Potentially Distributable Energy: Towards Energy Autonomy in Large Population of Mobile Robots

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Abstract – We issue a new concept, potentially distributable energy, in the field of autonomous mobile robots. Considering a system of multiple robots equipped batteries, each is no longer working than it's battery capacity. To extend working-life, the robot needs to replenish energy by recharging or exchanging batteries. To date, except some results for robots that are able to recharge battery with the fixed docking station have been achieved, no research of energy distribution to prolong working-life in a large population of mobile robots has been established. However, to use a rechargeable battery, the robots have to normally spend a charging-time much longer than working-life. This paper presents a system of mobile robots that are capable of carrying out and exchanging rechargeable batteries. Initially, we build a simulation of the system of multiple mobile robots, and then adding rules of battery exchange which is formulated by constraints of workload, distance and remaining capacity. Our simulation shows that: (a) a robot is able to be energetically autonomous if it's energy can be replenished by others or it can go back to the mother charging station to replenish itself; (b) energy of a robot tells us the distribution capability of such a robot in energy constraints with the mother charging station and the other robots; (c) distributed energy balance between a number of robots in a specific area and an ideal location of the repository in a large population. Finally, based on results of the simulation we adjust rules for our real multirobot system.

Index Terms – Potentially distributable energy, Sharing Energy, Multirobots, Self-distributed Energy

I. INTRODUCTION

Mobile robots are now researched and used widely in many applications, such as exploring, searching, and rescue in an unknown area, or hazardous environment. Normally, a robot built by several sensors, motors, and electronic components so power consumption of such components has to be taken into account. Due to economic scheme, mobile robot is mostly equipped rechargeable batteries. Thereby life of the robot is depending on life of the batteries. In the case, the law of energy conservation is importantly considerable.

However, on the law of energy conservation, we can easily see that energy can not be created or destroyed, but it can change its form. For mobile robots, it is necessary to be equipped with a tank of energy to power its operation until the tank can be fueled again. For examples, vehicles must be equipped a tank of energy to store fuel e.g. gas, petrol; most electric vehicles use rechargeable battery packs. Some special vehicles are equipped with a solar cell or a wind cell on the top to harvest natural sources. On the other hand, to create long-lived vehicles, the volume of fuel tank should be increased, or the fuel material should be more concentrated, or natural provision of sunlight and wind should be stable over time. However, criteria are impossibly fulfilled due to physical limitations of tank material, size, fuel concentration, natural condition, and operation environment.

Using classical methods of energy conversion, European researchers have investigated collecting and digesting food of natural animals, e.g. sugar, pistil, flies and a digestive mechanism of food to transfer naturally collected food to energy for mobile robot. Ecobot I [1] with a sugar digestive mechanism demonstrates the possibility of the biological method. Further, Ecobot II can catch home flies, and digest their exoskeleton and transform it into electrical energy. But, sugar or flies are sources not always available.

Another approach to long-lived mobile robot is recharging stations. The approach is widely applied for vacuum cleaning robots that autonomously move around to clean up and return to docking station to be recharged. Normally, such robots use rechargeable batteries as power sources and the batteries, of course must be recharged again within a few hours. Autonomous charging docking with possibilities of sensing and communication was added to guide robot to easily reach charging points. Silverman et al [2] and Seungjun Oh et al. [3] describe their implementation in which autonomous recharging docking mechanism is specially designed with infrared proximity and laser range sensors to guide robot to go back and firmly connect with the station using landing technique of airplane. Moreover, Hada and Yuta et al. [7] give results of a week-long repetitive docking experiment. The robot is equipped with infrared sensor and reflective tape on the floor to guide the robot to the docking station. Most difficult technique to successfully implement such systems is path planning that enables robot to contact charging station in precise direction. In this case, particle filtering or Kalman filtering algorithm has been usually chosen to estimate a path using proximity sensors. As an extension, multi-charging stations to maximize longevity of distributed robotic teams is considered in some practical cases. Nevertheless, the solution is only suitable for simple autonomous robot with low-level
mission, no high demand of charging time, and traveling time from target to charging station.

An approach to prolonging longevity of mobile robot’s power source is efficient energy in motion. Conventionally, hardware configuration of mobile robots comprises embedded electronic boards, actuator and sensors are integrated to run at low speed to save energy consumption. To save total energy of mobile robot, Sun et al. [11] found energy-efficient paths using topography information of the ground. Further, since electronic devices always consume a finite energy, the devices should be switched off to standby mode to save robot’s overall energy. For instance, Barili et al. [6] investigated concept of controlling velocities of DC-motors to save energy but did not consider trade-offs between motion planning and velocities. Another study of control algorithms to reduce the motion power of humanoid robot is issued by Yamasaki et al. [8]. Considering power consumption Liu et al. [12] proposed algorithm of power-aware scheduling for Mars rover. However, the techniques all are only to save overall power for mobile robot prolonging longevity of robot with battery life. It is not sufficiently capable of extending or changing the total energy for mobile robots.

Alternatively, Zebrowski et al. [9] proposes an interesting approach: a tanker robot that is specially deployed as “mother” robot. The robot traverses to record the temporal position of “worker” robots and then distribute energy cells to “worker” robots if demanded. This proposal is compared with daily work of gas trucks that usually deliver gas from main repository to local gas station or tanker aircraft to fighter aircraft on the sky. Advantages of the proposal are low cost, simpler complexity of worker robot and efficient energy of system. But drawback of specializing tasks of robots can be easily recognized: only single-task on each robot is assigned and traveling distance of tanker will be too long to any worker that is not close to fuel station. Thus a far away “worker” is not able to ask for new battery in emergency case. Furthermore, current results are presented in simulation, not practical achievement. Likewise, it does not show any direction of how to implement the described robotic system.

To overcome the mentioned obstacles, we present a group of mobile robots with mechanism of energy exchange that are capable of fairly collecting and carrying batteries to share with other robots. Rules of battery exchange are issued in section II. In section III we briefly describe our models of single robot and multirobot coordination control. In section IV we perform simulation of a number of robots and different location of the mother station. We discuss simulation results to suggest course of our real multirobot implementation. Finally, the paper is concluded in section VI.

II. RULES OF BATTERY EXCHANGE

Generally, energy consumption of a robot is approximately estimated from power consumption of electronic boards, sensors and motors, especially, wheel motors. Based on specification of robot we are able to create a power model of such a robot. Indeed the model decides working status of robot. In the simulation, we issue the algorithm to engage in battery exchange in a multirobot system in which each robot has to negotiate with other robot in its vicinity to exchange energy. The algorithm comprises potentially distributable energy of each robot, energy constraints among robots and mother station as well as deployment techniques of multirobot systems in a specific area.

Because our real robot are able to carry 8 batteries, we model maximum number of 8 batteries for a robot in which a battery is supposed to obtain 100 energy units. But, at a time, total energy of each robot is probabilistically synthesized of remaining capacity of number of batteries carrying. The amount is randomly changing in terms of a number of batteries exchanges and an assigned mission of the robots. Therefore, we suppose that at a time the robot has remaining energy capacity \( E_i \) that is collected from individual energy \( e_i \) of battery available in \( nob \) holders. Therefore, we can synthesize the total energy of the robot \( r_i \) on probabilistic number of batteries at a time:

\[
E_i(t) = \sum_{j=1}^{nob} e_j \quad (0.1)
\]

Also at time \( t \), there exist \( k \) robots in the robot \( r_i \)'s vicinity with corresponding distance \( d_{u,i} \) and itself is distance \( d_u \) away from the closest charging station. We define \( C_i(t) \) as the average energy consumption of the robot \( r_i \) freely moving in a unit of distance without other tasks. Thus, there exists two possibilities for robot \( r_i \) to be recharged: robot \( r_i \) consumes an amount of \( d_u * C_i(t) \) if it wishes to go back to the charging station to take fully charged batteries, and other robots \( r_k \) \( \{k:1...k,k \neq i\} \) consume energy \( d_{u,i} * C_i(t) \) if they wish to go to the current position of robot \( r_i \) to exchange batteries.

We assume that \( t + \Delta t \) is the time when robot \( r_i \) is already recharged. The total energy of robot \( r_i \) at time \( t + \Delta t \) is a substitution of the remaining energy at time \( t \) and energy consumed on traveling distance \( d_u \) and \( d_{u,i} \). At the time \( t + \Delta t \), the remaining energy of robots around the robot \( r_i \) is estimated:

\[
E_i(t + \Delta t) = E_i(t) - d_u * C_i(t) \quad (0.2)
\]

Because every robot itself always checks battery status and keep communication with other robots in its vicinity, thus a robot \( r_i \) needs to be charged if indicated by a battery management system, it will search for the closest charging station and other robots that can distribute energy. Thereby, we formulate local energy distribution in terms of the algorithm of comparison and negotiation of remaining energy of robots with respect to energy status shown in figure 5. We issue probabilistic algorithm of battery distribution for our
CISSbot, including two procedures: searching for the closest charging station and robots in robot \( r_i \)'s vicinity with the corresponding distances and the remaining energy; and decision:

**Algorithm: BATTERY EXCHANGE**

1. Initial: a set of predefined battery status \{ \( E_{\text{good}} \), \( E_{\text{standby}} \), \( E_{\text{self-contained}} \), \( E_{\text{stop working}} \) \}, maximum energy \( E_{\text{max}} \), number or robots in a local vicinity \( k \). a set \( d_{k_i} \) as a corresponding related distance of other robots to the robot \( r_i \), \( d_{k_i} \) is the absolute distance of a robot \( i \) to the station and the selected robot index

2. Searching: Find a number of robots in robot \( r_i \)'s local vicinity and put into list \( k \).

3. Energy Calculation: calculating the remaining capacity of robot \( r_i \) to go back to the charging station: \( E_{\text{good}} = E_{\text{good}} - d_{k_i} \cdot c_i \), and the remaining energy of the robot in the local vicinity after traveling to the robot \( r_i \)'s position: \( E_{\text{good}} = E_{\text{good}} - d_{k_i} \cdot c_i \).

4. Selecting & Controlling: Find \( \arg \max \{ E_{\text{good}}, E_{\text{max}} \} \) to show the index. If the index is in \{ \( E_{\text{good}} \) \}, guide the robot \( r_i \) to go back the closest charging station using MOTION PLANNING. Otherwise, the index is in \{ \( E_{\text{good}} \) \}, refer \( E_{\text{max}} \) to \{ \( E_{\text{good}} \), \( E_{\text{standby}} \), \( E_{\text{self-contained}} \), \( E_{\text{stop working}} \) \} to issue a decision in set \{ LOW POWER \( ( r_i ) \), STOP WORKING \( ( r_i ) \), CALL FOR EMERGENCY \( ( r_i ) \) \} before using MOTION PLANNING, depending on the current position of the robot \( r_i \), the robot \( r_{\text{index}} \), and the closest charging station.

III. MODEL OF MULTIROBOT

Instead of using other programming language, we have chosen Matlab to implement our simulation because Matlab supports a lot of graphical libraries to easily execute mathematical computation, or generate graphs and charts.

A. Model of Single Robot

We focus on the energetic autonomy of the multirobot so we are going to simplify robots as points moving on scanlines in the Euclidean space. Therefore, distance relation among robots is based on Manhattan space. We do not consider dynamic aspect of mass of robot, friction of wheels, or mechanical interaction with environment, instead we suppose to issue differences of power consumption of robots, using the Peukert’s discharging function \( C = \frac{1}{1 + kt} \) where \( k \) is depending on the battery manufacturer.

B. Model of Robot Coordination

To facilitate our approach to of battery exchange, we implement a coordination algorithm for the multirobot in which we are combining two algorithms of path planning and battery exchange. Briefly, the coordination control works as a supervisor. The supervisor collects input data of the robots: current coordinate \((X,Y)\) and current state of energy \( \text{STATE} \); deals with such updating data; issue output commands: NEXT STATE of energy, goal coordinate \((X_{\text{goal}}, Y_{\text{goal}})\). To be more detailed, algorithm of the battery exchange executes infinite loops of comparison of energy state and current position among the robots as well as the robots with the mother to issue commands of where robots go (goal of robots). Meanwhile path planner is going to guide the robots to move to directed goal and updating the next position of the robots, which is used as a feedback for the battery exchange algorithm to compute the next states of the robots.
IV. SIMULATION

We present early simulation results of our objectives. First we demonstrate that our robots are able to be truly energetically autonomous if it is able to exchange energy with other robots or the mother. Second we emphasize potential distribution of energy and its constraints among robots, and the mother station. Third, we examine how to optimize the energy consumption of the multirobot system under trade-offs of location of the mother and the robots.

In the simulation setup shown in figure 4, we present significant information of the system of truly autonomous mobile robots. It is shown by four graphical windows (left to right): animation of multirobot motion, potentially distributable energy of the mother and the robots, the energy state of the robots, and the task of the robots. That is, animation window shows us the motion planning of the robots; the potentially distributable energy window presents the remaining energy of the robots (height of the pyramids) and their capability to share energy with other (projected contour of the pyramids); window of the state of energy realizes the energy chart of the robots according to the instant; and the task window reports operating tasks of the robots. We also generate a register of the states of the robots in every experiment:

A. Energy Autonomy

In fact, robot will face the problem of providing food as animals. Most of the mobile robots are using rechargeable batteries as a power source. Thereby, it has only autonomous behaviour in the duration of the battery-life, e.g. free moving around to explore, free searching a way to carry heavy objects, or searching to rescue humans after earthquake. A robot is able to be absolutely autonomous if it has energy autonomy. Our simulation results are to prove that the robots are able to live forever, without human intervention if they are able to coordinate energy sharing with the other robots. The objective means that each robot is able to be energetically autonomous or assist other robots to be the same.
Figure 5 shows an experiment of 5 robots executing in 2000 steps. On the second column, we see that the potentially distributable energy of the mother can always cover the field. That is, every robot can be globally covered by the mother \((M)\) so it can be refilled if it is able to come to the mother. However, the potentially distributable energy of the robots \((A, B, C, D, E)\) is much lower so it can cover a local vicinity. Because the robot is moving, its potentially distributable energy becomes mobile sub-mother charging station for the other robots in its vicinity. Therefore, every robot can be a first-aid unit in the case of emergency in which other robots have not enough energy to go back to the mother station, or desire to finish their duty in a short time before coming back to the mother station. Additionally, referring to the fourth column, we see that at the instant 1201, \(A\) is going to \((\Rightarrow)\) share 100 eu with \(C\), and \(C\) stops working to save energy and waiting \((\Leftarrow)\) for \(A\). At the instant 1341, \(C\) still needs energy again since \(C\) has already consumed 100 eu, \(B\) is indicated to give battery for \(C\). Therefore, at the instant 1691, we can easily recognize that \(C\) has already come back to the mother in order to be fully replenished and is now working with an amount of 700 eu approximately. Due to the assistance of \(A\) and \(B\), \(C\) can survive to continue its duty, instead of being stuck somewhere on the field. To conclude, robots can have absolute autonomy if they are conditionally able to be energetically autonomous. Further, such a multirobot system can totally save energy and optimize their performance under constraints of time and energy.

**B. Potentially distributable energy & Its Constraints**

In this section we emphasize the potentially distributable energy and its constraints. As described in figure 6, the potentially distributable energy can be divided into two meanings: Height of the pyramids \((H)\) is to imply the remaining capacity of each robot while Contour of the pyramids \((C)\) is to determine how wide the robots are capable of distributing energy to the other robots. Actually, considering a robot with low energy, its pyramid peak, \(H\) is fully covered by the another pyramid, it means it is now in the space where the other robot is able to share energy - it is inside the potentially distributable energy of other robot -, and it will be definitely recharged if it needs energy. Otherwise, the robot must be waiting until the other robot is moving close to it. Further, interfering wave of Contour of the pyramids also tells us more about the distance and the energy relationship among the robots, and these with the mother station.

The blue lines in figure 6 show the energy and distance constraints between the robots, or between the robots and the mother. Moreover, creating the blue line is based on the gradient of the potentially distributable energy between the robots, or the mother. The slope of the blue lines shows us the reciprocal energy effects and the length of the projected blue lines to the corresponding distance.

Indeed, figure 6 is to perform that density of the potentially distributable energy is stronger when the number of robots is increasing (a): 2 robots, b): 3 robots, c): 4 robots, d) 5 robots) in the same field. We discuss that a robot in need of energy possess more opportunity to be recharged if the density of the potentially distributable energy in the field raises up, but it is more hard to reach other robots since the number of collision detection increases. Thereby, we have to estimate the balance of the number of robots and the mother location to deploy a multirobot system. We will make clear the argument the next section.

**C. Deployment of Multirobot**

First we experiment with reducing the number of robots in the same field. Figure 7 shows that if the number of robots increases (left to right) from 2 to 5, the number of battery exchange between robots also raises from 0 to 4. It is indispensable that the battery exchange between robots to energetically rescue is proportional to the number of robots since the robots that are far away from the mother need more
Consequently, keeping the same number of 5 robots, we try to change the location of the mother in the same field. The result of 100 experiments shows that the total number of the battery exchange is almost the same. That is, the overall energy consumption is proportional to the size of the field, and not depending on the mother location. However, in the distribution seen in figure 8, since the mother is at one of the corners of the field, robots must work in a more narrow area. Hence, they are preferable to be charged by the mother than the other robots (blue-line). Otherwise, in a wider area, more robots require battery sharing to prolong the working time, or to sometimes have enough energy to go back to the mother.

VI. CONCLUSION & FUTURE WORKS

This paper issues the concept of the potentially distributable energy in multirobot coordination. Initialization of the concept is originally borrowed from the artificial potential field in which the gradient of attraction is used to direct the robot to reach the goal. Considering a multirobot system, each robot is a mobile charging station, or is able to be self-sustained with energy if it is capable of sharing energy. Therefore, the robot involves the potentially distributable energy corresponding to the neighbours in the local vicinity. Under the constraints of distance, and remaining capacity, the highest peak of the potentially distributable energy is exactly the current location of the robot so each robot has its own potentially distributable energy. Further, comparing the potentially distributable energy of robots and the mother location, we examine techniques of deploying a number of robots in a specific area and a feasible location of the mother charging station to optimize the power consumption of the robot in order to work longer.

Next, based on initial results of the simulation, we are going to experiment with our testbed of the real multirobot system. First, to simplify high requirements of localization and approaching, our mobile robots are also following the lines in a grid so the robot is able to know its current location. In this way it is rather easy to approach to contact to the mother station, or the other robot in order to exchange batteries. We will improve the techniques of sensor fusion for such robots to remove the grid, so our robots can be more sociable. They can be applied for home, office or manufacturer environments. Early implementation results can be found in the paper [13].

REFERENCES