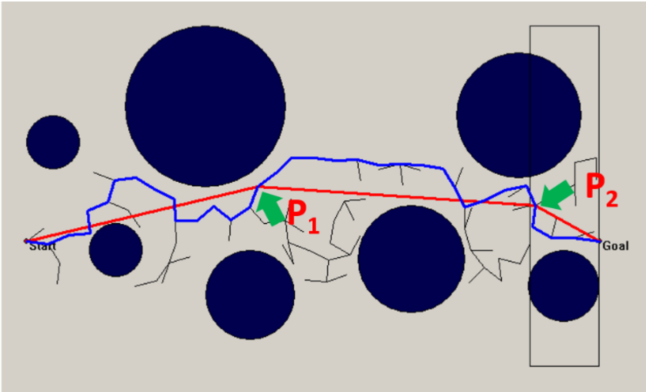

Figure 5. Simple illustration of describing the tree growing of RRT

As a consequence, P_1 and P_2 are intermediate points (i.e., sub-goals). For a general case, the final path is formed as “Start” – P_1 – P_2 – P_{im} – P_F – “Goal”, where P_{im} is intermediate locations between the “Start” and “Goal” locations; *im* is a non-negative integer (*im* = 1 to *F*); *F* is the number of intermediate points. Finally, the navigation of the robotic wheelchair is eventually defined as:

1. The robotic wheelchair begins from the “Start” location.
2. The first sub-goal is “P_1” location, and the robotic wheelchair follows the path “Start” to “P_1” by avoiding obstacles.
3. When the robotic wheelchair reaches the “P_1, the sub-goal is changed to “P_2”. Hence, the robotic wheelchair follows the path “P_1” to “P_2” by avoiding obstacles. This process is repeated via navigating the path from “P_{im-1}” to “P_{im}” until *im* equals *F*.
4. When the robotic wheelchair reaches “P_F”, the sub-goal is changed to “Goal”. Hence, the robotic wheelchair follows the path “P_F” to “Goal” by avoiding obstacles.

It is noted that the obstacle avoidance of each internode path uses APF approaches, and it will be elaborated in the next subsection.

3.3. Artificial Potential Field (APF)

Artificial potential field (APF) [20] is a simple and light-weight computing approach to realize the obstacle avoidance paradigm while toward moving to the destination for autonomous mobile robots. By following the aforementioned convex reduction path, the sub-goals are defined as the targets of the internode paths.

The APF approaches in this paper uses the LiDar to detect the front obstacle location for knowing the obstacles’ distribution, so that the mobile robot tries to avoid them. In addition, the target location is used to guide robotic wheelchair to reach the destination. Hence, both the target location and obstacle distribution information evaluated in the manners of attractive potential and repulsive potential respectively to find the steering and drive commands for robotic wheelchairs. The target location is formed as attractive potential (E_{att}); the obstacles’ distribution is formed as repulsive potentials (E_{rep}). As a consequence, E_{att} demands the robotic wheelchair to reach the target location; E_{rep} takes the robotic wheelchair away surrounding obstacles. Fig. 6 illustrates the APF navigation.

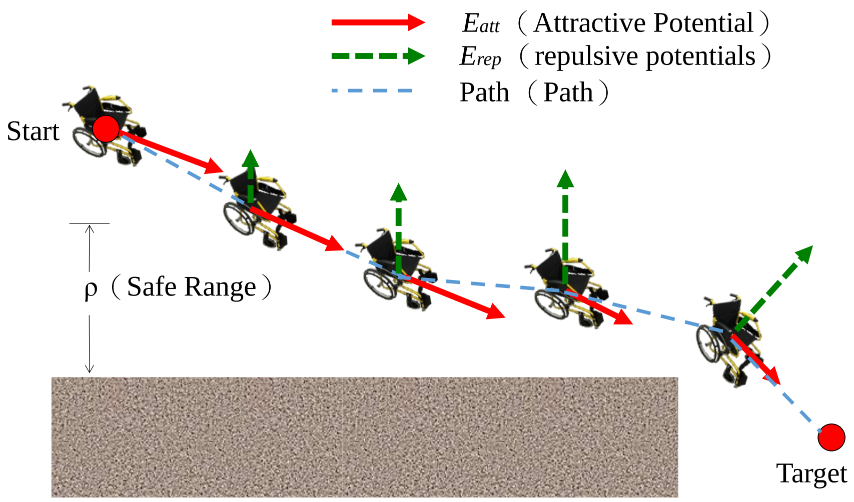

Figure 6. Elaboration of the APF navigation by combing attractive and repulsive potentials

The attractive and repulsive potentials can be accumulated to form a resultant potential (E_{res}), and the potential is a vector form, as indicated in (1). Fig. 7 illustrates the forming of resultant potential in terms of attractive and repulsive potential's gains. It is noted that K_a and K_r can be arranged to meet practical obstacle avoidance experiences.

$$\vec{E}_{res} = K_a \vec{E}_{att} + K_r \vec{E}_{resp} \tag{1}$$

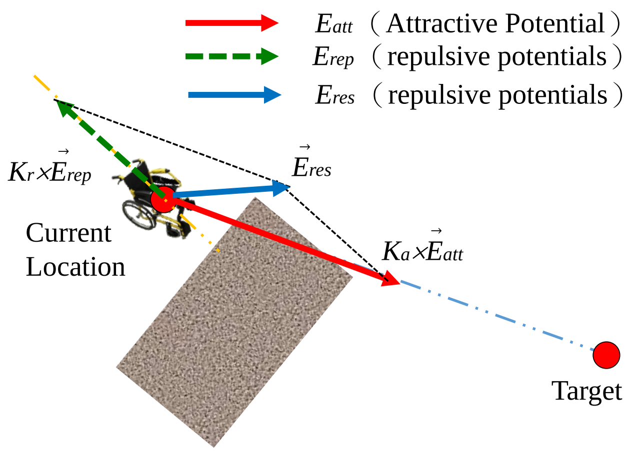

Figure 7. Resultant potential forming by introducing attractive and repulsive potentials' gains

Finally, the magnitude and direction of the potential vector represents the linear velocity and steering commands of driving the proposed robotic wheelchair. The details of obtaining E_{att}, E_{res}, and E_{res} can be referred to our previous work on the obstacle avoidance navigation of an autonomous humanoid robot [8].

4. EXPERIMENTS AND DISCUSSIONS

4.1. Computer Simulation

Before the experiments, a computer simulation program coded with Microsoft Visual Studio IDE with C++ programming language has been done. The simulation loaded a map with a wall (formed with three blue rectangles) in the center of the environment, as shown in Fig. 8. At the beginning, the RRT works with the convex reduction process to find two intermediate points.

In addition, a dynamic obstacle (indicated with a yellow rectangle) is controlled manually via the computer mouse. The movement of this dynamic obstacle introduce interference to the planned internode paths. The dynamic obstacle appeared at two moments. The first appearance is shown in the first internode path (as indicated in the left-hand-side of Fig. 9); the second appearance is shown in the second internode path (as indicated in the right-hand-side of Fig. 9). It is obvious that the robotic wheelchair changed its original path to the sub-goal to successful avoid the sudden interference of a dynamic obstacle.

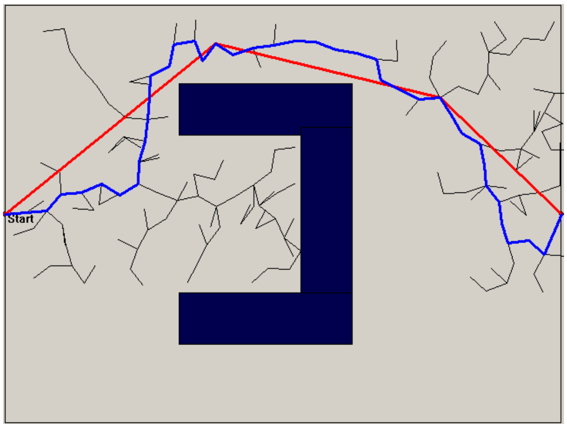

Figure 8. Computer simulation for validating our autonomous navigation approaches

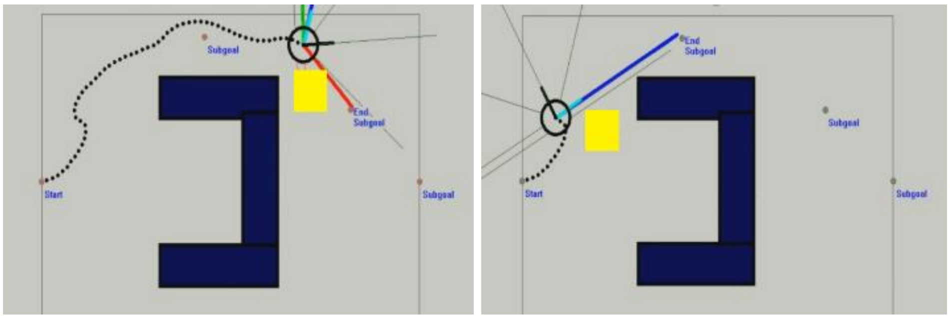

Figure 9. Computer simulation for validating our autonomous navigation approaches

4.2. Experiment of an Environment Without Any Obstacle

Based on the successful experience of computer simulation, an environment at the 6F doorway of EE building of National Taiwan University of Science and Technology is arranged without considering any obstacles. The remote GUI indicated in Fig. 2 is shown in Fig. 10. The user is capable of setting the destination via this GUI. After activating this system, the RRT with the convex reduction process was done first to define the sub-goals. As a consequence, a feasible path was generated as the connected red line segments.

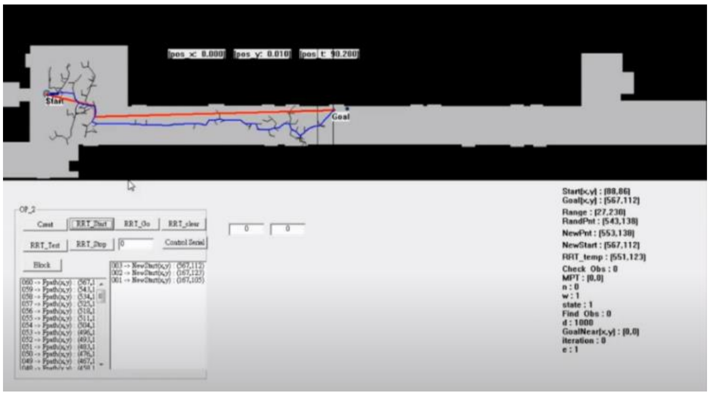

Figure 10. Computer simulation for validating our autonomous navigation approaches

When the path is generated, the robotic wheelchair follows the guidance of sub-goals for internode path navigation in terms of APF. It is noted that the current location can be found from the remote GUI. Fig. 11 shows the experimental environment and remote GUI picture. Because the navigation is executed dynamically, a video of this experiment is provided in YouTube for the investigation of successful navigation behaviours. The YouTube link is shown at https://www.youtube.com/watch?v=iqg3_tEGFf0 .

Figure 11. Experiment of a environment without any obstacle

4.3. Experiment of an Environment with Static/ Dynamic Obstacles

The second experiment was done at the basement doorway of the EE building of National Taiwan University of Science and Technology. Static obstacles and a person is considered in the loop for experiments. It is noted that static obstacles in this experiment were not scanned during the SLAM map construction stage. Hence, the RRT path planning will not consider this condition. In addition, the person in the loop is to walk in the environment to act as a dynamic obstacle interference. The RRT with the convex reduction process was also done first to define the sub-goals, as shown in the upper part of Fig. 12. When the path is generated, the robotic wheelchair follows the guidance of sub-goals for internode path navigation in terms of APF.

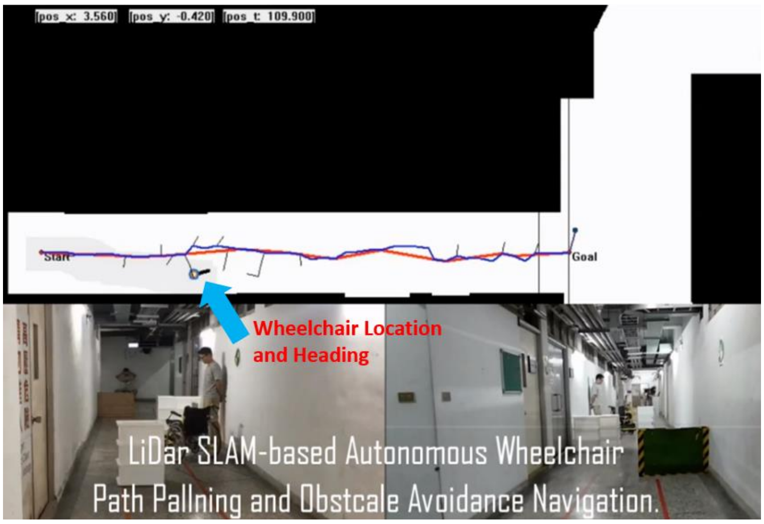

Figure 12. The second experiment done with considering static and dynamic obstacles

In Fig. 12, two white cases and a person indicating static and dynamic obstacles are involved in the loop. The light blue indicates the wheelchair current location and heading. It is apparent that the wheelchair was not on its originally planned internode path because of avoiding obstacle. The video recording of this experiment is also provided in YouTube for the investigation of successful obstacle avoidance navigation behaviors. The YouTube link is shown at https://www.youtube.com/watch?v=PrTuvUTwToc

5. Conclusion and Future Works

This paper presents the development of an autonomous robotic wheelchair navigation system. The proposed employing Hector ROS SLAM for the map construction and wheelchair localization. Because of utilizing open source codes, the efforts of this paper can be majorly focused on the path planning and obstacle avoidance. The path planning was realized in terms of applying RRT and the convex reduction process to obtain a feasible path containing a number of intermediate sub-goals and internode paths.

The APF obstacle avoidance approaches were further applied to navigate the robotic wheelchair to finish the desired internode paths. More specially, static and dynamic obstacles were considered during autonomous navigation. In order to validate the proposed approaches, a computer simulation and two practical experiments were arranged in this paper. From the experiment results and provided YouTube experiment videos, the proposed navigation approach combing RRT and APF could be properly validated.

In the future, improving safety would be the most important measure of robotic wheelchair practical applications. Furthermore, deep learning AI solutions combing machine visions and visual SLAM approaches would be another study aspect to reduce the cost of using the expensive LiDar sensor as well as to improve the robustness.

Acknowledgements

This work was partially supported by the National Science Council, Taiwan, R.O.C. under Grants MOST 106-2221-E-011-004-MY3 and the “Center for Cyber-physical System Innovation” from

The Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education (MOE) in Taiwan.

REFERENCES

[1] Linda Fehr, W. Edwin Langbein, Steven B. Skaar, (2000) "Adequacy of power wheelchair control i terfaces for persons with severe disabilities: A clinical survey," Journal of Rehabilitation Research and Development, vol. 37, no. 3, pp. 353 - 360.

[2] C. Wang, M. Xia, and M.Q. H. Meng, (2020) "Stable autonomous robotic wheelchair navigation in the environment with slope way," IEEE Transactions on Vehicular Technology, vol. 69, no. 10, pp. 10759 - 10771.

[3] H. Wang, Y. Sun, and M. Liu, (2019) "Self-supervised drivable area and road anomaly segmentation using RGB-D data for robotic wheelchairs", IEEE Robotics and Automation Letters, vol. 4, no. 4, pp. 4386 - 4393.

[4] Hector ROS SLAM, http://wiki.ros.org/hector_mapping, access date: 3 April, 2020

[5] J.H. Zhou and H.Y. Lin, (2011) "A self-localization and path planning technique for mobile robot navigation," 2011 9th World Congress on Intelligent Control and Automation, pp. 694-699.

[6] Y. Zhu, T. Zhang and J. Song, (2009) "An improved wall following method for escaping from local minimum in artificial potential field based path planning," IEEE Conference on Decision and Control, pp. 6017-6022.

[7] Y. Wang, J. Wang and S. Yin, (2009) "An object-based path planning using grids-potential fields for intelligent robot," International Conference on Genetic and Evolutionary Computing, pp. 150-153.

[8] A. Mihailidis, P. Elinas, J. Boger, and J. Hoey, (2007) "An intelligent powered wheelchair to enable mobility of cognitively impaired older adults: an anticollision system," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 15, no. 1, pp. 136 – 143.

[9] Mario Rojas, Pedro Ponce and Arturo Molina, (2018) "A fuzzy logic navigation controller implemented in hardware for an electric wheelchair," International Journal of Advanced Robotic Systems, vol. 15, iss. 1, pp. 1-12.

[10] Jiangbo Pu, Youcong Jiang, Xiaobo Xie, Xiaogang Chen, Ming Liu, Shengpu Xu, (2018) "Low cost sensor network for obstacle avoidance in share-controlled smart wheelchairs under daily scenarios," Microelectronics Reliability, vol. 83, pp. 180 - 186.

[11] Njah Malek, (2020) "Safety Wheelchair Navigation System," Journal of Microcontroller Engineering and Applications, vol. 7, pp. 6–11.

[12] Indushekhar Prasad Singh and Ashish Patel, (2019) "Intelligent Autonomous Wheelchair for Indoor Navigation,"International Research Journal of Engineering and Technology, vol. 6, pp. 209 - 217.

[13] Amira Elkodama, Donia Saleem, Samer Ayoub, Clark Potrous, Mostafa Sabri, and Mohamed Badran1, (2020) "Design, Manufacture, and Test a ROS Operated Smart Obstacle Avoidance Wheelchair," vol.9, no. 7, pp. 931 - 936.

[14] Eun Yi Kim, (2016) "Wheelchair Navigation System for Disabled and Elderly People," Sensors, vol. 16, pp. 1 - 24.

[15] Amiel Hartman and Vidya K. Nandikolla, (2018) "Human-Machine Interface for a Smart Wheelchair," Journal of Robotics, vol. 2019, pp. 1 - 11.

[16] Shun Niijima,Yoko Sasaki &Hiroshi Mizoguchi, (2019) "Real-time autonomous navigation of an electric wheelchair in large-scale urban area with 3D map," Advanced Robotics, vol. 33, pp. 1006 - 1018.

[17] Danny Wee-Kiat Ng, Sing Yau Goh, (2020) "Indirect Control of an Autonomous Wheelchair Using SSVEP BCI,"Journal of Robotics and Mechatronics, vol. 32, pp. 761 - 767.

[18] Ananda Sankar Kundu, Oishee Mazumder, Prasanna Kumar Lenka and Subhasis Bhaumik, (2018) "Hand Gesture Recognition Based Omnidirectional Wheelchair Control Using IMU and EMG Sensors," Journal of Intelligent & Robotic Systems, vol. 91, pp. 529 - 541.

[19] Yang Yu, Yadong Liu, Jun Jiang, Erwei Yin, Zongtan Zhou, Dewen Hu, (2018) "An Asynchronous Control Paradigm Based on Sequential Motor Imagery and Its Application in Wheelchair Navigation,"IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 26, pp. 2367 - 2375.

[20] C.H. Kuo, H.C. Chou, S.W. Chi, Y.D. Lien, (2013) "Vision-based obstacle avoidance navigation with autonomous humanoid robots for structured competition problems," International Journal of Humanoid Robotics, vol. 10, no. 3, 1350021-1 - 1350021-36.