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Autonomous Landmine Detection Robot Using SLAM navigation Algorithm

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ABSTRACT

This paper presents a robot that can navigate and perform its required functions autonomously for landmine detection. The proposed prototype can detect obstacles and avoid these obstacles then plot a new path to continue the mine detection operation in the desired area. The autonomous navigation and obstacle avoidance techniques are used based on the robot operating system (ROS) by building a map using simultaneous localization and mapping algorithms (SLAM). The mechanical design, theoretical calculations, and the modeling of the suggested prototype are presented. The main components of the land mine detection robot include the raspberry pi 3 model (B+) which will act as the primary communication device between the Arduino mega and the computer. The camera module V2, Inertial Measurement Unit (IMU) sensor, and LIDAR sensor are used to track robot acceleration and angular velocity. a metal detector sensor is used for the detection of anti-personnel landmines. The robot can accomplish the mine detection task autonomously with minimum human interaction through the suggested software algorithms.

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1. Introduction

Buried landmines are a problem that was given birth to by several acts of war over the years. There are two types of buried landmines anti-tank mines and anti-personnel landmines. The two types can be activated by pressure [1]. The problem of landmines has caused many casualties and injuries among unarmed civilians, and these injuries are estimated in the millions over the past years. Therefore, any land infested with mines is considered a prohibited area [2]. This problem has been the main concern for many countries as the demining operations are slow, complicated, and dangerous. The main problem isn't the removal of landmines, it is locating the landmine position accurately. This entire operation is still done manually which causes the demining rates to be very unsatisfactory. Since that for every mine removed 20 times more mines are being planted [3]. Therefore, a more suitable approach that is based on the application of recent technologies is crucial, thus minimizing the risk while increasing the rate of mine clearance and the accuracy of the procedure. This approach is the usage of autonomous vehicles for the detection of landmine locations. Based on the inspection of the available mine detection techniques, it was found that the most broadly used sensor for the discovery of landmines is the metal detector, which has turned out to be so sensitive that it can discover tiny portions of metal. The prototype should be affordable so that it can be used by poor countries. As well as have a simple design that can be easily maintained and copied. Figure 1 and 2 illustrates the robot Solidworks design and the experimental robot, respectively. Previous studies were interested in designing a high-efficiency mine detector robot with a satisfactory and accurate rate of detection. Dawson et al. [4] investigated the widely used landmine detection methods. It was discovered that there were two widely used approaches to locate the anti-personnel landmines, which are known are prodding and remote sensing. The method includes a sharp tool that is plunged into the soil in search of the landmines.

Gasser et al. [5] investigated the use of different types of rotary prodders. The experiments conducted by the authors showed that the rotating prodders could penetrate homogenous and hard-dried soil with high speed but low force. However, it was concluded that to enhance the manual mine detection and removal approach by using prodders with a proper user interface design, in order to provide the deminer with the ability to distinguish between a mine and other buried objects when searching for potential landmines. This would be the manual approach that has been associated with risk even with trained

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demines and improved prodders. Other available methods are tackled more thoroughly.

Figure 1: Isometric view of the landmine detection robot

Figure 2: Autonomous landmine detection robot

The method depends on the use of remote sensors, which can search for potential landmines. The remote sensors involve Ground penetrating radar [6], sensors based on electromagnetic induction [7], and other sensors with the ability to search beneath the ground surface. The author targets the idea of fusion between various remote sensors to increase the accuracy, reliability, and speed of the process. Metz et al. [8] introduced the idea of developing an unmanned ground vehicle that is equipped with advanced sensors that can search for buried landmines. The unmanned ground vehicle aims to accomplish the mine detection operation with no risk to any human life. The robot design includes a manipulator that carries the sensors the performance of sensors depends on the position, the scanning area parameters, and the scanning speed. Näsholm et al. [9] the author investigated the development of a software system that was based on the implementation of simultaneous localization and mapping algorithms. Using a ground vehicle with a rotating LIDAR mounted on top that will detect the presence of the mine and an Ariel vehicle to mark the mine’s location on the map. [10] Proposed a four-wheeled robot mechanical design that controls both the lateral and angular deviations as well as gives the robot high-precision tracking with no grip on the robot. Which will allow the robot to navigate in almost all-terrain conditions. Zhenjun et al. [11] Introduced an image processing system using a camera that allows the robot to avoid obstacles, the author also uses wireless communications that allow for a real-time monitor of the robot's activities.

Several solutions were introduced to enhance the robot's ability to detect the presence of mines and the robot control and navigation process in general. Some of these solutions focused on optimizing the localization and mapping of the robot [9, 12]. The others were more concerned with having an optimal mechanical design that could handle rugged terrain types [10, 13], and other studies focused on the idea of using an image processing system that will allow the robot to navigate more efficiently while avoiding any obstacle in the way [11, 14].

In the present work, a design of an autonomously operated mine detection robot is introduced. The mine detector robot is designed to start navigating any desired area, the area of interest is already mapped for the robot and the robot navigates through this area according to a predefined algorithm. The sensors that provide the feedback data to the path-tracking controller are a LIDAR sensor and an Inertial Measurement Unit (IMU) sensor, as well as a mine detector sensor for the detection of anti-personnel landmines.

The paper organization is as follows. The second section includes the requirements of the robot’s dynamic motion. Which includes the forward motion and skid steering dynamic requirements. The third section illustrates the mechanical design of the robot and the finite element analysis of the mine detection robot. The fourth section covers the hardware selection of the robot and the relationship between the electronic components. The fifth section tackles the software implementation of the robot path planning and navigation techniques using the robot operating system (ROS) packages. Finally, the conclusion can be drawn from the experimental results.

2. Dynamic motion requirements

A study of the forces acting on the robot was a necessity to obtain the desired performance, therefore the dynamic motion requirements of the robot are divided into two parts, forward dynamic requirements, and skid-steering dynamic requirements.

2.1 Forward dynamic requirements

When the robot is moving in a longitudinal direction multiple forces are acting on the robot. Rolling resistance on both front (R_{rf}) and rear tires (R_{rr}). There is also grade resistance and the total tractive effort of both the front (F_f) and rear tires (F_r). The aerodynamic resistance (Ra) is neglected since the robot navigates at a low speed. When expressing the equation of motion there are also additional factors to be considered, including the longitudinal displacement (x) acceleration (a), acceleration due to gravity (g), the robot’s mass (m), and the robot's weight (w) [15]. The equations of motion of the robot are used to calculate the required total torque (td) for all the wheels as follows:

$$\frac{d^2x}{dt^2}m = \frac{w}{g}a = F_f + F_r - R_{rf} - R_{rr} - F_c - R_g \qquad (1)$$

Introducing the concept of the inertia resistance force, the above equation can be express as:

$$F = R_r + F_c + R_g + \frac{aW}{g} \qquad (2)$$

Where F is the total tractive effort and R_r is the total rolling resistance of the vehicle. The following Figure illustrates the forces that act on the robot.

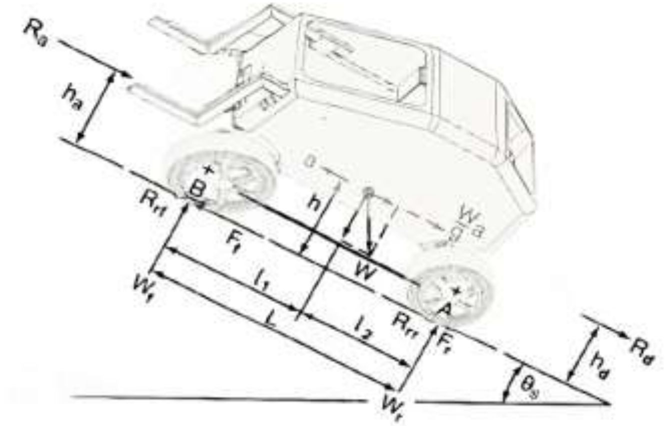

Figure 3: Forces acting on the robot.

The minimum torque required for longitudinal motion can be determined using the following equations:

Rolling resistance

$$R_r = W\, C_{rr} \qquad (3)$$

Grade resistance

$$R_g = W \sin(\theta) \qquad (4)$$

Inertia force

$$F_a = ma \qquad (5)$$

Tractive effort

$$F_t = R_r + R_g + F_a \qquad (6)$$

Wheel driving torque

$$t_d = F_t R_d \qquad (7)$$

Where the rolling resistance force R_r is generated when the robot tire rolls on a surface. It is the product of both the robot weight and the coefficient of rolling resistance of the tire moving on the sand (C_{rr}). The grade resistance (R_g) is the gravitational force acting on the robot. Which is the resistance due to the vehicle climbing an inclination of any sort. Inertia force (F_a) is the opposition to the acceleration force that is acting on the robot, which is equal to the product of the acceleration force and the robot mass. The mathematical equations are used to calculate the required total torque (td) for all the wheels of the robot. The total driving torque required for all wheels is equal to 8.67 N.m. Therefore, the torque per one wheel is equal to 2.167 N.m.

2.2 Skid-steering dynamic requirements

Landmine robot components were chosen according to the fact that it is imperative to obtain driver motors with the highest torque required by the robot [16]. Also regarding the fact that the robot is equipped with four rigid wheels that are driven independently. Skid steering is achieved by creating a speed differential between the inner and outer wheels. Where the steering angle of each wheel is fixed at zero degree. While the traveling speed is low which means that the robot stays in a steady state. Now skid-steer vehicles have the advantage of both high mobility and maneuverability. This originated from the fact that the vehicle is an all-wheel drive vehicle that has equal vertical load distribution on all wheels. Constant coefficient of lateral resistance between tire and ground [17]. A turning center is at the center of gravity, tire sinkage is negligible and all tires have equal contact patches dimensions. Figures 4 and 5 show the comparison between explicit steering and skid steering.

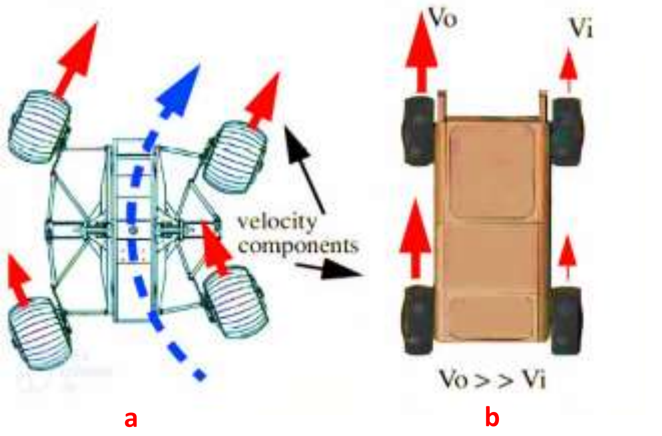

Figure 4: (a) Explicit-turning (b) Skid-steering turning

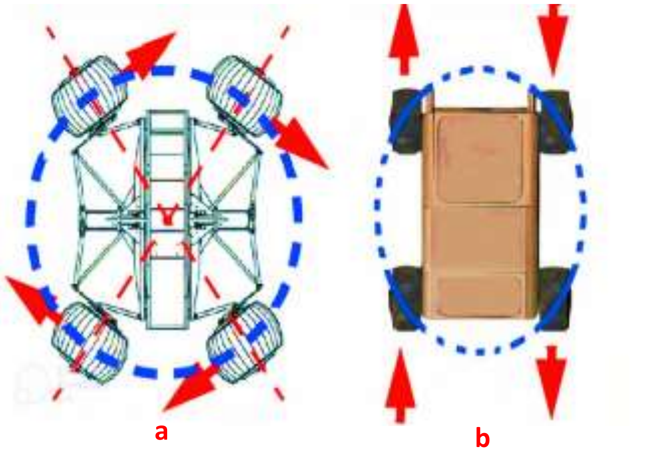

Figure 5: (a) Explicit-point turning (b) Skid-steering point turning

The coefficient of lateral resistance (μ_t) is chosen to be 0.15 to overcome the turning resisting torques caused by the terrain, the choice of wheel material is essential to overcome the terrain resistance during rotation. Table 1 lists the parameters of the landmine detection robot along with their values

Table 1: Parameters of the autonomous landmine detection robot

S/N	Symbols	Value	Description	unit
1	**m**	**30**	**Robot mass**	**kg**
2	**w**	**293.3**	**Robot weight**	**N**
3	C_{rr}	**0.15**	**Coefficient of tire rolling resistance**	-----
4	**θ**	5^0	**Inclination angle**	-----
5	R_d	**0.11**	**The dynamic radius of wheels**	**m**
6	**a**	**0.3**	**Acceleration**	m/s^2
7	R_r	**44.14**	**Rolling resistance**	**N**
8	R_g	**25.65**	**Grade resistance**	**N**
9	F_a	**9**	**Acceleration force**	**N**
10	F_t	**78.79**	**longitudinal motion tractive force**	**N**
11	t_d	**8.67**	**Longitudinal motion torque**	**N.m**
12	t_d	**2.167**	**The torque required per wheel**	**N.m**
13	μ_t	**0.15**	**Coefficient of lateral resistance**	-----
14	***L***	**0.6**	**Wheelbase**	**m**
15	**B**	**0.419**	**Wheel track**	**m**

3. Mechanical design

The system proposed design is low on cost, efficient, simple, and operates autonomously to only allow for minimum human interference, thus minimizing the risk to human lives in the process. For the mine detection rate accuracy to be satisfactory modern technologies must be used thus the project's goal is to employ advanced technology including a mechanically efficient design that includes enhanced sensors, a reliable detection strategy, and a well-developed motion system. The purpose of this section is to explore the design of the proposed landmine detection robot. The robot is driven by four brushless DC motors. A pneumatic tire is used for the robot to provide shock absorption on rough and uneven roads. There are two front arms above the ground level where the metal detector sensor will be placed. Figure 6 illustrates the exploded view of the robot's mechanical design.

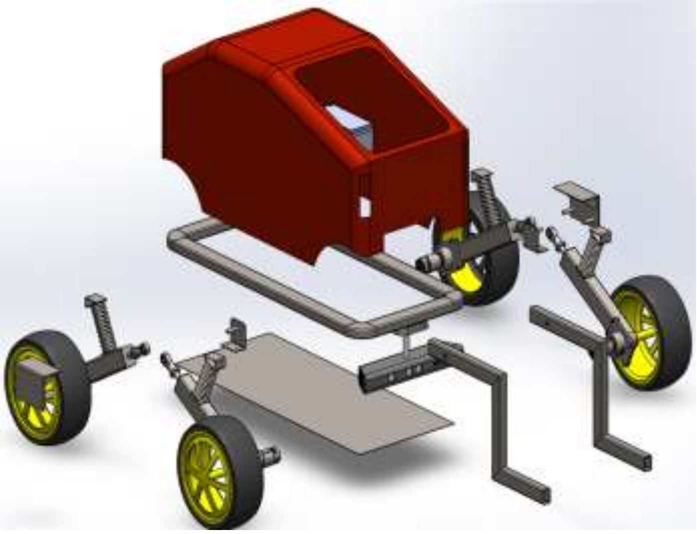

Figure 6: Exploded view of the landmine detection robot

3.1 Finite element analysis

The aim of the stress analysis of the mechanical parts is to test them against mechanical stress. Since the failure of mechanical parts is usually due to stress. The testing operation shows what will happen when multiple forces act on the tested mechanical parts and thus shows how much stress this part can handle before breaking down, the chosen parts are critical for the design to function [18]. The testing is done using a finite element method (FEM). The entire mechanical design can go through testing as well as specific critical parts. The system mesh structure is created using ANSYS and contains 71362 Nodes and 33329 elements as shown in Figure 7. The maximum and minimum total deformation for assembly were 0.20306mm and 0.22562mm, respectively. The structure of the system is analyzed using steel 37. The maximum stress is generated on the frame and the three-point hitch system. When the appropriate surface of the assembly unit and frame was applied with the maximum reaction force of 8000 N in the –Y direction, the maximum stress of the whole assembly was 2270 and 11353 Mpa, respectively. The structure of the system is analyzed in a static structure of strain of equivalent elastic strain was 0.022562mm minimum and 0.20306mm maximum.

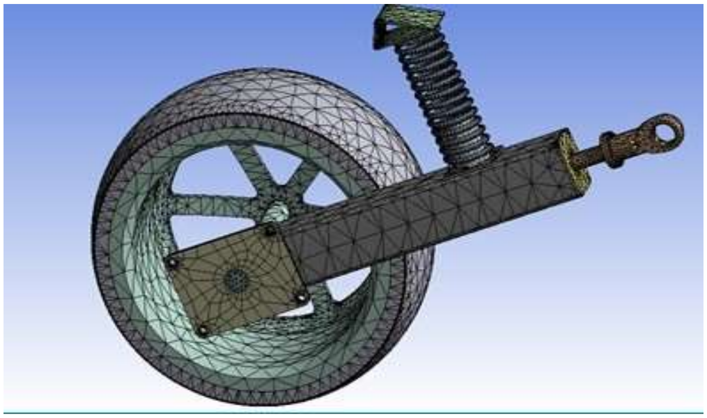

Figure 7: Model mesh structure

4. Hardware and electronics

This section covers the electronic components selected for the landmine detection robot. Figure 8 shows the wiring diagram of a landmine detection robot.

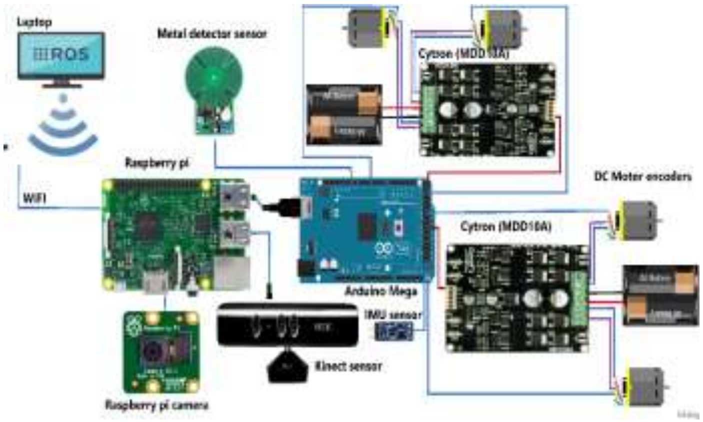

Figure 8: Wiring diagram of the landmine detection robot

The raspberry pi 3 model B+ (RPI) function is to communicate with the Arduino by sending control signals to the motors and read wheel encoder data. The Arduino reads control signals from RPI and transforms them into motor commands, which it sends to the platform motors. As well as read the data from the wheel encoder sensor and forward it to RPI. Wheel encoders to estimate the distance each track has traveled. An inertial measurement unit is mounted in the center of the robot platform, communicates with RPI, and operates at a frequency of 50 Hz. The IMU contains accelerometers, gyroscopes, and magnetometers for the estimation of the platform acceleration and angular velocity in all three dimensions. DC motor driver (two channels) citron its purpose is to drive the two-brushed DC motors with a current that can reach up to 13A continuously, it offers a fast response time and eliminates both wear and tear from the mechanical relay. The board is completely compatible with the Arduino and can give an output signal of 3.3v-5v. Figure 9 shows the internal circularity of the autonomous landmine detection robot

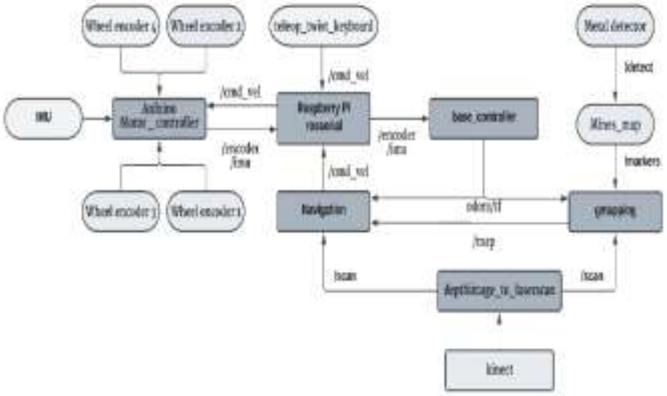

Figure 9: Block diagram of the internal circularity

4.1 Metal detector sensor

The metal detector sensors consist of three main parts the Inductor capacitor (LC) circuit, the proximity sensor, and the output buzzer as shown in Figure 10.

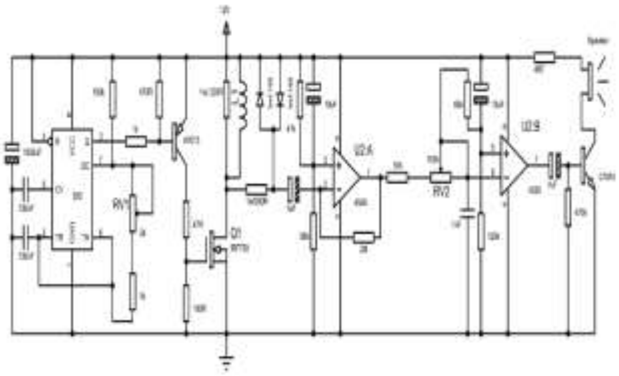

Figure 10: Metal detector circuit of the landmine detection robot

The LC circuit has an inductor and capacitor connected in parallel. The working principle is that it starts resonating when there is a material of the same frequency nearby. The metal detector requires single-frequency electromagnetic wave transmission, therefore a very low frequency that can transmit signal continuously is best suited because it transmits under 8 kHz which can be excellent for large and highly conductive targets such as anti-personnel landmines. As it acts as an oscillator, it will create a magnetic field that will induce the current in the coil to change the signal flow. Therefore, the metal detector signal will detect its presence when any metal is near it [19]. The proximity sensor does not require any physical hardware as it emits a signal to the ground and will not accept any output until the signal is reflected. If the detected signal is from the real metal, the sensor output will be ten mA, the output port will be high, resistor R3 will supply voltage to transistor Q1, and the buzzer will be energized. If no metal is detected the sensor output signal will be one mA. The anti-personnel landmines are usually buried at a depth of 10 to 15 cm underground. Therefore, coil diameter of 22 to 25 cm that can detect up to 20 cm deep will be more than enough to detect the presence of the landmines.

5. Software implementation

Autonomous navigation and obstacle avoidance techniques are used based on the robot operating system (ROS) due to the flexibility of the framework and the navigation stack. That can be achieved by building a map using the simultaneous localization and mapping feature (SLAM) [20], which keeps on updating the built map using data gathered from the input sensors. The SLAM algorithms also allow the robot to scan the surrounding area and generate a path to avoid colliding with obstacles on its way by using the global planner in the navigation stack, which aims to deliver the robot to the desired location in the shortest time possible. Since the robot is a wheeled robot therefore by implementing the Odometry system, the robot can receive data from the wheel encoders to determine the robot's position and localization. The ROS setup contains multiple packages to achieve the requirements of the navigation stack. GAZEBO simulator is used for simulation and map generation, which is a ROS graphical simulator that allows for the setup of an environment in which the robot will move around. The data is then passed to Robot operating system visualization

(Rviz) which is the visualization software that will visualize the simulation and create the map [21]. Figure 11(a) and Figure 11(b) show the robot system main components and the Landmine robot communication and movement flowchart, respectively.

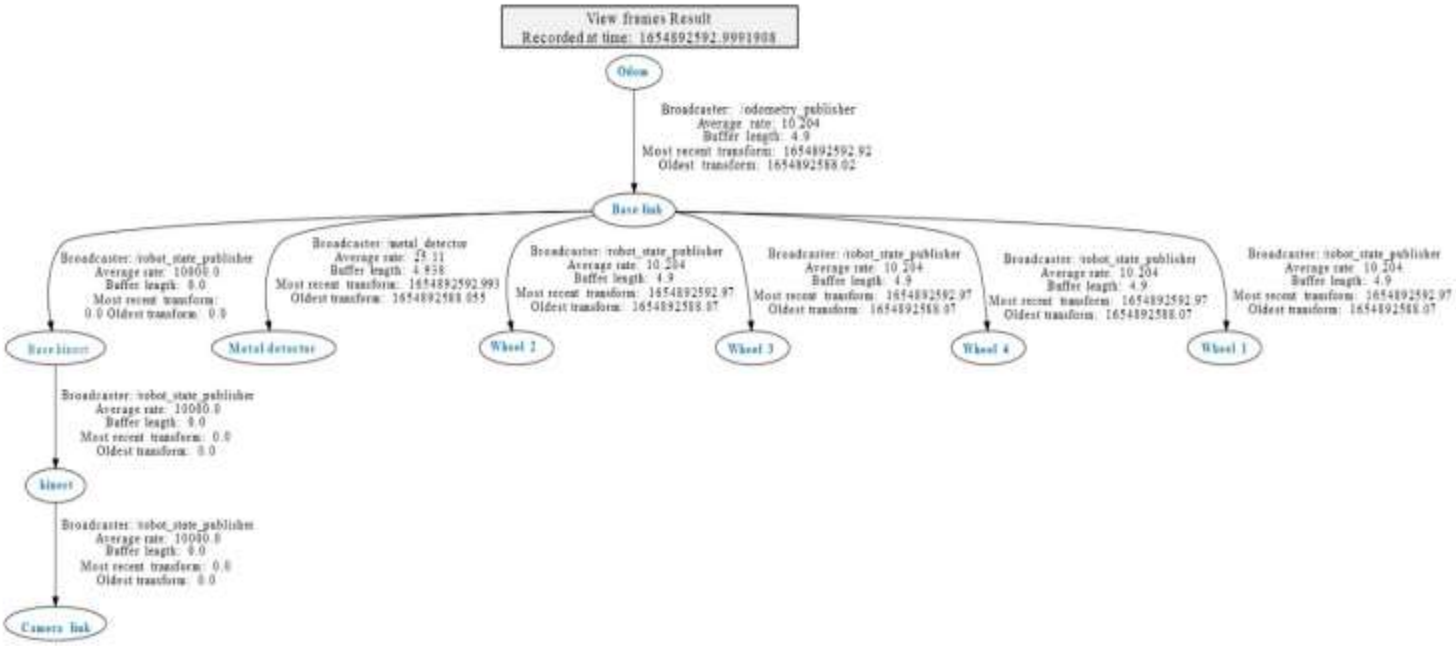

Figure 12: Transform flow tree

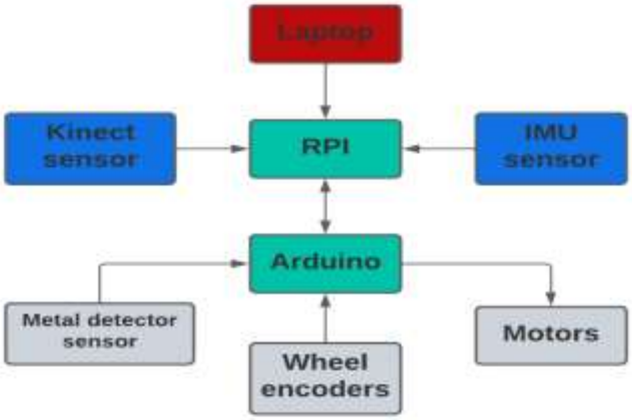

Figure 11 (a): Robot System main components.

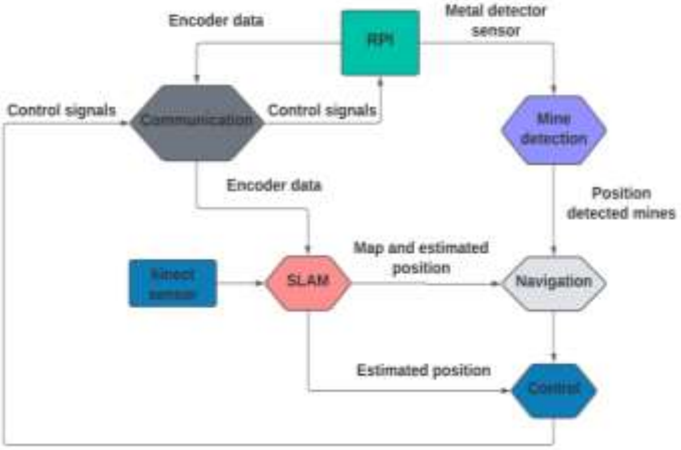

Figure 11 (b): Landmine robot communication and movement flowchart

5.1 ROS navigation stack packages

ROS navigation and path planning depends on the implementation of many ROS packages [22, 23]:

a) Sensor transform package: it aims to create a transform tree of the robot, which determines the position of the robot and the sensors which are used as input data sources. Figure 12 shows the relationship between the odometry, the base link, and the sensors.

b) Base controller package: which is responsible for controlling the motor, by storing linear and angular velocity commands.

Using these commands the motor can be controlled based on the velocity commands.

c) Odometry source package: the odometry package is required to maintain the orientation and provide this information to the navigation stack. The orientation position is acquired from the data that is received from the encoders and the IMU.

D) Teleoperation package: responsible for converting the keyboard commands into velocity commands. It is related to the controller command but instead of it being automatically it is done manually with the keyboard keys, which is important in case the autonomous navigation meets an unexpected error

E) Landmine Marker package: the package is responsible for receiving a signal from the landmine sensor informing the robot of the landmine position which depends on the transformation between the sensor link and the base link.

Then the position of the landmine is marked in the map that is generated by rviz and as it keeps on scanning for potential landmines the map keeps getting updated

5.2 Navigation system

Simulation of the autonomous landmine detector robot path planning is conducted by converting the SolidWorks model into a unified robot description format (URDF) which can be used in the robot operating system (ROS), which includes a navigation package that receives input data from the sensors. In this case, the laser sensor is the one used to provide the input data because it can support map building and localization [24].

The robot uses this map as a guide to move from the initial position to the intended target. The URDF specifies the joints and links in the robot's model, which then can be visualized on the rviz simulation tool. The point of the simulation is to allow the transition from one link to another by defining the transform frame using ROS packages. Figure 13 and Figure 14 show the URDF model view on RVIZ and the defined joints and links, respectively.

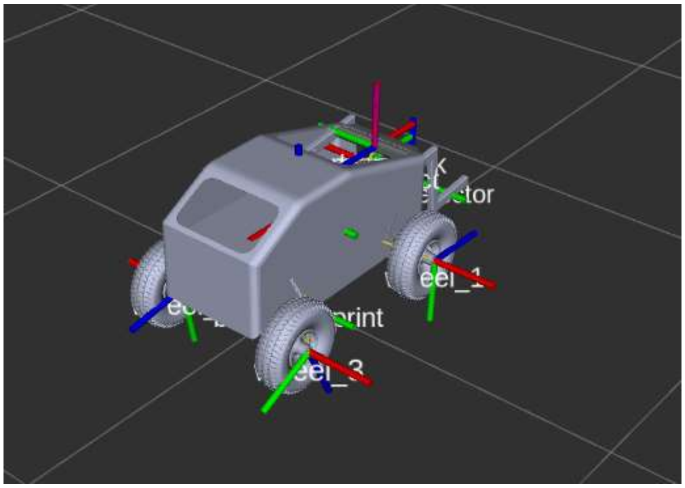

Figure 13: URDF model simulation on rviz

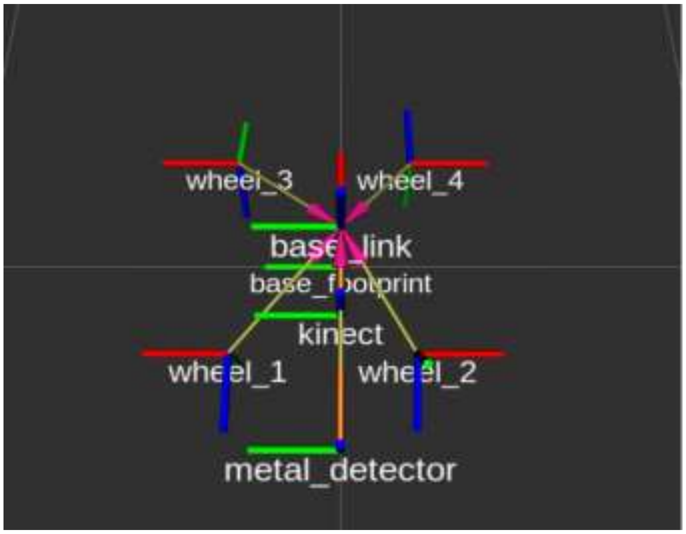

Figure 14: Defined joints and links

5.3 Path planning and Gmapping

The Gmapping is a package that provides laser-based SLAM (Simultaneous Localization and Mapping), as a ROS node called SLAM_Gmapping. Path planning of the autonomous landmine detection robot depends on using a proper path planning algorithm for the desired area. The robot is supposed to scan for potential landmines with predefined dimensions and according to the path planning strategy [25].

The pitch area is about 16 m^2. The goal of the proposed path is to guide the robot to reach a particular objective. Path planning requires the generation of an environmental map. This map must be accurate in determining the location of various objects that are located in the proposed area. The purpose of the map is to help the robot plot and follow the best possible path to the desired location. The autonomous landmine detection robot must be able to adapt to unpredictable terrain. The Gmapping uses data from laser scanning to adapt to the new environment. The robot keeps on updating the already predetermined map that is located in the map server. Figure 15 and Figure 16 show the path planning algorithm simulation and the generated map using SLAM, respectively.

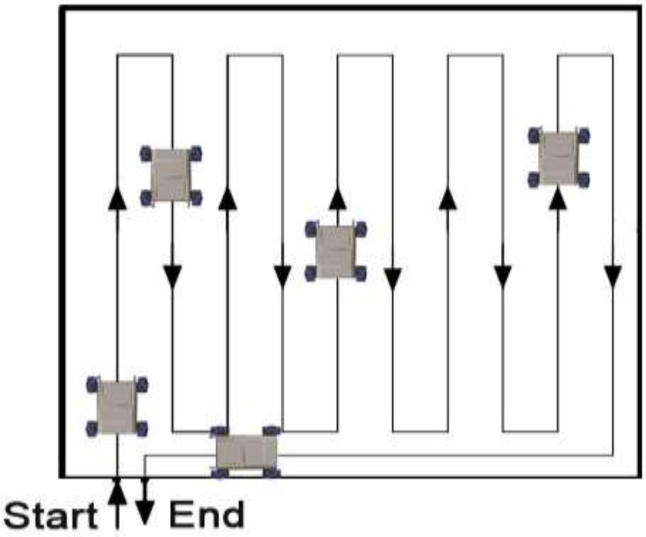

Figure 15: Path planning algorithm simulation

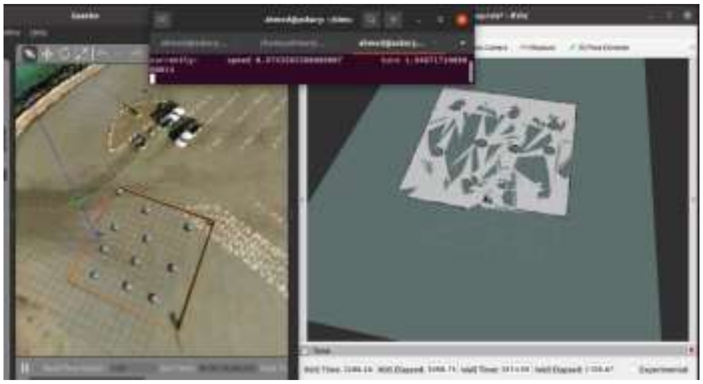

Figure 16: Slam Gmapping map simulation

5.4 Obstacle avoidance

The obstacle avoidance idea of autonomous landmine detection robot is based on using continuous mapping and localization techniques. That allows for the localizing of the robot's position while the map is updated using Gmapping [26]. The purpose behind this is to adjust the parameters to allow the robot to navigate the new map and reach the desired location while avoiding potential obstacles on the way. The trajectory planner gives the robot a trajectory path, which is the new path that allows the robot to avoid obstacles along the way. The local planner sends the commands, which allow the robot to stick to the trajectory path. This is done by estimating the position of the robot through the data received from the laser scanner [27]. Figure 17 and 18 show how the robot navigates a new path to the desired location and the updated map using SLAM, respectively.

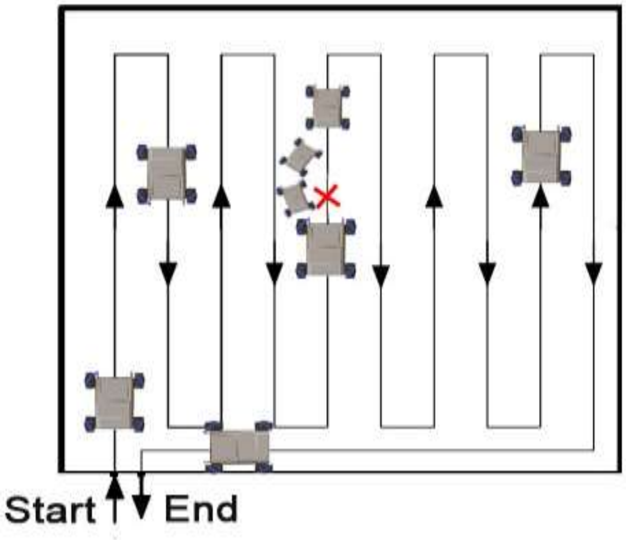

Figure 17: Obstacle avoidance strategy

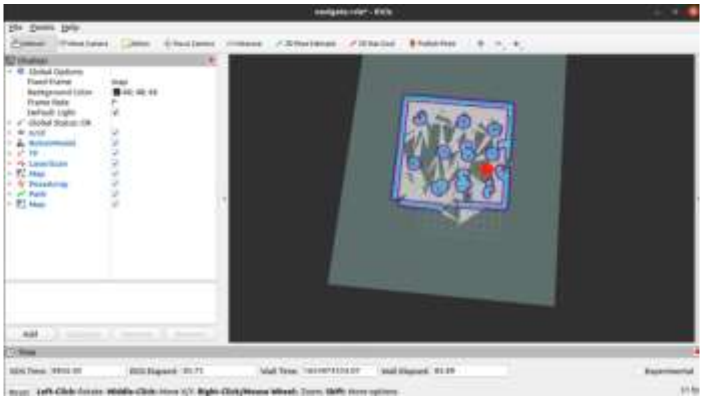

Figure 18: SLAM Gmapping updated map

6. Experiment setup and results

The purpose of the experiment is to evaluate the robot's functionalities and ensure that it is capable of accomplishing the required tasks. This includes testing the robot's ability to navigate autonomously and create a map of the surrounding environment using laser scanning. The capability to detect the obstacles and avoid them, plotting a new path to reach the goal location. The wheel encoder Odometry and the kinematics parameters of the robot are used to achieve the required speed for the task and the SLAM implementation is correct.

The robot velocity is set to 0.2 m/s to achieve the required fixed navigation speed in the X-direction. The maximum robot velocity (θ) is set to 0.55 m/s, with an acceleration limit in the X-direction of 0.03 m/s. The simultaneous localization and mapping techniques are used based on the ROS packages to generate a map of the test environment through the rviz visualization. The navigation stack packages settings require a good conversion through trial and error. The robot velocity is controlled manually by sending velocity commands, which are then transformed into motor commands using the Odometry package. The robot can navigate the test environment and avoid obstacles throughout the process, when metal objects that have been placed in the robot's path are detected, the landmine detector sensor will send a signal and then the position of the metal will be determined in the map generated by rviz The interface and map will be updated. Finally, the robot will reach the desired final destination without hitting any obstacles.

Table 2: Robot velocity and acceleration parameters

S/N	Symbol	Value	Description	unit
1	V_x	0.2	maximum velocity in the X direction	m/s
2	V_x	-0.2	Minimum velocity in the X direction	m/s
3	V_θ	0.55	Maximum velocity (θ)	m/s
4	V_θ	-0.55	Minimum velocity (θ)	m/s
5	a_θ	0.6	Acceleration limit of (θ)	m/s
6	a_x	0.03	Acceleration limit in the X direction	m/s
7	a_y	0	Acceleration limit in the Y direction	m/s

The first test environment is as shown in Figure 19, where the robot manages to navigate autonomously and plot a new path to the desired location in case the robot meets an obstacle on the way. The robot managed to detect the presence of the walls and boxes presented in Figure 20, thus creating a detailed map of them while reaching its intended goal location which is the end of the hallway.

Figure 19: The test environment for the first experiment.

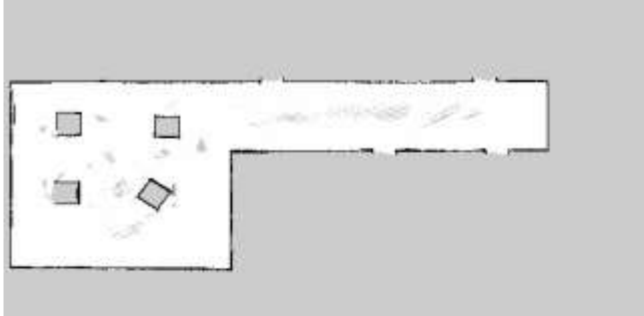

Figure 20: Generated map of the test environment

In the second test, the robot's ability to navigate the desired area and locate a piece of metal position was tested. The test location is displayed using google maps as shown in Figure 21. After marking the desired area for the test the robot navigates according to the path planning algorithm that was shown in Figure 15. The robot trajectory is displayed on google maps in Figure 22 and in case of detecting an obstacle, the robot will change its path accordingly to avoid collision as the robot continues to scan the desired area and eventually reaching the desired location which concludes the entirety of the map. In Figure 23, the robot manages to find the piece of metal and then mark it on the map.

Figure 21: The test environment for the second experiment [30.05397, 31.40092]

Figure 22: The test environment path planning algorithm

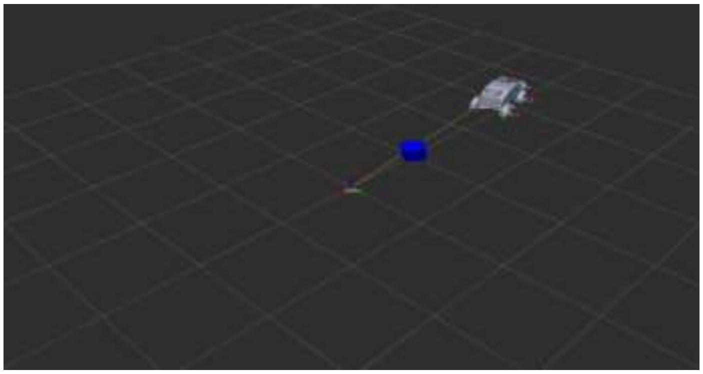

Figure 23: The position of a piece of metal detected and marked

Conclusion

This paper discussed the analysis and design of a landmine detection robot, which is suitable for many rough terrains. The calculations of both forward longitudinal dynamics and forward skid-steering requirements are presented. The stress analysis of the critical parts that may cause failure is investigated. The raspberry pi board is used as a master microcontroller while the Arduino is acting as a slave, which allows for a fast response time. The metal detector sensor can detect the presence of landmines at the desired depth with a satisfying accuracy rate. The landmine detection robot can operate remotely or autonomously with minimum human interaction. Therefore, there is no risk to human life. The robot uses multiple navigation ROS packages to control the robot autonomously. The sequence of operation includes navigation, avoiding obstacles then plotting a new path to the desired location while scanning for the location of potential anti-personnel landmines. The work can be extended for the implementation of a full-scale model in real-life applications.

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