

A Comparison of Ultrasonic and Laser Sensor-Based SLAM Algorithms Applied to Carlike Vehicles

Nevzat Yağız Tombal¹ , Tarık Veli Mumcu² 

¹Department of Electric and Energy, İstanbul Gelisim University Vocational School, İstanbul, Turkey

²Department of Electrical-Electronics Engineering, İstanbul University-Cerrahpasa Faculty of Engineering, İstanbul, Turkey

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ABSTRACT

Simultaneous localization and mapping (SLAM) is the process of building a consistent map of the environment an autonomous mobile robot travels while simultaneously determining its position on the map when it is placed in an unknown location in an unknown environment. SLAM is used in technologies such as autonomous vehicle systems, post-disaster recovery, and life detection, mine or dent map extraction. SLAM aims to improve today's autonomous robot technology and build a near-perfect autonomous robot technology in the future. With this thought, researchers' interest in the SLAM problem and studies on it have continued increasingly. In this way, SLAM gives results closer to reality. One of the most important criteria of an autonomous robot is its ability to perceive its environment. Sensors placed on the robot transform environmental conditions information into signals suitable for processing by the robot. Proper sensor selection is very important as it affects the quality and quantity of environmental condition information presented to the robot. The study aims to determine the sensor technologies used in SLAM and their contribution to the solution of the SLAM problem. In this study, data were acquired in a specific environment using a single sensor.

Index Terms— Autonomous, localization, mapping, robot, sensor.

I. INTRODUCTION

The frequency of robots being used in daily life and industry is increasing today. The scope of the robotics industry encompasses various areas, ranging from basic home devices to complex machinery used in factories and manufacturing facilities. As the needs differ and diversify in the world we live in, the robotics industry is evolving to keep up with this change. There are different usage areas where robots can produce solutions for various needs. One of these areas of use is the scanning of the environment or space by moving the robot in a random environment or space [1]. The importance of using robots in tasks where human life may be at risk cannot be understated, as it helps prevent potential loss of life or injuries [2]. For robots operating in unknown and unpredictable conditions, the ability to make autonomous decisions, whether partially or entirely, while performing tasks becomes vital [3]. These specialized robots, which are produced for research in different environments and can draw a road map on their own, are called autonomous robots.

Autonomous robots perform the necessary operations sequentially by synthesizing the data they receive from external sensors and using the decision-making mechanism they have created. If it is explained in a user-friendly way, robots that collect information from their environment from the sensors they have and make this information meaningful in their own microprocessor and decide how to do the task are called autonomous robots [4].

The primary condition for a mobile robot to work autonomously is to recognize the environment in which it will perform its task. Often, it may not be possible for the robot to load a previously prepared map as information and to travel from the starting location of the robot on a route created according to the map data. Even if there is a chance to load map data to the robot before the mission, the need for the recognition of the environment will continue as the conditions and objects may change in dynamic environments. Therefore, autonomous robots must demonstrate their ability to continuously detect their positions and simultaneously map the objects around them with their location or environment. When an autonomous robot starts its journey from an

Corresponding author:

Nevzat Yagiz Tombal

E-mail:

yagiz.tombal@gmail.com

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unknown location in an environment with no prior information, and successfully creates a realistic map of its surroundings while simultaneously marking its own position within that map, this process is known as SLAM [5].

Randall Smith et al. [6] explained with an example that an autonomous robot determines the objects around it and generates position information in a two-dimensional environment. In this example, the autonomous robot performs some steps sequentially.

The robot detects object 1 and continues its movement. Then the robot detects another object. Since he already knows his position, the direction he is moving, and the distance he has traveled, he decides that the object he has just perceived is a different object than the previous one. It defines this object as object number 2. In the end, the robot rotates around itself and detects objects 1 and 2 again, thus learning its true location. This iterative process of the robot updating its observations whenever it changes its position is referred to as loop closure detection in the literature [7]. These steps can be seen in Fig. 1.

The objects detected around the robot are named landmarks. If the robot calculates its distance from landmarks during its motion, it can map the environment. SLAM logic can be summarized in a simple way with this method.

Robots have been used in dangerous environments for many years. Stone and Edmonds [8] designed a robot that can detect and classify hazardous substances in the environment and help eliminate the problem caused by chemical leakage or similar conditions. Tojo et al. [9] designed a robot with a special handle to facilitate the use of robots designed to detect and destroy mines in areas where transportation is difficult. Bengel et al. [10] designed a robot for use in oil refineries in the oceans. Nawaz et al. [11] studied a robot designed to be used in the observation and detection processes of nuclear waste collection ponds. Caves and mines are also some of the environments where robots can be used [12-14]. Autonomous robots are used in many different areas like these today. The tasks assigned

to robots will also become more detailed in the following years. In order for the robot to catch these developments, it must process and make sense of the data around it as much as possible. The approach and improvement studies to the SLAM problem are done precisely for this reason.

One of the most basic measurements a robot has to make is the instantaneous measurement of its distance from surrounding objects. Many different sensor types are used today for distance calculation. Sound sensors working with the logic of reflection of the sound, laser sensors working with the reflection of light, and vision sensors with cameras are the most commonly used sensor types for distance measurement. Each sensor type has advantages and disadvantages in different environments and conditions. In this study, it is aimed to compare the advantages of different sensor types to each other and their contribution to the SLAM problem.

II. SIMULTANEOUS LOCALIZATION AND MAPPING

SLAM is the marking of an autonomous robot on the map in which it has created its position while mapping the environment it travels. Different algorithms and methods have been applied for mapping and localization in the solutions offered to the SLAM problem since the years when the problem was first addressed.

The process of extracting spatial data while exploring environmental features is called mapping. Mapping is a process created by displaying the real measurement values of the environment planned to be mapped on a computer. While mapping, a laser sensor can be used for environmental detection. Laser sensors are radar-like sensors used to detect the positions of surrounding objects. They can be used for both aerial mapping and ground mapping and geolocation. With this technology, two- and three-dimensional models of surfaces are produced in many areas [15].

The SLAM problem is a research area where a definitive solution cannot be achieved, but continuous improvements are possible. Various unpredictable errors can occur in different applications, therefore, solutions are developed using probabilistic methods in many SLAM

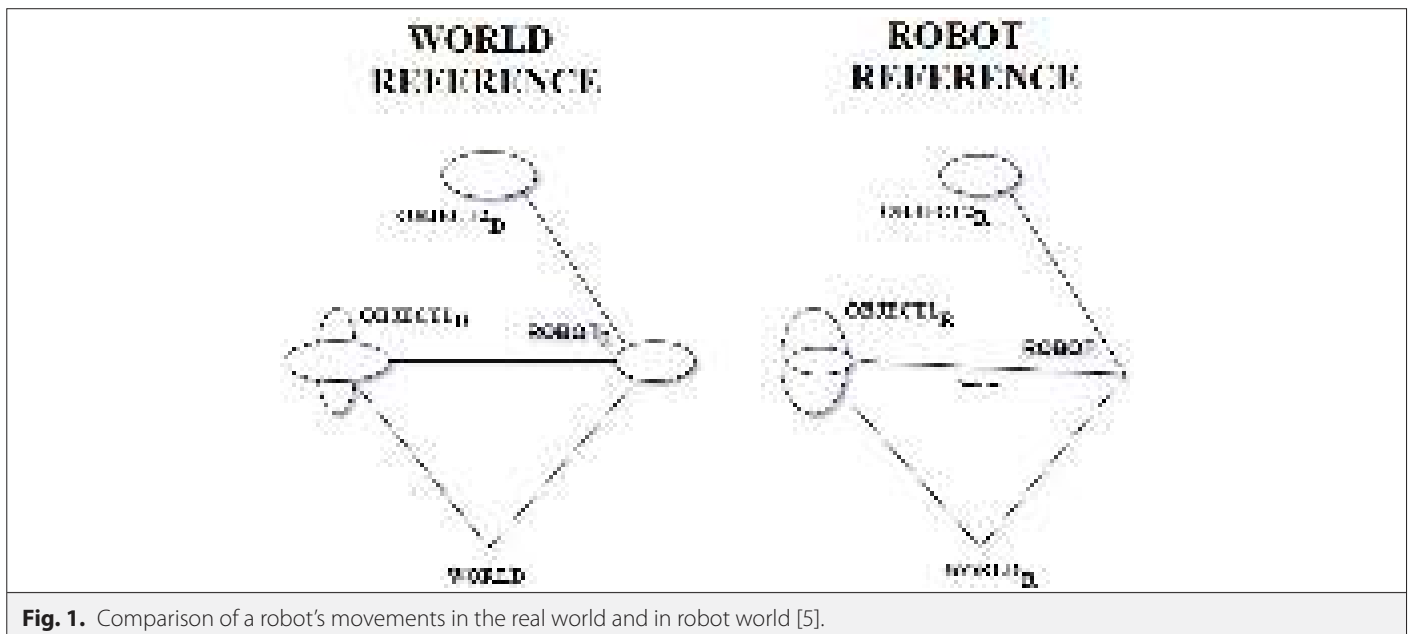


Fig. 1. Comparison of a robot's movements in the real world and in robot world [5].

applications. In some of these techniques, all measurements taken from the sensors are utilized to produce near-accurate outputs. However, in other cases, only selected measurements, which the robot can clearly interpret, are used to reduce the processing load and memory requirement [16].

The probabilistic SLAM problem was first discussed in 1986 in San Francisco, California. In the IEEE Robotics and Automation Conference, it was stated that probabilistic methods are a technique that should be discussed in the SLAM problem [17]. Later, studies would show that these relationships will indeed grow with successive observations. After a while, Smith [6] combined these studies and published an article on landmarks. As a result of this article, one of the critical breaking points in the SLAM problem has been discovered. While the autonomous robot continues to update its location information, it must record the objects it has measured and identified with the sensors so that it can be referenced later to update its map again in an improved form. In this way, the fixed reference point saved in memory is called the landmark [18].

The location of the autonomous robot from the start to the end of the given task, the frequency of its steps, its movements, the speed and direction of its movements, the frequency of observation and its results, its angle in a random coordinate, and many other data are subject to change or update. These data sets can be classified as follows [18]:

x_k : State vector showing the vehicle's position and direction

u_k : Control vector applied at time $k - 1$ to bring the tool to x_k state at time k

m_i : the default i . vector defining the location of the bookmark

z_{ik} : An observation from the vehicle of the location of i . landmark at time k

Thus, data sets can be expressed as:

$x_{0:k} = \{x_0, x_1, \dots, x_k\} = \{X_{0:k-1}, x_k\}$: location and direction history of the autonomous vehicle

$u_{0:k} = \{u_0, u_1, \dots, u_k\} = \{U_{0:k-1}, u_k\}$: control vector history of autonomous vehicle

$m = \{m_1, m_2, \dots, m_n\}$: set of landmarks

$z_{0:k} = \{z_0, z_1, \dots, z_k\} = \{Z_{0:k-1}, z_k\}$: set of landmark observations

One of the methods used in mapping is gmapping. Gmapping is an algorithm based on the Rao Blackwellized particle filter. With this algorithm, while the map is divided into grids, the observations made are included in the probabilistic calculations [19]. The distribution function in this method is as follows (1):

$$p(x_{t+1}, m | z_{t+1}, u_{t+1}) = P(m | x_{t+1}, z_{t+1}) \cdot P(x_{t+1} | z_{t+1}, u_{t+1}) \quad (1)$$

The structure of this algorithm can be expressed in four main steps. The next-generation particles to be used in the sampling step are calculated with the help of the previous generation. Then, a weight significance is determined for each particle (2). The particles in hand are reselected in proportion to their weight values. And finally, map estimation is made for each particle.

$$w_t^{(i)} = \frac{p(x_t^{(i)} | z_{t+1}, u_{t+1})}{\pi(x_t^{(i)} | z_{t+1}, u_{t+1})} \quad (2)$$

Particle weights need to be revised with each new observation. As the distance traveled by the robot increases, this process becomes more difficult to implement effectively. Therefore, the following distribution function is used to determine the importance weights of the particles (3):

$$\pi(x_t | z_{t+1}, u_{t+1}) = \pi(x_t | x_{t-1}, z_{t+1}, u_{t+1}) \cdot \pi(x_{t-1} | z_{t-1}, u_{t-1}) \quad (3)$$

Using formulas in 2 and 3, weights are calculated as follows (4):

$$w_t^{(i)} = \frac{p(z_t | m_{t-1}^{(i)}, x_t^{(i)}) p(x_t^{(i)} | x_{t-1}^{(i)}, u_{t-1})}{\pi(x_t | x_{t-1}^{(i)}, z_{t+1}, u_{t+1})} \quad (4)$$

In cases where the sensors are more sensitive than the robot state prediction, the sensor observation is also taken into consideration in the proposal distribution function (5).

$$p(x_t | m_{t-1}^{(i)}, x_{t-1}^{(i)}, z_t, u_{t-1}) = \frac{p(z_t | m_{t-1}^{(i)}, x_t) \cdot p(x_t | x_{t-1}^{(i)}, u_{t-1})}{p(z_t | m_{t-1}^{(i)}, x_{t-1}^{(i)}, u_{t-1})} \quad (5)$$

Using the equation in 5, the weights are recalculated as follows (6):

$$w_t^{(i)} = w_{t-1}^{(i)} \int p(z_t | x') p(x' | x_{t-1}^{(i)}, u_{t-1}) \quad (6)$$

When moving robots are modeled with sensitive sensors such as laser, it is more appropriate to use the improved suggestion distribution function. The Gauss approach can also be used on data to obtain new-generation samples. During this process, the scan-match algorithm is used to identify the meaningful area of the observation similarity function. The Gauss parameters are calculated by the following formulas respectively (7, 8);

$$\mu_t^{(i)} = \frac{1}{\eta^{(i)}} \cdot \sum_{j=1}^K x_j \cdot p(z_t | m_{t-1}^{(i)}, x_j) \cdot p(x_j | x_{t-1}^{(i)}, u_{t-1}) \quad (7)$$

$$\Sigma_t^{(i)} = \frac{1}{\eta^{(i)}} \cdot \sum_{j=1}^K p(z_t | m_{t-1}^{(i)}, x_j) \cdot p(x_j | x_{t-1}^{(i)}, u_{t-1}) \cdot (x_j - \mu_t^{(i)}) (x_j - \mu_t^{(i)})^T \quad (8)$$

The normalization factor used for each particle is shown as follows (9):

$$\eta^{(i)} = \sum_{j=1}^K p(z_t | m_{t-1}^{(i)}, x_j) \cdot p(x_j | x_{t-1}^{(i)}, u_{t-1}) \quad (9)$$

In this way, the optimum suggestion distribution function is used to determine new generation particles. Using the proposal distribution function, the weights are recalculated as follows (10):

$$\omega_t^{(i)} = \omega_{t-1}^{(i)} \cdot \eta^{(i)} \quad (10)$$

The normalization multiplier here is the same as the normalization multiplier used during the calculation of the Gauss parameters mentioned in the calculation of the new proposal [20].

III. IMPORTANCE OF SENSOR CHOICE FOR SLAM

Sensors on the robot enable the microprocessor of the robot to process environmental factors by converting environmental conditions into electrical signals. The correct selection of sensors increases the accuracy of the spatial information provided to the robot. The framework followed by the SLAM problem generally consists of distance measuring, landmark estimation, reference point creation, combining and matching of data, exposure estimation, and updating the map. These operations form the fundamental backbone of the SLAM method. The performance of internal and external sensors integrated into the robots plays an important role in the success of the SLAM process. Autonomous robots can perform the localization process by the rotational movements of their wheels or by a global positioning system. Global positioning system determines coordinates using multiple satellites and is known by the abbreviation GPS. However, both of these procedures may cause incorrect results due to errors that may occur. There may be unexpected slippage of the wheels of the robot due to environmental effects. Although GPS gives good results in open environments, it may give wrong results in indoor environments due to the lack of signal strength or communication with the robot may be completely interrupted. For these reasons, in order to accurately position an autonomous robot, it is necessary to use sensors to provide the position and direction information of the robot in the map to be created.

Sensors on the robot transform the environment conditions into electrical signals suitable for processing by the robot. The sensor selection should be compatible with the environment specifications. The quality and amount of environmental data detected vary according to which sensor is used. With the correct sensor selection, determining which SLAM algorithm to use can be easily accomplished [5]. There are different needs for air robots, land robots, underwater robots, and land-air robots. Therefore, different SLAM algorithms are

used for different vehicle types. Using the appropriate sensor type for different SLAM algorithm applications is also necessary.

A. Acoustic Sensor

An acoustic sensor is a type of sensor that operates by measuring the distance traveled by a sound wave. It considers the time it takes for the transmitted sound wave to return to its source after being reflected from an object in the environment, taking into account the speed of sound propagation in the air [21]. It uses piezoelectric crystals that can make bidirectional conversion between electrical energy and acoustic energy in order to generate the required frequency while performing this process [22]. The process can be seen in Fig. 2.

Ultrasonic sensors are the least costly environment-sensing devices used in autonomous robots. They are compatible with many surface types, metal or nonmetal, clean or opaque, as long as the surfaces of the objects in the measurement environment have the ability to reflect sound waves at a sufficient level.

B. Laser Range Finder

Laser-based systems are one of the most preferred technologies in the SLAM problem. With laser sensors, accurate and fast results can be obtained both indoors and outdoors. High-speed operation and good measurement accuracy make laser sensors preferred for precise measurements.

Laser sensors are a type of sensor that works with the method of measuring the distance traveled by the laser beam, taking into account the time it takes for the sent laser beam to return after reflecting from an object in the environment and the propagation speed of the light in the air. The working logic of laser sensors can be seen in Fig. 3. Generally, a solid object will reflect back a certain part of the light energy coming from it. Even a small amount of the signal returned to the sensor is sufficient for the sensor to function properly [23, 24].

C. RGB-D Sensor

The most preferred image sensors in robotics are RGB-D sensors. These sensors are a new generation of sensors that can measure

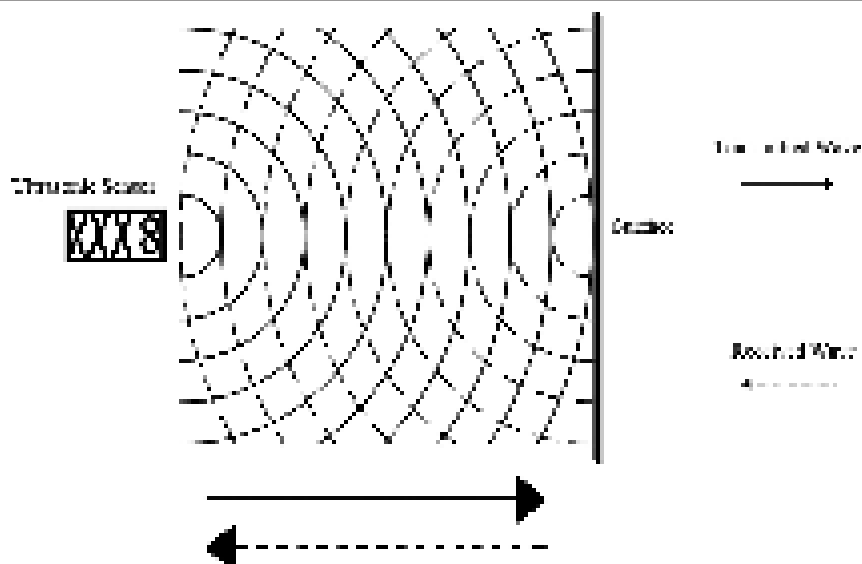


Fig. 2. Working principle of acoustic sensor.

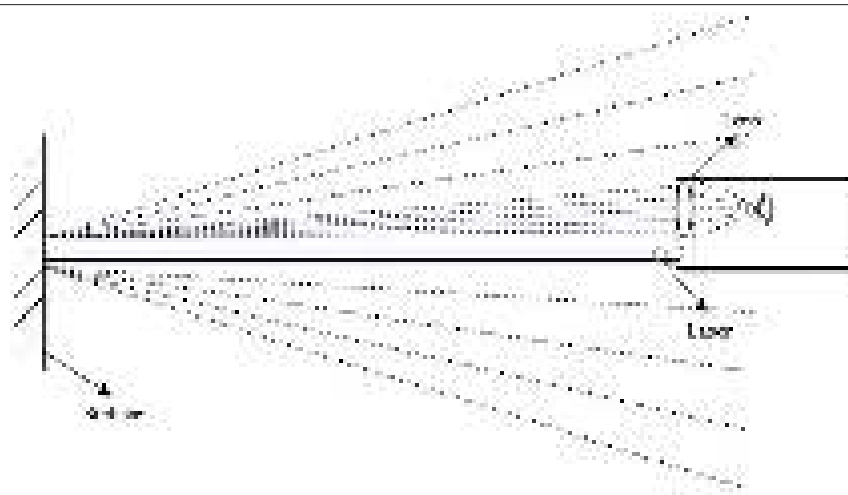


Fig. 3. Working principle of laser range finder.

depth by reflecting structured infrared spectrum light detected by an infrared camera. The RGB-D sensor provides a snapshot by encoding the depth data detected by the camera with colors in the RGB system for approximately 300,000 different points. The pixels in this image are shown in warm colors if they describe far distances, and in cool colors if they describe close distances [25].

D. Comparison of Sensors

In recent years, SLAM-solving techniques have made rapid progress. Various SLAM algorithms using ultrasonic sensors, laser scanners, RGB-D cameras, and other similar distance sensing sensors have been developed to predict robot pose and simultaneously generate 2D and 3D maps. Sensors, one of the components of robot hardware, are imperfect; therefore, sensory data is slightly different from the real world. Poor quality sensors can cause more errors in results. Therefore, observation error is an important issue that requires efficient solutions to the SLAM problem [26].

Acoustic sensors use the time of flight (ToF) technique to determine location. Ultrasonic sensors, a type of acoustic sensor, are often used in robots. Ultrasonic sensors are compatible with almost all surface types. However, the low detection quality, sensitivity to environmental conditions, and slow processing compared to other sensors create problems in the use of ultrasonic sensors in robots. Ultrasonic sensors generally provide a low-cost advantage, but the low data quality compared to other sensors also causes a serious disadvantage.

Laser sensors use phase shift techniques as well as ToF to measure distance. The high speed and accuracy of laser rangefinders enable robots to create precise distance measurements. In this way, solid results are obtained both indoors and outdoors. Therefore, laser sensors are highly preferred in solving SLAM problems. A laser scanner is the best sensor to detect walls, stones, or any object that determines the boundaries in the environment due to the dense range of data it provides. However, the price of a quality laser sensor is also quite high.

Acoustic sensors and laser sensors generally work in the same way. They only use the distance from the surface to position and identify objects. They cannot use surface features. Whereas, image sensors

use color and grayscale as well as a wider set of information for robots to identify and locate features in the environment.

Visual sensors are mainly three types of monocular cameras, stereo cameras, and RGB-D cameras. Most SLAM systems use RGB-D cameras that generate 3D images through structured light or ToF technology, both of which can directly provide depth information. But the disadvantage of RGB-D camera sensors is their limited applicability in direct sunlight.

Laser sensors are significantly more sensitive compared to acoustic sensors and other sensors. Therefore, it is preferred in applications where high-speed vehicles such as autonomous vehicles are used. Laser sensors' ability to measure with high accuracy is suitable for SLAM systems [27].

IV. SIMULATION

Various simulation programs can be used to solve the SLAM problem and to conduct experimental studies. Using these programs, the autonomous robot and the process of creating the environment map of the robot by modeling a map can be extracted through simulation. However, in the simulation environment, some of the external factors may not be taken into account. Many environmental factors such as wind, dust, roughness, slope, humidity, and light amount may cause not to predict the robot's movements and the map to be formed. These errors caused by external factors in the SLAM problem are tried to be minimized by probabilistic methods such as Kalman filter. In the simulation environment, it should be known that more predictable and smooth results will be obtained than the real world.

The sensor effect in mapping can change in different environments and under different conditions and can be observed in simulation environments. In a SLAM project, before starting the fieldwork, modeling work should be done on a map that is as similar as possible to the environment where the robot will travel, and it should be determined which sensor type and setting will result better for the robot in that environment. For the selection of the sensor to be used in the project; features such as indoor or outdoor environment, the reflectivity of the objects in the environment, and the amount of light in the environment are extremely important. Studies have revealed which sensor type is generally more useful for these

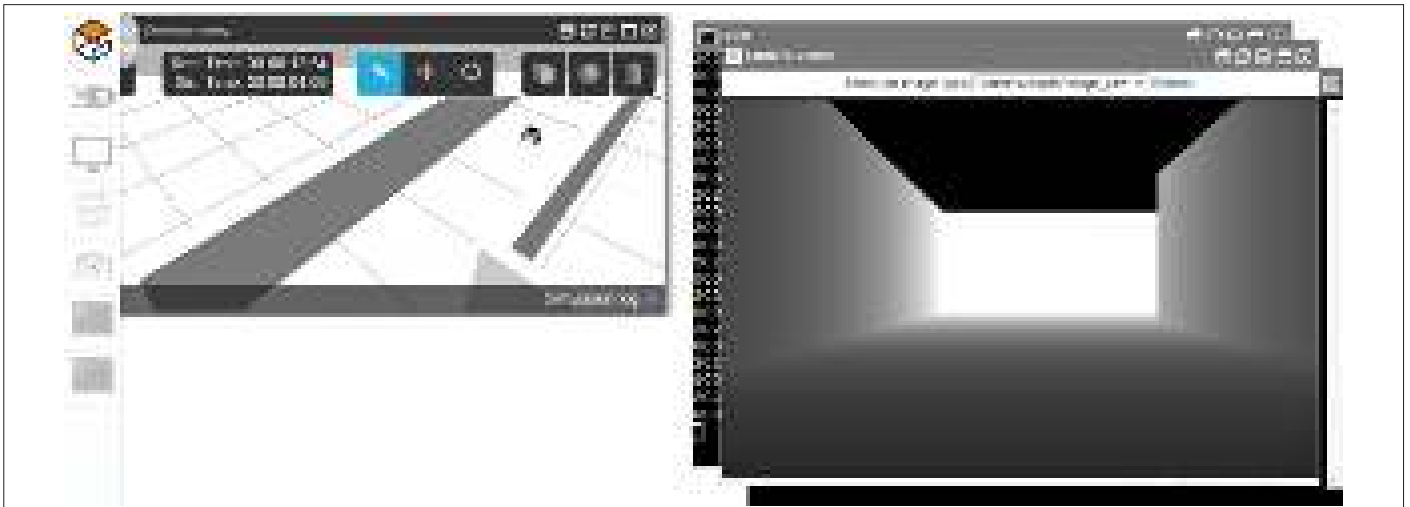


Fig. 4. A robot pose created in a simulation environment.

environmental properties. However, if some features in the environment provide advantages for one sensor type while other features in the same environment also provide advantages for another sensor type, then the importance of modeling for the correct sensor selection emerges.

An example of an open space environment and any instant pose of the robot in this environment is shown in Fig. 4. In this environment, mappings were made with a laser sensor. In addition, the surrounding walls and objects have good reflective properties. In this simulation, the robot was moved around the environment with the laser sensor.

Fig. 5 shows the map of the environment extracted in a simulation. A random room is simulated on ROS and a robot with a laser sensor is hovered in the environment. As a result of this study, the map of the room in the simulation environment was created except for minor errors.

In this study, a robot with a laser sensor has mapped a real space. The instantaneous poses of the robot while mapping the space can be seen in Fig. 6.

In this mapping, critical details in real space can be better observed. In this study, it has been observed that the accuracy of the map

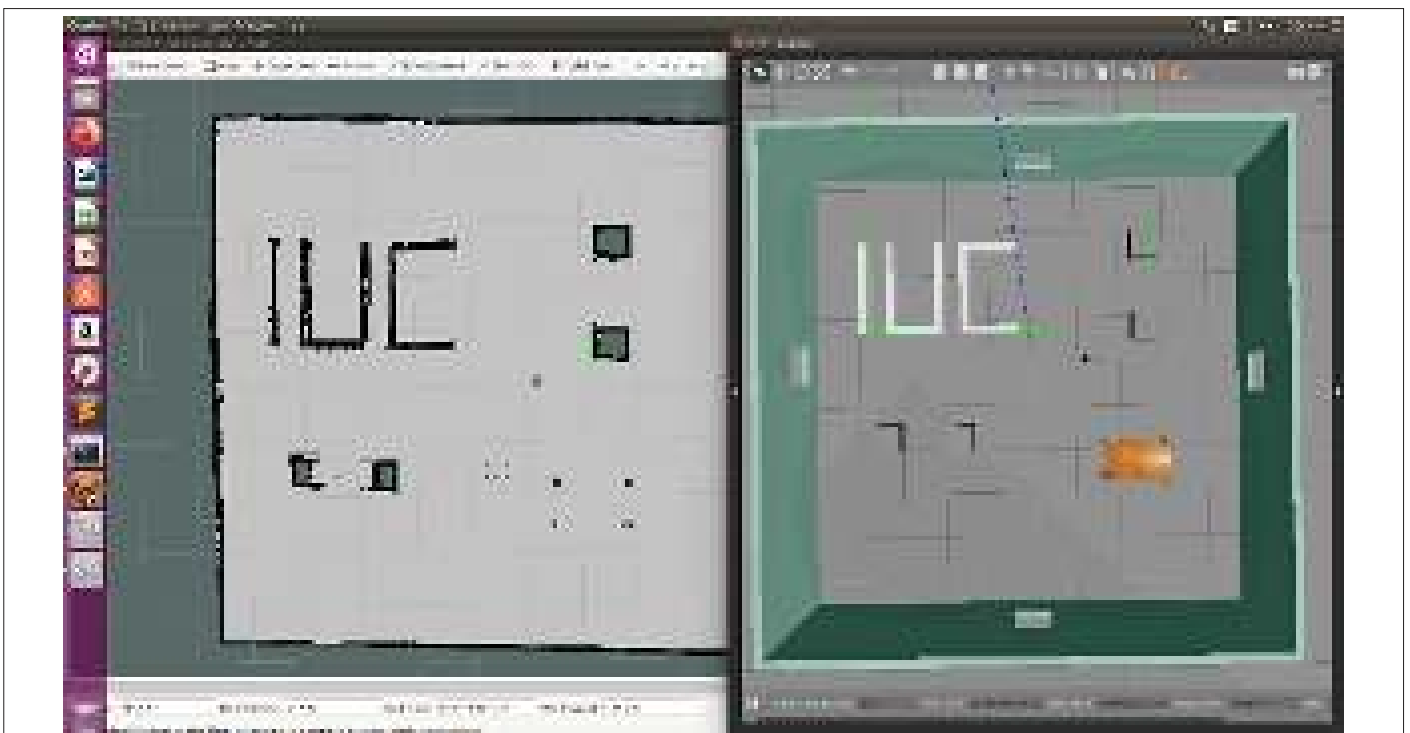


Fig. 5. Extraction of the map created in the simulation.



Fig. 6. Pose of a robot with laser sensor in real environment.

increases as the robot moves in the real environment. The final map created after the robot completes the mapping can be seen in Fig. 7.

The same laser sensor robot was placed in another closed environment. The robot pose in this new environment can be seen in Fig. 8.

The map produced by the robot in the new environment can be seen in Fig. 9.

A similar study was done with a mobile robot with an ultrasonic sensor. The pose of the mobile robot in the environment can be seen in Fig. 10.

The map produced by the robot in this environment can be seen in Fig. 11.

The laser sensor is generally the most efficient sensor for SLAM. However, considering the cost of the project, an ultrasonic sensor or image sensor can also be used instead. Sensor selection is crucial for good mapping and localization. The cost factor is also a determining factor in sensor selection. Sensor selection should be made after determining the appropriate sensor for the environmental conditions and comparing the price/performance ratio.



Fig. 8. Pose of a robot with laser sensor in real environment 2.

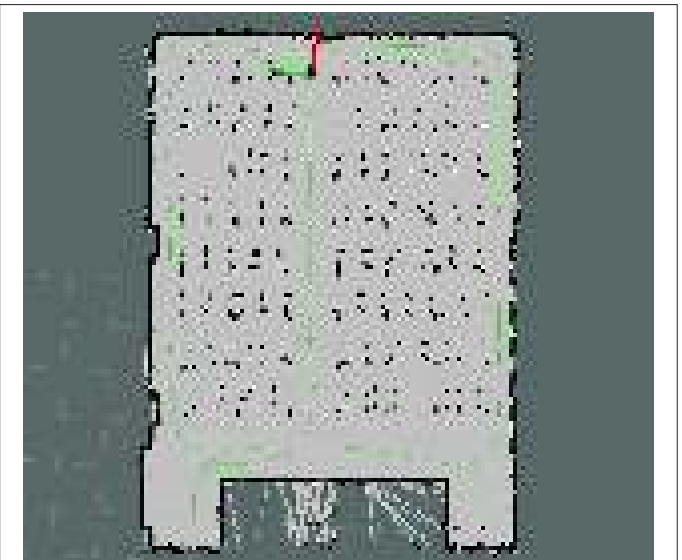


Fig. 9. Map created with laser sensor 2.

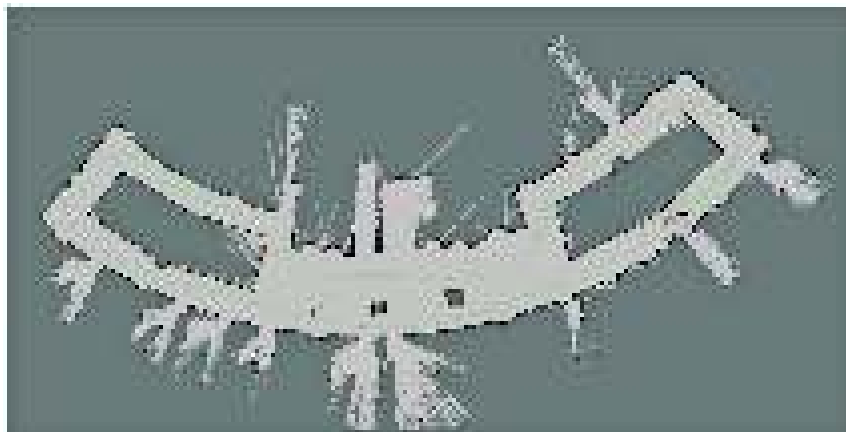


Fig. 7. Map created with laser sensor.



Fig. 10. Pose of a robot with ultrasonic sensor in real environment.

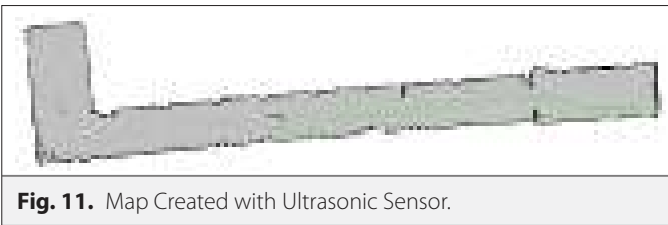


Fig. 11. Map Created with Ultrasonic Sensor.

V. DISCUSSION AND CONCLUSION

In this study, the advantages and disadvantages of using different types of sound, laser, and vision sensors in autonomous robots are emphasized. However, under any circumstances, it is possible for the autonomous robot to make a mistake in the mapping. Due to external factors, data from sensors may not be accurate. In addition, it is possible for the robot to move in a way different from the commands in the control mechanism and change its direction due to environmental conditions. Therefore, the possibility that mapping with autonomous robots may contain incorrect data at the first stage should be considered.

In this study, two autonomous robots with laser sensor and ultrasonic sensor are eventually operated in a real environment to map the environment. As a result of the map studies, it has been observed that laser sensors produce better and more detailed results than ultrasonic sensors. However, the possibility of making erroneous results by being affected by specular reflection should not be overlooked when robots with laser sensors are traveling around the environment. While ultrasonic sensors are generally cheaper than laser sensors; if the environment contains materials that provide sound insulation, it may cause an error. We aim to test the same robots in different environments and to increase data as a continuation of this work.

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Nevzat Yağız Tombal received his BSc degree from Yıldız Technical University in 2012. He received his MSc degree at İstanbul University—Cerrahpaşa in 2021. He has been continuing his academic life as a lecturer at İstanbul Gelişim University since 2018.



Tank Veli Mumcu received his Ph.D. degree in Control Engineering from Yıldız Technical University (YTU) in 2013. Currently, he is working as an Assistant Professor at İstanbul University-Cerrahpaşa, Electrical and Electronics Engineering Department. His major research interests are simultaneous localization and mapping, multi-rotor copters, modern control techniques, intelligent control systems.