Autonomous Path Planning and Navigation of a Mobile Robot with Multi-Sensors based on Fuzzy Logic in Dynamic Environment

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Abstract

The mobile robot is applied widely and investigated deeply in industrial fields, meanwhile, mobile robot autonomous path planning and navigation algorithm is a hot research topic. In this paper, firstly mobile robot is introduced, the general path planning and navigation algorithms of the mobile robot are reviewed, then a fuzzy logic with filter smoothing is proposed based on the data from the laser scan sensor and GPS module, which is useful for mobile robot to find the best path to the destination automatically according to the position and size of the gaps between the obstacles in the dynamic environment, finally our designed mobile robot and corresponding Android APP are introduced, the path planning and navigation algorithms are tested on this mobile robot, the testing result shows that this algorithm is globally optimized, quickly responded, battery power and hardware cost saved compared with other algorithms, it is suitable for the mobile robot that is running on the embedded system and it can satisfy our design requirement.

Keywords: Mobile Robot, Path Planning, Navigation, Fuzzy Logic, Embedded System.

1. INTRODUCTION

Nowadays there are extensively and widely applications of the mobile robot in various fields, such as moving, testing and performing the scientific experiments on the Mars, serving and running as a servant in a restaurant or house, transporting or moving the heavy goods to the designated destinations in the warehouse etc.

The mobile robot should be designed to be more sensitive, intelligent and networked as it plays an important role in more and more crucial occasions, it can judge and learn the operation according to the multisensory fusion algorithm, meanwhile, it can complete and take place of the humans' work with high efficiency through its human-like properties [1].

As an intelligent standard of the mobile robot, path planning and navigation algorithms become hot and critical research fields for the mobile robot [2], in order to reach the designated destination while avoiding the obstacles automatically in the dynamic environment, many path planning and navigation algorithms were proposed and investigated to get the best path to destination like humans moving in a real dynamic environment, the path planning and navigation algorithms should be designed according to the following standards: responding quickly, shorter path distance, less time consumption, optimality, completeness, reasonability, meeting the constraints.

The early path planning algorithm is to try finding a best path in a static environment that the locations of the obstacles are fixed, in which A* algorithm is an assessment system of the resource cost from the initial point to the designated point. Visibility graph algorithm can find the best path according to the line that linked the top points of all the obstacles. With the rapid development of path planning algorithms, the path planning algorithm that is suitable for running in the dynamic environment is put forward, such as the artificial potential field algorithm that can optimize the path in the partial scope, but it is not effective for the global situation, so the generic algorithm arises which can optimize the path in the global area, but it needs high standard hardware to calculate and the hardware cost is increased [3].

Also many navigation algorithms of the mobile robot are proposed along with the development of the mobile robot, such as the generic algorithm which can collect the information of the surrounding environment and judge the next step operation. Neural network technology can accumulate the knowledge of the environment through the training of the self-organizing neural network. The behavior algorithm will divide the navigation function into many little function modules which have their own navigational judgments. The above algorithms are usually running on a computer to make sure the enough processing efficiency and fast responding [4]-[5].

Because the computer is power consumption, expensive, big and heavy for the mobile robot, so most of the mobile robot is running on an embedded system platform to save battery power and cost, as well as easy to carry and move, therefore, in order to design a better path planning and navigation algorithm that is hardware cost reduced, battery power saved, responding quickly and globally optimized for the mobile robot, the fuzzy algorithm is proposed because of quickly responding and less calculation, it is suitable for the mobile robot that is running on the platform of embedded system in a dynamic environment.

According to the above analysis, we design and manufacture a mobile robot with the platform of “ARM” CPU and embedded Linux system, running path planning and navigation algorithms with fuzzy logic and filter smoothing processing. Android APP and video monitoring with internet browser function are added in the system. This mobile robot is tested and the testing result of path planning and navigation algorithm can meet the design requirement.

2. PATH PLANNING AND NAVIGATION

2.1 Multi-Sensor Data

The laser sensor is used to measure the angle, distance, signal quality, synchronized bit of each obstacle within 6 meters, it is produced by Rplidar company of China, the data of obstacles is output from laser sensor per round as Figure 1 shows.

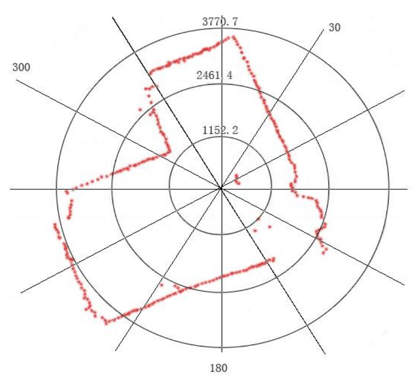

FIGURE 1: Laser Sensor Scanning Data Graphic.

The Figure 2 shows the corresponding simulated environment, in which the measured line OC is the longest distance, the line AB is the gap between the two obstacles.

It is necessary to get the accurate position of the mobile robot to see whether it has reached the destination, so the GPS sensor is needed to output the real-time longitude and latitude, which is helpful for the mobile robot to reach destination after comparing with the designated longitude and latitude. The mobile robot should also detect its moving direction which helps the mobile robot to correct its moving direction in order to get closer to the destination [6].

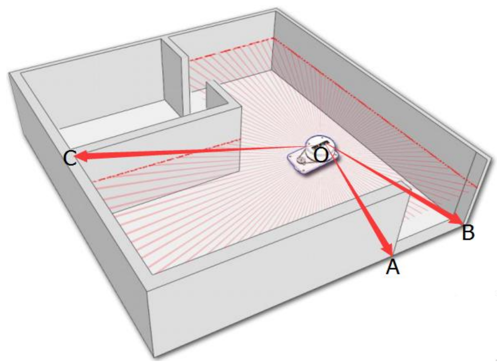

FIGURE 2: Simulated environment according to the laser sensor scanning data.

In order to make sure that the position and direction judgement are accurate, the flight control module is added in the system which integrates the GPS sensor, gyroscope, accelerometer, magnetometer and electronic compass sensors together, it is "HT-Hawk" module which is produced by "HengTuo" company, the integrated GPS sensor is the new version UBLOX GPS module NEO-M8N, the outputted longitude and latitude can reach the accuracy of 0.9 meters.

2.2 Path Planning

The mobile robot's width is about 580mm and the length is about 800mm, this is a constraint condition to process the laser sensor data, so it is necessary to draw the graphic of the obstacles and gaps surrounded for further analysis.

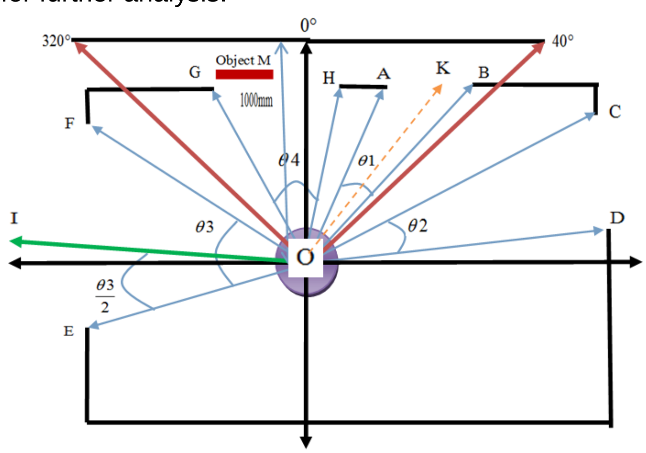

FIGURE 3: Laser Sensor Scanning with Gaps.

The laser sensor will process it as a gap if the measured distance is larger than 6 meters, in Figure 3, the gap size AB can be calculated by law of cosines:

$$AB = \sqrt{OA^2 + OB^2 - 2 \times OA \times OB \times \cos\theta 1} \quad (1)$$

For the scanning data in the gap of AB, such as the K point, they are

$$distance(OK) = 0\text{ , } signal\_qudity(OK) = 0 \quad (2)$$

The distance data on the obstacles are all positive values, such as the distance data of points on line HA, so the points of A, B can be confirmed, the distance OA, OB and the angles between point A and B can be attained

$$\theta_1 = \theta_B - \theta_A \tag{3}$$

The other distance and angles can be acquired in the same way, such as distance of OC, OD, OE, OF, OG, OH, gaps size of CD, EF, GH, angle of θ_1, θ_3, θ_4, it should be noted that the gap GH across the $0°$, the θ_4 can be calculated by

$$\theta_4 = \theta_H + 360° - \theta_G \tag{4}$$

For the consideration of the mobile robot's width and the corresponding redundancy, the mobile robot will choose the gap size which is larger than 600mm to compare each other to find the max gap size, in Figure 3, the max gap size in one round is EF, so the mobile robot should run to the direction of gap EF, it is suitable to move to the angle of the middle position of gap EF and it is:

$$angle(OI) = angle(OE) + \frac{\theta_3}{2} \tag{5}$$

It is worth noted that if there is an obstacle in front of the mobile robot, such as the red "Obstacle M" in Figure 3, the mobile robot can't move forward and the constraint condition is:

If the laser sensor scanning angle is in $320° \sim 40°$, checking:
if $distance < 1000mm$, *the variable* $stop\_forward = 1$
else $stop\_forward = 0$

It is the same way to process the situation for moving backward of the mobile robot:

When the laser sensor scanning angle is in $160° \sim 200°$, checking:
if $distance < 1000mm$, *the variable* $stop\_backward = 1$
else $stop\_backward = 0$

The $angle(OI)$ in formula (5) is the destination angle, the following Table 1 shows the relationship between destination angle and corresponding turning direction of the mobile robot, if $stop\_forward = 1$ or $stop\_backward = 1$, the mobile robot will turn right as the default direction.

Destination angle	Turning direction
$340° \sim 20°$ while $stop\_forward = 0$	forward
$340° \sim 20°$ while $stop\_forward = 1$	right
$20° \sim 160°$	right
$160° \sim 200°$ while $stop\_backward = 0$	backward
$160° \sim 200°$ while $stop\_backward = 1$	right
$200° \sim 340°$	left

TABLE 1: Relationship of destination angle and turning direction.

2.3 Navigation

Based on the above analysis, the largest gap can be located and the mobile robot can turn the direction to go through the largest gap, but it is meaningless because this only provides the widest path for mobile robot to move ahead while avoiding the obstacles on the path, in order to reach the destination to fulfill some works for the mobile robot in the real world, it is necessary to designate the destination and mobile robot can arrive the destination in dynamic environment, the destination position can be located through designating the longitude and latitude on the Android APP, the mobile robot should navigate and plan the path according to the sensors fusion algorithms [7]-[8].

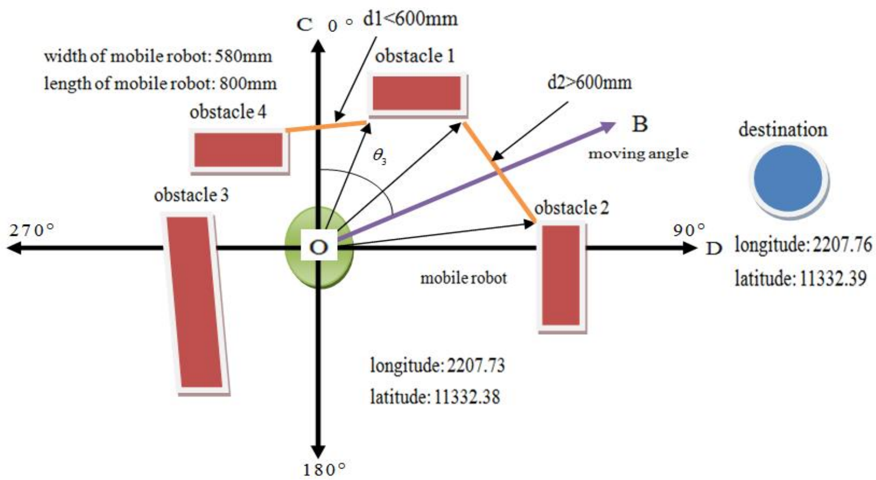

FIGURE 4: The navigation without rotation of the mobile robot.

As Figure 4 shows, compared the designated and detected longitude and latitude, it can be confirmed that the destination is on the northeast position of the mobile robot, according to the above path planning algorithm, the mobile robot will find the max gap in the scope between OC and OD to judge the max gap direction, if there is no rotation of the mobile robot, the forward direction of the mobile robot points to $0°$ which is just the north direction, in this case

$$angle(OC) = 0° \tag{6}$$

$$angle(OD) = 90° \tag{7}$$

The mobile robot will find the max gap between $0°$ to $90°$ which is towards to the northeast direction of the mobile robot, in Figure 4, there are two gaps between $0°$ to $90°$: d1 and d2, because d1 is less than the width of the mobile robot and d1 cannot be chosen, d2 satisfy the condition and the max gap between $0°$ to $90°$ is d2, so the mobile robot will turn right to rotate θ_3 and will move towards to the OB direction.

But in most instances, the mobile robot will rotate to some degrees and the forward direction is not towards to the north, in Figure 5, the mobile robot rotates θ_1 and its forward direction is towards to OA now, because the destination is still on the northeast position of the mobile robot, it will find the max gap between OC and OD, but the OC is not $0°$ and OD is not $90°$ for mobile robot now, so it is necessary to do some degree transformation in this situation.

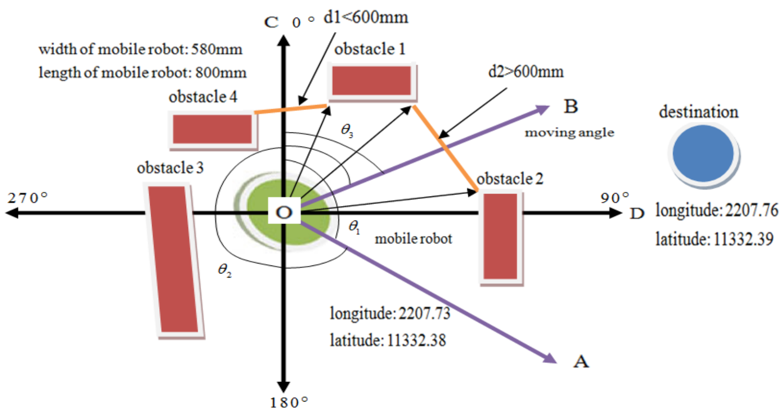

FIGURE 5: The navigation with rotation of the mobile robot.

In order to obtain the max gap between the scope of OC and OD, it is necessary to calculate the degree of OC and OD in this situation, in Figure 5, the mobile robot has been rotated θ_1 with respect to north direction, the reference system will also rotate θ_1 to meet transformation of coordinates, so all the degrees will reduce θ_1 to make the new coordinate effective.

$$angle(OC) = -\theta_1 \tag{8}$$

$$angle(OD) = 90° - \theta_1 \tag{9}$$

$$\theta_2 = \theta_3 - \theta_1 \tag{10}$$

If the destination orientation is not on the northeast position after comparison of the designated and detected longitude and latitude, such as the mobile robot is on the southeast, southwest and northwest position of the destination, the $angle(OC)$ and $angle(OD)$ are different and they can be listed in the Table 2.

Destination orientation	Degree scope of finding max gap	
Northeast	$angle(OC) = -\theta_1$	$angle(OD) = 90° - \theta_1$
Southeast	$angle(OC) = 90° - \theta_1$	$angle(OD) = 180° - \theta_1$
Southwest	$angle(OC) = 180° - \theta_1$	$angle(OD) = 270° - \theta_1$
Northwest	$angle(OC) = 270° - \theta_1$	$angle(OD) = 360° - \theta_1$

TABLE 2: Relationship between destination orientation and degree scope.

If there is minus degree, it needs the correction:

$$\text{If } angle(OC) < 0, \; angle(OC) = 360° - \theta_1 \tag{11}$$

$$\text{if } angle(OD) < 0, \; angle(OD) = 90° - \theta_1 + 360° \tag{12}$$

$$\text{if } \theta_2 < 0, \quad \theta_2 = \theta_3 - \theta_1 + 360° \tag{13}$$

In Figure 5, mobile robot scans the gaps between OC and OD and attaches the max gap d2, the mobile robot should turn left according to Table 1 to go towards to d2, scanning obstacles and attaining gaps need the help of the laser scan sensor, the comparison of the longitude and latitude is fulfilled with the help of GPS sensor, detecting the rotation direction of the mobile robot is completed through the data from gyroscope, accelerometer, magnetometer and electronic compass sensors [9].

There is another situation that there is no gap satisfying the condition between the OC and OD, just as d1 and d2 in the Figure 6 shows, both of d1 and d2 are less than 600mm and the mobile robot can't go through the space from OC to OD, so the laser scan sensor will find the max gap in other space to get the satisfied gap, as the Figure 6 shows, OA is the forward direction of the mobile robot, and the mobile robot finds two satisfied gaps which is d3 and d4, according to the above path planning algorithm, d4 is the largest gap and it should go to the d4 towards to the OE direction, but for the navigation, it not only focuses the gap size, more important factor is the gap direction which is crucial for the mobile robot to get closer to the destination, after transformation of the coordinate, it finds that the d3 is closer to the destination, so the mobile robot will turn right according to Table 1 to go through d3 and move towards to the OB direction.

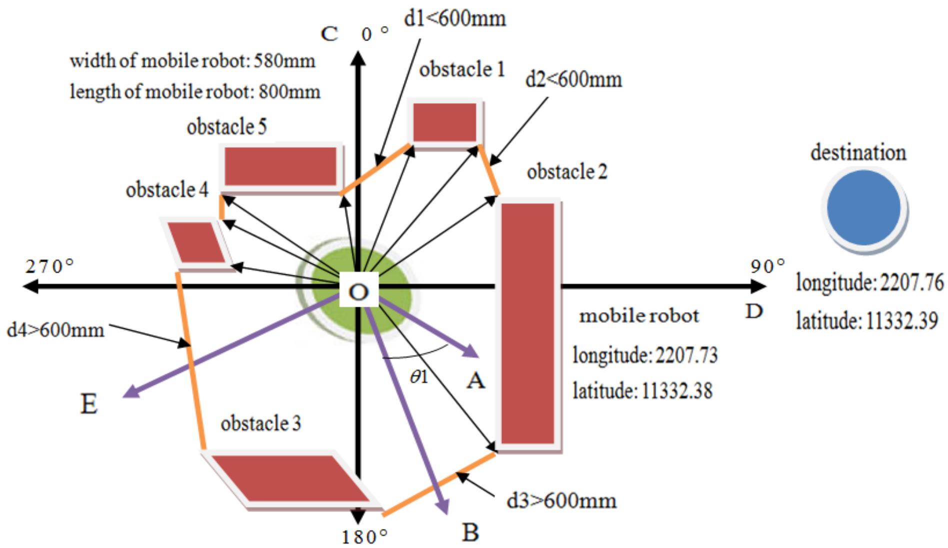

FIGURE 6: The navigation of mobile robot without satisfied gap.

If there is no satisfied gap whose length is more than 600mm in the whole round, the mobile robot will stay static and not move, until there is a satisfied gap available again and it will move according to the above algorithm to reach the destination.

2.4 Fuzzy Logic

From above analyses, it is clear that fuzzy logic is suitable to process the path planning and navigation of the mobile robot, which makes the turning direction of the mobile robot more stable and reliable [10]-[11].

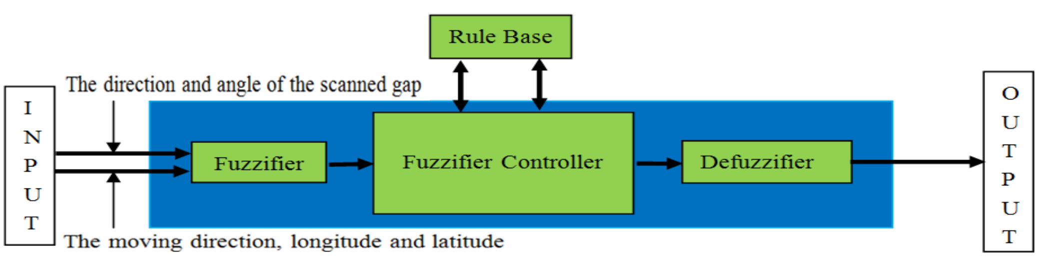

FIGURE 7: Fuzzy logic for path planning and navigation of the mobile robot

The Figure 7 shows the fuzzy logic for the path planning and navigation of the mobile robot, the input variables are the measured direction and angle of the scanned gaps, as well as the moving direction, longitude and latitude of the mobile robot, the membership functions can be listed as follows.

$$d_{forward} = \begin{cases} \frac{a}{20} & a \le 20 \\ \frac{a-340}{360-340} & 340 \le a < 360 \\ 0 & 20 < a < 340 \end{cases} \quad (14)$$

$$d_{right} = \begin{cases} \frac{a-20}{160-90} & 20 < a \le 90 \\ \frac{160-a}{90-20} & 90 < a < 160 \\ 0 & a \le 20 \;\; or \;\; a \ge 160 \end{cases} \quad (15)$$

$$d_{backward} = \begin{cases} \frac{a-160}{200-180} & 160 \le a \le 180 \\ \frac{200-a}{180-160} & 180 < a \le 200 \\ 0 & a < 160 \, or \, a > 200 \end{cases} \quad (16)$$

$$d_{left} = \begin{cases} \frac{a-200}{340-270} & 200 < a \le 270 \\ \frac{340-a}{270-200} & 270 < a < 340 \\ 0 & a \le 200 \;\; or \;\; a \ge 340 \end{cases} \quad (17)$$

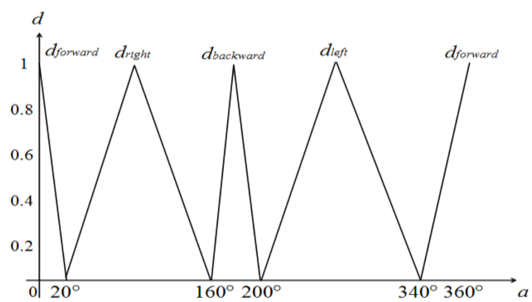

FIGURE 8: The membership function of fuzzy logic.

The mobile robot rotates according to the turning direction until it reaches the forward or backward direction, this process repeats continuously for the mobile robot till it moves to the destination [12]-[13].

The application of fuzzy logic can save the CPU calculation and respond quickly, which is suitable for the mobile robot that is designed on a platform of the embedded system.

2.5 Filter Smoothing

In the test, the mobile robot changes moving direction very quickly sometimes, about 2 to 3 times per second, so the mobile robot can't move stably on the attained path, after the debug information comes from the serial port, there are some angle noises data inducing the incorrect turning direction in Table 1, because the laser sensor scanning work is running in one thread, the time slice task management in the Linux system will induce the time of entering the laser sensor scanning thread is uncertain, it is possible that the laser sensor only scans a part of the space and gets the incomplete data when it enters in the thread, so it is necessary to count the turning direction result per second to make the turning direction data more smoothly [14]-[15].

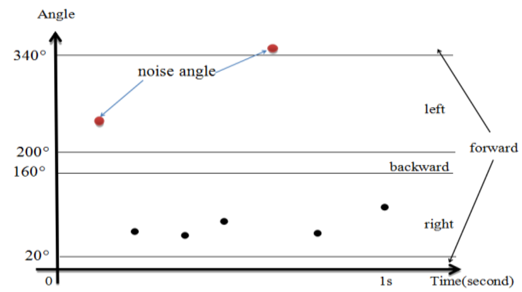

FIGURE 9: Noise angle and normal angle distribution in each second.

In order to make sure the mobile robot to turn the direction smoothly, the noise angle should be deleted through the statistics of angles' number in different turning direction per second, in Figure 9, there are total 7 angles, according to Table 1, the number of angles in right direction scope is 5, which is more than the number of other directions, so the other 2 angles are the noise angles with the red circles, the mobile robot will move right in this second, this process continues per second to make the mobile robot move more stably and accurately.

3. TEST RESULT

In order to test the path planning and navigation more practically in the real dynamic environment, we have designed a mobile robot running on the embedded platform with "ARM" CPU and embedded Linux system as Figure 10 shows.

In order to intensify the moving driven power of the mobile robot, the DC motor connects with a gear motor with the reduction ratio 1:50 to increase the turning torque, the belt connects two wheels together on each side and there are total 4 wheels on this mobile robot. According to the testing results, the mobile robot can move properly when there is a man whose weight is 86KG standing on the mobile robot, so this mobile robot can carry the heavy goods in the real life applications.

FIGURE 10: The designed mobile robot.

There are three parts of the hardware platform for the mobile robot, the first part is ARM development board with "S5PV210" CPU which is running the embedded Linux system, it can realize the function of the camera video display, LCD display, operation on touch screen, laser scan sensor data collection, data fusion of GPS and other sensors, bluetooth and wifi data transmission, path planning and navigation algorithm.

The second part is another MCU board that connects to the ARM board through serial port, which could transmit the motor control command and the feedback speed of motors with the designed protocol, because there is calling and task schedule delay for the Linux system, this MCU board is designed to read the 25KHz motor speed feedback pulse accurately.

The third part is the "SCM6716" board to supply the large current and power to drive the motor running normally, the peak current can reach about 1.8A and this will make sure the mobile robot can bear and carry the heavy objects in the real life applications.

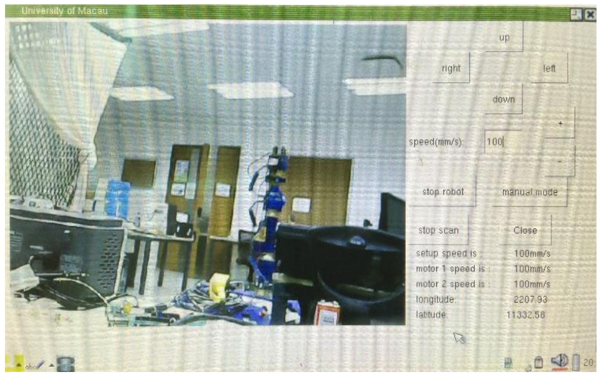

FIGURE 11: The LCD and touchscreen with camera video display that is running in the embedded Linux system.

The other hardware contains LCD and touch screen, the 2.0M camera, Serial-bluetooth module, USB-wifi module, laser scan sensor, GPS sensor, gyroscope, accelerometer, magnetometer and electronic compass sensors.

The GUI utilizes QT graphic library to show the widgets on the LCD as shown in Figure 11, through calling the corresponding signal and slot function, the QT API fulfills the LCD and touch screen programming work in the Linux developing environment.

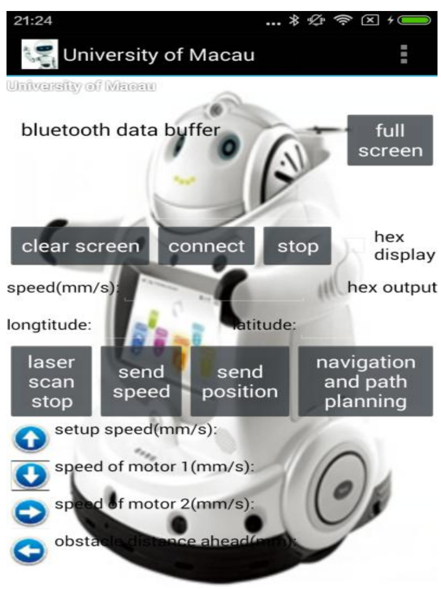

FIGURE 12: Android APP.

The Android APP is designed to control the mobile robot more easily and freely, it communicates with the ARM board with Serial-bluetooth module to control the mobile robot running status, working mode, moving direction and speed, designated longitude and latitude etc.

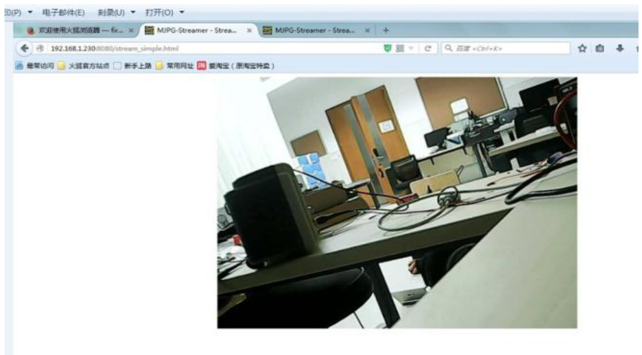

FIGURE 13: Remote monitoring with internet browser.

The mobile robot should be more networked along with the network technology developing, the mjpeg-stream is used to transmit the camera video data to the internet browser cross various platforms with the TCP/IP protocol, it can remotely monitor on the Firefox, browser it is transplanted in the embedded Linux system of the mobile robot, the testing result shows it can work properly and it is helpful to know about the status of mobile robot immediately via the internet browser.

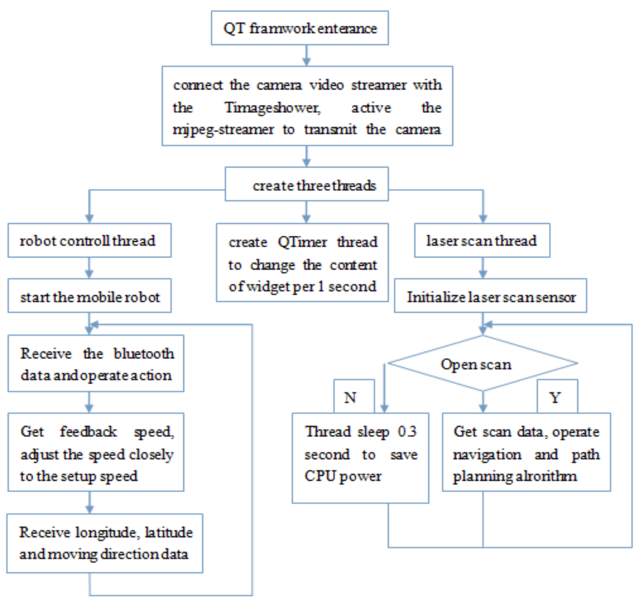

FIGURE 14: Linux programming software logic structure of the mobile robot.

The GUI framework is the Linux programming software entrance, it points to the QT interface pointer, after transmitting and displaying the camera data to the QT interface, it creates three threads to finish the work of motor controlling, laser sensor scanning, the path planning and navigation algorithm, refresh the widget content [16].

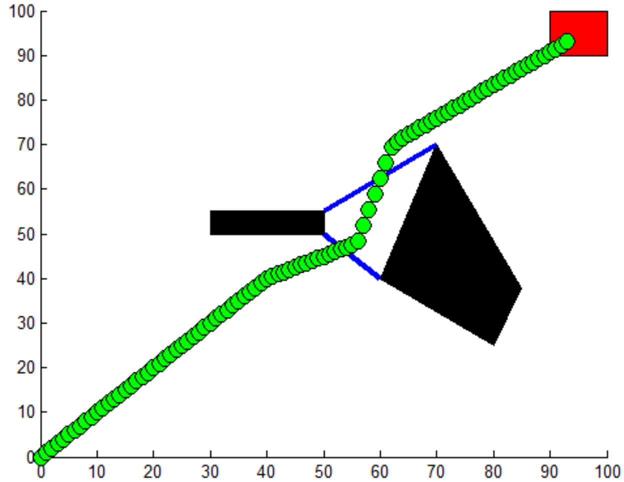

FIGURE 15: Matlab simulation for navigation of mobile robot with stratified gap.

Figure 15 shows the Matlab simulation for the navigation of the mobile robot when there is satisfied gap between two obstacles, the green circle is the mobile robot, the black object is the obstacles, the red rectangle is the destination, the mobile robot can detect the direction and distance of the gap between the obstacles through the laser scan data, if there is a gap that is wider than the width of the mobile robot, it could go through the gap and reach the destination.

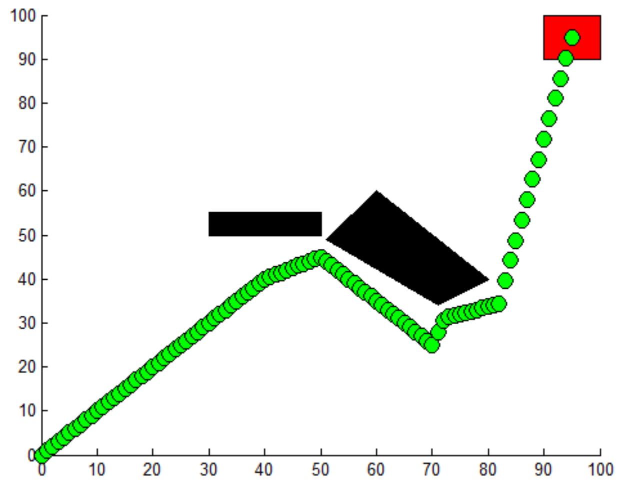

FIGURE 16: Matlab simulation for navigation of mobile robot without stratified gap

In the Figure 16, the gap between two obstacles is too narrow and there is no stratified gap between them, the mobile robot should find other ways to bypass the obstacle as shown in the Figure 16, this operation continues until there is a satisfied gap detected on the path, and it will go to the destination finally. Optimal path planning will be investigated via PSO algorithm [17]-[19].

4. CONCLUSION

The testing result shows that the proposed path planning and navigation algorithm based on fuzzy logic and filter smoothing are effective and real-time responding, compared with other algorithms, it is simply computed and realized for the mobile robot designed on the platform of the embedded system that is running in the real dynamic environment.

In the designing process, one of the most challenges is showing the real-time camera video on the LCD screen, because the video is stream data in Linux system and the data is too big to be processed immediately. The other challenge is to get rid of the noise data from the laser sensor, it is difficult to analyze and find the data errors when reading a lot of scanned data in a short time, but the final testing results show that our designed mobile robot can run normally with the designed path planning and navigation algorithm.

The advantage of this algorithm is easy to realize, respond quickly, save reacting time, save CPU calculations, further save power supply comparing with other algorithms, they are especially important for the embedded system with the limited CPU calculation and battery power, this can make sure the mobile robot process the sensors fusion data and find the best path to navigate quickly and accurately, the testing results show that it can meet our design requirements.

5. ACKNOWLEDGEMENT

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