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# Energy Optimized Path Planning and Decision Making for Multiple Robots in Rough Terrain

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**Abstract:** This study defined the problem of motion planning for multiple unmanned tracked robots that minimize energy consumption in terrain with obstacles. The energy consumption of a DC motor is widely known to be dependent on its angular speed and acceleration. The transnational velocity and acceleration of a robot are controlled by the angular speed and acceleration of the driving DC motor. This study examines the method for estimation of a robot's path and velocity profile such that it uses the optimum energy while maneuvering. Moreover, the battery backup of UGVs is limited, and a robot's power supply has an impact on its performance and leads the robot to stop during the mission. This failure directly hinders the success of the assigned task and/or mission. In this paper, an algorithm for identifying the suitable robot for the instantaneous task during the rescue operations is proposed. In addition, using the optimal trajectory of each robot within a multi-robot system and monitoring the battery status of each robot.

**Keywords:** Unmanned tracked vehicle; Tracked vehicle dynamics; Battery management; Mobile autonomous robots

## 1. INTRODUCTION

During man-made and natural disasters, the applicability of rescue robots becomes vital [1]. Among the various situations where robots can assist human operators, safety security and rescue robotics (SSRR) activities are one of the areas where they can have a greater impact. Path planning, autonomous navigation of the robot, and supply of sufficient power are some of the key challenges for such critical missions.

The robots are deployed for the long run with the responsibility of gathering vital data, the amount of energy source available is always a hindering factor in the completion of rescue missions. In most cases the battery is the main source, particularly Lithium polymer battery (Li-Po). Nowadays a wide range of researchers is being carried out in SSRR in the fields of optimization of motion, speed, data management, hardware usage, and maintenance to enhance battery backup. Due to the importance of this energy unit and ongoing limitations, battery management and energy consumption strategies for rescue robots are crucial.

The rescue robots work in potentially hazardous and dangerous locations, it must be able to operate autonomously or with minimum human intervention. Therefore, rescue operations should be performed with minimal energy consumption is salient. Because the availability of battery backup on the robots is always not fulfilled. In this scenario, the selection of the suitable robot for the instantaneous tasks is crucial when they are working together in the rescue operations. Selecting such a robot depends on its battery backup and trajectory to the target. The robot with the shortest trajectory does not have to have sufficient battery backup to complete the assignment. Likewise, The path taken by the robot with the most battery backup is not the shortest. In such a case an algorithm is needed to identify the appropriate robot based on its path and battery backup.

Sattayasoonthorn et al. [2] provided battery management for rescue robot operations. This indicates that good management and maintenance can be used to increase battery life. Mei et al. [3] present a case study of mobile robots' energy consumption and conservation techniques. In order to prevent frequent changes in speed and save energy, Barili et al. [4] provide a technique to regulate the travel speed of an autonomous mobile robot. Sun et al. [5] proposed an algorithm for finding an efficient energy path on terrains. Mei et al. [6] developed an energy model for a mobile robot called Palm Pilot Robot Kit (PPRK) and they compared the energy consumption of different routes. Which is a general approach to finding the energy efficiency of different motion plans. The proposed method is different from previous work because the emphasis is on calculating the energy-efficient paths of the different paths and identifying the right robot with the maximum battery backup to complete the task.

## 2. METHODOLOGY

The over view of the problem statement is illustrated in Figure.1, and is explained with the help of operations of bunch of terrain rescue robots (UGV) and a aerial robot (UAV) with mapping capabilities and algorithm for the same is represented in Figure. 2.

The working model starts with collecting the real-time battery status of the individual mission robots, in which the collected data's include thermal status, current and voltage. Meanwhile, the mapping technique is implemented for each

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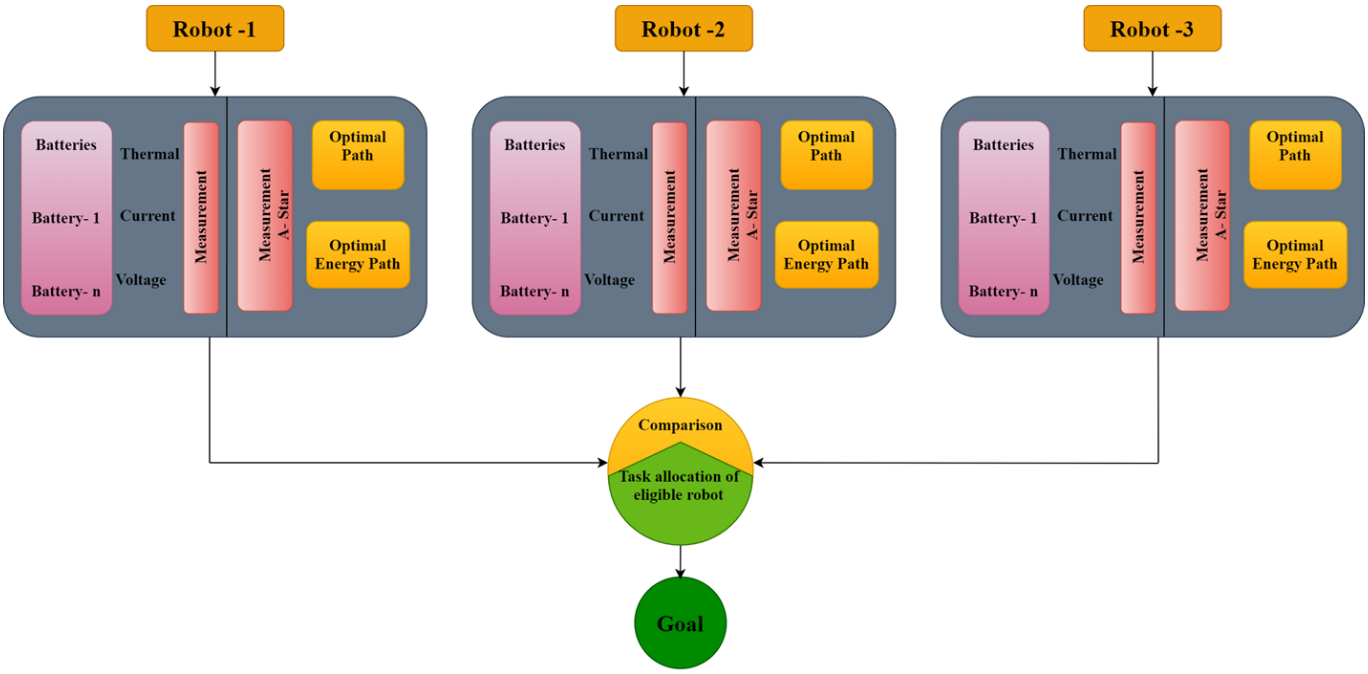


Fig. 1: Planning Framework

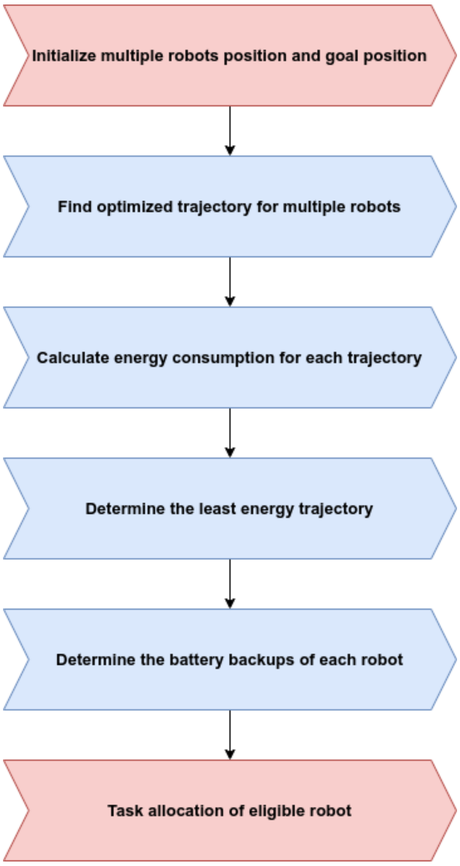


Fig. 2: Planning Framework

robot for forecasting the shortest path for accomplishing a particular task, with the help of this information's optimal path and optimal energy path are predicted individually for all the mission robots. Data sets for the four robots are collected and decisions are made using a predetermined algorithm, which instantly selects the most appropriate one from the robots in different locations for an instantaneous task.

The mapping algorithm determines the best path, however, this does not imply that it is the most energy-efficient path. As a result, finishing the trajectory by terrain robots is required to optimize the path with energy and to address the issue of total energy. Also, if the trajectory given by the Mapping system is linear, so it would cause the velocity to be discontinuous at the beginning and end of the motion. To create a smooth path with continuous position and velocity, we need to add a parabolic blend region at each path point [7]. The individual mission robots' real-time battery state (Remaining energy ($E_{ri}$) and optimum path are now available. From the trajectories of individual robots, it can identify which robot ($T_i$) has the smallest trajectory. For this calculation, we can use the parameter $\kappa$;

$$\kappa = \frac{E_r}{T_i} \tag{1}$$

The Value of $\kappa$ can determine the most appropriate robot for assigning the particular task to achieve the goal. Which robot with maximum value of $\kappa$ is the most suitable one. Since the robot with the shortest trajectory does not necessarily have to satisfy the task's battery requirements. Similarly, the path taken by the robot with the biggest battery backup is not the shortest.

### 2.1. Kinematics

The inertial frame (X, Y, Z) and the body-fixed frame (x, y, z) with its origin at the vehicle's center of mass (COM) are both introduced (Fig.3). The Z coordinate remains constant since the robot is navigating on a plane. Furthermore, it is assumed that COM corresponds with the centroid of the robot body to simplify the formulation. Assume that the robot is moving at a linear speed.

$$v_B = \begin{bmatrix} \dot{x} & \dot{y} & 0 \end{bmatrix}^T$$

If $\theta$ is the angle between the local coordinate frame $\mathcal{B}$ and the inertial frame $\mathcal{I}$. The rotation matrix $R_{2X2}$ that carries inertial frame $\mathcal{I}$ into local coordinate frame $\mathcal{B}$ [8]

$$R(\theta) = \begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix}$$

Several strategies for addressing path planning and tracking difficulties for a terrain robot were developed from the viewpoint of systems and control [8, 9]. However, most control algorithms in the literature either employ a simple kinematic model in the inertial frame as [10].

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \end{bmatrix} = R(\theta) v_B$$

When maneuvering, slipping / skidding are taken into consideration, the robot speed can be obtained as [9]

$$V = \frac{r}{2cos\alpha}[\omega_L(1 - i_L) + \omega_R(1 - i_R)] \tag{2}$$

Where $\alpha$ is a slip angle, r is the radius of the sprockets, and $\omega_L$, $\omega_R$, and $i_L$, $i_R$ denote the left and the right track rotational velocities and slips[11], respectively. The following equation can be used to compute rotational velocity :

$$\dot{\theta} = \frac{r}{b}[\omega_L(1 - i_L) + \omega_R(1 - i_R)] \tag{3}$$

Where,

$$i_L = 1 - \frac{v_{t,L}}{\omega_L r} = 1 - \frac{\dot{x} + (b/2)\dot{\theta}}{\omega_L r} \tag{4}$$

$$i_R = 1 - \frac{v_{t,R}}{\omega_L r} = 1 - \frac{\dot{x} + (b/2)\dot{\theta}}{\omega_R r} \tag{5}$$

and the slip angle

$$\alpha = arctan\frac{\dot{y}}{\dot{x}} \tag{6}$$

The turning radius *R*, with slip taken into consideration, can be calculated using Equations of vehicle speed (2) and rotational velocity (3):

$$R = \frac{V}{\dot{\theta}} = \frac{b}{2cos\alpha} \frac{\omega_L(1 - i_L) + \omega_R(1 - i_R)}{\omega_L(1 - i_L) - \omega_R(1 - i_R)} \tag{7}$$

Because velocity in the body frame can be represented as a function of speed and slip angle, we may derive the following equation:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = V \begin{bmatrix} cos\alpha \\ sin\alpha \end{bmatrix}$$

In the inertial frame

$$\dot{X} = \frac{r}{2}[\omega_L(1 - i_L) + \omega_R(1 - i_R)][cos\theta - sin\theta \; tan\alpha] \tag{8}$$

$$\dot{Y} = \frac{r}{2}[\omega_L(1 - i_L) + \omega_R(1 - i_R)][sin\theta + cos\theta \; tan\alpha] \tag{9}$$

$$\dot{\theta} = \frac{r}{2}[\omega_L(1 - i_L) - \omega_R(1 - i_R)] \tag{10}$$

### 2.2. Dynamics

In this research, it is assumed that the service brake is not applied, and the friction brake force is not generated. A moving terrain tracked robot is solely subjected to track-terrain interaction forces like Tractive forces (F), Longitudinal resistance forces (R) , Lateral forces ($F_y$) and Moment of turning resistance ($M_r$) induced by the resistive forces. The forces acting in the longitudinal direction cause the turning moment, so that

$$M = (F_L - F_R)\frac{b}{2} \tag{11}$$

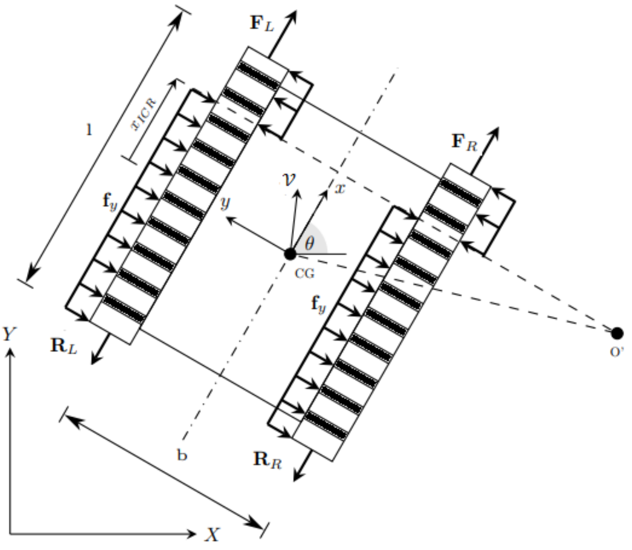


Fig. 3: Free-body diagram of terrain tracked robot

### 2.3. Drive Model

The robot is controlled by a PID controller and is powered by DC motors. The rotor current $i_a$ and the motor torque $\tau_m$ are assumed to have a linear relationship [12].

$$\tau_m = k_m i_a \tag{12}$$

where $k_m$ is a motor torque constant.

### 2.4. Equations of Motion

The system's kinetic energy is calculated by assuming that the energy of rotational tracks may be ignored [8].

$$E_T = \frac{1}{2} m \mathbf{v}^{\mathbf{T}} \mathbf{v} + \frac{\mathbf{1}}{\mathbf{2}} \mathbf{I} \omega^{\mathbf{2}} \tag{13}$$

Where m and I are the mass and moment of inertia about the COM of vehicle respectively. Because the magnitude of velocity is independent of the reference frame, the above equation can be rewritten as follows [8]:

$$E_T = \frac{1}{2} m(\dot{X}^2 + \dot{Y}^2) + \frac{1}{2} I \theta^2 \tag{14}$$

### 2.5. Energy Consumption Model

Estimating the significance of the total energy utilized by the robot in an instantaneous operation leads the optimization merely negligible.

$$E_{Total} = E_{DC} + E_K + E_F + E_E + E_G \tag{15}$$

Where, $E_{DC}$, $E_K$, $E_F$, $E_E$,and $E_G$ are energy consumption by DC Motors, energy losses of the robot motion, energy losses due to friction, energy losses of the on-board electronics, and energy losses due gear, respectively.The energy consumption of a DC motor is widely known to be dependent on its angular speed and acceleration. The transnational velocity and acceleration of a robot are controlled by the angular speed and acceleration of the driving DC motor. This study examines the method for estimation of a robot's path and velocity profile such that it uses the optimum energy while traveling. Because, the battery capacity of UGVs is limited, and a robot's power supply has an impact on its performance and may force the robot to stop during the mission. This failure directly hinders the success of the assigned task and/or mission. However, by using the optimum battery management system, this risk can be reduced.

The power consumption of each electrical component is commonly mentioned on the product's specification and is assumed to be reliable. The rescue robot is mostly used for high- and low-level control. Motors, sensors, microcontrollers, and embedded computers are the most energy-consuming components [2]. Power models could be used to estimate the power consumption of these components [3].

The power consumption of motion power ($p_m$) is the sum of the output mechanical power and the transforming loss ($p_l$) in motors.

$$p_m(m, \mathbf{v}, \mathbf{a}) = \mathbf{p_l} + \mathbf{m}(\mathbf{a} + \mathbf{g}\mu)\mathbf{v} \tag{16}$$

where m represents the robot's mass, a denotes its acceleration, and $\mathbf{v}$ indicates its speed. The constants are gravity (g) and ground friction ($\mu$). So, this model shows, the transforming loss decreases as the speed increases in DC motors.

For sensing power ($p_s$), the power consumption from sensing components such as video cameras, laser rangers, and other sensors can be represented as a function of sensing frequency ($f_s$).

$$ps(f_s) = c_{s0} + c_{s1}(f_s) \tag{17}$$

where $c_{s0}$ and $c_{s1}$ are the positive constant coefficients of sensors. Javied, Tallal, et al. study shows that motion consumes almost 50% of the power consumption. The torque of each actuator and the rotation angular velocity of the motors constitute mechanical power. As a result, the energy optimization problem becomes the trajectory optimization problem [13].

## 3. IMPLEMENTATION OF ALGORITHM

The Dynamic Window Approach DWA [14] is a popular strategy for avoiding local obstacles in mobile robots. Because of the robot's acceleration and velocity constraints, if it is run at a set frequency, only a limited number of velocities may be commanded to it. A reward function is proposed to choose the optimal velocities to follow from this set of velocities (which can change with each iteration) [15]. The objective function for the optimization is written as :

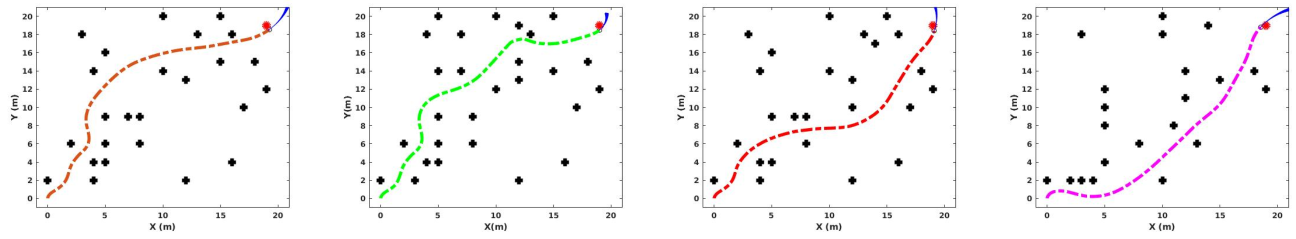
$$G(v, \omega) = \sigma(\alpha.heading(v, \omega) + \beta.dist(v; \omega) + \gamma.vel(v, \omega)) \tag{18}$$

where *heading* is a measure of progress towards the goal location, *dist* is the distance to the closest obstacle on the trajectory, and *vel* is the forward velocity of the robot and supports fast movements. The initial and final positions of the four robots were taken to be the same when implemented this strategy in our research. But the trajectory of each robot is different due to the obstacles they are avoiding through traveling to the target position. Each robot's trajectory was generated using DWA, and the kinetic energy of each robot was estimated. It is not compulsory that the robot with the shortest trajectory path should have the lowest kinetic energy consumption to complete the task. This statement is supported by our simulations for trajectory generation and kinetic energy calculation.

Now we have the real-time battery status ($E_{ri}$) of the individual mission robots, optimized path, and kinetic energy which is enough to choose the most appropriate robot for assigning the instantaneous task to achieve the goal. In this work, we didn't consider the power consumption from the sensing components, energy losses due to gear and friction. For a known value of real-time battery status ($E_{ri}$) of the individual mission robots, optimized path, and kinetic energy which is enough to choose the most appropriate robot for assigning the instantaneous task to achieve the goal.

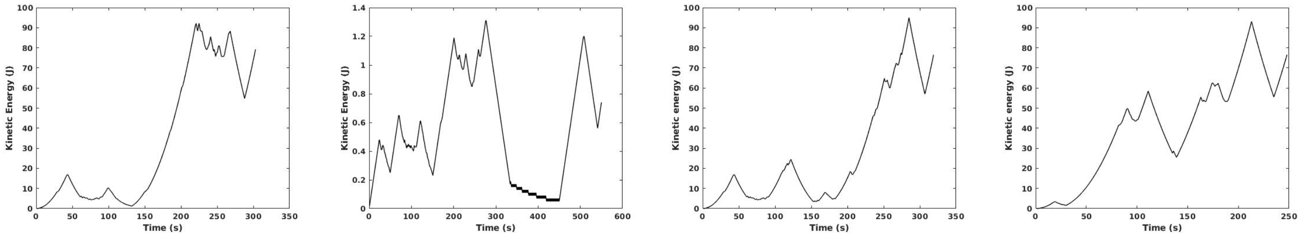
## 4. RESULTS

The proposed architecture has been tested with four robots for identifying the suitable robot for the instantaneous task during the rescue operations. As the system computes optimum trajectories for each robot within the multi-robot system, the system also monitors the battery status of each of



(a) (b) (c) (d)

Fig. 4: (a) Path of Robot-1 (b) Path of Robot-2 (c) Path of Robot-3 (d) Path of Robot-4



(a) (b) (c) (d)

Fig. 5: (a) Kinetic Energy of Robot-1 (b) Kinetic Energy of Robot-2 (c) Kinetic Energy of Robot-3 (d) Kinetic Energy of Robot-4

the robots. Fig. 4 and 5, depicts that the Robot-4 has the shortest trajectory but it has maximum kinetic energy. That means the increase in the torque on the motor shaft results in a linear increase in the armature current, which drains battery capacity.That is, a robot with the maximum value of $\kappa$ can be predetermined before the instantaneous task. In the case of robot-4, its kinetic energy is always rapidly changing during the operation that may result in energy loss due to gear and friction. Robot-1 and Robot-3, they using less kinetic energy compared to the rest of the others, but the amount of battery backup determines they are eligible or not.

## 5. CONCLUSION

This research outlines the challenge of motion planning for multiple autonomous tracked robots in terrain with obstacles with the goal of selecting eligible robots. While the system calculates optimal trajectories for each robot in the multi-robot system, it also estimates each robot's battery state. The functions showing optimum trajectory and battery state are quantified and utilized to calculate parameter $\kappa$, which can be used to choose the best ideal robot for assigning an instantaneous task to achieve the goal. To put it another way, a robot with a maximum value of $\kappa$ is considered extremely suitable.

## 6. ACKNOWLEDGEMENT

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