Energy-aware Operation and Task Allocation of Autonomous Robots

Falko Dressler, Gerhard Fuchs
University of Erlangen-Nuremberg
Autonomic Networking Group, Department of Computer Science 7
Martensstr. 3, 91058 Erlangen, Germany
Email: {dressler,gerhard.fuchs}@informatik.uni-erlangen.de

Abstract

Energy-aware operation is one of the visionary goals in the area of autonomous systems research. This is especially the fact as small and mobile nodes become available and application scenarios emerge, which lead to much higher requirements in terms of reliability, long-term operability, adaptation, and self-organization. In this paper, we focus on energy control and battery management in mobile robot systems. We show an approximation technique to derive the remaining energy of the local system. The mechanism is based on a model of all energy-consuming parts of the robot system and the corresponding characteristic curves. The results are used for task allocation and behavior adaptation of each autonomously acting system. The proposed methodology increases the probability of completing globally assigned tasks. Therefore, the algorithm contributes to the performance and reliability of the global system. Additionally, each node in the overall system becomes able to employ its energy resources much more efficiently. We see this energy-aware concept for task allocation as a basis for further extensions used for studies on energy efficient communication in mobile sensor networks.

1 Introduction

The objective of this paper is to describe a coordination scheme useful in autonomous systems environments. Basically, this scheme focuses on energy estimation of ongoing and planed tasks. This approximation is compared to the measured remaining energy of individual nodes. Using this scheme, a local decision process can be initiated in order to accept/reject tasks for further processing as well as to continue/re-allocate a task in progress. On a global point of view, a task allocation procedure is initiated after the arrival of a new job or the cancellation of an ongoing task. The allocation procedure includes several parameters including the estimated energy requirements.

This energy-aware task allocation scheme for autonomous robots fits into a much larger goal. Our objectives are to build autonomous systems, which organize themselves to show an emergent behavior.

In general, our approach is based on a model of the individual robot system reflecting all parts and operations that are involved in energy consumption. The model can be decomposed until the energy requirements are determinable. We developed an experimental setup for measurements on our specific robot platform. The measurement results were used to create characteristic curves reflecting the energy constraints of particular operations.

Studies on energy-aware operation and task allocation in stationary sensor networks are work in progress in a number of research groups. Exemplarily, the work done by Mishra should be mentioned [4]. Other fields, especially in operating system design [2] and new methodologies for efficient communication [5, 10] are focused on as well. Mobile systems based on autonomous behavior are very promising. Coordination issues were presented by Estrin et al. [9] and Batalin et al. [1]. Issues of cooperation and coordination between mobile robot systems and sensor networks are discussed in [3].

The rest of the paper is organized as follows. Our ongoing research project ROSES[1], which builds the framework for our studies on energy-aware cooperation of autonomous robot systems is described in section 2. The application scenario for this research work is shown in section 3. Section 4 depicts the energy measurements developed for the Robertino platform including the reference measurements required for energy estimation. In section 5, the global context, the task allocation mechanism for an energy-aware cooperation is presented as well as some conclusions and an outlook on further research work.

2 The ROSES Project

The development and the control of self-organizing, self-configuring, self-healing, self-managing, and adaptive communication systems and networks are primary research aspects of the Autonomic Networking group at the chair for Computer Networks and Communication Systems. The employed embedded systems, e.g. sensor motes and mobile robots, are getting smaller, more mobile, and more energy-aware. Novel mechanisms in operating systems, in the communication infrastructure, and in applications provide enormous energy savings [8]. Sensor motes are used e.g. for the collection, the processing, and the communication of measurement data. Another research aspect of our group is the combination of mobile robot systems with stationary sensor networks. Such mobility enhancements as well as the limited resources in typical sensor networks lead to new problems, challenges, and solution spaces in terms of efficient data management and communication. In addition to engineering methods, we investigate in bio-

[1] Project homepage: http://www7.informatik.uni-erlangen.de/~dressler/projects/roses/

inspired methodologies learnt from cell and molecular biology to address these issues [11].
In the ROSES (Robot assisted Sensor Networks) project, we focus on the following research goals [6]:

- Energy efficient operation, communication, and navigation
- Sensor assisted localization and navigation
- Quality of service aware communication in heterogeneous mobile networks with dynamic topology
- Optimized task allocation and communication based on application and energy constraints
- Secure communication and data management in mobile sensor networks

In order to address these objectives, we employ novel models for energy and application aware communication, combine different localization techniques for optimized high-precision navigation, research on bio-inspired communication methods for information exchange and task allocation, and work on the integration of mobile robots and stationary sensor nodes to autonomous mobile sensor/actuator networks [7, 8]. In our labs, we employ the Robertino[2] robot platform as well as the Mica2 sensor motes running TinyOS[3] developed at the University of Berkeley.

3 Application Scenario

One main application scenario in our project is the exploration and supervision of unknown surroundings. In this context, we are working on algorithms for efficient task allocation strategies. Besides this particular scenario, the principle mechanisms and the proposed algorithm for energy-based task allocation can appropriately be used in almost all scenarios.
The mentioned scenario is depicted in Fig 1. Two tasks are allocated: Robot R1 is about to drive to measurement points M1, M2, and M3 (in this order). At each measurement point, the local sensors, e.g. the video camera, are employed for room monitoring. Robot R2 is working on measurement points M4 and M5. R3 is idle and waiting for further jobs.
In summary, it can be said that there are several ongoing tasks involving movement, sensor technology, and communication. All these actions require a different amount of energy for successful execution. Therefore, we prepared an electronic circuit to measure the energy draining for each individual operation. Using the characteristic curves, we became able to create an energy model describing also complex tasks by splitting these complex tasks into already analyzed sub-tasks. The energy estimation and the ensuing local algorithm for energy checking and task management are shown in the following section.

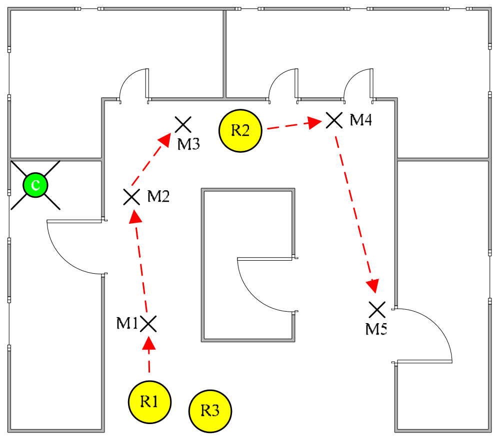

Fig 1. Scenario description. Three robot systems R1-R3 are monitoring a floor marked by five measurement points M1-M5

4 Energy Estimation

4.1 Energy Measurement

The Robertino system consists of an embedded Linux PC/104 board, wireless LAN communication, and sensor and actuator facilities. Two primary lead rechargeable batteries provide the energy for all these components. In order to estimate the energy drain during the operation of the robot system, the (rest) capacity of the batteries has to be measured. For this purpose, we build a small but efficient electronic circuit that allows to adapt the voltage of the batteries to a range measurable by the available analog/digital converter. The used circuit is shown in Fig 2. Because both batteries are connected in row, we measure the overall voltage U and the voltage detectable at battery one U_1. The main features of the circuit are its independence from the battery type and its adaptation to the available AD converter.

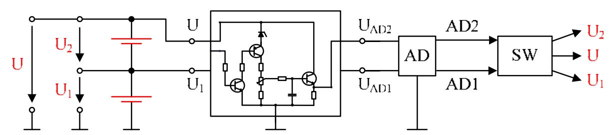

Fig 2. Electronic circuit for battery management

4.2 Reference Measurements

The functionality was verified by measuring the typical characteristic curves for different tasks of the robot system. The following operations were examined as a reference for complex job descriptions and subsequent energy estimations:

- Movement (driving engine)
- Communication (Wireless LAN)

[2] Project homepage: http://www.openrobertino.org
[3] Project homepage: http://www.tinyos.org

- Calculations (CPU processing)
- Idle

All the time, we measured the voltage at the batteries and the operating time. The results are shown in Fig 3. It can be seen that the voltage drop shows a linear decline until some critical value. After that point, the voltage drop speeds up and there is few remaining time left for an emergency program.

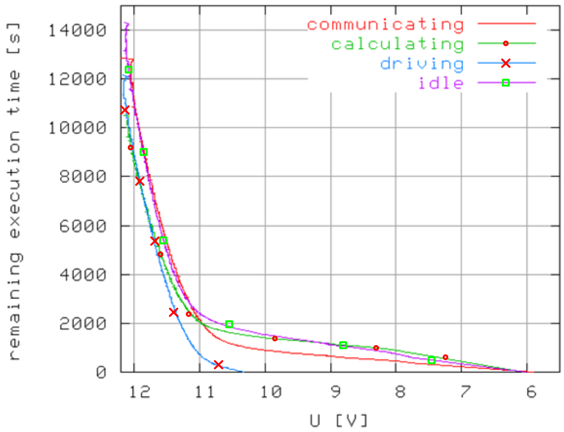

Fig 3. Characteristic curve of voltage drop while working on simple operations

The effects around the critical value can be seen more clearly in the magnified diagram in Fig 4. At about 11V, the critical point is reached. Thus, the algorithm for an emergency action should be based on exactly that point. If other batteries should be employed or if other actions should take place, a new characteristic curve must be created in order to locate that critical point but no change to the algorithm or the methodology is required.

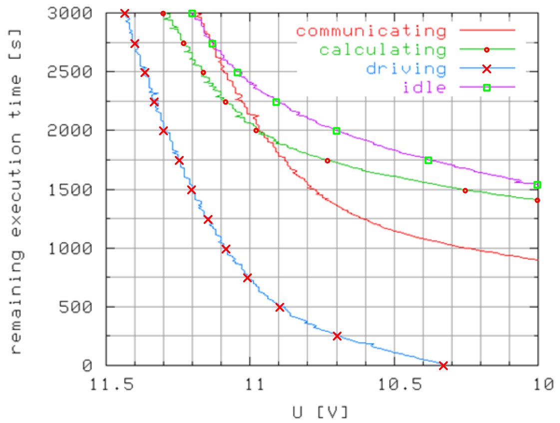

Fig 4. Magnified characteristic curve

4.3 Estimation of Remaining Energy

As mentioned in the previous section, the first required action for meaningful energy estimation is the location of the critical value (E_{crit} / U_{crit}) in the reference measurements. Additionally, the maximum energy (E_{max} / U_{max}) after the initial voltage drop must be measured in order to calibrate the approximation. Between both points, the reduction of the voltage shows a linear digression useful for directly estimating the remaining energy. Exemplarily, this quantification is depicted in Fig 5 and Fig 6. The second linear part as can be seen in Fig 5 is not of relevance because it is beyond the critical value.

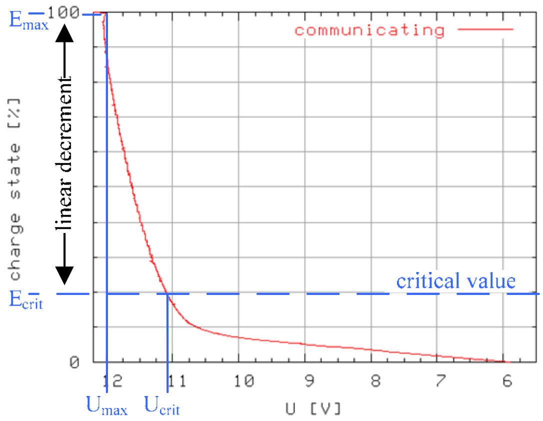

Fig 5. Critical value for wireless communication

Based on the measured values, the energy estimation can be started. As the total capacity of the battery is known as well as the current voltage, the remaining power in the interval between full capacity and the critical value can be approximated.

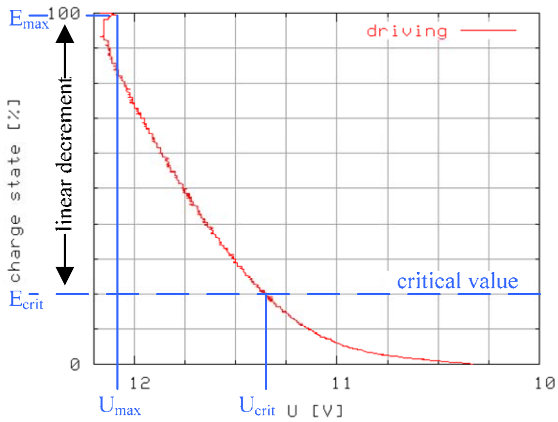

Fig 6. Critical value for movement

Our measurements have shown that that interval covers about 80% of the complete capacity, which is quite good enough for meaningful energy estimation:

$$E_{remain} = E_{crit} + \frac{E_{max} - E_{crit}}{U_{max} - U_{crit}} (U_{curr} - U_{crit}) + \varepsilon \qquad (1)$$

Below the critical value, i.e. if U_{curr} is smaller than U_{crit}, no adequate approximation can be done. This is no particular problem because the critical value represents the point at which the remaining power drops under a useful value, i.e. an emergency program has to be started. Such a program might include actions to “find” energy sources or to initiate a new round of the task allocation mechanism. The additional parameter ε is discussed in the following section.

4.4 Refinement and Validation

The shown formula for the estimation of the remaining energy is only a raw approximation. Some refinement is required by specifying the adaptation value ε. As shown in Fig 7, various possible adaptation schemes exist:

ε =0: no adaptation

ε =x (x<0): linear pessimistic approximation

ε =f(U)+x: adaptation depending on U, e.g. a regression straight line

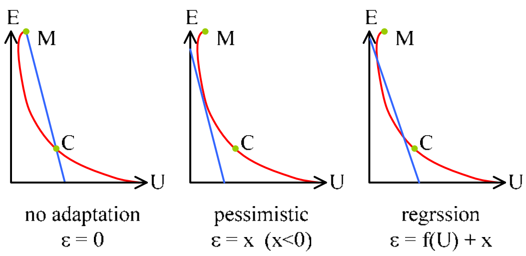

Fig 7. Possible adaptation values ε. M and C are specifying the maximum energy and the critical value, respectively

To validate the adaptation rules, a new measurement was started (action driving). In this experiment, the initial capacity of the batteries was about 75% of the initial capacity during the measurement of the characteristic curve.

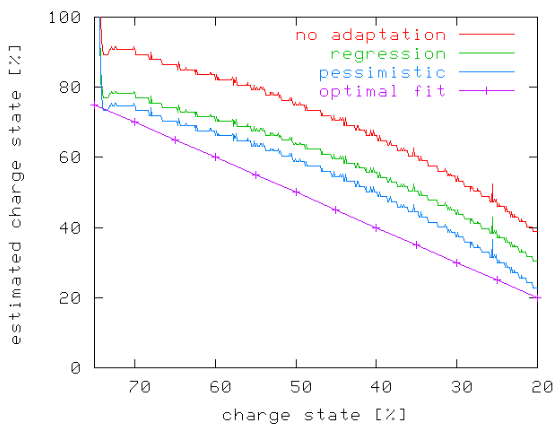

Fig 8. Quality of approximation rules: without calibration

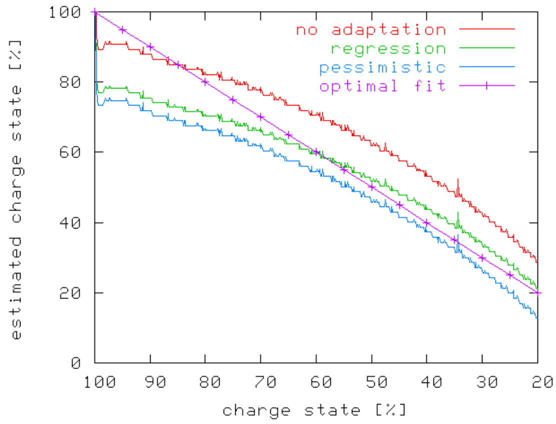

Fig 9. Quality of approximation rules: with calibration (initial capacity set to 100%)

The quality of the approximation using the described methods for calculating ε is shown in Fig 9 and Fig 9. Here, the voltage (U_{curr}) was measured and the energy (E_{remain}) was calculated using our formula and the previously analyzed characteristic curve. Obviously, (Fig 9) all approximations do not simulate the real behavior. Therefore, an additional calibration is required: the estimation of the initial capacity of the batteries. A second analysis (Fig 9) depicts the possible improvement. In this case, the regression shows the best results.
The calibration can be done by performing some initial task for which the energy consumption is well known (characteristic curve).

4.5 Local Task Verification / Termination

Based on the estimated remaining energy and the required energy for completing the task, a node, in our case the robot system, is able to figure out whether an ongoing/requested job can be continued or not. This depicts the local behavior of an autonomous system. Such a single system can be described using well-known state charts because it can easily be examined to verify this state.
The proposed local task verification algorithm can be summarized as follows:

```
while(TRUE)
{
        E_task = estimateRequiredEnergy()
        E_remain = estimateRemainEnergy()
        if(E_remain - E_crit < E_task) {
                reallocateTask()
        }
        if(E_remain < E_crit) {
                emergencyProgram()
        }
}
```

If a system comes into the critical range of the battery status, it must initiate the following two actions:

- If the system is currently working on a particular task, this task must be re-allocated to another node.
- An emergency program should be initiated if the remaining energy is falling under the critical value. Such a program might include actions for securing the charging of the batteries and the propagation of collected knowledge to another node.

In Fig 10, a state chart describing the possible system states and the performed actions is shown.
As already mentioned, the local control for energy-aware operation is only one part of the story. We solved this issue by developing an appropriate circuit for our robot platform. The adaptation is provided by the presented algorithm which allows a smooth integration into existing task management systems.

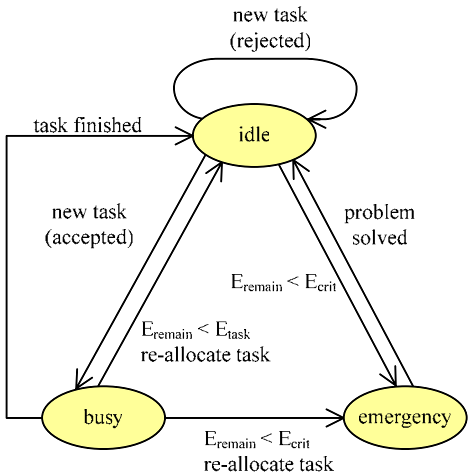

Fig 10. State chart describing the performed actions at a local system

4.6 Extensibility

Even if the algorithm is currently focused on energy requirements only, it is extensible into multiple dimensions. First, time constraints and priorities of the individual tasks can easily be included. One obvious vision is to build a real-time system able to work in a self-coordinating environment. Other aspects regarding the global point of view are discussed in section 5.

4.7 Application Example

Using the scenario depicted in section 3, the usability of the energy measurement is demonstrated.

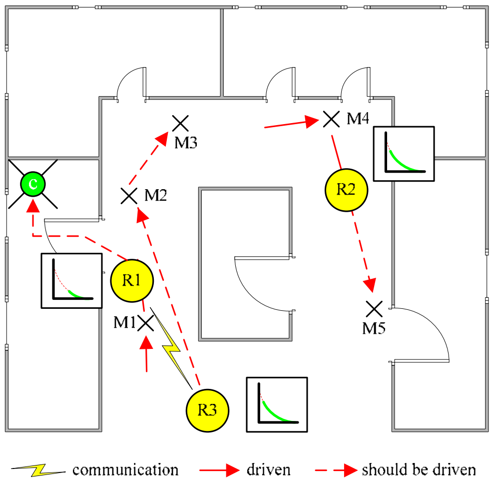

Fig 11. Burn-out of R1 leads to a re-allocation of the monitoring task to R3

Fig 11 shows that the robot systems R1 and R2 are working on their current tasks while R3 is waiting for new tasks. The algorithm running on R1 detects a low energy situation. Thus, the task is re-allocated to R3 that instantaneously starts the operation. In addition, the emergency program is initiated at R1. A possible action (instead of just stopping all actions) would be the movement to the next charging point (c). The navigation module in combination with the energy approximations can estimate the required time and energy for the reloading procedure.

5 Future Work and Conclusions

5.1 Energy-aware Coordination

Efficient task allocation for self-organizing autonomous systems is a complex operation. First, there have to be communication protocols, which allow the detection of all available nodes as well as a reliable communication platform. Several groups are working on novel methodologies for stateless coordination and communication in such environments [8]. Secondly, numerous parameters have to be considered for an all-embracing coordination and cooperation. There might be time constraints and required resources that must be available for completing a job. Energy is only a single of these parameters. Thus, the algorithm shown in the previous section can be enhanced to reflect multiple parameters

- for task allocation, and
- for verification of task allocation.

Here, our local task verification algorithm is employed to verify the required energy for a particular task with the remaining available energy:

```
while(TRUE)
{
      waitForTask()
      if(verifyReqEnergy() &&
         verifyTimeConstraints() &&
         verifyReqResources()) {
            acceptTask()
      }
}
```

Furthermore, a profile can be created for individual robot systems based on our model and the basis measurements.

5.2 Conclusions

In conclusion, it can be said that we were able to build an experimental energy measurement for autonomous robot systems. It builds the basis for empirical estimation of the energy consumption of individual parts and operations of the single robot system. The resulting model is extensible and can be refined via decomposition. Here, we showed the different energy costs of different operations.

Using approximation techniques and a local task verification algorithm, such a system becomes able to figure out its remaining energy, the required remaining energy for the current / allocated task, and, therefore, the local state of the desired operation.

For example, the local and global task management can be arranged to increase the probability of task completion. At least, an ongoing task can be interrupted and moved to another node if the remaining energy falls below a given limit.

Thus, we provided a first part of a much larger mosaic showing the global task allocation in self-organizing autonomous systems. Of course, there is much more work to do in order to get to an emergent behavior of the global system.

Because the probability of completing tasks is increased, the shown methodology contributes to the performance and reliability of the complex system. Additionally, each node in the overall system becomes able to employ its energy resources much more efficiently.

References

[1] M. A. Batalin and G. S. Sukhatme, "Coverage, Exploration and Deployment by a Mobile Robot and Communication Network," Proceedings of International Workshop on Information Processing in Sensor Networks, Palo Alto, USA, April 2003, pp. 376-391.

[2] F. Bellosa, "The Benefit of Event-Driven Energy Accounting in Power-Sensitive Systems," Proceedings of 9th ACM SIGOPS European Workshop, Kolding, Denmark, September 2000.

[3] J. Buttler, "Robotics and Microelectronics: Mobile Robots as Gateways into Wireless Sensor Networks," in *Technology@Intel Magazine*, 2004. (http://www.intel.com/update/contents/it05031.htm)

[4] D. Dewasurendra and A. Mishra, "Scalability of a scheduling scheme for energy aware sensor networks," *Wireless Communications and Mobile Computing*, vol. 4, pp. 289-303, April 2004.

[5] F. Dressler, "Bio-inspirierte effiziente Datenkommunikation in mobilen Netzen," Proceedings of 1. GI/ITG KuVS Fachgespräch Systemsoftware für Pervasive Computing (Syssoft04), Stuttgart, Germany, October 2004.

[6] F. Dressler and G. Fuchs, "ROSES - RObot assisted SEnsor networkS," Dept. of Computer Sciences, University of Erlangen-Nuremberg, Erlangen, Germany, Poster, November 2004.

[7] F. Dressler, "Efficient and Scalable Communication in Autonomous Networking using Bio-inspired Mechanisms - An Overview," *Informatica - Special Issue on Ant Colony & Multi-Agent Systems*, 2005. (accepted for publication)

[8] F. Dressler, B. Krüger, G. Fuchs, and R. German, "Self-Organization in Sensor Networks using Bio-Inspired Mechanisms," Proceedings of 18th ACM/GI/ITG International Conference on Architecture of Computing Systems - System Aspects in Organic and Pervasive Computing (ARCS'05): Workshop Self-Organization and Emergence, Innsbruck, Austria, March 2005.

[9] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar, "Next Century Challenges: Scalable Coordination in Sensor Networks," Proceedings of ACM/IEEE International Conference on Mobile Computing and Networking, Seattle, Washington, USA, August 1999, pp. 263-270.

[10] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed diffusion: A scalable and robust communication paradigm for sensor networks," Proceedings of 6th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCOM'00), Boston, MA, USA, August 2000, pp. 56-67.

[11] B. Krüger and F. Dressler, "Molecular Processes as a Basis for Autonomous Networking," *IPSI Transactions on Advances Research: Issues in Computer Science and Engineering*, vol. 1, pp. 43-50, January 2005.