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Research Article

Design, Construction and Control of an Autonomous Mobile Rescue Robot with Visual Feedback

Ibrahim Hasan[1], Tolgay Kara[2]

[1] Gaziantep University, Department of Electrical and Electronics Engineering, Gaziantep, Turkey (ORCID: 0000-0003-3991-8524), kara@gantep.edu.tr
[2] Gaziantep University, Department of Electrical and Electronics Engineering, Gaziantep, Turkey (ORCID: 0000-0001-8203-3225), en.ibrahim4.hasan4@gmail.com
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Abstract

The construction of a smart autonomous mobile robot system that can operate in an anonymous environment can be difficult. Building an autonomous mobile robot requires collecting data from sensors and cameras in order to recognize the surrounding environment, get knowledge of existing landmarks, and figure out its position and orientation. Many research studies have been carried out in recent years providing algorithms for achieving autonomous motion of mobile robot systems and object detection. The most common platform utilized for robot motion design is ROS (Robot Operating System) and for object detection YOLO (You Only Look Once) is a common choice. Additionally, the autonomous system needs motion planning in a systematic way to avoid obstacles by using LIDAR or other sensing methods generating the feedback signals required for control of motion around occupied spaces. One of the most effective and versatile feedback systems for mobile robot control can be constructed using visual feedback, which relies on a high-resolution camera that processes the image in real-time and the result is fed back to the control system for decision making. Visual feedback can be employed alone without sensors for feedback control of autonomous mobile robots, and it can be used for multiple tasks like path planning, obstacle avoidance, object detection, object recognition in addition to motion control. In this research, results of design and construction of an autonomous mobile rescue robot for finding victims through video data are presented. It is aimed to find victims via applying video as a data collection and feedback generation tool in the autonomous mobile robot control system. The visual feedback and YOLO v3 are used not only for finding victims but also for motion control. Our autonomous mobile robot is designed to move smoothly to the victim's direction and avoids obstacles by using ROS Global Planner. The robot is tested in multiple scenarios in different locations, various obstacle and victim numbers, and satisfactory results with good performances are obtained.

Keywords: Autonomous mobile robot, ROS, YOLO, Motion planning, Obstacle avoidance, LIDAR, Visual feedback system.

Görsel Geri Beslemeli Otonom Mobil Kurtarma Robotunun Tasarım, Üretim ve Kontrolü

Öz

Bilinmeyen ortamlarda çalışabilen akıllı otonom mobil robot sistemi üretimi zorluklar içerebilir. Otonom mobil robot geliştirilmesi için çevreyi tanımlamak amacıyla algılayıcılar ve kameradan veri toplanması, mevcut köşe noktalarının bilinmesi ve robotun konumu ve yönünün anlaşılması gerekir. Son yıllarda mobil robotların otonom hareketi ve nesne belirleme hedefleri için yazılmış algoritmalar sunan çok sayıda araştırma yapılmıştır. Robot hareket tasarımı için en yaygın kullanılan platform ROS (Robot İşletim Sistemi) iken, nesne belirleme içinse YOLO (You Only Look Once) genel kabul görmektedir. Ek olarak, otonom sistemlerde lidar ve diğer algılama yöntemleriyle engeller içeren ortamlarda hareket kontrolü için gereken geri besleme işaretini üretmek üzere sistematik hareket planlamaya ihtiyaç duyulmaktadır. Mobil robotlar için en etkili ve çok yönlü geri beslemeli sistemlerden biri, yüksek çözünürlüklü kamerayla gerçek zamanlı görüntü işleme ve geri beslemeli kontrol karar işareti üretimine dayanan görsel geri besleme yoluyla imal edilebilir. Görsel geri besleme otonom mobil robotların algılayıcılar olmadan geri beslemeli kontrolü için kullanılabileceği gibi, hareket kontrolüyle birlikte yol planlama, engelden kaçınma, nesne belirleme, nesne tanıma gibi çoklu görevlerde de kullanılabilir. Bu çalışmada, akan görüntü verisi kullanılarak kurban / kazazedeleri bulmaya yarayan otonom mobil robot sisteminin tasarım ve üretimi ile ilgili sonuçlar sunulmaktadır. Burada kamera görüntüsünü hem veri toplama hem de otonom mobil robot sisteminde geri besleme işaretini üretme amacıyla kullanarak kurban / kazazedeleri bulmak amaçlanmıştır. Görsel geri besleme ve YOLO v3 sadece kurban / kazazedeleri bulmak için değil aynı zamanda hareket kontrolü için kullanılmaktadır. Ürettiğimiz otonom mobil robot, ROS küresel planlayıcı ile kurban / kazazede yönüne doğru yumuşak bir hareketle ilerlemek ve engellerden kaçınmak için tasarlanmıştır. Robot farklı engel ve kurban / kazazede sayıları için değişken ortamlardaki senaryolar için test edilmiş ve yüksek başarımlı tatmin edici sonuçlar elde edilmiştir.
Anahtar Kelimeler: Otonom mobil robot, ROS, YOLO, Hareket planlama, Engelden kaçınma, LIDAR, Görsel geri beslemeli sistem.

1. Introduction

The cutting-edge robotic technologies have assisted mankind in the past few decades, and robots have been employed universally in several fields for various functions to carry out significant duties. Robots are designed to operate in various environments with or without human intervention, and many times the main purpose is to help humans in their tasks and even save their lives in certain cases. They can operate and achieve the goals in environments where all special tangible characteristics have to be under control. Autonomous mobile robots can carry out searching and rescuing jobs where conditions are tremendously risky for humans. In such scenarios, robots must have autonomous expertise and capabilities of certain human skills, even so, they do not suit human intervention. Examples of the requirement of applying autonomous human detection and rescue can be wars, earthquakes, building collapses, mine collapses, and similar. In these situations, there are possibly large numbers of victims who encounter risk of death, not to mention those who sacrifice their lives in rescuing others. Search and rescue operations are the main cause of demise along with other collateral damage in such environments. The design and construction of an autonomous mobile robot that can operate autonomously in catastrophic areas for search and rescue missions has vital value and can save lives of the potential victims and protect rescue teams as well.

2. Material and Method

In areas after wars or natural disasters, many members of the rescue teams lose their lives, in addition to many victims who are trapped under the rubble or in places that are difficult to reach. In our research, we have designed a simple prototype of an autonomous mobile rescue robot that can search for victims. The mission of our robot is to search for, find and locate victims autonomously. We have used the Robot Operating System (ROS), which is a set of software libraries and tools that help to build any robot, and You Only Look Once (YOLO), which is an object detection algorithm that includes localization of objects in a picture and guessing the class to which it belongs. In disaster places, it is likely to suffer from weak internet and in many cases the lack of internet connection. We have solved this problem by saving the video data on the computer hard disk. The control system we have used is traditional visual servoing, where we have used the desired site of the current position of the feature point in the image and the feature point in the image. We have used RPLIDAR A1M8 to avoid obstacles, which is based on the laser triangulation ranging principle and uses high-velocity sight acquisition and processing devices. The navigation stack in ROS consists of a mobile robot motion planner and controller that creates a 2D map for the surrounding area to bypass the obstacles and move the robot until it reaches its destination. I should be noted that this node transmits the commands to the robot base as a speed vector for translation motion and single rotation speed variable as rotation speed around the z-axis. Move base is a part of the navigation stack that is responsible for robot motion behaviour. In analysing video data, we have relied on YOLO which detects a person from the camera feed and passes the detected bounding box to box2goal node that takes the detected bounding box from YOLO and current position from the moving base and generates a 2D point as a new goal to the motion base. Arduino bridge is the node responsible for translating the motion variables that come from the navigation stack to the locomotion model and producing a torque control for each wheel of the robot (velocity PID control for each motor). One of the expected results in our research is to know the number of victims in the disaster area before starting the rescue mission and to know and prepare the necessary equipment for the mission to save time.

2.1. Robot signal flow and visual servoing

The web camera of the robot can be considered as the robot's eye. The camera records a live video of the place where the robot is operated and sends the recorded video to YOLO, which analyses the video data in order to identify the desired object that is a victim in our case. After selecting the required object, the data is sent to the ROS, which is on our computer to send/receive instructions to/from Arduino and receive from RPLIDAR A1M8 and web camera. We have used an RPLIDAR A1M8 and ultrasonic sensor for our robot to avoid obstacles, also the RPLIDAR A1M8 sends the data captured by the laser scanner to the ROS. ROS is considered our robot's brain, which programmatically links all these elements together and sends/receives data from all the elements. Similarly, we have used the Arduino to control the process and connected it to the ROS programmatically and to the L298N driver physically. The L298N driver is connected to the two motors physically, and it sends control signals to the two motors at the same time, also receiving data from both motors' encoders. Finally, we have used LED to turn on when the mobile robot finds a person and turn off when there is no person detected. Our signal flow diagram is given in Figure 1.

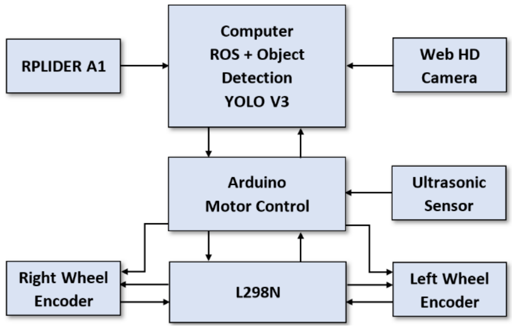


Figure 1. Communication pathways to all hardware of the designed autonomous mobile robot.

2.2. Control Law

A general look at the methods that can be implemented for generating the control signal reveals that the visual operation can be divided into two parts based on the image data used, the first one being the position-based approach and the second one being the image-based approach (Lang et al. 2016). The block diagrams are the same for the two traditional methods, with only difference in the terms of the control system and the processed data received from the video feedback, as shown in Figure 2.

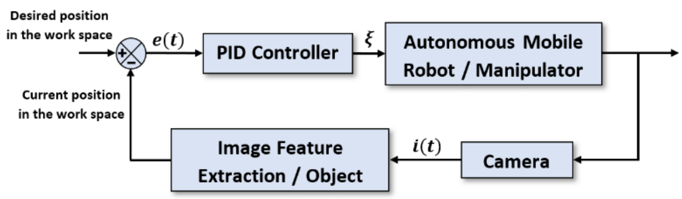


Figure 2. The block diagram of the visual servoing.

The aim of the control system is the reduction of the position error of the image or the position error of the object in 3D space, for the two alternative methods respectively. In controlling the motion of the mobile robot, in our study it is implemented that the mobile robot moves towards the victim and tries to put the box shown in YOLO in the middle of the screen. We can write the error as follows:

$$\boldsymbol{e(t)} = \boldsymbol{s(i(t), c)} - \boldsymbol{s_r} \quad (1)$$

Where

$\boldsymbol{e(t)}$ is the error between measured and desired positions,
$\boldsymbol{s}$ is the measurement from the image or it can be estimate by using computer vision,
$\boldsymbol{i(t)}$ is a set of picture measurements,
$\boldsymbol{c}$ are parameters describing additional information about the system (e.g 3D object model or camera parameters),
$\boldsymbol{s_r}$ are desired values of the features,
$\boldsymbol{s(i(t), c)}$ and $\boldsymbol{s_r}$ can be specified depending on which kind of visual servo control is used.

A standard method is to design a speed control system, which needs the relationship between the time variation of $\boldsymbol{s}$ and the camera velocity. Let us write the spatial velocity of the camera as $\boldsymbol{\xi} = (\boldsymbol{v}, \boldsymbol{w})$; where v is the linear speed of the origin of the camera and ω is the angular speed of the camera. The relationship between $\dot{\boldsymbol{s}}$ and $\boldsymbol{\xi}$ is given by:

$$\dot{\boldsymbol{s}} = \boldsymbol{L\xi} \quad (2)$$

Where

$\dot{\boldsymbol{s}}$ is the speed of the target objects,
$\boldsymbol{L}$ is the interaction matrix,
$\boldsymbol{\xi}$ is the speed vector of the webcam.

By solving (1) with (2), the dynamic equation for the error can be written as:

$$\boldsymbol{e(\dot{t})} = \boldsymbol{L\xi} \quad (3)$$

Where $\boldsymbol{e(\dot{t})}$ is the time variation of the error. The Lyapunov function can be used as a control law for the square-of-error,

$$\dot{\boldsymbol{s}} = \boldsymbol{L^{-1}}(-\boldsymbol{ke}) \quad (4)$$

2.3. Mathematical Model of Image-based Visual Servoing

The purpose of the image-based visual serving is to reduce positional errors of the target objects in images captured by the camera when the autonomous mobile robot is in motion. The control system continuously adjusts the velocity of the mobile robot wheels based on the outputs of the control system (Lang et al. 2016), so that the paths of the target objects $\boldsymbol{u_i}, \boldsymbol{v_i}$ navigate to the wanted sites $\boldsymbol{u_{di}}, \boldsymbol{v_{di}}$ on the camera picture. Thus, the error vector of the target objects in the image plane is written as follows:

$$e = \begin{bmatrix} \boldsymbol{u} & -\boldsymbol{u_d} \\ \boldsymbol{v} & -\boldsymbol{v_d} \end{bmatrix} = \begin{bmatrix} -\boldsymbol{s_x}(\boldsymbol{r} - \boldsymbol{r_d}) \\ -\boldsymbol{s_y}(\boldsymbol{c} - \boldsymbol{c_d}) \end{bmatrix} \quad (5)$$

Where

$\boldsymbol{s_x}$ and $\boldsymbol{s_y}$ both of it delineate scales of image pixels of the camera,
$\boldsymbol{r}$ and $\boldsymbol{c}$ are pixel coordinates

The speed of the target objects can be written by the following equation:

$$\dot{\boldsymbol{e}} = \begin{bmatrix} \frac{\boldsymbol{d(u-u_d)}}{\boldsymbol{dt}} \\ \frac{\boldsymbol{d(v-v_d)}}{\boldsymbol{dt}} \end{bmatrix} = \begin{bmatrix} \dot{\boldsymbol{u}} \\ \dot{\boldsymbol{v}} \end{bmatrix} \quad (6)$$

By substituting (6) into (3), we get the equation as follow:

$$\begin{bmatrix} \dot{\boldsymbol{u}} \\ \dot{\boldsymbol{v}} \end{bmatrix} = \boldsymbol{L\xi} \quad (7)$$

If we suppose the error dynamics satisfies $\dot{\boldsymbol{e}} = -\boldsymbol{ke},$ a proportional controller based on Lyapunov theory can be designed as follows:

$$\boldsymbol{\xi} = \boldsymbol{L^{-1}}(-\boldsymbol{ke}) \quad (8)$$

Here $k > 0$ and k is proportional gain, thus the control law can be obtained by substituting (5) into (8) as follows:

$$\boldsymbol{\xi} = -\boldsymbol{kL^{-1}} \begin{bmatrix} -s_x(r - r_d) \\ -s_y(c - c_d) \end{bmatrix} \quad (9)$$

Here, $\boldsymbol{r}$ and $\boldsymbol{c}$ describe the pixel coordinates in the captured figure via camera. The required speed of the camera at the 3D space can be computed from the image measurements. Furthermore, the improved controller guarantees asymptotic stability in a closed-loop design. Equation (9) contains the interaction matrix that explains the motion relationship between the camera in three-dimensional space and the target objects in the image in terms of their respective speeds. We can write the interaction matrix in a detailed formulation as follows:

$$\begin{bmatrix} \dot{\boldsymbol{u}} \\ \dot{\boldsymbol{v}} \end{bmatrix} = \boldsymbol{L\xi} = \begin{bmatrix} -\frac{\boldsymbol{\lambda}}{\boldsymbol{z^c}} & \boldsymbol{0} & \frac{\boldsymbol{u}}{\boldsymbol{z^c}} & \frac{\boldsymbol{uv}}{\boldsymbol{\lambda}} & -\frac{\boldsymbol{\lambda^2+u^2}}{\boldsymbol{\lambda}} & \boldsymbol{v} \\ \boldsymbol{0} & -\frac{\boldsymbol{\lambda}}{\boldsymbol{z^c}} & \frac{\boldsymbol{v}}{\boldsymbol{z^c}} & \frac{\boldsymbol{\lambda^2-u^2}}{\boldsymbol{\lambda}} & -\frac{\boldsymbol{uv}}{\boldsymbol{\lambda}} & -\boldsymbol{u} \end{bmatrix} \boldsymbol{\xi} \quad (10)$$

Where

$\boldsymbol{\lambda}$ is the focal length,
$\boldsymbol{z^c}$ is the distance between the camera coordinate in 3D space and the object of interest.

To complete the interaction matrix, the distance must be either approximated or measured. In some applications, if we do not have a direct way to measure the distance, we can estimate it.

3. Construction of Autonomous Mobile Rescue Robot

The construction of the mobile robot is based on many studies and models (Baldemir et al. 2020, Bhondve et al. 2014, Bishop et al. 2005, Dissanayake et al. 2006, Habibian et al. 2021, Kayisli et al. 2017, Keçeci 2009, Liu et al. 2016, Sucuoğlu et al. 2018, Tyugin et al. 2019, Zhang et al. 2020), the structure should be suitable for the anonymous environment as much as possible. Depending on many previous studies, the autonomous mobile robot relies on suitable motor torques, sufficient to carry the tools used for mobile robot and low speed. Schematic representation of system electronics and their connections is given in Figure 3. A high-resolution camera is used for capturing live video images of the surrounding environment. A laptop computer with CORE i7 processor is used in the robot. A detailed list of other equipment used in robot construction is provided in Table 1.

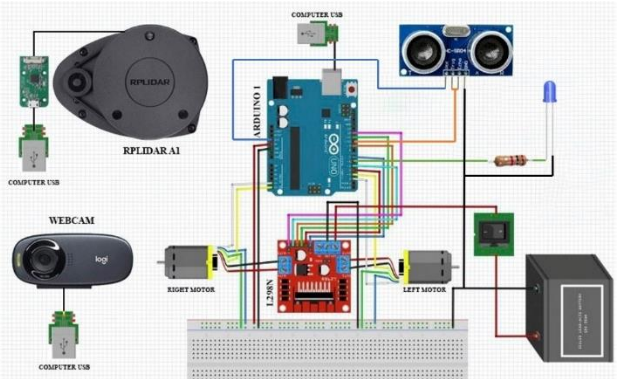


Figure 3. Electronic circuit of autonomous mobile robot.

In this study, it is aimed to design a small prototype of the mobile robot as shown in Figure 4 to test the control design part. The dimensions of the robot are 45 cm in length, 35 cm in width, and 42 cm in height. total weight is 3.5 kg including the electronic equipment used for mobile robot and to recognize the victims easily. In designed robot structure, completely open box on the left side is preferred to provide convenience in input-output connections of the laptop as shown in Figure 4.b, and the right side is made up of three shelves placed in the form of stairs in order to connect the wires easily as shown in Figure 4.a. The RPLIADER is placed at the front of the top of the upper shelf because the surrounded area should be empty to give accurate values. The camera is placed in the middle of the second shelf in order to record live videos of several positions of the victims like the victim completely on the floor, half lying on the ground or half lying on a chair. The ultrasonic sensor is used in order to stop the robot when it approaches the victim at a very small distance before crashing into them as shown in Figure 4.d. The LED is supposed to turn on when the camera captures the victim and turn off when no victim is captured. We rely on two wheels from the back Figure 4.c and castor wheels in the front for ease of movement in different directions as shown in Figure 4.d.

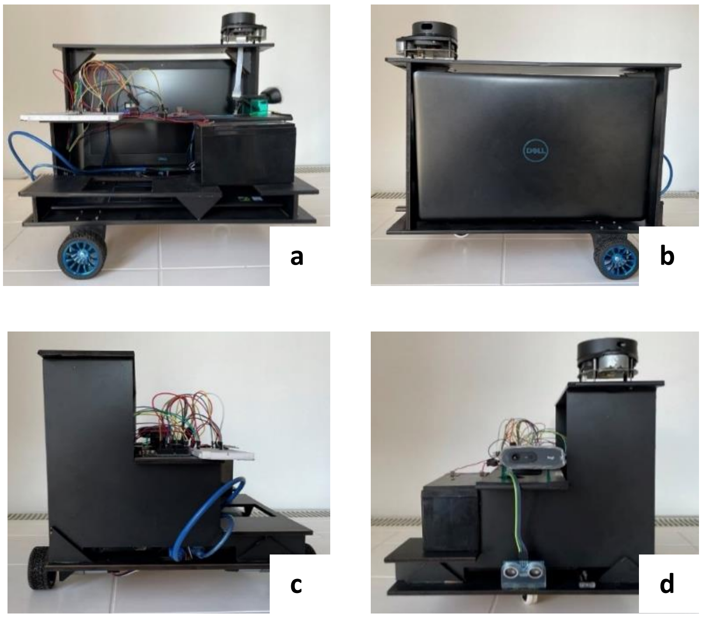


Figure 4. Physical structure of constructed autonomous mobile robot as seen in right view (a), left view (b), back view (c), and front view (d)

Table 1. Equipment used in robot construction

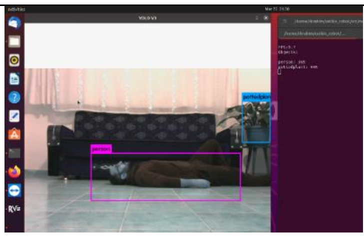
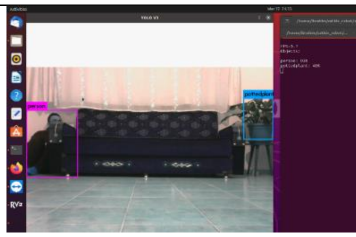
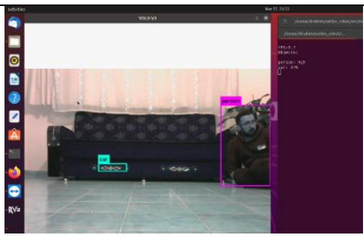
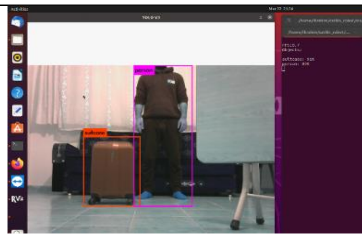
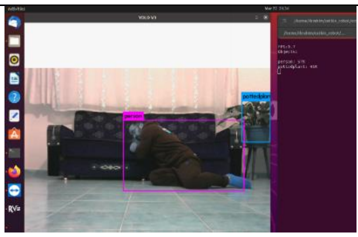
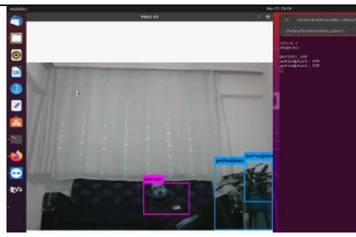
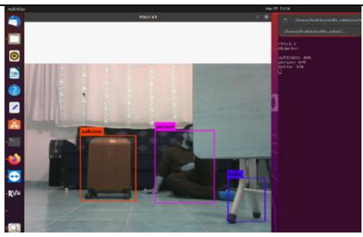
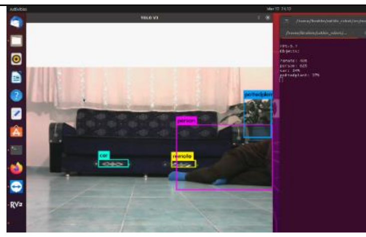
USB Webcam	The C270 HD webcam can record video data obviously and smoothly with max resolution 720p/30fps in a widescreen format with a diagonal 55° field.
Computer	The specification of used computer: • Processor Intel(R) Core (TM) i7-8750H CPU @ 2.20GHz 2.21 GHz • Installed RAM 16.0 GB (15.9 GB usable) • System type 64-bit operating system, x64-based processor
RPLIDAR A1M8	Based on the laser triangulation scope principle, which uses high-velocity vision acquisition and processing devices. RPLIDAR A1M8 is a 2D laser scanner and can perform a 360 scan within 12 meters range (6 meters range of A1M8-R4). The 2D points created can be used in mapping, localization and obstacles avoidance. RPLIDAR A1 can work perfectly in indoor environments.
Arduino	It is an open-source electronics platform that is easy to use as hardware and software. The Arduino board can read inputs such as sensor signals, pushbuttons, or a tweet message and convert them into an output such as turning a motor on/off, turning LED on/off.
DC motor	Two DC motors with an encoder are used with a power supply of 12v, speed 76 RPM and current 0.2 A. In the maximum efficiency 12v, speed 66 RPM and current 0.74 A.
L298N	The L298N control the direction and speed of two motors at the same time because it has a dual H-Bridge motor driver and generates PWM single.
Ultrasonic Sensor	Distance ratings between 0.2 to 18 meters.
Power Supply	TTEC plus FP1270 12V 7AH-20HR is preferred for it does not need maintenance.
The castor wheels	Which allow the robot to move in any direction are also used.
Signal LED	Blue LED turn on when the robot detects the victim and turn off when the robot does not detect the victim.

Table 2. Test results of mobile robot for different scenarios

Location	Applied tests	Accuracy	Applied tests	Accuracy	Applied tests	Accuracy
House	32 tests, no obstacles	96.875 %	32 tests, different types of obstacles, sparsely located.	81.250 %	32 tests, different types of obstacles, closely located.	62.250%
Laboratory	8 tests, no obstacles	87.500%	8 tests, different types of obstacles, sparsely located.	75.000%	8 tests, different types of obstacles, closely located.	50.000%
Office	12 tests, no obstacles	91.667%	12 tests, different types of obstacles, sparsely located.	83.334%	12 tests, different types of obstacles, closely located.	58.334%

Accuracy = number of successful tests / number of test cases.

Table 3. Victim detection results in different positions

The victim is completely on the floor and the YOLO detection percentage for the victim is 38%.		The victim is sitting on the floor next to the sofa and the YOLO detection percentage for the victim is 93%.	
The victim is half laying on the ground and the YOLO detection percentage for the victim is 92%.		The victim is between two obstacles (suitcase and table) and the YOLO detection percentage for the victim is 91%.	
The victim is half lying on the sofa and the YOLO detection percentage for the victim is 57%.		Only the upper part of the victim is visible and the YOLO detection percentage for the victim is 34%.	
The victim is sitting on the floor between two obstacles (suitcase and table) and the YOLO detection percentage for the victim is 89%.		Only the lower part of the victim is visible and the YOLO detection percentage for the victim is 49%.	

3. Results and Discussion

Experimental results with various environments have been tested in real environments with different positions of obstacles, and the results have shown the flexibility of the mobile robot in avoiding obstacles as well as detecting victims accurately. The results are satisfactory for many search and rescue applications of various scenarios, as presented in Table 2 and Table 3. The first experimental test is in a house with two rooms, the size of the whole perimeter is $5.5 \times 5.5 = 30.25\ m^2$ as shown in Figure 5. The second experimental test is conducted in laboratory, 12 meters in length and 8 meters in width as shown in Figure 6. The third one in an office with three rooms as shown in Figure 7. The victims in various situations are detected successfully by using YOLO V3 as shown in Table 3. Also, obstacle avoidance is achieved successfully by using RPLIDAR A1M8 and an ultrasonic sensor. Many tests have been conducted depending on victims and obstacles, the first test is for one victim without obstacles in the tested area and the robot moves directly to the victim smoothly. For the case of one victim with one obstacle on the mobile robot path, the tests have shown accurate results to reach the final goal and avoid the obstacle. For the case of one victim with more than two obstacles on the path, the tests have shown good results except that the mobile robot loses the path to reach the final target many times if the two obstacles are too close to each other, if the distance between the obstacles is less than 50 cm. Finally, in narrow corridors less than 50 cm wide, the mobile robot cannot pass easily and in some cases, it is stuck in the corridor. All test scenarios conducted separately in three different locations are given and results are summarized in Table 2.

Finding victims in a disaster area is a difficult problem for rescue teams, so many robots have been designed and developed to perform the process of recognizing victims using object recognition algorithms. Among the most commonly used single-stage detectors are YOLO v3, YOLO v2, Retina Net and SSD that satisfy this aim (Gelan 2019). For all body postures in different positions in cases of fully visible and partially occluded, the tests show that the YOLO algorithm has the highest precision rates (Redmon 2016). In our study, we use the YOLO v3 algorithm to identify victims in various positions, such as lying, under the rubble or trapped, and when their bodies may be partially visible. We capture images of victims from the mobile robot with the camera situated at 35cm from the ground level, and results of victim detection performances are depicted in Table 3.

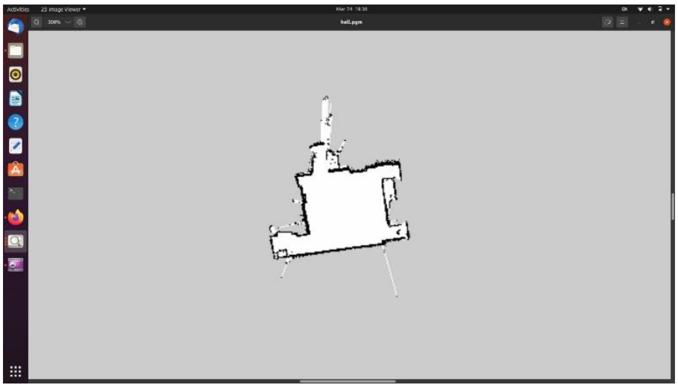


Figure 5. A map created from the tested house.

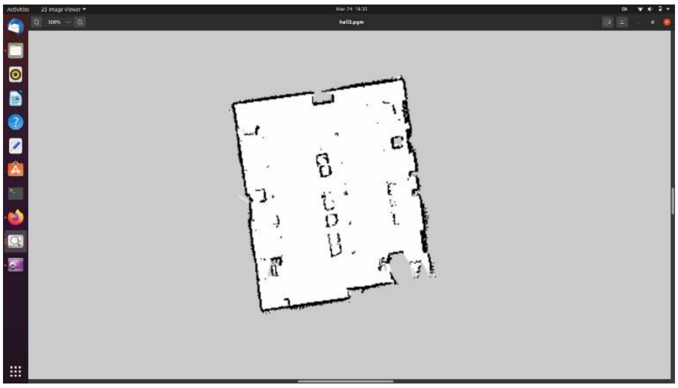


Figure 6. A map created from the laboratory.

Figure 7. A map created from the office.

4. Conclusions and Recommendations

In this research, the design and construction of an autonomous mobile rescue robot with visual feedback is presented. The autonomous mobile robot is designed to search for the victims in indoor areas after disasters like earthquakes or explosions, and also to transfer the collected data about the area and the victim's position. The designed prototype of the autonomous mobile robot has given sufficiently accurate results. Experiments have been conducted in the real environment in order to observe robot movement and validate the results on victim detection, map construction and path planning. Test results justify the prospective value of the designed autonomous mobile robot in search and rescue missions. In future, further improvements on the robot are planned via optimisation in robot design for real rescue missions in harsh environments.

In the upcoming studies, further improvements on the autonomous mobile robot are planned via optimization in robot design for actual rescue missions in harsh environments. First, the prototype of an autonomous mobile robot can be developed to do more tasks, such as helping victims or carrying them to safer places, also in some cases delivering first aid to locked people under rubbles. Our autonomous mobile robot could be integrated with other mobile robots to do full missions, for example, connect with a robot arm to carry victims. On the other hand, the victim detection algorithm could be developed to determine whether the people in disaster areas stay alive, injured or dead, and achieve the necessary process to save their life.

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