Sharing Charging Stations for Long-Term Activity of Autonomous Robots

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Abstract

To operate over a long period of time, autonomous mobile robots must have the capability of recharging themselves whenever necessary. In addition to be able to find and connect to a power source, robots must also consider taking actions to preserve and share energy in an environment where energy is a limited resource. Coordination is then required to ensure the survival of the group and the accomplishment of the robots' tasks. This paper explores these issues by allowing robots to predict and reason about their energetic capabilities, as individuals and as a group. The approach described allows robots to determine when to recharge, when to change their activity level and how long they should recharge. Validation of the work is done in simulation to demonstrate the versatility of the approach for different numbers of robots and power sources. Experiments with Pioneer 2 robots are also reported.

1 Introduction

Robots, like humans, need energy to survive. Maslow's Hierarchy of Needs Theory recognizes physiological needs (hunger, thirst, breathing, sleeping, etc.) as the most basic ones. For mobile robots, this means to have energetic autonomy, also referred to as self-sufficiency [1], self-reliance [9], self-feeding [14], continuous or perpetual operation [8], life-long experiments [9], long-term or prolonged activity [5, 6, 9].

Since most of our machines are not mobile and remain connected to a power source, we sometimes forget that energy is a limited resource for a mobile robot. It is worth noticing that the first mobile robots were capable of autonomous recharging. Grey Walter's tortoises (1950) were capable of entering a lighted recharging hutch, and the Hopkins Beast (1960), of Johns Hopkins University, was able to plug itself in black wall outlets, using photocells and a special recharging arm that slided on the wall. Research then began focussing in mobile robotics on navigation and more cognitive capabilities. But recently, energetic autonomy is regaining interest with projects like robotic rovers for space exploration (e.g., Sojourner, using solar panels), Museum Tour Guides [9], teleoperated web-based robots [10], security and surveillance [4], and life-long learning [8, 9].

For an individual robot, energetic autonomy means answering the following two questions:

1. How can a robot find and connect itself to a power source?

2. When is it appropriate for a robot to recharge?

These problems are usually solved by using landmarks or beacons to localize a charging station or a power outlet, and by comparing the battery voltage level with a pre-determined threshold. Depending on the perceptual and localization capabilities of the robots, it may be difficult to anticipate how long it will take to find a power source and how much energy is remaining to allow the robot to stay operational (which may vary depending on the age of the batteries). Answering question 2 becomes a bit more difficult if we consider contraints associated with what a robot has to accomplish in its environment. For instance, a robot may need to recharge while it is accomplishing a critical task. And so, an additional question may arise:

3. How long the robot should recharge itself?

Finally, it is usually assumed that there is no limit to the amount of energy available for recharge. However, if access to a power source cannot be immediate, one last question needs to be answered:

4. What can be done to preserve energy?

For instance, a humanoid robot may inhibit moving different parts of its body when energy is getting low [15]. The research project presented in this paper addresses all of these issues in the context of having a group of mobile robots share a limited number of charging stations in an enclosed area, while having to accomplish a task. This is a spatial and temporal coordination problem, where each robot can influence the behavior of the others in space and in time (e.g., by gaining access to a charging station for a certain amount of time). Robots need to be able to analyze their energetic capabilities and communicate their states to determine what to do in regard to the situations experienced by the group.

This paper is organized as follows. Section 2 describes the experimental setup used for the project, and more specifically the robots and our charging station. Section 3 presents the theoretical analysis of the problem, deriving criteria to evaluate if sufficient energy is available for the group and what is the optimal number of robots to do the task while sharing power sources. Section 4 describes the algorithm we developed, allowing a group of robots to share a number of power sources. Since long-term activity of a group of real robots necessarily involves experiments over many days, we use simulation to validate our algorithm in relation to characteristics about the group and the power sources. As a first step in doing experiments with real robots, Section 4 presents analysis of the batteries voltage level of one robot in order to characterize its energetic capabilities. Section 5 presents related work, followed in Section 6 by the conclusion and future work.

2 Experimental Setup

To conduct experiments that allow robots to autonomously recharge themselves, a power source that they can find and use is required. It is possible to emulate autonomous recharging by having the robots go to a specific location and have somebody replace batteries or manually plug the robot to a power supply. But situations such as a potential malfunction or getting physical access to the power source cannot be completely addressed.

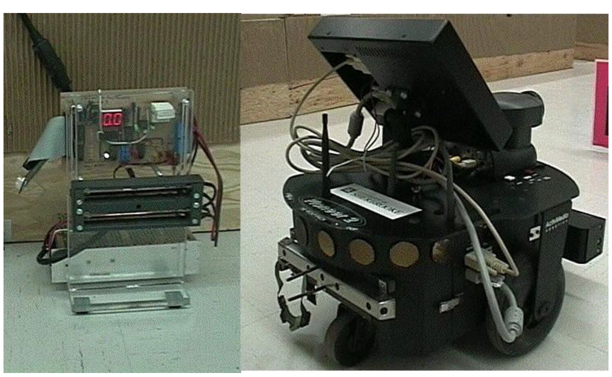

Figure 1: *Our charging station (left), with one robot (right) seen from the back, with the IR detectors.*

To experiment with real robots, we use up to six Pioneer 2 robots, three indoor and three outdoor models. Each robot is equipped with 16 sonars, a compass, a gripper, a pan-tilt-zoom (PTZ) camera with a frame grabber, a RF Ethernet-modem connection and a Pentium 233 MHz PC-104 onboard computer. Each robot has three sealed Lead Acid of 12V, 7 AH. With the battery level at 10V, the robot cannot continue operating reliably. To detect and dock into the charging station, we installed on the back of each robot a ring of seven infrared receivers with two metal pins, shown in Figure 1. The charging station is shown on the left side of Figure 1, and emits an infrared signal that can be detected from the back or the sides of a robot. The robot docks into the charging station by backing up so that the charging pins located above and below the infrared ring make contact with the charging station. The charging station is designed to adapt the amount of current generated to recharge the batteries as fast as possible. The robot can detect the charging station from a distance of 6 meters, and dock into the station on average in less than 45 seconds.

3 Theoretical Analysis

If we consider only one robot in a closed environment with one power source, it can either be in *Activity* (accomplishing its tasks), *Searching* for a power source, *Charging*, or *Shutting-down* (in case the robot is experiencing problems and it was not able to recharge). With a number of robots having to share a smaller number of power sources, an additional state is required in order to preserve energy: *Waiting* (or saving energy) for a power source to become available.

To determine when to wait for a power source, or even to determine that a robot is sufficiently charged so that it can leave the power source to others, we need to have a variable that approximate the amount of energy available to a robot. Different approaches can be taken to determine when it is appropriate to recharge, like a threshold on the robot's battery voltage level [10] or activation variables [5, 6]. The approach proposed in this paper is to predict the energetic capabilities of a robot based on a model of its battery levels. We chose to express this parameter in terms of time because it is more practical than to use the voltage level directly (which varies a lot depending on the actions taken by the robot, or on the types of robot). Suppose that a robot can approximate its "time of activity" (*toa*), i.e., the amount of time it can be in the Activity mode, approximated from the voltage level of its batteries. It is assumed for now that at 11V, the robot would starts searching for a power source (eventually the time to find a power station would be learned by the robot). So, at 11V, *toa* is equal to 0. Assume also that a robot knows or can determine the following parameters:

- T_A: the maximum amount of time a robot can operate in the Activity mode, going from full charge of its batteries to 11V.
- T_W: the maximum amount of time a robot can survive in the Waiting mode, going from full charge of its batteries to 11V. Note that we assume that a robot requires less energy in the Waiting mode than in the Activity mode, and so $T_W > T_A$.
- T_C: the maximum amount of time a robot requires to fully recharge its batteries, starting at 11V. Note that this, of course, depends on the charging station used.

Based on these parameters, it is possible to approximate interesting information about the global state of the group. For instance, Equation 1 can be used to detect that the amount of energy of the group is getting low, in an environment where the number of robots N_R is greater than the number of power sources N_P.

$$\sum_{i=1}^{N_R} toa_i < \frac{\sum_{j=1}^{N_R} \frac{T_{A_j} - toa_j}{\frac{T_{A_j}}{T_{C_j}}}}{N_P} \quad (1)$$

The left side of the equation represents the amount of energy of the group, and the right side is an approximation of the amount of time required to re-energize the group: the numerator approximate the amount of time spent in activity divided by the ratio of active time over the charging time; the denominator indicates that energizing the group can be distributed over N_P power source. If this inegality becomes true, it means that we can anticipate that the group is going to have a shortage of energy if all robots wait until their toa reaches 0 to search for a power source. In the case where the number of robots is lower or equal to the number of power sources, there is more than enough power sources. The right side of Equation 1 can be set to an arbitrary value (like 10 minutes) as a security factor, to compensate for the possible divergence between the predicted time and real life contingencies.

Another interesting criteria is the amount of energy available to the group for survival, taking into consideration that robots can go into the Waiting mode. Obviously, if the number of robots is lower or equal to the number of power sources, no problem should occur. But in the other case, Equation 2 can be used. The left part of the inequality represents the averaged ratio of time that can be spent waiting over the time required to charge. The right side of the inequality is the ratio of the number of robots that cannot be recharged simultaneously over the number of charging stations (assuming that the charging stations have all the same energetic capabilities).

$$\frac{\sum_{i=1}^{N_R} (\frac{T_{W_i}}{T_{C_i}})}{N_R} \geq \frac{N_R - N_P}{N_P} \quad (2)$$

4 Sharing Scenario

Our algorithm for making each robot accomplish tasks and share power sources in a group environment is illustrated by the state diagram shown in Figure 2. This algorithm assumes that robots can communicate their toa, T_A, T_W, T_C and their states (or modes).

Link A represents the conditions for which a robot will start searching for a power source. If a power source is available and toa is lower than 0, the robot goes into the Searching mode. With a group of robots, Equation 1 is used to anticipate a potential shortage of energy. If so, the robot with the minimum toa will start looking for a power source. Such conditions are valid for robots that are in activity or waiting for a power source to become available. Link B monitors similar conditions to link A, but to determine when to go from the Activity mode to the Waiting mode. Obviously, when no power source is available and that toa is lower or equal to 0, the robot should wait for a power source. At the group level, if a shortage of energy is anticipated and that the robot is not the one with minimum toa, the robot will also wait for a power source to become available.

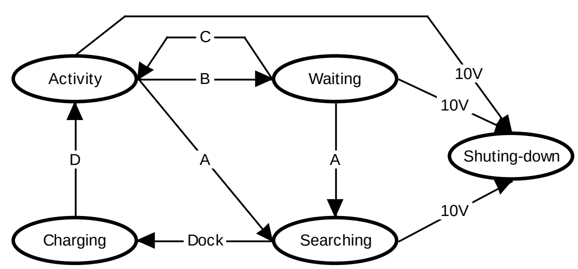

Figure 2: *State diagram of our approach. It represents the decision process followed by each robot.*

Link C allows a robot in the Waiting mode to become active again because it anticipates that it can go back into the Activity mode without compromising the survival of the group. For instance, a robot may have waited for a certain amount of time to allow the energy of the group to be sufficiently high. This possibility is anticipated by finding the minimum toa

between the robots that are not in a Charging mode, and to evaluate that after this time is passed if Equation 1 is verified. If not, the robot with the smallest toa for the robots in a Waiting mode, will go in the Activity mode. Finally, link D monitors conditions like no energy sensed at the power source or maximum energy reached for the batteries to make a charging robot leave a power source. In the case of a group, a charging robot i can also leave a power source to a robot that is in the Waiting mode if robot i has the most energy compared to other charging robots, and that it has received enough energy to leave its power source. The criterion used to determine if a robot has received enough energy to leave its power source is arbitrarily set to $toa > 10$ minutes.

4.1 Simulation Results

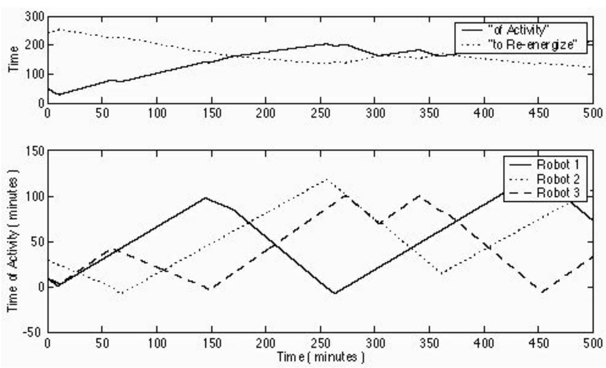

Figure 3: *Graphs representing the summation of toa for the group (middle), and the toa (bottom) of three robots and with two power sources, in relation to time (in minutes). The experimental conditions are* $T_A = [150, 120, 100]$*,* $T_W = [300, 240, 200]$*,* $T_C = [210, 180, 120]$*, and* $toa = [10, 30, 10]$.

Validation in simulation of this algorithm is important because it allows to determine the theoretical limit of the approach based on the number of robots, the number of power sources, the characteristics of the robots and of the power sources. For different combinations of N_R, N_P, T_{A_i}, T_{W_i} and T_{C_i}, the simulator evaluates the different states/modes the robots reached in relation to time. The simulator assumes that at each cycle the toa of a robot is decreased by 1 if it is in activity, by $\frac{T_A}{T_W}$ if it is waiting for a power source, and increased by $\frac{T_A}{T_C}$ if it is charging. Also, the conditions for the simulation are ideal, i.e., T_{A_i}, T_{W_i} and T_{C_i} are precise and constant, and there is no physical interference between the robots.

Figure 3 shows an experiment with three robots and two power sources. The graph on top illustrates the two expressions of Equation 1 (the dotted line represents the right side of the equation), and allows to compare the energy of the group with the energy required for charging the group. The graph on the bottom represents the evolution of the toa of each robot in relation to time. At $t = 60$ min, robot 3 leaves the power source to let robot 2 (in a Waiting mode, as seen by the slowly decreasing toa slope) take the charging station. Robot 3 had at this time recharged sufficiently its batteries to share the power source. The same phenomenon occurs around $t = 145$ with robot 1. However, since the energy of the group is too low, the robot goes right away into the Waiting mode. By recharging robot 3, the group then get passed a critical point at time $t = 170$, at which the energy of the group becomes greater than the energy required for charging the group. Robot 1 then goes into the Activity mode (as seen with higher decreasing toa slope). The opposite situation occurs at time $t = 305$ and robot 3, the non-charging robot with the smallest toa, goes to charge in anticipation of a lack of energy.

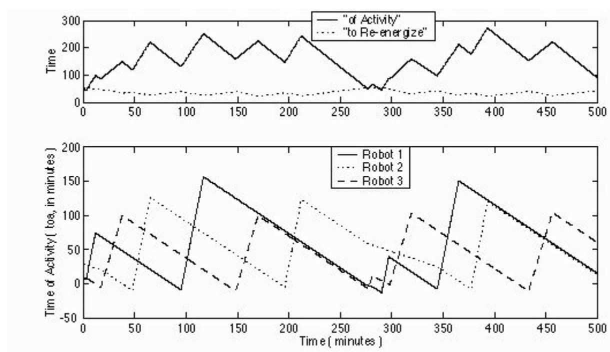

Figure 4: *Graphs representing an experiment with three robots and with one power source, with* $T_A = [150, 120, 100]$*,* $T_W = [300, 240, 200]$*,* $T_C = [20, 15, 20]$*, and* $toa = [10, 30, 10]$.

Figure 4 illustrates the same graphs but with a different set of experimental conditions, mainly by using faster recharging sources. The figure shows that the energy of the group is bigger, but still the robots can get in a situation where the energy of the group becomes lower than the energy required for charging the group, making robots go into a Waiting mode (around $toa = 280$).

An interesting performance criteria for such experiments is the Percentage of Activity of the Group, PAG, defined as the ratio of the sum of time spent by the robots in activity over the total time of the experiment. With only one robot, the PAG would necessarily be lower than 1 since a robot needs time to recharge. But with two robots sharing one charging station, PAG can be greater than 1 depending on the energetic capabilities of the charging station. Equation 3 defines PAG in terms of the proportion of time spent in Activity (P_A) and Waiting (P_W) over one period of charging/discharging.

$$PAG = \sum_{i=1}^{N_R} \frac{P_A \cdot T_{A_i}}{P_A \cdot T_{A_i} + P_W \cdot T_{W_i} + T_{C_i}} \qquad (3)$$

For the group to survive, the amount of time spent charging by the group must be lower or equal to the amount of time spent in activity or waiting: otherwise robots will be shuting down. So the critical case occurs when both amounts are equal, as expressed by Equation 4. The multiplicating factor of the right side of the equation is to take into consideration the ratio of robots not charging in relation to the number of power sources.

$$\sum_{i=1}^{N_R} \frac{T_{C_i}}{T_{A_i}} = \left(P_A + P_W \cdot \frac{N_R}{\sum_{i=1}^{N_R} \frac{T_{W_i}}{T_{A_i}}} \right) \cdot \left(\frac{N_R - N_P}{N_P} \right) \qquad (4)$$

Assuming that the robot is either in activity or waiting during discharge, $P_A + P_W = 1$, we can resolve these equations to determine PAG for different values of N_R, N_P, T_{A_i}, T_{W_i} and T_{C_i}. Note that one additional constraint is required: P_W must be greater than or equal to 0. A negative value would mean that the robot could spend more energy than usual when in activity, which is not a possibility considered in our experiments.

5 Energetic Analysis

Having demonstrated in simulation the algorithm proposed, the next step is to see how can it be implemented on real robots. The algorithm relies on the capability of approximating toa using the voltage level of the robot's batteries. To see how such parameter can be characterized, we conducted experiments having one robot operate continously for days, in a pen. The robot starts searching for the charging station when its batteries are at 11V, and leaves the charging station when they are fully charged. During the operation of the robot, we monitor the voltage level of the batteries during operation and during charging. Figure 5 shows typical charge and discharge curves observed during such experiments. The graph on the left shows that the battery voltage level is noisy and does not vary linearly. Using a standard curve fitting algorithm (discrete least square), we tried 3rd degree polynomial equations to model the charge and the discharge curves. Such equations are expressed in the form $toa = f(v)$, v being the battery voltage level. However, even though the model is adequate at the beginning of the experiments, the batteries change over time. This demonstrates that to work, the model needs to be adapted dynamically.

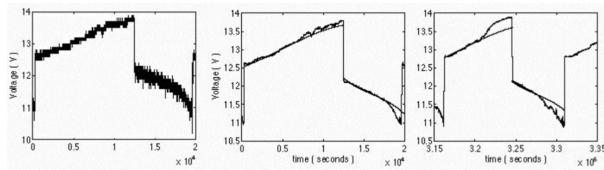

Figure 5: *Samples of charge and discharge curves for a robot operating continuously for 94.4 hours.*

6 Related Work

Different methods have been implemented to allow a robot to be self-sufficient, energetically, as innovative as hunting and catching slugs [3] to more conventional ones like having a robot go underneath a copper-plated, hinged roof, and make contact with a spring fixed on the wall [8]. Another method consists of two parallel horizontal plates fixed on a wall, and with which the robot comes in contact for recharging [2]. A robot can also dock into a charger by following an optical line [13]. Compared to these methods, our charging station is much smaller, cheaper, simpler, and offers fast charging capabilities.

One famour self-sufficient robot is SAGE [9], a robot tour guide in a museum that can dock into an unmodified plug. The outlet is localized using a 3D visual marker, perceived by the robot using a CCD camera. The docking process occurs over a distance of 4 meters and takes two to three minutes. The robot has eight hours of autonomy and can measure the charging and discharging current of the batteries, as well as their voltage levels. This information is used to determine the batteries' state relative to a discharge curve (which is not provided in the paper). The robot has a mean time before failure of 224 hours (9 days), including the time the robot is recharging (which is not indicated) and probably not working when the museum is closed. Oh et al. [10] also have developed a robot tour-guide teleoperated via a web-browser is capable of autonomously dock into a power plug in two or three minutes over a 4 meter distance. Their charging station is detected using IR beacon, sonars and a special grid mechanism detected by a laser scanner. Torres-Jara [14] is also working on a docking mechanism for regular outlets, using a digital color camera. With these approaches, the robot has to carry its own power supply to recharge the on-board batteries (which are usually lead-acid batteries).

Concerning the energetic needs of a group of robots, one project involves two robotic agents in an ecosystem in which competition for energy occurs [1, 12]. Light boxes placed in the environment are artificial artifacts that are draining energy available for recharging, and agents have to cooperate to make one agent recharge while the other is inhibiting the light sources. Egoism and altruism are addressed by setting up the experiment so that one agent cannot survive on its own. We do not consider limitation in the amount of energy available to the group other than the number of charging stations in the environment. Another project called MICRobES [11, 7] involves making robots recharge themselves autonomously, but by having robots helping each other out when necessary, like pushing a robot that has no energy left for moving into a charging station. Robots are allowed to communicate information to others. The charging station used allows for extremelly fast recharge (around 20 minutes), using a different kind of batteries.

7 Conclusion and Future Work

As outlined in the introduction, this paper addresses four important issues for the long-term use of a group of robots. However, it does not resolve them all. The approach proposed is a starting point to conduct more elaborated experiments with a group of heterogeneous robots over long period of times. Such experiments on long-term adaptation in a social environment can serve as a good benchmark for distributed autonomous robotics systems [16]. Performance criteria can be based on the amount of time the robots can survive, or the amount of time the task is being accomplished (which will be greater than 100% if more than one robot is involved), studied in relation to the availability of the charging station and the amount of information communicated. We are currently simulating conditions involving large numbers of robots (up to a 100), and initial results suggest that as the number of robots grows, the proportion of number of charging stations required increases, with a decrease of their efficient use (since more robots needs to recharge more frequently). Experiments with real robots (which is always the difficult part, especially with a group of robots) are underway, and future work will address adaptation of parameters [9] and models of energetic capabilities, and other approaches for energetic analysis and prediction using activation variables [5, 6].

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References

[1] A. Birk. Robot learning and self-sufficiency: What the energy-level can tell us about a robot's performance. In *Proc. European Workshop on Robot Learning*, pages 109–125, 1997.

[2] Y. U. Cao, T.-W. Chen, M. D. Harris, A. B. Kahng, M. A. Lewis, and A. D. Stechert. A remote robotics laboratory on the Internet. In *Proc. INET'95 Hypermedia*, 1995. URL: www.isoc.org/HMP.

[3] I. Kelly, C. Melhuish, and O. Holland. The development and energetics of Slugbot, a robot predator. In *Proc. 6th European Conf. on Artificial Life*. Springer-Verlag, 2001.

[4] R. Laird, H. Everett, G.A. Gilbreath, R. Inderieden, and K. J. Grant. Early user appraisal of the MDARS interior robot. In *proc. 8th Topical Int. Meeting on Robotics and Remote Systems*. American Nuclear Society, 1999.

[5] F. Michaud and J. Audet. Using motives and artificial emotion for long-term activity of an autonomous robot. In *Proc. 5th Autonomous Agents Conf.*. ACM Press, 2001.

[6] F. Michaud, E. Robichaud, and J. Audet. Using motives and artificial emotion for prolonged activity of a group of autonomous robots. In *Proc. AAAI Fall Symp. on Emotion*, 2001.

[7] A. Munoz-Melendez and A. Drogoul. Le principe de la coopération située. In *Proc. Journée Francophone d'Intelligence Artificielle Distribuée*, 2001.

[8] U. Nehmzow. Continuous operation and perpetual learning in mobile robots. In *Proc. Int. Workshop on Recent Advances in Mobile Robots*, 2000.

[9] I. Nourbakhsh, J. Bobenage, S. Grange, R. Lutz, R. Meyer, and A. Soto. An affective mobile robot educator with a full-time job. *Artificial Intelligence*, 114(1-2):95–124, 1999.

[10] S. Oh, A. Zelinsky, and K. Taylor. Autonomous battery recharging for indoor mobile robots. In *Proc. Australian Conf. on Robotics and Automation*, 2000.

[11] S. Picault. Robots as a social species: the microbes project. In *Proc. AAAI Fall Symp.*, 2000.

[12] L. Steels. A case study in the behavior-oriented design of autonomous agents. In *From Animals to Animats 3. Proc. 3rd Int. Conf. Simulation of Adaptive Behavior*, pages 445–452. The MIT Press, 1994.

[13] H. Surmann. A five layer architecture for real time object detection in indoor environment. In *Proc. IFAC Symp. on Artificial Intelligence in Real Time Control*, pages 319–324, 2000.

[14] E. Torres-Jara. A self-feeding robot. MIT AI Lab Research Abstract, 2001.

[15] K. Ueno and O. Koyama. Battery-driven legged robot and method of controlling the same. United States Patent Application 862401, May 2001.

[16] S. Yuta and Y. Hada. Long term activity of the autonomous robot - proposal of a bench-mark problem for the autonomy. In *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, pages 1871–1878, 1998.