Analysis and Evaluation of the safety of Vision-based Navigation Method for Autonomous Robot in Healthcare

Huang Binghao[1]

[1] *University of California, San Diego, Jacobs School of Engineering, California, La Jolla*

Abstract— With the outbreak of the COVID-19 and the subsequent medical pressure, many innovations were emerged to deal with the huge workload, especially the medical assistant robots. Autonomous robots have already shown great potential in such an emergency. Since healthcare robots interact closely with humans, the navigation method and obstacle avoidance method should be more intelligent in the busy environment of the hospital. This paper will describe vision-based navigation methods for mobile robots in indoor environments and find the best method for the indoor environment.

Keywords— Autonomous mobile robot, Computer vision, Navigation, Evaluation criteria, Safety Regulations

I. Introduction

Robots have been increasingly popular in the hospital, especially in today's sit-uation with the spread of the COVID-19 pandemic. Using teleoperated or autonomous mobile robots is a certain direc-tion, which can keep healthcare workers safe and largely re-duce their workload.

A crucial situation for healthcare workers in a COVID-19 Centre is that they need to face numerous repetitive work and a huge workload, like delivery of goods. On the one hand, in such a short-age of medical care, workers who work inside the intensive care areas cannot leave the room to do other nursing works which may waste their time. On the other hand, if healthcare workers come in and out of the isolation areas frequently, it will largely increase the danger of being infected. Conse-quently, using robots to take some of the workloads will be important. However, the corridors of hospitals are usually very busy, which means robots need to face a lot of challenges to go through them, without disturbing the normal workers. This requires our robots to be smarter to guarantee the normal order, safety, and human-machine interaction so that the robots can help healthcare operators and optimize lo-gistics in hospitals. The navigation method of the robot needs to be improved and there may need more schemes of obstacle avoidance to deal with many different kinds of scenarios.

Healthcare robots interact closely with humans, often sharing the same workspace and sometimes physically attaching to humans[3]. More elements need to be considered especially the safety of the autonomous mobile robot. In busy corridor environments, there are a lot of pedestrians, like common patients, nurses, and doctors, and sometimes there is a patient who is being transferred to the emergency room. The robot not only has to complete its workload, but also should consider the different situations to make decisions. So, in this paper, I consider the importance of the safety or safety-relevant topics of mobile robots, like designing of the safety functions and robot sys-tem, safety regulations, and evaluation system.

From a systems perspective, protecting the users is a challenging issue and it must be the design itself that makes the robot inherently unable to injure its user. The goal of inherent safety, however, is often at odds with high performance and adequate payload for real-life tasks[3]. Thus, in other words, how to balance safety and working efficiency is also a very important problem.

The paper is organized as follows. Section II illustrates some methods for SLAM and vision-based navigation, and the most important thing is that it proposes a better way for safe indoor navigation. Section III gives the safety analysis for the proposed method both in safety analysis for motion planning in ROS and vision-based obstacle avoidance method. Section IV has a further in-depth discussion of a safety robot system and future application and provides some regulations and evaluation criteria of safety.

II. Vision-base Navigation in Indoor-Environment

In this section, I will illustrate vision-based navigation and introduce some common methods or key technologies, like

Contact data: Huang Binghao, b6huang@ucsd.edu

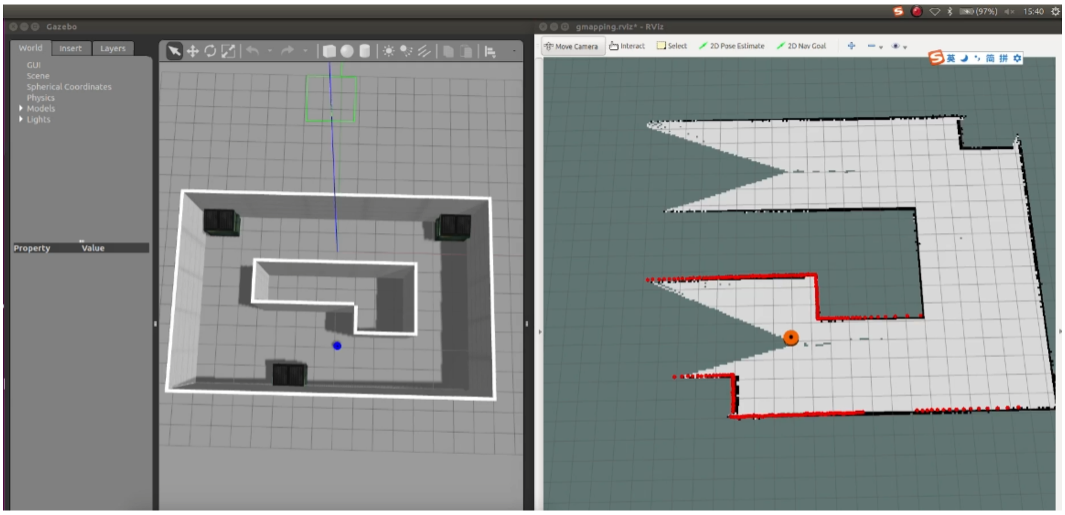

Fig. 1: Construction of Map by using Gmapping Algorithm

Gmapping, HectorSLAM and object detection. Moreover, I will propose some safety problems faced by the system designers.

a. Simultaneous Localization and Mapping

The SLAM problem is defined as follows. A mobile robot roams an unknown environment, starting at a location with known coordinates. Its motion is uncertain, making it gradually more difficult to determine its global coordinates[3]. As it roams, the robot can sense its environment. The SLAM problem is the problem of building a map of the environment while simultaneously determining the robot's position relative to this map[3].

In an indoor environment like a hospital, Simultaneous Localization and Mapping plays a very important role, which can be applied for various application. SLAM can provide the robot with the intelligence to find a destination autonomously. In order to find a better mapping construction and autonomous path planning, I compare and analyze the advantages and disadvantages of several SLAM methods such as Gmapping, HectorSLAM, Cartographer, and *ORB_SLAM*. After comparing and analyzing different algorithms, the Gmapping algorithm becomes the best choice in this indoor scenario. Although the Gmapping algorithm also has many problems like other algorithms, such as cumulative error, Gmapping has a relatively lower calculation requirement and higher accuracy especially in small scene maps in an indoor environment. On the one hand, the Gmapping algorithm requires a lower lidar frequency and has higher robustness than HectorSLAM which always has a high requirement of hardware[6]. On the other hand, the Gmapping algo-rithm has a lower calculation requirement with similar ac-curacy, because cartographer, which can provide 2D and 3D map construction, needs to mand particles and detect loops when constructing[1]. As Fig.1, it shows the process of con-structing a map with a gmapping algorithm with the virtual robot.

As a result, I think Gmapping algorithms are more competitive than the basic SLAM method of such an indoor environment. To achieve autonomous navigation and a certain degree of obstacle avoidance, it is convenient to install the ROS navigation package which contained *global_planner*. As Fig.2, it shows the mobile robot model with the previous map and radar information in rviz.

b. Vision-based navigation and Obstacle Avoidance

Vision-aided navigation with multiple sensors has indeed become an active research field as the rapid development of the technology of computer vision, like object detection, etc. There are two fundamentally different approaches to visual servo control: Position-Based Visual Servo(PBVS) and Image-Based visual servo(IBVS)[13]. First, Position-Based visual servoing uses observed visual features, a calibrated camera, and a known geometric model of the goal object to determine the vehicle's pose with respect to the camera and then transforms to the pose with respect to the robot[13]. The robot then moves toward that pose and the control is performed in task space. Good algorithms have the advantages of accurate estimation for the pose, but they need more expensive computational power and accuracy of the camera. Second, Image-based visual detection usually uses the image feature directly, but it will omit the pose estimation, which means they need to be combined with other data to get accurate estimation[13]. The desired camera pose with respect to the goal is defined implicitly by the image features are a highly nonlinear function of camera pose[13].

For the other approach of computer vision, vision sensors like monocular cameras and stereo cameras help us in performing most of the perception tasks[7]. However, visual information processing is a quite complex task in real-time perception. One of the great algorithms is YOLO whose architecture is deployed for extracting visual features from the environment and identification of each feature in real-time which performs very well and reduces time complexity from other cases[7]. As shown in Fig. 3, this is a screen callback information of the object detection algorithm. By applying YOLO on the ROS system, it is easy to fuse radar data with camera data from the robot. The output of the YOLO model combined with radar data can find the distance between the object and the robot and the angle of the object from a mobile platform. Thus, the navigation of robots can be more intelligent when they can gather more detailed information about

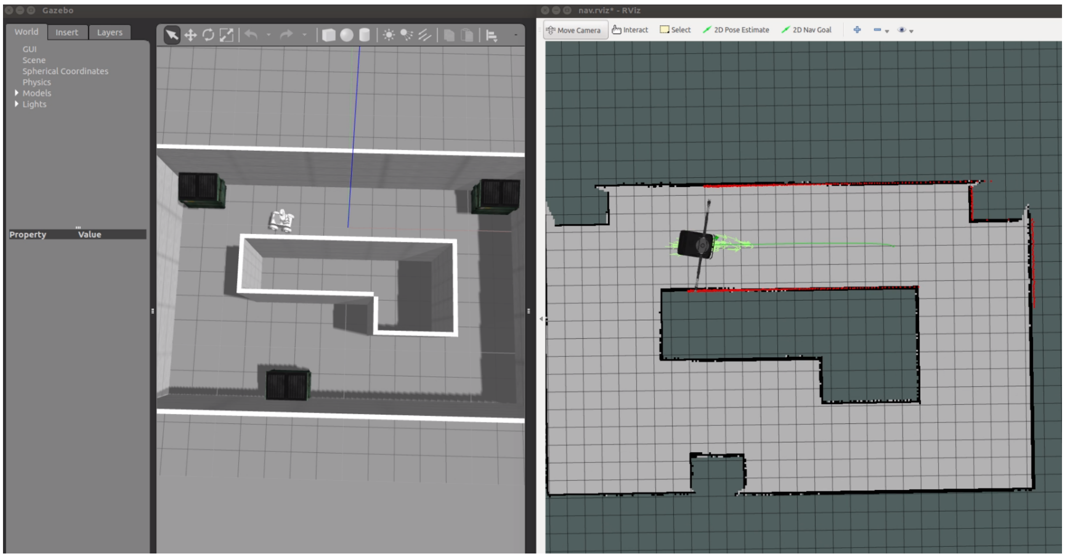

Fig. 2: Simulation model of Real Mobile Robot for Navigation in Ros

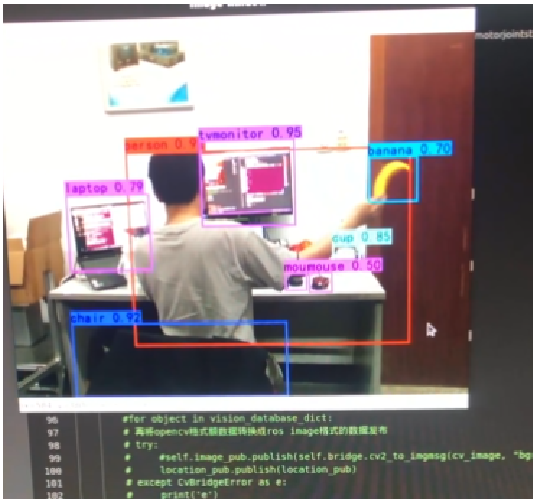

Fig. 3: Object detection of YOLO Algorithm

objects.

c. Kinematics Model of four-wheeled mobile robot

As shown in Fig. 4, the basic technique of Gmapping relies on the robot odometry data, tf transform data, map data from the previous laser scan, and real-time laser data.

Odometry data can be calculated from the encoder of motors. Odometry data is of considerable importance for the robot to estimate the initial posture and position and follow trajectory data. Odometry can be calculated by the formulas below:

$$\begin{cases} X = \int dx = \int (v_x \cos\theta - v_y \sin\theta)dt \\ Y = \int dy = \int (v_x \sin\theta - v_y \cos\theta)dt \\ \theta = \int d\theta = \int \omega dt \end{cases} \tag{1}$$

Tf transform data shows the position and posture between two coordinate frames, which can show position vector and quaternion. Tf transform data can be published by a robot. We subscribe tf transform data not only to know the status of the robot but also to do some adjustments to accomplish obstacle avoidance operation.

In order to describe the motion of the four-wheeled mobile robot in a plane, equations can be written as:

$$\dot{p} = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} cos\theta & 0 \\ sin\theta & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} v \\ \omega \end{pmatrix} \tag{2}$$

Where $\dot{p} = \begin{pmatrix} \dot{x} & \dot{y} & \dot{\theta} \end{pmatrix}^T$ is the present pose of the robot in the world Cartesian coordinate system, the inputs to the vehicle model are the linear velocity v and the angular velocity ω which can be achieved by applying the steering angle:

$$\gamma = tan^{-1} \frac{\omega L}{v} \tag{3}$$

In order to describe the navigation method, the equation of the trajectory and orientation of mobile robot can be described as:

$$M(p)\dot{m} + V(p,\dot{p})m + G(p) = \tau \tag{4}$$

$$\lim_{t \to \infty} (p_r(t) - p_c(t)) = 0 \tag{5}$$

Where τ is the input vector, $m = (v, \omega)^T$ is the vector of velocities,$M(p)$ is a symmetric and positive definite inertia matrix, $V(p,\dot{p})$ is the centripetal and Coriolis matrix, and $G(p)$ is the gravitational vector[12]. For a given reference trajectory $p_r(t)$ and orientation of mobile robot, it needs a suitable torque τ so that the current robot position $p_c(t)$ achieves the desired reference position $p_r(t)$[12].

d. A method combined with traditional navigation and vision

Here is a proposed scheme of my project for a healthcare robot that combined traditional navigation method with gmapping and computer vision for object detection to ensure real-time obstacle avoidance in an emergency. Ubuntu 14.04 is installed in the industrial computer as the control system. Researchers also install ROS Indigo as the robot operating system. The remote computer can connect with the industrial computer through WI-FI. Further, by building ROS

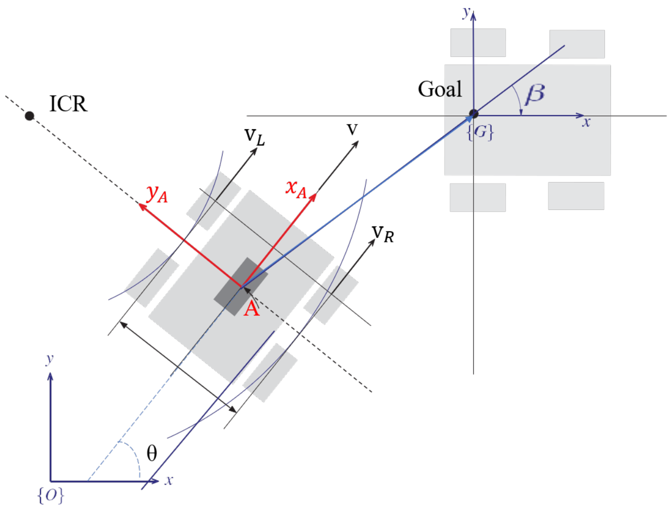

Fig. 4: Polar coordinate notation for the vehicle moving toward a goal pose

network, operators could have the same ROS nodes running both on the industrial computer in robot and remote computer. The robot could transfer information, such as images, maps, and voice, to the remote computer through the ROS network. Thus, not only can the remote computer send commands to the robot, but also the status of the robot can be monitored in real-time remotely before the navigation or during navigation. In addition, ROS allows establishing a connection between the sensors, making the system more integrated. A ROS node can be distributed to different hosts and nodes can communicate with each other by topics. ROS network allows developers to combine different messages from different sensors more flexibly.

As shown in Fig. 5, an operator could use a laptop to send a goal with the map which gets from the laser scans. After sending the goal, the robot could start navigation to the goal. When the robot passes through the busy corridor with the preparation of three different conditions, static obstacles, moving pedestrians, and moving emergency bed.

As shown in Fig. 6, the visual information is captured by a depth camera. The image message will be stored in the camera topic and transferred to the remote computer through the ROS network for computing object detection. Then the image message will be transformed in OpenCV format data by cv_bridge and then transformed to image data by OpenCV. Subsequently, image data is collected and processed framewise in real-time to extract the region of the object accordingly by the YOLOv4 algorithm. Identified obstacles are bounded with boxes and each box's position data can also be collected.

In the part of visual tracking, we need one of the three motors in the robot body to rotate to help the camera of the robot body face the object all the time. Names of objects are corresponding to the positions of their boxes so that we can calculate the center of the object. Then, by comparing the center of the certain object with the center of the screen, the computer could send left or right velocity commands to the robot to control the motor. Based on the distance from the center of the object to the center of the screen, the velocity command sent to the motor will also change by the distance. Thus, the camera could always face the object until the object

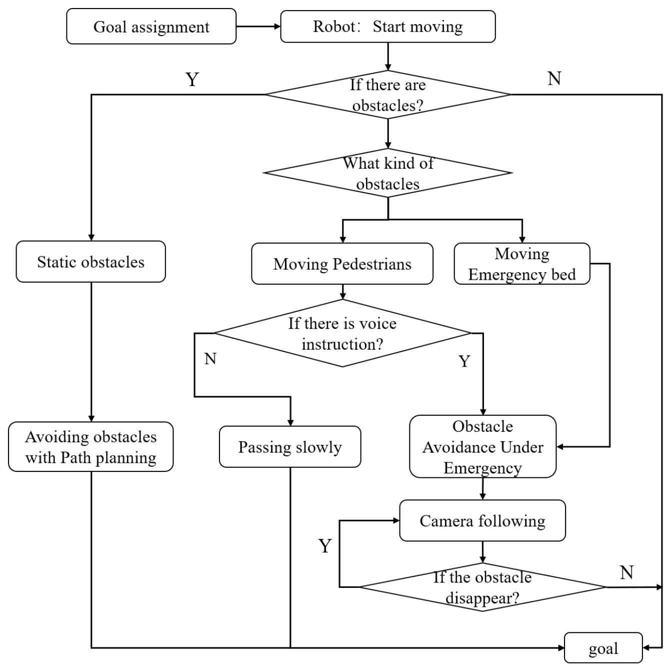

Fig. 5: Block diagram of a navigation scheme of multi-strategies for the hospital.

is out of the range of rotation and disappear, which can be set up customarily.

The part that takes the main role of obstacle avoidance is the robot platform. By using the ROS navigation package and Rviz visual interface, we could see the position of the robot on the map and send some basic commands, such as position command or velocity command. Apart from the navigation package, we have added more intelligent features to it by using python. Once the camera detects the emergency, the platform of the robot will abort the original plan to the goal and begin to avoid and move to the one side of the corridor. The robot needs to know if the object has passed through, so the visual tracking described above plays an important role. After the object has disappeared from the vision range, the robot will restart the path planning to the original goal without the human's additional operations.

III. SAFETY ANALYSIS FOR THE METHOD

This section provides analysis and evaluation for the vision-based navigation method described above using the methods learned by this class.

a. Safety Analysis for motion planning in Ros

As we described in the previous section, the navigation of the robot applied the gmapping algorithms to ensure the basic SLAM function. The robot will construct the map at first, and then the operation could send the target to the robot for navigation. This needs another technology, motion planning that in the navigation package of ROS. Applying reliable motion planning to the robot is very important for safety. Not only does the robot needs to get to the target as quickly as possible, but also it should guarantee safety.

Move_base node provides the implementation of the action for the mobile robot and it provides a visualized interface for sending commands and showing the robot's position on

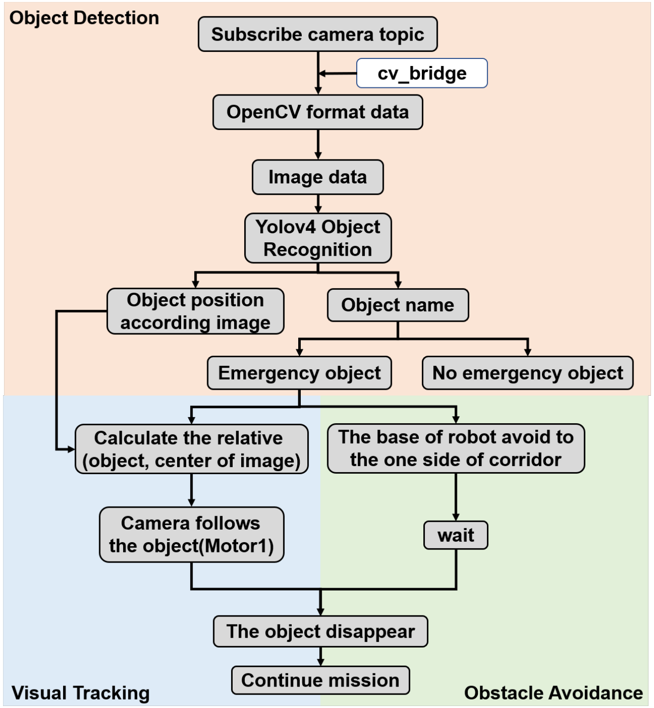

Fig. 6: Details of the proposed vision based obstacle avoidance

the map. As shown in Fig. 7, it combined different kinds of information to guarantee the reliable running of navigation, like sensor sources, map server, odometry source, amcl.

Another function of *Move_base* node is that it can provide a package to modify the configures of the navigation according to the situation. As shown in Fig. 8, it can show the different information during the navigation. We can see several colors in the picture. The red dots show the radar information. The green arrows can show the real-time estimation of the position of the robot. The area that has denser arrows, has the greater probability of the robot in this position. The purple lines show the real-time obstacle data within 2m square frame, which can be modified and adjusted according to requirements. The blue area is the expansion coefficient of the obstacle and the robot will not enter this range. In the experiment, we set the radius of expansion coefficient r=0.5m, and this expansion coefficient r can be modified and adjusted according to the situation. Once the robot received the goal, motion planning will provide an optimal path based on the map constructed before. These different types of information described above can be combined to ensure the safety of the robot during the way moving to the target.

However, such a navigation method only based on the radar needs to be improved. On the one hand, Inertial navigation systems (INS) develop navigation errors over time due to the imperfectness of the inertial sensors, like the Inertial measurement unit(IMU). On the other hand, even though the robot can easily avoid static obstacles, it has limited abilities to avoid dynamic obstacles, which may cause stops of the robot until the dynamic obstacle was disappeared, or even abortion of the navigation, which will waste time or even cause safety problems. The problem will largely decrease the efficiency of the hospital, especially in a busy time.

b. Safety Analysis for Vision-based Obstacle Avoidance

Through the above paragraph, we can know it is not enough to ensure safety and effectiveness by using the navigation package alone. Thus, more obstacle avoidance techniques need to be applied, which means that vision-based technology also has the importance to install on the system to ensure the robot has the ability to drive to the destination. After sending the goal, the robot could start navigation to the goal. When the robot passes through the busy corridor, we set three kinds of conditions:

(1) Static obstacles: When there is a static obstacle like tables or boxes, the laser will detect it and the robot can deviate from the straight line and start the obstacle avoidance process.

(2) Common situation: When the robot detects that there are pedestrians on the corridor, it will choose to lower its speed to guarantee safety. Such a situation is so common in hospitals that do not need additional avoidance. In the meantime, the robot has speech recognition. If pedestrians have voice instruction, the robot will begin its additional avoidance strategy and then move to one side of the corridor. In addition, such function can also reduce physical contact in the hospital.

(3) Emergent situation: Robot must not hinder hospital flow when there is some emergency that happened, like an emergency bed, which needs to be transferred to the operation room as soon as possible and maybe blocked by the robot in the middle of the corridor. Thus, the new method based on computer vision can solve the problem. When the robot detects an emergency bed, it will avoid and move to one side of the corridor. As soon as the emergency bed had passed through the corridors, the robot will continue its mission to reach the goal.

We can see that we set three kinds of conditions to ensure that the robot could largely enhance the working efficiency and guarantee safety in the meanwhile. This can largely reduce the deficiency of the traditional motion planning of the Ros package. This is like the use of double insurance so that the robot will not hurt people in essence. And the characteristics of visual color tracking can also make the robot more intelligent to ensure that the moving obstacles have passed.

To validate the proposed new navigation method, we need more comparison experiments with the traditional navigation method. Experiments can be carried out in the hospitals, like validation of the overall system's performance, recording of the trajectories of both methods. Only if these experiments are carried out, will we know the true performance of the method. However, it takes time to finish these experiments especially in this period in which getting permission to have experiments in a hospital is very hard. I hope to take more experiments and validation in the future.

IV. SAFETY REGULATIONS FOR MOBILE ROBOT IN INDOOR ENVIRONMENT

This section will provide some existing regulations and evaluation criteria of safety for a mobile robot. First, we will discuss several safety-related topics. Second, we will focus on some safety standards for human-robot interaction which

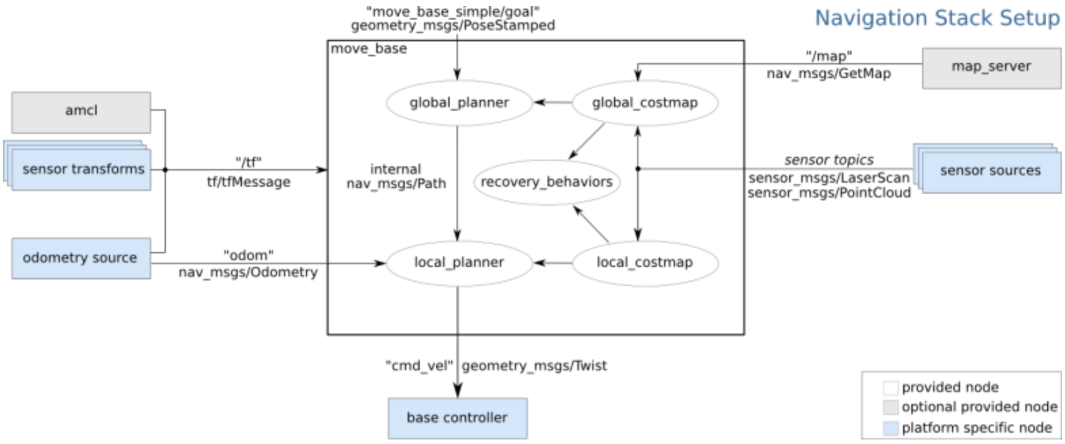

Fig. 7: Overview of move_base node

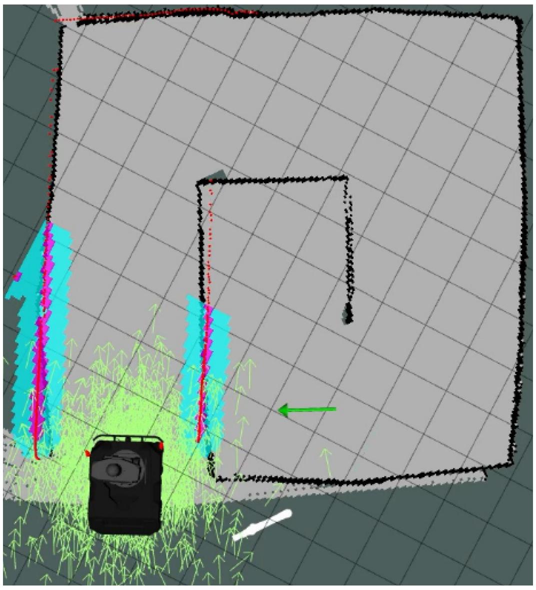

Fig. 8: Visualized Information during the Navigation of mobile robot

need to be attached to considerable importance. By making clear the standard, it can help researchers to build a safe and efficient autonomous system for the robot.

a. Safety-related topics

- HRI:Human-robot interaction becomes increasingly important nowadays, concerning communication between humans and robots. However, robots are distinct from computers in that they physically embody the link between perception and action[3]. Thus, human-robot interaction must be of considerable importance to the advance of future robot technology. What needs to be noted is that humans and robots can cooperate with each other and work together in the same place. In order to achieve this, assisted robots, rehabilitation or medical robots will be designed, which associate with the topics in this paper.

- Automated Health Care Monitoring and Care: An automation system provides solutions for people of disability, which can assist people without creating other dangers like most of the robots do. Thus, the intelligence of the robot must be improved, like safe autonomous navigation, quick response to human's multiple commands, and intelligent monitoring, etc.

b. Regulations and Evaluation Criteria

I will find e xist s everal s tandards a nd g uidelines. While industrial robots have benefited f rom I nternational Organization for Standardization(ISO) user safety regulations, the standard of human proximity to robots for personal, service, and healthcare need more focus[3].

Safety standard, which has been almost completed in most of the robot industries, is of importance to the healthcare robot. In order to solve such safety problems in the close contact between humans and robots, these standards must be more restricted than the others. The present landscape for robotics standards includes well-established national standards (ANSI-RIA for the US, CSA in Canada, DIN in Germany, etc.), that are collected and harmonized by the International Organization for Standardization (ISO)[3]. Safety for industrial robots is addressed both by general standards on safety of machinery and by robot-specific s tandards. The main ISO safety standard for robots is ISO 10218, which dates back to 1992 [3]. However, robot safety in hospital and medical environments needs to be more strict.

V. Conclusions

For this passage, we introduce some basic knowledge of the navigation of the robot, like traditional navigation of gmapping and vision-based navigation. Especially in the period of COVID-19, a teleoperated and auto-navigation robot can largely protect both the medical staff and patients.

First, I simulate the construction of the map by moving the robot with radar and then use the map for motion planning to complete the teleoperation. Second, in order to have better performance in safety, I proposed a new method by using object detection to accomplish obstacle avoidance. Third, the paper evaluates both the motion planning and the obstacle avoidance method for the safety problem and discusses some safety regulations for the medical environment. For further research, I think the algorithm of the motion planning still has plenty of room for improvement, like safety for a learning-based planner. Moreover, for part of vision-based navigation, there could be more methods for 3D perception to guide the navigation.

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