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Original Article

Design of an Autonomous Three-Wheeled Robot for Water Leak Detection Using Geophones

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Abstract - *Water is distributed through pipeline networks that may suffer deterioration and leaks, making leak detection essential to save significant amounts of water and related costs. A portable, low-cost, three-wheeled robot car equipped with two geophones was proposed for leak detection. The robot can move autonomously on horizontal surfaces using ultrasonic and infrared sensors to search for leaks. For operation on vertical surfaces, it is equipped with a handle that allows the user to manually position it against walls. First, the robot's specifications and functions are detailed. Second, the selected components, movement algorithm, and geophone signal evaluation process for locating leaks are explained. Finally, it was found that the robot's energy consumption for 8 hours of operation is 91.52 Wh, which is fully supported by the selected 180 Wh battery, providing a low-cost alternative to GPR-based leak detection robots on the market and a more user-friendly solution compared to manually operated geophones that rely on user expertise.*

Keywords - *Leak detection, Acoustic method, Geophone, Robot car, Mechanically control system, Velocity.*

1. Introduction

The Sustainable Development Goal (SDG) 6 addresses the sustainability of water and sanitation access by focusing on the quality, availability, and management of freshwater resources [1, 2]. Water is distributed through pipeline networks, which may experience deterioration and water leaks [3]. The factors contributing to deterioration can include pipe corrosion, pipe defects, poor workmanship, excavations, ground movements, or climate conditions. As a result, water loss through leaks has been reported to be approximately 20% to 30% of the total water supplied in different countries [4]. Therefore, the importance of leak detection is clear, as it can potentially save a large quantity of water and related costs.

Leak detection methods can be classified into acoustic and non-acoustic methods. Non-acoustic leak detection methods include gas injection [5], Ground-Penetrating Radar (GPR) [6], and thermal infrared imaging [7], among others. Acoustic leak detection approaches can be further classified into non-intrusive and intrusive methods [8]. Non-intrusive approaches include correlators, ground microphones or geophones, and listening devices [9]. On the other hand, intrusive methods involve wireless sensor networks and hydrophones, as these devices must be in direct contact with water when operating [10]. In the case of plastic water pipes, the pipe-wall and water are strongly acoustically coupled [11]. Consequently, water leak detection can be performed using correlation techniques applied to data collected from the surroundings or the pipe. This includes velocity data from geophones [12], acceleration data from accelerometers [11], and acoustic pressure data directly from the water using hydrophones [13].

Geophones, which measure vibration velocity data of the pipe wall or the ground above the pipe, typically work in conjunction with listening devices equipped with signal amplifiers and noise filters [9]. Traditionally, the presence of a leak is evaluated by the user, and the effectiveness of this method relies heavily on user experience. However, geophone signals can be post-processed, reducing the dependence on user expertise [14]. A previous study employed thermal image-based surveying to obtain an approximate location of an underground water leak, followed by using two geophones to triangulate the precise leakage location [15]. The geophone data were used to calculate Interaural Time Differences (ITD) and interaural Phase Differences (IPD). These values were then fed into a machine learning model to estimate the angle of the leak location relative to each geophone.

Commercially available portable geophone-based leak detection solutions rely heavily on user experience [9, 16]. In contrast, GPR-based leak detection methods are less dependent on user expertise and have been integrated into commercially available robot cars [17]. While this approach is more robust, the high cost of these devices limits their accessibility.

In this study, a low-cost, small robot car equipped with two geophones is proposed for leak detection. The robot can move autonomously, avoid obstacles, and search for leaks, providing an alternative to high-cost commercial GPR-based leak detection systems integrated into small robot cars.

Unlike commercially available geophone-based leak detection systems, the proposed robot does not require user interaction when operating on horizontal surfaces. First, the design process and evaluated alternatives are detailed. Then, the proposed design is presented, including the selected sensors, their placement, and the motors used. Finally, the robot's functionality, leak detection process, electrical energy consumption evaluation, and fabrication cost are discussed.

2. Materials and Methods

The VDI 2221 guideline is utilized for the design process [18]. This guideline consists of three phases. The first phase involves a list of design specifications and function structures; in the second phase, multiple solutions are evaluated; and in the third phase, the robot car is developed.

2.1. Specification

Table 1 shows the list of specifications for the robot car for leak detection. The specifications are classified into four categories.

Table 1. Robot car specification list

Category	Specification
Design	Incorporate stable support for the geophones and a ball screw assembly, ensuring proper placement of the geophones and accurate signal reading.
Function	Detect and measure vibrations of pipes to identify possible water leaks.
Energy	Maintain a constant input voltage for all components and a continuous operation for at least 8 hours.
Control	A microcontroller (ESP32) must process geophone data and store it in a MicroSD.

2.2. Function Structures

Figure 1 shows the functional structure of the proposed design. The robot car can move autonomously and avoid obstacles in a predetermined area while searching for leaks. First, vibration data is obtained every time the robot stops and deploys its two geophones. Afterwards, the two geophones return to their original position inside the robot. The frequency data and leak distance relative to each sensor are displayed on the screen of an OLED display module.

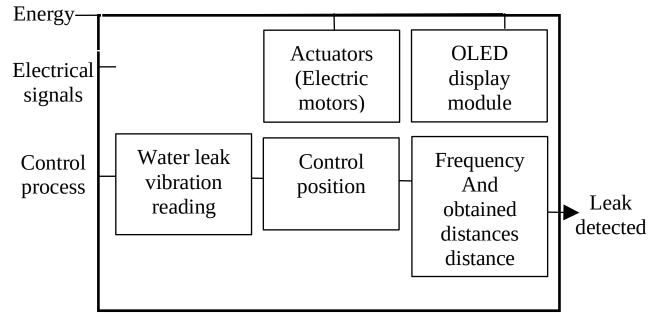

Fig. 1 Function structures

2.3. Principal Solutions

One common option for the detection of obstacles is to use ultrasonic sensors. These sensors essentially consist of two sonar transducers installed on an electronic board: one called an emitter and the other a receiver. For example, a small three-wheeled autonomous robot was equipped with five SRF05 ultrasonic sensors, and using a neural network, it could recognize objects as it navigated [19].

An alternative approach is to use ultrasonic sensors in conjunction with infrared sensors. The infrared sensor also uses an emitter and receiver, but the distance is measured according to the intensity of the reflected signal, in contrast to ultrasonic sensors that use the reflection time. This scheme is favourable as it permits using simpler algorithms compared to neural networks, and it has been implemented in a small robot in a previous work [20].

3. Electrical and Control System

3.1. Autonomous Robot Car

Figure 2 shows the proposed small robot car for water leak detection. The car's dimensions are 15 cm in width, 21 cm in length, and 16 cm in height.

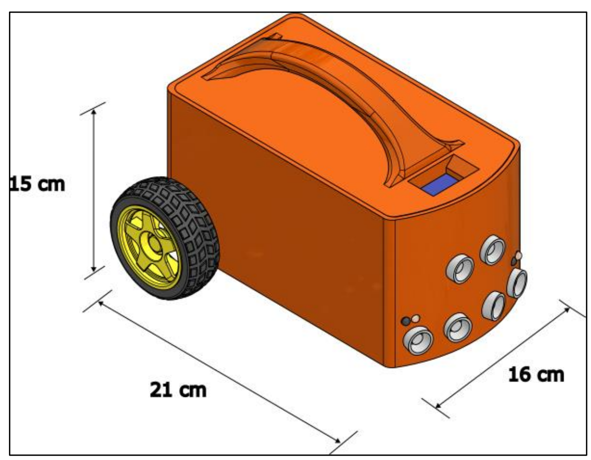

Fig. 2 Robot car dimensions

For leak detection, the robot deploys two geophones. The selected geophone model is SM-24, with a 10 Hz to 240 Hz bandwidth. This geophone is appropriate as signals below 10

Hz are typically dominated by background noise. Additionally, this sensor has been used successfully for leak detection in previous studies [11].

The robot car uses a small ball screw assembly driven by a micro-DC encoder motor to position the two geophones. Each geophone is attached to the screw assembly using a special case. The geophones are positioned at ground level to initiate autonomous operation.

For autonomous operation, three HC-SR04 ultrasonic sensors and two KY-032 infrared sensors are placed at the front of the small robot car. The SR04 operating voltage is between 3V and 5V, and the detection range is 2 cm to 400 cm. The KY-032 maximum detection range is 10 cm. Since the infrared sensors' performance depends on lighting conditions, they are used as auxiliary sensors for distance measurements of small objects. Figure 3 shows a detailed view of the components.

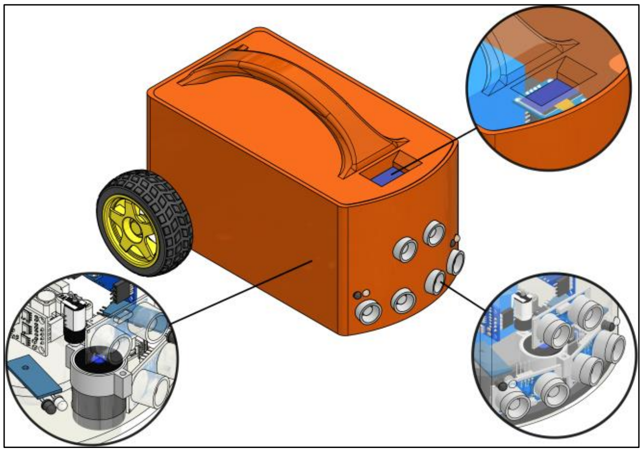

Fig. 3 Isometric view of the robot car

Figure 4 shows an exploded view of the small robot car. All the components are enumerated and shown in Table 2.

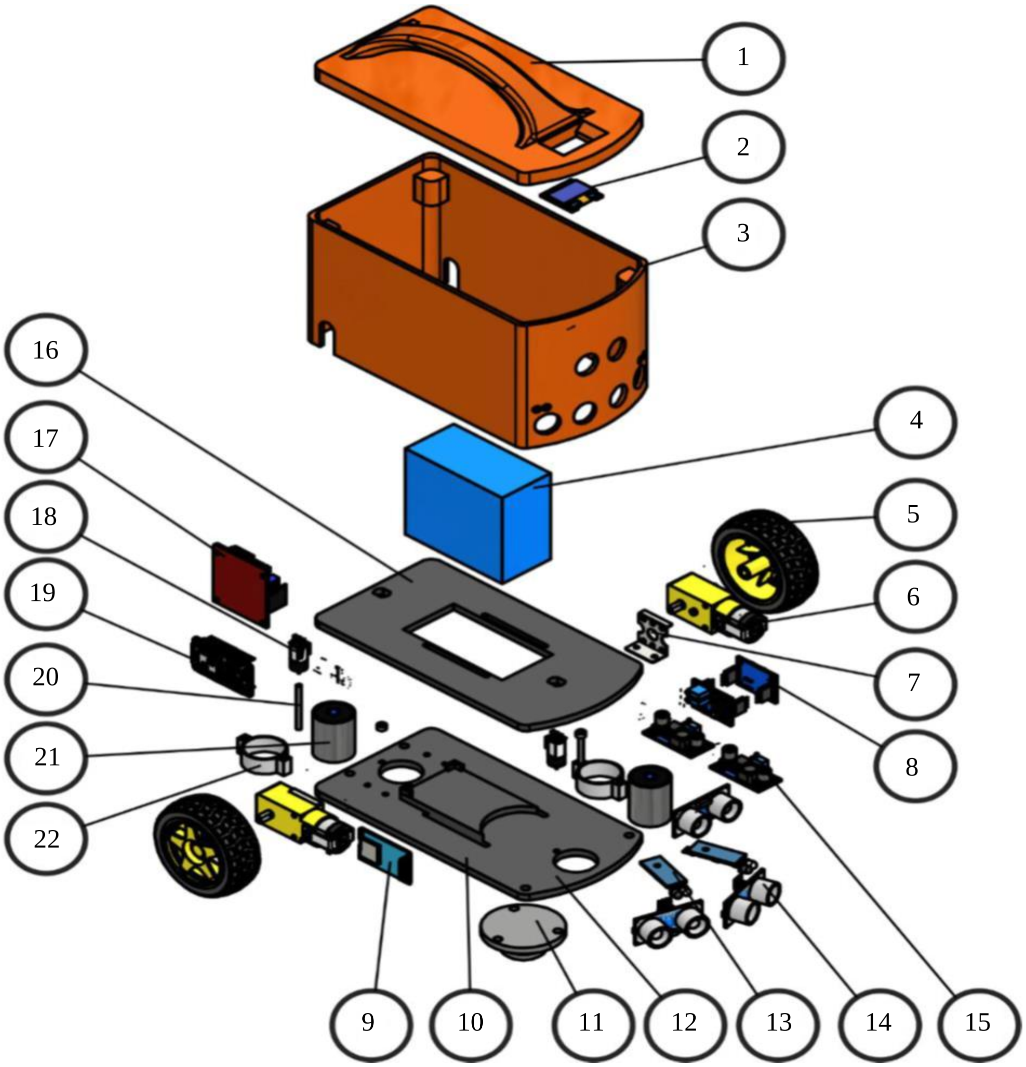

Fig. 4 Robot car exploded view

Table 2. List of components

Number	Part	Number	Part
01	Face cover	**12**	Shaft motor coupling 3mm
02	Display OLED 0.96" I2C 128*64	**13**	IR Sensor KY032
03	Case	**14**	Ultrasonic Distance Sensor HC SR04
04	Lithium Battery 12v 15Ah	**15**	DC-DC Buck Converter Module LM2596
05	Wheel D65x25	**16**	Frame
06	DC Gearbox Motor TT Motor 6V 200RPM	**17**	Motor drive controller board H L298N 2A
07	Mounting Clamp for BO Motor	**18**	Micro DC Reducer Motor
08	Instrumentation Amplifier Module AD620	**19**	Geared Mini DC Motor GA12 N20
09	MicroSD module 74LVC125A	**20**	Micro Lead Screw 3mm
10	Chassis	**21**	Geophone SM24
11	Roller ball transfer bearing	**22**	Geophone's case

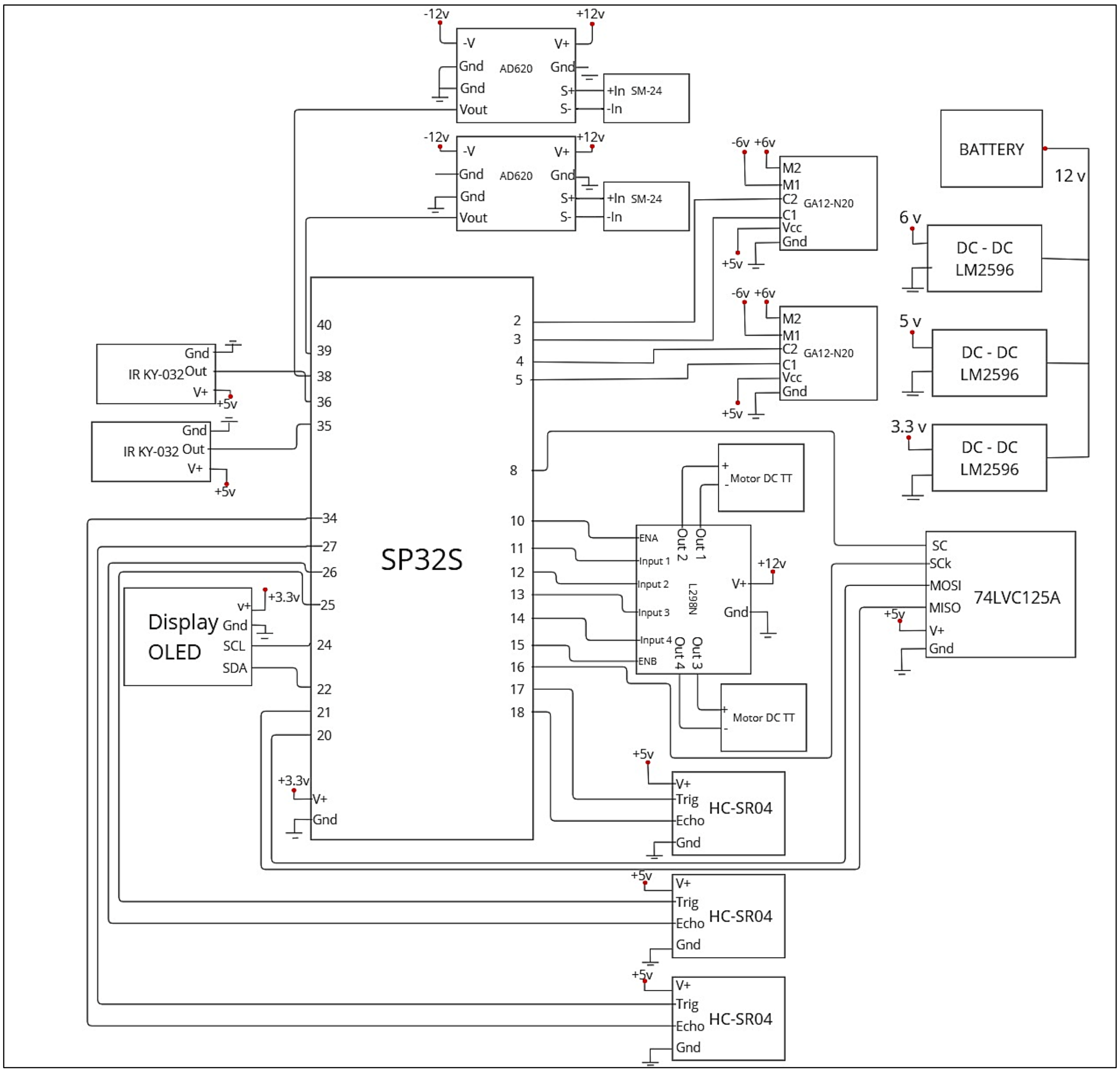

Fig. 5 Electrical and control schematic diagram

Figure 5 shows a schematic circuit diagram of the small robot car. The schematic diagram represents the electrical and control system for a small three-wheeled autonomous robot equipped with geophones (SM-24) for water leak detection. The system is centred around an SP32S microcontroller, which manages the operation of various sensors and actuators. The robot uses two DC motors (GA12-N20) to drive the wheels, each controlled by the SP32S via an L298N motor driver. The motor driver receives a 12V input and distributes power to the motors, which operate at 6V. Power to the entire system is supplied by a 12V battery, which is regulated down to 5V, 6V, and 3.3V by three DC-DC converters (LM2596) to meet the voltage requirements of different components. The robot is equipped with three HC-SR04 ultrasonic sensors and two KY-032 infrared sensors for obstacle detection. Ultrasonic sensors are connected to the SP32S to measure distances, which helps avoid obstacles, while infrared sensors detect irregularities or edges of the surface, improving navigation accuracy. The geophones (SM-24) are connected to the system via AD620 instrumentation amplifiers, which amplify the small signals from the geophones for better processing. These amplifiers operate on dual ±12V supplies derived from the battery through the DC-DC converters. The amplified signals from the geophones are then fed into the SP32S for analysis. An OLED display connected to the SP32S via I2C provides real-time feedback to the user, showing critical data such as sensor readings and system status. Communication between the SP32S and the display is facilitated by the 74LVC125A level shifter, ensuring proper voltage levels are maintained.

3.2. Navigation Algorithm

Figure 6 shows a flowchart of the operational process of a small three-wheeled autonomous robot designed for water leak detection using two geophones (SM-24). The robot begins its operation by initializing the timer to zero and holding the DC motors in place. Once the motors are stabilized, the robot deploys the two geophones, which are used to measure the ground vibrations indicative of water leaks. After the measurement is completed, the robot evaluates the data. If the measurement process is successful, the robot moves forward for three seconds. During movement, the robot continuously checks for obstacles using its HC-SR04 ultrasonic sensors and KY-032 infrared sensors. If an obstacle or wall is detected in front of the robot, it stops and assesses the direction of the obstacle.

Based on the direction of the obstacle, the robot will either turn 90 degrees to the left or 180 degrees to the right, adjusting its path to avoid the obstacle. After the turn, the robot continues its operation. The cycle repeats until the robot reaches the required motor operation time, at this point, the robot returns to the DC motors' holding state, and the process starts again. This ensures the robot systematically covers the area, efficiently detecting potential water leaks while avoiding obstacles.

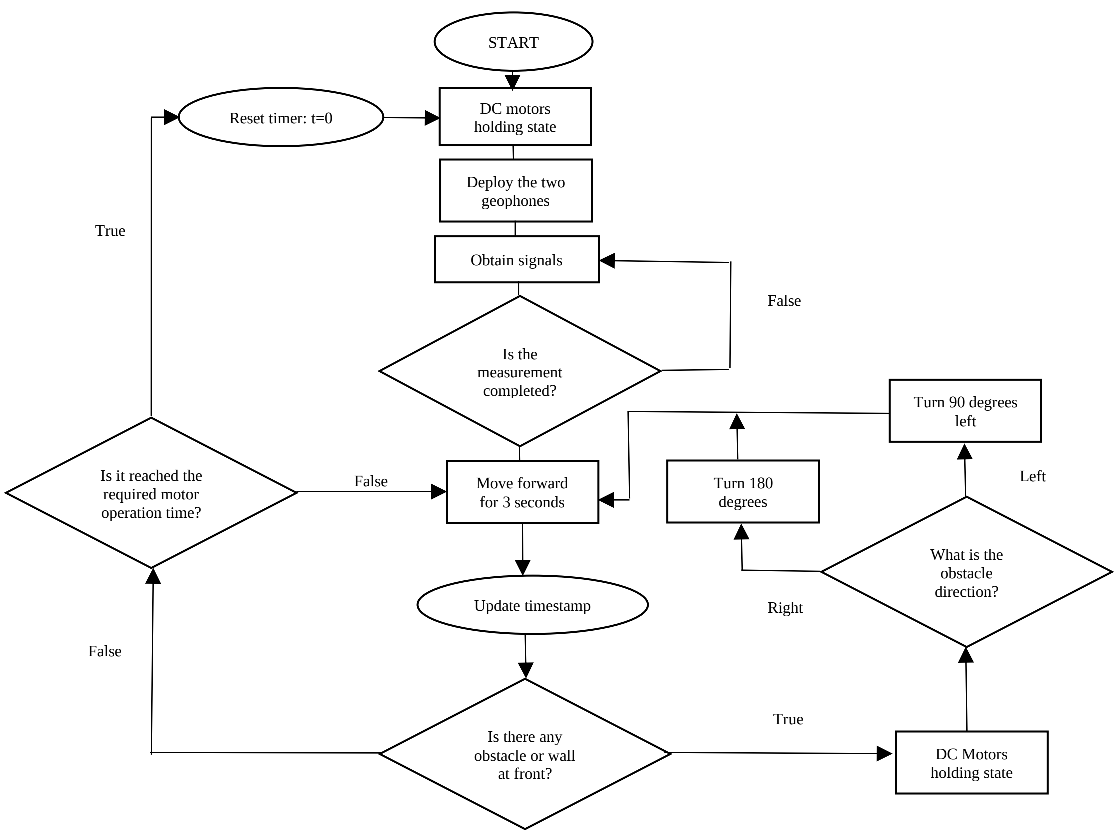

Fig. 6 Robot car flowchart

Figure 7 shows the S-shaped movement expected from the proposed small robot car. Previous works have demonstrated that this type of movement can be achieved using a 'snake' algorithm. Additionally, using a random walk algorithm as a base [20] or coupling the snake algorithm with other algorithms such as A*, PRM, RRT, or RRT Smooth [21] can improve the robot's autonomy and versatility according to the application field.

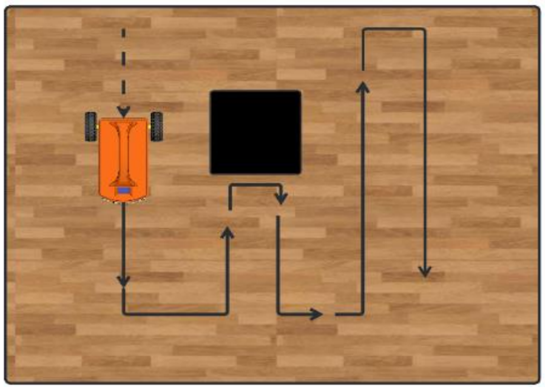

Fig. 7 Robot car autonomous movement pattern

3.3. Signal Processing Using Cross-Correlation Techniques

Although the angle of the leak location relative to each geophone can be obtained using machine learning models [15], the leak signals measured by the geophones at two different positions can also be used to estimate the water leak location from the peak of these signals in a cross-correlation function [22].

Figure 8 shows that if a water leak exists in the pipe between the first geophone and the second geophone, at distances of d1 and d2, respectively, then a peak can be obtained using a cross-correlation function. The time delay until the peak is observed, τ, represents the difference in the signal arrival time between the two geophones. Thereafter, the leak location can be estimated using the time delay τ, the distance between sensors d, and the propagation wave speed of the leak noise on the pipe, c, as shown in Equation (1) [22, 11]:

$$d_1 = \frac{d - c\tau}{2} \quad (1)$$

The time delay is estimated by analyzing a cross-correlation function between the geophone signals, with the peak in this function indicating the delay. The accuracy of this estimation relies on carefully selecting the frequency bandwidth and considering how the pipe and sensors filter the noise. For a detailed explanation, the reader is referred to [11]. The precision of water leak detection using cross-correlation techniques in plastic and metal pipes varies depending on several factors. These techniques have generally been more effective in metal pipes than in plastic pipes due to the differences in the acoustic properties of the materials.

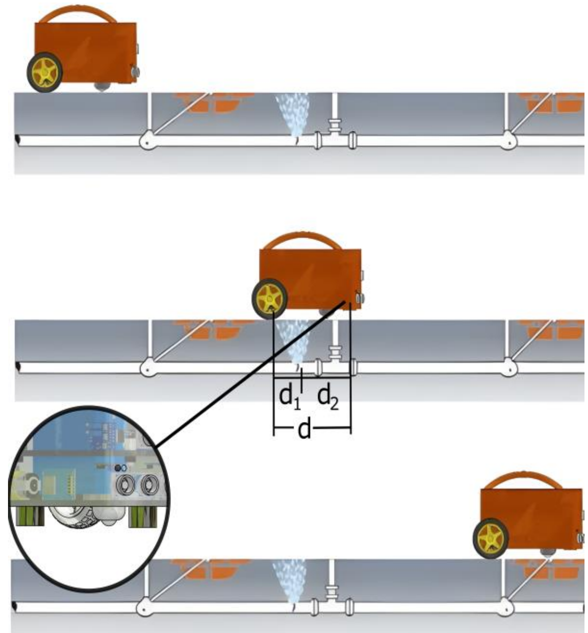

Fig. 8 Water leak localization process using cross-correlation method for robot car

4. Results

A small, three-wheeled robot equipped with two geophones was developed for leak detection. The robot moves autonomously, avoids obstacles, and uses cross-correlation to locate leaks on horizontal surfaces. For vertical surfaces, a handle allows manual positioning, ensuring accurate geophone readings. This feature extends the robot's functionality to vertical inspections, which is essential for comprehensive leak detection in buildings. Figure 9 shows the robot in use for water leak detection.

Fig. 9 Manual displacement of the robot car in the vertical plane

Table 3 presents the power consumption of the three-wheeled robot car's electrical and electronic components. The total power requirement of the robot is calculated to be 11.44 W. The robot is designed to operate continuously for at least

8 hours without charging, producing a total energy consumption of 91.52 Wh. To achieve this continuous operation, the energy consumption was estimated by multiplying the total power consumption (11.44 W) by the operating time, yielding approximately 91.52 Wh. Although this calculation is simplified, additional factors such as conversion losses, component efficiency variations, and battery degradation were considered through literature review and simulation data extracted from manufacturer datasheets, as done in [23]. Considering typical conversion efficiencies (assumed to be around 90-95%) and a safety margin of approximately 20–30%, the selected 12V, 15Ah lithium-ion battery, with a nominal capacity of 180 Wh, provides sufficient energy to ensure reliable operation. Table 4 shows the cost of each component required for the small robot car. The total fabrication cost, excluding 3D printing, is $312.45.

Table 3. Energy consumption

Component	Amount	Total Consumption (W)
ESP32	1	0.8
Geophone SM-24	2	0.1
Amplifier module AD620	2	0.09
MicroSD module	1	0.1
OLED screen 128x32	1	0.06
Ultrasound HC-SR04	3	0.045
IR sensor KY-032	2	0.03
H-bridge driver L298N	1	2
DC Gearbox Motor TT Motor 200 RPM 6V	2	2.5
DC Motor GA12-N20	2	5
DC-DC boost converter LM2596	3	0.72
Total		**11.44**

Table 4. Bill of materials

Component	Amount	Cost per Unit	Total Cost
ESP32	1	$ 10.95	$10.95
Geophone SM-24	2	$ 64.50	$129
Amplifier module AD620	2	$ 5.95	$11.9
I2C OLED display module	1	$ 12.99	$12.99
Ultrasound HC-SR04	3	$ 4.50	$13.5
IR sensor KY-032	2	$3.00	$6.00
DC-DC boost converter LM2596	1	$14.95	$14.95
H-bridge driver L298N	2	$7.00	$14.00
DC Motor GA12-N20	2	$1.81	$3.62
DC Gearbox Motor TT Motor 200 RPM 6V	3	$8.00	$24.00
Robot car chassis	1	$22.99	$22.99
Rechargeable lithium-ion battery 12V 15 Ah	1	$48.55	$48.55

5. Discussion

The proposed robot car for leak detection consumes 11.44 W, which compares favourably to a similar robot car equipped with ultrasonic and infrared sensors reported in [20] that consumed 12.38 W. An important aspect of the proposed design is its weight, as it is intended to be portable and lightweight for comfortable manual operation on vertical surfaces. The total weight of the robot consists of the robot car itself (0.821 kg) and the lithium battery (0.8 kg), resulting in a total of 1.621 kg. This weight is comparable to that of commercially available robot car alternatives (1.5 kg) [17] and significantly lighter than other previously presented robot car solutions (3.5 kg) [20]. Regarding the dimensions of the small robot car (21 × 16 × 15 cm), they are comparable to those of commercially available GPR-based leak detection robot cars (22.1 × 18 × 14 cm) [16]. The total cost of the proposed robot car for leak detection is $312.45, which aligns with other low-cost robotic solutions. For example, in [24], a low-cost, smallsized unmanned surface vehicle for water quality monitoring was fabricated at a total cost of $200, including 3D printing. Additionally, it offers a more affordable alternative to GPR-based robot car solutions, which can cost hundreds of dollars.

6. Conclusion

An autonomous three-wheeled robot car equipped with two geophones was proposed for leak detection while avoiding obstacles on horizontal surfaces. The robot is equipped with a handle for operation on vertical surfaces, allowing the user to manually position it against these surfaces. It was found that the robot's total energy consumption, considering all selected components, is 91.52 Wh for 8 hours of uninterrupted operation. The selected battery can provide 180 Wh, thus meeting the energy requirements. Finally, the total fabrication cost of the robot car is $312.45, offering a low-cost alternative to GPR-based leak detection robots on the market and a more user-friendly solution than manually operated geophones. Future work will explore implementing the proposed robot car for leak detection in real-case scenarios and compare the performance of the two equipped geophones with accelerometers.

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