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A Low Cost Single Board Computer Based Mobile Robot Motion Planning System for Indoor Environments

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Abstract: In this study, a low cost, flexible and modular structure is proposed for mobile robot motion planning systems in an indoor environment with obstacles. In this system, the mobile robot has to follow the shortest path to the target avoiding obstacles. It is designed as three main modules including image processing, path planning and robot motion blocks. These modules are embedded on a single board computer. In the image processing module, the image of the indoor environment, including a mobile robot, obstacles and a target, having different colors is taken to the single board computer with a wireless IP camera. This image is processed to find the locations of the mobile robot, obstacles and the target in C programming language using OpenCV. In path planning module, the shortest and optimal path is generated for the mobile robot. Generated path is applied to the robot motion module to produce necessary angles and distances for the mobile robot to reach the target. Since the structure of the proposed system is designed as modular and flexible, similar or different hardware, software or methods can be applied to these three modules.

Keywords: *Genetic Algorithms, image color analysis, mobile robots, open source software, open source hardware, path planning.*

1. Introduction

Mobile robot based applications are increasing with the rapid advance in engineering science. Mobile robots are commonly employed in space researches, military applications, natural disasters, factories, offices, hospitals and houses. A large number of academic and industry surveys have been performed with this advance in mobile robot application topics. These studies focus on localization, path planning and obstacle avoidance in an indoor environment. A mobile robot can get knowledge around it by using different kinds of sensors or visualization devices such as lasers, sonar or cameras. Thus, it can localize itself, decide next movement, avoid obstacles and reach the target with this knowledge.

Basic applications on mobile robot based studies deal with localization, surrounding objects detection, navigation, avoiding obstacles and reaching the target. Localization of mobile robot and detecting the surrounding objects are essential to be known for its performing next task successfully. Also, mobile robot should get to the target without any collisions with moving or fixed obstacles. Furthermore, the shortest path to the target takes an important place and many studies on path planning are met in literature. Mobile robot based studies deal with localization, obstacle avoidance and path planning together.

Numerous studies on vision-based mobile robot navigation can be found in literature. Visual navigation for mobile robots is presented in [1] as a survey paper expressing two major approaches, visual map based and mapless navigation. In map based navigation, map of the environment, including robot, obstacles and target is constructed using images acquired from different angles. Map based navigation methods used in an indoor environment are listed as force fields, occupancy grids, absolute localization, incremental localization, topological map, landmark tracking, stereo 3D reconstruction in [1]. Optical flow [2-4], appearance based navigation [3] are listed as indoor mapless navigation methods in [1].

In mobile robot navigation, obstacle avoidance is another problem to be solved. In literature, fuzzy based algorithms [5-6], the potential field approach [7], the artificial potential fields approach [8], the follow the gap method [9], Q-learning with neural networks [10], the distance function approach [11], the vector field histogram (VFH) [12], Kalman Prediction Based VFH [13], VFH^{+} [14], the dynamic window approach (DWA) [15-16] and the rule based (RB) approach are the techniques used for obstacle avoidance [5].

Path planning used to determine the shortest way to the target is the other study area besides obstacle avoidance. The common techniques applied to path planning are Fuzzy logic [17], genetic based approaches [18-21], ant colony algorithm [22], Particle Swarm Optimization (PSO) based algorithms [23], hybrid path planning methods [24], Asexual Reproduction Optimization (ARO) [25].

Single board computers having a significant role among embedded systems have got an increasing popularity. With the growth of popularity of these computers, they are likewise going to be utilized in mobile robot applications. They are mounted to the mobile robots and communicated with the mobile robot and other devices such as sensors and cameras using different communication interfaces [26]. In literature, laptops, notebooks, on-board PCs or PCs are used in the most of the studies on the mobile robots [15, 20- 21, 23], [27-32]. These devices increase the cost of the mobile robot systems. Both their volume and weight are bigger and they spend more space. So, the mobile robot has to be big and powerful enough to carry them. The mobile robot has to spend additional energy for carrying them. The BeagleBoard-xM is used as a single board computer in this work. Because, it has lower power consumption, lower cost,

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lower weight and smaller space than the devices as Laptops or PCs. Licensed software such as Windows Operating System and MATLAB are used in laptops or PCs. This sort of software requires higher cost, higher power consumption and higher processing capability compared with the software used in the BeagleBoard-xM. Open source software, Angstrom as an operating system and C programming language with OpenCV are utilized in the BeagleBoard-xM. Therefore, no software cost is required, either. In addition, wireless communication with the camera is used to control the mobile robot in this study. This saved us from unnecessary cable cost and complexity of the working environment. Some studies in literature used PC controlled robots with long cables [29]. The mobile robot systems with bigger and heavier devices on top or long cables for communication are not realistic solutions for real life. Thus, the BeagleBoard-xM with lower power consumption, lower cost, lower weight and smaller space is used on the top of the mobile robot with a wireless IP camera mounted to the ceiling in this study. The camera or cameras can be located along the cover of the mobile robot in different studies.

This paper is a follow-up study of the paper in [33]. This paper is improved by significant developments in this study. The reference [33] proposes a motion planning system for a mobile robot. A system is developed including a computer, MATLAB and USB camera. It is improved making the system become modular, embedded, low cost and mobile.

In this study, a system is designed, including three modules named as Image Processing Module (IPM), Path Planning Module (PPM) and Robot Motion Module (RMM) using the BeagleBoard-xM for the mobile robot motion planning system. The proposed system is built for the mobile robot to navigate from starting point to the target avoiding obstacles using the shortest path. The image of the environment, including the mobile robot, the obstacles and the target is taken by a wireless IP camera mounted to the ceiling. This image is processed to generate the map of the environment in the IPM. Whereas generating the map of the environment, color detection technique is used to determine the locations of the objects in different colors by the BeagleBoard-xM. Different detection techniques such as object or contour recognition can be applied instead of color detection in this module. The environment map generated in the IPM is applied to the second module, PPM as an input. In the PPM, the shortest path of the mobile robot is obtained using GA. Some other algorithms such as tabu search, ant colony, simulated annealing, particle swarm optimization and A^* can also be applied in this module. The shortest path is transferred to the RMM to produce the necessary motion commands of the mobile robot to arrive at the target. Pioneer P3-DX is used as a mobile robot here, but the BeagleBoard-xM based system can be adapted to a different robot by slight changes.

The BeagleBoard-xM placed on the mobile robot has an essential role in the system. Taking the image from the camera, processing this image, producing the map of the environment, generating the shortest path and applying the motion commands to the mobile robot are performed by the Beagleboard-xM. Since the proposed system has a modular structure, it is adaptable for different mobile robots, image processing techniques or path planning algorithms. So, the proposed system has advantages of being flexible, modular and cheap for real mobile robot applications.

This paper is organized as follows: Section.2 describes designed and realized system in three subsections as 2.1. Image Processing Module, 2.2. Path Planning Module and 2.3. Robot Motion Module. The experimental results are explained in Section.3 and finally, obtained results are commented and discussed in the 4.Conclusion.

2. Realized Application

In this study, the mobile robot has to reach the target through the path generated by GA avoiding obstacles. With this purpose, an experimental setup including a Pioneer P3-DX robot, a BeagleBoard-xM, a wireless modem and a wireless IP camera is built up for indoor applications. An external battery is applied to supply the BeagleBoard-xM. The BeagleBoard-xM is placed on the Pioneer P3-DX robot to mobilize the system itself. The BeagleBoard-xM communicates with the Pioneer P3-DX robot using RS-232 serial port. A wireless IP camera is mounted to the ceiling to take the image of the experimental area, including the mobile robot, the obstacles and the target. The wireless IP camera is communicated with the BeagleBoard-xM through the wireless modem.

In this application, BeagleBoard-xM developed by Texas Instruments (TI) and Digi-Key is one of the major components as open source hardware. The Angstrom operating system running on the BeagleBoard-xM, is accessed via remote desktop connection. Image processing, path planning and robot motion processes are executed on this card. The detail information about the BeagleBoard-xM is given in [34-35].

A wireless IP camera, a wireless modem and a USB wireless adapter are employed to take the image of the indoor application environment. The received image is processed by using OpenCV. The OpenCV is developed by Intel using C and C++. It has Berkeley Software Distribution (BSD) license and includes a great number of computer vision algorithms. The details about OpenCV can be found in [34, 36].

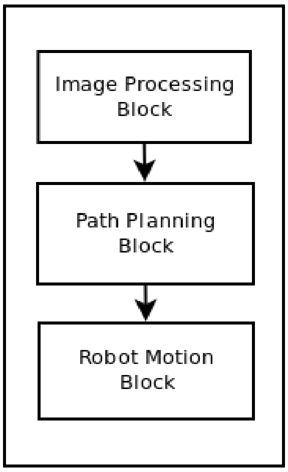


Figure 1. Modular block diagram of the application

In the experimental studies, the communication between BeagleBoard-xM and the Pioneer P3-DX mobile robot is provided via RS232 serial port and the software running on the BeagleBoard-xM is developed by using C programming language and the OpenCV. The architecture of the designed system including three main modules, IPM, PPM and RMM is depicted in (Figure.1).

The overall detailed block diagram of the system is shown in (Figure.2). This Figure, includes all the three modules of the system. In the IPM stage, the image of the indoor environment is obtained by the wireless IP camera on the ceiling. The locations of the mobile robot, obstacles and the target are determined from this image and a matrix is generated showing their locations. In the PPM, GA based path planning is realized to find the shortest path to the target using this matrix. In the last stage, RMM, the generated path is applied to the mobile robot as motion commands to reach the target avoiding obstacles.

In this study, GA is used in PPM stage. However, since the system is designed as modular, different methods or algorithms such as tabu search, ant colony, simulated annealing, particle swarm optimization can be applied instead.

In addition, this study can be applied to any other robots by slight changes as the communication protocol. In short, different methods or algorithms can be applied to the IPM stage of this system.

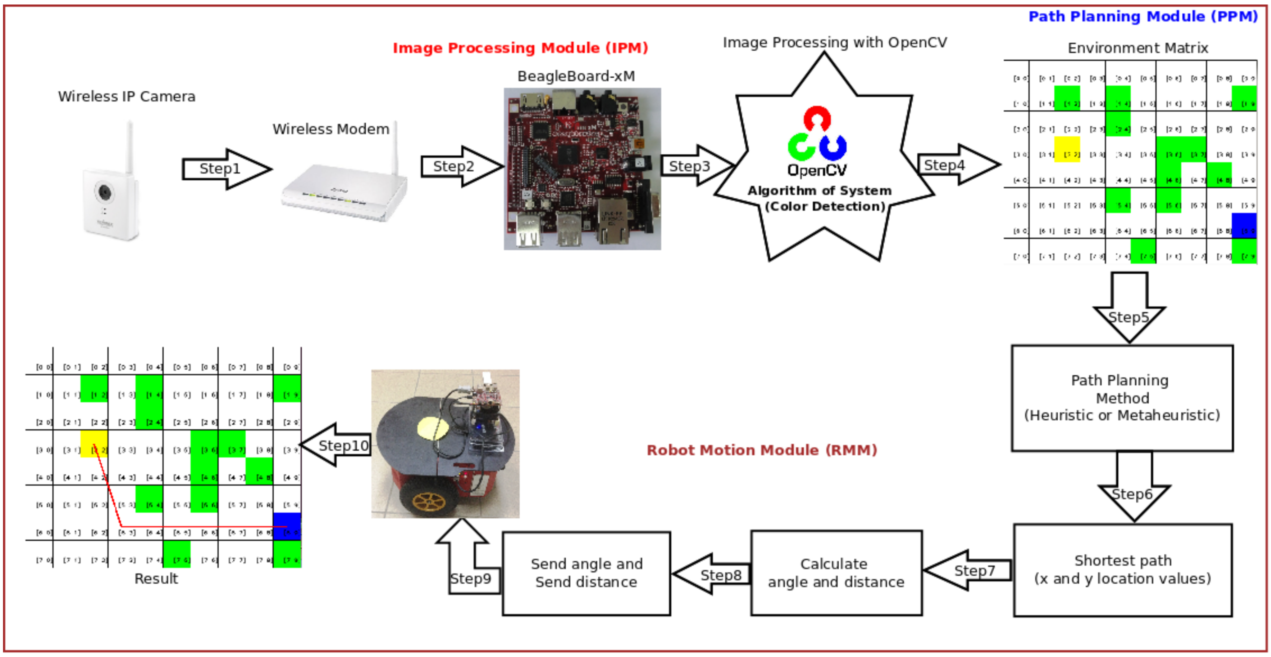


Figure 2. The block diagram of the overall system

2.1. Image Processing Module (IPM)

This module is used to generate the matrix of indoor environment. The block diagram of the IPM is given in (Figure.3).

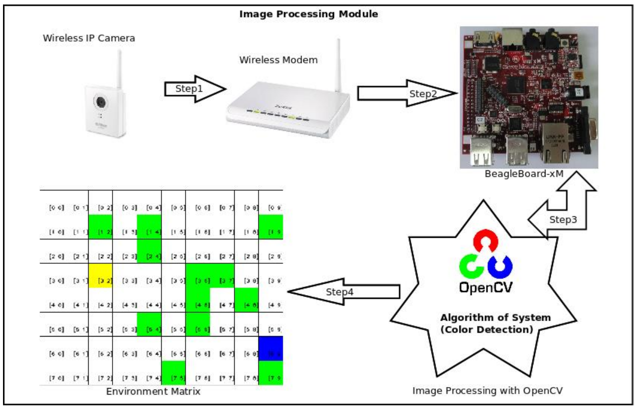
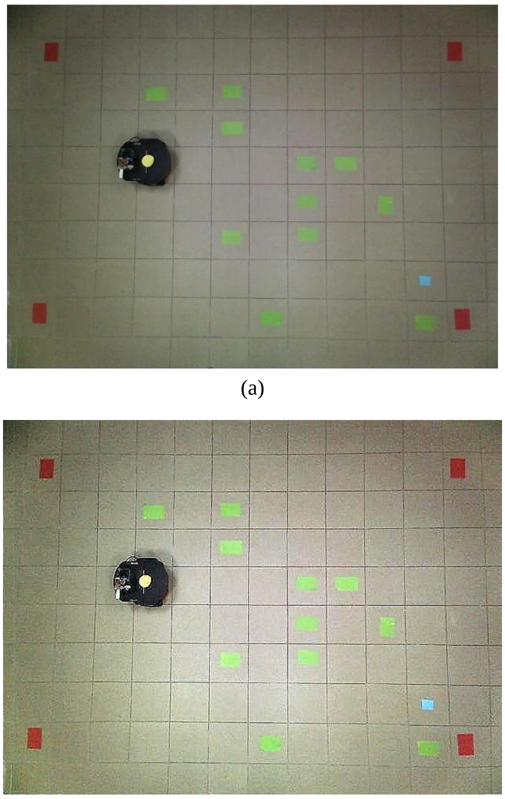


Figure 3. IPM Diagram

In (Figure.3), IPM has three main stages as

- Taking the image from the wireless IP camera and transmitting this image to the BeagleBoard-xM via modem
- Obtained image is then processed using image processing (color detection) algorithms in OpenCV Library
- Creating an indoor environment matrix

At this stage, the image of indoor environment with obstacles, the target and the mobile robot is obtained by a wireless IP camera on the ceiling as seen in (Figure.4(a)). Generated image using convolution process is presented in (Figure.4(b)).



(a)

(b)

Figure 4. The images before and after the convolution process (a) the image of the indoor application environment, (b) the image sharpened by using the convolution process

In the convolution process [37], a Kernel matrix given in Equation (1) is used. The output value of each pixel is computed using Equation (2) [38]. In this Equation, matrix of the image is taken as *src*, output matrix is taken as *dst* and Kernel matrix is taken as *K*. The center element of the Kernel matrix has the coordinates, x (K_{cx}) and y (K_{cy}). Since sharpening, clarifying the image and detecting the colors are aimed here, Kernel matrix coefficients obtained by experimental studies are used in Equation (1).

$$K = \begin{vmatrix} 0 & -1 & 0 \\ -1 & 5 & -1 \\ 0 & -1 & 0 \end{vmatrix} \tag{1}$$

$$dst(x,y) = \sum_{i=0}^{K.cols} \sum_{j=0}^{K.rows} K(i,j) * src(x+i-K_{cx}, y+j-K_{cy}) \tag{2}$$

The color detection based location map of the indoor environment is derived using this convolution processed image. Related RGB (Red Green Blue) image taken by the wireless IP camera is converted to HSV (Hue, Saturation and Value) color space [34] using the Equations shown below. RGB values are between 0 and 255. For getting HSV values, the first step is to reduce the RGB range of the obtained image from 0-255 to 0-1 range using Equation (3).

$$\left.\begin{aligned} R_1 &= \frac{R}{R+G+B} \\ G_1 &= \frac{G}{R+G+B} \\ B_1 &= \frac{B}{R+G+B} \end{aligned}\right\} \tag{3}$$

Maximum, M and minimum, m values of R_1, G_1 and B_1 are calculated and the value C is derived from M and m values using Equation (4).

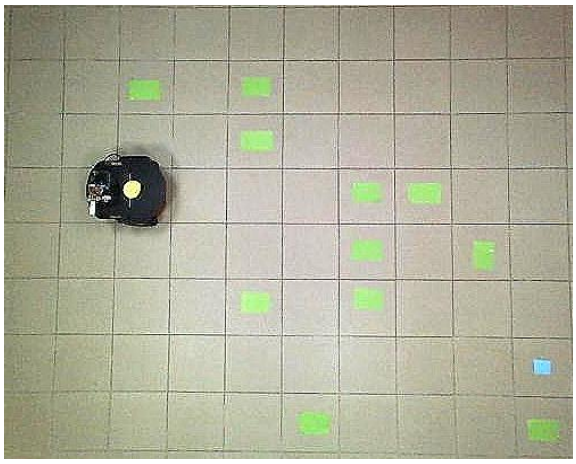
$$\left.\begin{aligned} M &= \max(R_1, G_1, B_1) \\ m &= \min(R_1, G_1, B_1) \\ C &= M - m \end{aligned}\right\} \tag{4}$$

H_1 value is derived using the values R_1, G_1, B_1 and C as in Equation (5).

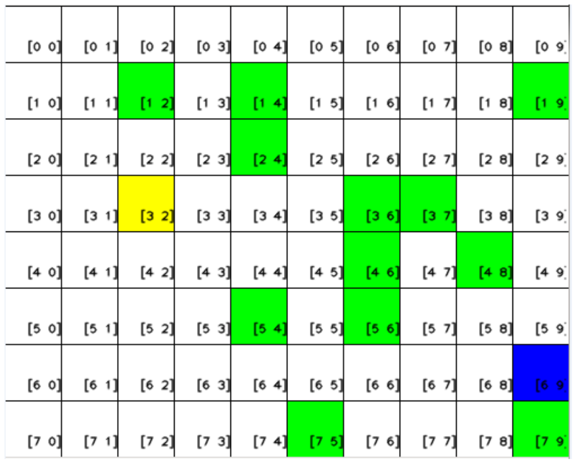
$$H_1 = \begin{cases} \dfrac{G_1 - B_1}{C} \bmod 6, & if\ M = R_1 \\ \dfrac{B_1 - R_1}{C} + 2, & if\ M = G_1 \\ \dfrac{R_1 - G_1}{C} + 4, & if\ M = B_1 \\ undefined, & if\ C = 0 \end{cases} \tag{5}$$

Finally, the H value using H_1, V value using M, S value using C and V are obtained using Equation (6). The H value is produced multiplying H_1 by 60˚ for converting H_1 to a degree between 0˚ and 360˚ [34].

$$H = 60^0 x H_1 \qquad V = M \qquad S_{HSV} = \begin{cases} 0, & if\ C = 0 \\ \dfrac{C}{V}, & if\ C \neq 0 \end{cases} \tag{6}$$



(a)



(b)

Figure 5. The navigation environment and obtained matrix (a) the limited navigation environment of the mobile robot, (b) 8x10 matrix obtained from the IPM

After converting RGB image to HSV color space, the borders of the area in which the mobile robot can travel are limited by the red objects, locating at the corners as seen in (Figure.4(a) and (b)). A new image of the limited area is shown in (Figure.5(a)). This image is used to determine the locations of the obstacles, the target and the mobile robot. The target may be anywhere in the limited area. An 8x10 matrix generated using the image given in (Figure.5(a)) is seen in (Figure.5(b)). This matrix is the output of the IPM. In the generated matrix, yellow point shows the location of the mobile robot, green points show the locations of obstacles, blue point shows the location of the target and white area shows the free space the mobile robot can travel.

2.2. Path Planning Module (PPM)

This module generates the shortest path using heuristic or metaheuristic optimization techniques. In this experimental study, GA is used for path planning. This module includes three sections named input, method and output as seen in (Figure.6). The matrix generated by the IPM is applied to this module and the method section of this module produces the GA based shortest path as an output. This output is taken as the input of the RMM. The obtained result of this module demonstrates the path from the starting point of the mobile robot to the target step by step as x-y values.

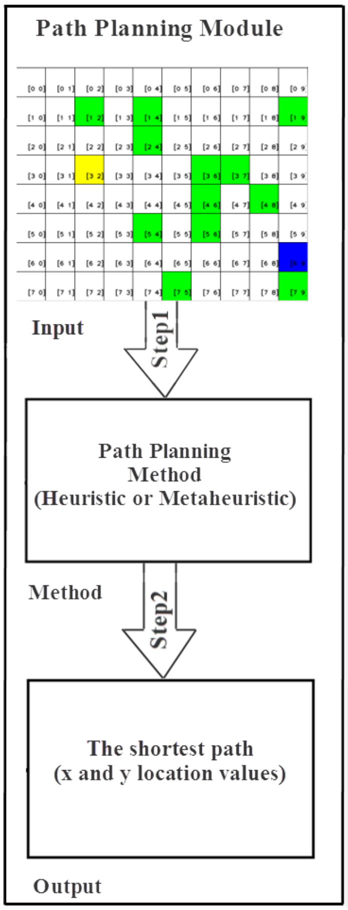


Figure 6. The block diagram of PPM

2.2.1. Genetic algorithm (GA) used in this study

In experimental studies, a heuristic method, GA is used to generate the shortest path. The flowchart of GA used in this study is presented in (Figure.7).

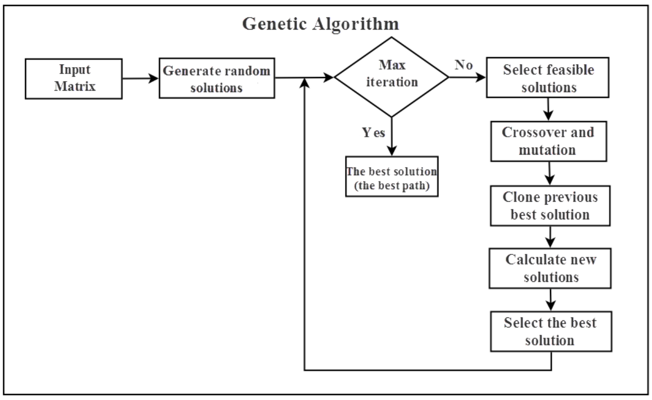


Figure 7. The flowchart of GA

The matrix obtained from IPM is taken as the input of this flow chart. The random solution set is generated using this matrix. Some solutions of this set may be unfeasible for this problem. These unfeasible solutions are discarded and the other feasible solutions are accepted as an initial solution set. Crossover and mutation operators are applied to the feasible solutions to generate new different solutions (offspring). The best one of the previous solution set is transferred to the new solution set to obtain an optimum solution set. All steps except getting the initial solution set are repeated up to the maximum iteration number. When the iteration number reached to the maximum, the last solution set is created. This final result set includes different solutions. The optimum path among these solutions is selected as the output path for RMM. The output of GA contains x-y coordinates of the optimal path that the mobile robot follows from the starting point to the target.

Fitness function is given in Equation (7) [33]. In this Equation f: fitness function, p_k: k^{th} gene of the chromosome, n: length of the chromosome. This Equation is used to calculate if the solution is feasible or unfeasible.

$$f = \begin{cases} \sum_{k=1}^{n-1} d(p_k, p_{k+1}) & \text{, for feasible paths} \\ \sum_{k=1}^{n-1} d(p_k, p_{k+1}) + penalty & \text{, for unfeasible paths} \end{cases} \tag{7}$$

Single-point crossover used in this study is shown in (Figure.8). Parent 1 and Parent 2 are two of feasible solutions obtained from the environment matrix. The two parent chromosomes are used to form the Offspring1 and Offspring2 [33].

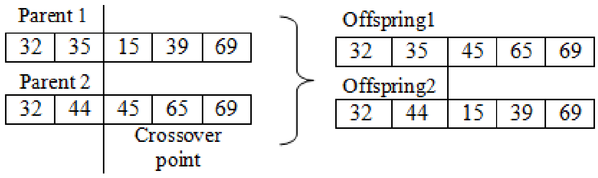


Figure 8. Single-point crossover

2.3. Robot Motion Module (RMM)

RMM is a module providing the mobile robot to follow the path from the starting point to the target. It produces the distance and direction of the mobile robot by processing the shortest path information obtained from PPM. Block diagram of the RMM is seen in (Figure.9).

The coordinates obtained from PPM are used as the input of RMM. The motion of the mobile robot from the point A to the point B for a step is seen in (Figure.10). In (Figure.10), d shows the distance between the point A and B while θ shows the rotation angle of the mobile robot. The angles and the distances from starting point to the target are calculated for each step using the Equations (8) and (9), then transferred to the mobile robot via RS232 serial port. The (A_x, A_y) is the coordinate of the mobile robot while (B_x, B_y) is the coordinate of the next step which the mobile robot reaches. The Pioneer P3-DX mobile robot travels along the path to the target using the information of these distances and angles taken from the RMM.

$$d = \sqrt{(B_x - A_x)^2 + (B_y - A_y)^2} \tag{8}$$

$$\theta = \arctan\left(\frac{B_y - A_y}{B_x - A_x}\right) \tag{9}$$

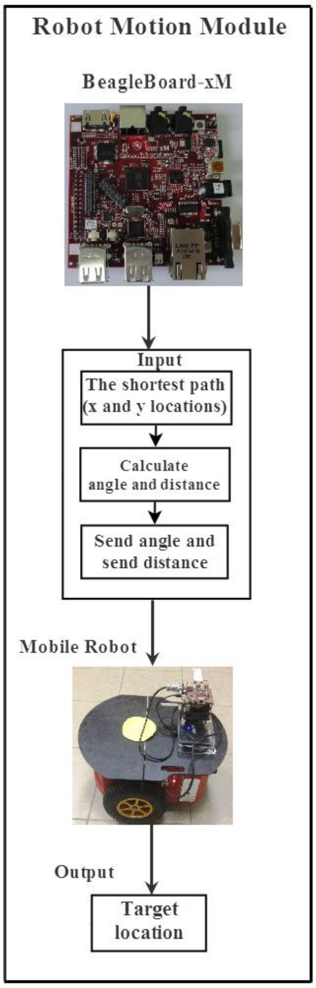


Figure 9. The block diagram of RMM

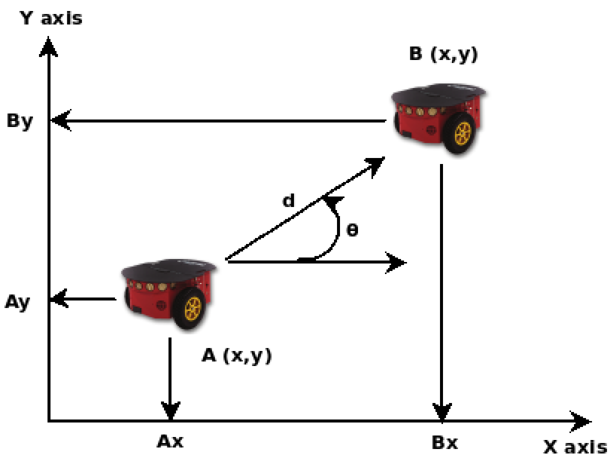
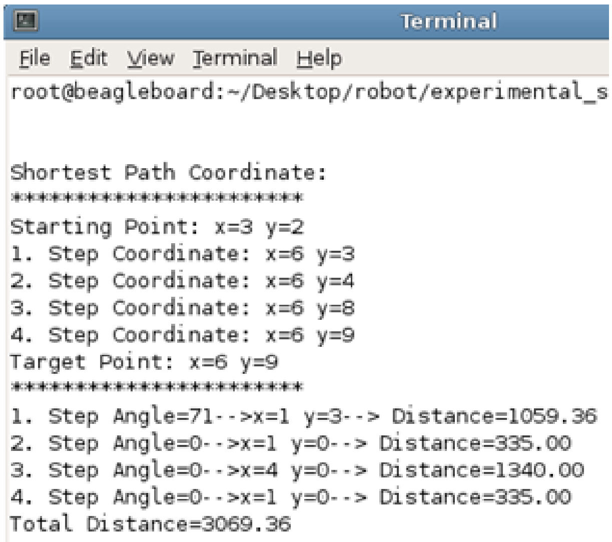


Figure 10. The motion of the mobile robot from the point A to the point B

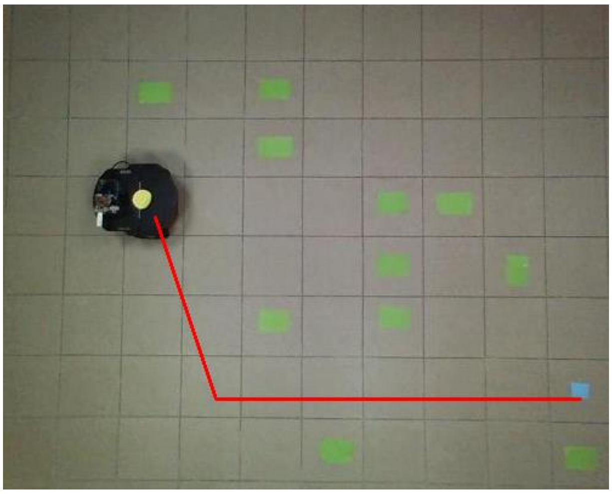
3. Application Results

In this study, an indoor environment image, including green obstacles, blue target, yellow mobile robot and red borders is taken by the wireless IP camera. The new image limited by the red borders is made up as a working area. A matrix including the locations of colored obstacles, target and mobile robot is produced utilizing the limited image. These processes are realized in IPM.

The matrix obtained in the IPM is practiced as an input of PPM. GA based PPM produces the shortest path to the target for the mobile robot. Because a limited indoor environment is used in this study, 100 iterations and maximum 5 steps are utilized to produce the shortest path in GA and satisfying results are obtained.



(a)



(b)

Figure 11. The mobile robot's motion results (a) the shortest path result screen, (b) the image of the mobile robot's path

The shortest path locations produced by PPM is applied to the RMM to mobilize the robot. In (Figure.11(a)), the shortest path produced by PPM is listed under the title, "*Shortest Path Coordinate*". Then, this path list is applied to the mobile robot as a rotate angle with the direction and distance step by step. In this experimental study, the mobile robot reaches the target in four steps. These four steps are given as the rotate angle, the direction and the distance on the screen as viewed in (Figure.11(a)). In RMM, the direction of the mobile robot is accepted as straight to the target. In this experimental study, the obtained shortest path the mobile robot follows from starting point to the target is seen as a red line in (Figure.11(b)). In (Figure.11(b)), it is depicted in the image taken by the wireless IP camera.

4. Conclusion

In this study, a low cost, flexible and modular mobile robot motion planning system is realized in an indoor environment with obstacles. A mobile robot motion system is designed by placing the BeagleBoard-xM on the top of the mobile robot, getting the image wirelessly. The mobile robot motion planning system is designed in three modules including IPM, PPM and RMM. The color detection technique is employed to generate the map of the environment in the IPM here. Different detection techniques such as object or contour recognition can be applied instead in this module. Although GA is used in PPM to find the shortest path in this study, this module can be improved using different methods or algorithms such as tabu search, ant colony, simulated annealing, particle swarm optimization. Similarly, the obtained results from RMM can be conformed to any other robot by slight changes. Since these three modules are independent from each other, this system has a flexible and adaptable structure for different mobile robot applications.

The most of the studies in literature concentrate on the methods used for path planning and these methods are generally simulated on the computers. Some realized systems in literature use Laptops, on-board PCs or PC having higher cost, higher power consumption, bigger space, higher weight and the necessary licensed software as Windows Operating System and MATLAB requiring higher costs, higher processing capability and power consumption. On computers using especially the Windows Operating System, some extra software or processes exist running in the background. This causes the computer consume more power and lessen the processing capability.

Nevertheless, the BeagleBoard-xM has low cost, low power consumption, smaller space, lower weight and utilizes open source software as Angstrom and OpenCV requiring lower processing capacity with no monetary value. The operating system utilized in the BeagleBoard-xM can be optimized according to the designed system. Thus, there is no unnecessary software or processes running on the background. In addition, a wireless IP camera is used to take the photo of the environment. This prevents the system from using long cables owning cost and making the environment complex. A realistic, useful and practical model for mobile robot navigation systems is proposed in this work. This proposed model can be used in closed areas such as factories, warehouses. The camera or cameras can be located along the cover of the mobile robot in future studies for both outdoor and indoor applications. Since a wireless modem is used in this system for communication between BeagleBoard-xM and the wireless IP camera, this study can be ameliorated to a remote controlled mobile robot application in future surveys.

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