Towards Socially Constrained Power Management for Long-Term Operation of Mobile Robots

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Abstract— **In the near future robots are expected to be part of our everyday life and we will use them in our homes, offices and other human social environments just like we use other devices or appliances today. For robots to operate in real social environments they should be capable of operating with a great degree of autonomy. This poses several challenges, as the robot should be able to sustain and operate over a longer period of time. Most autonomous mobile robotic systems draw power from batteries which have a limited power life. This poses even greater challenges for an autonomous robot to plan its tasks while being aware of the time required to recharge its batteries via a power source. Management of power resources is therefore important for autonomous robotic systems. In this paper we focus our attention on the significance of power management for long-term operation of autonomous robots. We establish the motivation for power management in the context of autonomy, and future socio-economic impact on the global energy usage. We then discuss some of the challenges in terms of battery technology, power estimation and auto recharging. We also describe some approaches, which deal with power management on robots. In our future work we plan to address the challenge of power management for long-term operation of mobile robots taking into account social considerations.**

I. INTRODUCTION

Electric power is a basic necessity for any electronic device to operate. In order for robots to be fully autonomous with minimal or no human intervention, power management issues are critical and require special attention. Power management is thereby an important feature for the robot to possess. Many devices today like mobile phones and laptops operate on batteries. Research on power-management has been a topic of interest in the automotive [1], [2] and the home electric appliance field [3]. The same applies to autonomous robotic systems. Currently most autonomous mobile robotic systems draw power from batteries carried on the robot [4] in order to operate various sensors and actuators and perform tasks. Batteries have a limited power life, which thus constrains the operational time of the robot. An autonomous robot planning tasks must be aware of power resources available, tasks on hand and the time required to recharge its batteries [5]. A robot operating in a social environment must also take social constrains into account when planning recharge of its battery.

In some niche robotic applications like space, underwater robotics and social robotics, planning the power budget poses even greater challenges given the trade-off between task execution and recharge time has to take into account the uncertainties of operating in an unstructured and unpredictable environment [6]. For successful long-term operation, management of power resources is critical for power efficiency and the sustainability of the robot itself [7].

In this paper we discuss the need of power management for long-term operation of mobile robots, focusing on issues involved, which relies on power estimation, auto-recharging and social constrains. In Section II we discuss the motivation of our research in context of autonomy and future socio-economic impact on the global energy usage. Section III gives an overview of the related work in terms of immediate challenges for true energy autonomy in mobile robots with respect to battery technology, power estimation and auto recharging. Section IV will discuss some relevant work done in context of power management; Section V gives an overview about our future work, followed by the conclusion in Section VI.

II. MOTIVATION

A. Autonomy

The term “autonomy” has been ascribed to robotic systems to demonstrate their ability to perform tasks without human supervision. For robots to be autonomous they have to manage resources, such as energy, which can be related to the so-called self-sufficiency of animats and they have to be able to sustain themselves over extended periods of time [8]. Autonomy in robots has often been linked to foraging behaviour found in animals and insects, where robots are capable of searching for food and collecting (or capturing) food for storage or consumption. Hölldobler and Wilson [9] describe a more comprehensive taxonomy of insect foraging as a combination of strategies for (1) hunting, (2) retrieval and (3) defense. Many actual or potential real-world applications for robotics are examples of foraging robots, for instance cleaning, harvesting, search and rescue, land-mine clearance or planetary exploration. Since robots are machines that perform tasks, which requires energy, power management is important; if, for instance, the robot is foraging for its own energy then balancing its energy needs with the energy cost of foraging is also critical. However, the term “autonomy” can be somewhat flexible. For example, consider the case of a robot whose batteries are charged by a

This work is partially supported by European Community (EC) and is currently funded by the EU FP7 ICT-215554 project LIREC (LIving with Robots and IntEractive Companions). The authors are solely responsible for the content of this publication. It does not represent the opinion of the EC, and the EC is not responsible for any use that might be made of data appearing therein. `www.lirec.eu`

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human and then released to carry out its task without further external intervention. This can raise the question of "true autonomy" as it will keep the human operator in the loop and also demand maintenance on the part of the human. We believe that for robots to be fully autonomous, they should be able to manage their own energy.

B. *Future Socio-Economic impact*

The issue, which seems to have been overlooked by robotics research until now, is the socio-economic impact of future robotic applications. The interdisciplinary nature of robotics research integrates different areas, such as computing, electronics and mechanics. Energy consumption is affected by all layers of a robotic system, ranging from computing, to sensors. The latest report from world robotics in 2009 [11], suggests that *out of 7.3 million service robots sold in 2008, out of which 4.4 million units were sold for personal use for home applications (vacuuming and lawn mowing bots) and about 2.8 million for entertainment and leisure (toy robots, hobby systems, and educational bots). In 2008 alone about 940,000 vacuum cleaning robots (like the iRobot Roomba 562 Pet Series above) were sold, almost 50 percent more than in 2007.* The report estimates that 49,000 professional service robots and 11.6 million personal service robots will be sold between 2009 and 2012. In order to better illustrate how this scenario could impact the global energy consumption costs, the Roomba vacuum cleaning robot from iRobot [12], typically consumes approximately 100 Watts of electrical power for 2 hours (1 full recharge) of cleaning. If Roomba robot were used for twice a week, throughout the year it would consume about 10 KWatts of electrical energy for around 100 sessions (2 hours each for 52 weeks), which account up to £1 in a year per Roomba (average electric energy cost per KW in UK is around 10p/KW).

Considering almost a million vacuum cleaning robots were sold alone in 2008, the cumulative cost mounts up to £1 million. Not to mention the electrical power losses during re-charging and battery aging which reduces the power efficiency. One must also consider that there is no formal supervision to determine whether the robot actually managed to achieve a desired level of cleanliness or just wasted power getting stuck in a corner of a room. The future mobile robotic applications will perform more than just one task unlike Roomba and significantly consume more electric power. For instance the commonly used mobile robot platform in research, Pioneer P3AT robot by ActivMedia [17] uses up to 252 Watts on single recharge to deliver an operational time of 3-4 hours. A robot like Pioneer running for about 12 hours daily in a home environment would consume nearly 1 KW of electric power daily and about 365 KW a year, costing up to £36 a year per robot. The idea of having millions of such robots in human social environments within next few years should not be overlooked. Although a power consumption, potential monetary savings comparison between the current vacuum cleaning system and future replacement robotic equivalent may not be sensible at this point as they both have different way of operation (current vacuum cleaners: human operated, robotic systems: autonomous).

From an environment perspective, the report from McKinsey [10], *estimates the carbon footprint associated with Information and Communications Technologies (ICT), including laptops and PCs, data centers and computing networks, mobile phones, and telecommunications networks, and on all levels of emissions associated with use of energy their manufacturing and distribution. The report affirms, in 2008, that ICT technologies were accountable for about 2% of the CO2 emissions added to the atmosphere globally (0.86 metric gigatons per year). That is equivalent to all the emissions from the global aviation sector, or a quarter of the global car industry annually.* We anticipate that future autonomous mobile robot technology will follow the same trend of ICT technology domains, in terms of carbon footprint. Hence we believe that power management for developing power efficient mobile robots is thereby not only necessary, but also relevant due to the global energy consumption and its potential socio-economic consequences.

III. RELATED WORK

This section gives an overview of the related work in terms of immediate challenges for true energy autonomy in mobile robots with respect to battery technology, power estimation and auto recharging.

A. *Battery Technology*

Almost all mobile robots use batteries as their power source. Lithium ion, nickel-metal hydride, lead acidic, alkaline manganese etc. are the main types of batteries in use [13]. These vary in several important aspects according to the cell chemistry and the technologies used. Choosing a suitable battery technology often involves a trade-off based on characteristics such as cost, charge-discharge properties, weight, charge retention [14], energy density etc. However, common to all of them is the weakness of low continuous operational time. A Honda humanoid robot can barely walk for 30 minutes with a battery pack on the back [15]; battery life is the most important challenge for mobile robots. Rybski et al. [16] show that power consumption is one of the major issues in their robot design.

Furthermore, the recharging of batteries also takes significant time. For example, a Pioneer P3AT robot by ActivMedia [17] with an onboard computer takes about 3-4 hours to recharge and delivers about 3-4 hours of operational time. Roomba [12] takes about 3 hours to recharge and gives about 2 hours of operational time on single recharge. As we see from these examples, if a mobile robot has to perform over a long period then it would spend about the same amount of time recharging itself as performing tasks. The recharging issue highlights the need for some kind of power aware scheduling of tasks in the design of robotic systems [21], especially where tasks take more time than the battery can last on a single recharge. A good estimate of the remaining battery power will be useful for task scheduling.

B. Power Estimation

An accurate estimate of the remaining battery power that the robot is carrying is needed in order to schedule recharging. There are a number of methods for making such estimates. The accuracy of these approaches varies depending upon the battery chemistry and methods by which the monitoring is conducted. Such an estimation requires knowledge of battery structure, chemical composition, temperature, capacity, etc. [4]. One empirical model in [5] computes the battery efficiency of multi-battery systems through the usage of interleaved power supply and load splitting. Other models use Weibull fitting [18] in addition to simple empirical measurements. In [19], capacity is estimated via a discrete-time stochastic prediction model. Electrical circuit models discussed in [6] and [20] attempt to model the entire system in terms of passive circuit elements, however these methods result in the largest observed estimation error [21]. Current challenges with battery technology urge the requirement of power management systems for power efficiency.

C. Autonomous charging and docking

Estimations of the remaining power on the robot can be used to decide when to recharge. A second challenge for long-term operation of mobile robots is autonomous recharging. The mobile robot should be able to dock and re-charge itself, without any human intervention. There have been several approaches in developing auto-docking mechanisms. We will discuss a few; late 1940's Grey Walter developed the first autonomous recharging for mobile robots, "Tortoises" [22]. These robots used a light following behaviour to find their way into a hut containing a light beacon and a battery charger that made electronic contact when the robot entered.

In the late 1990's Hada and Yuta [23], [24], [25] proposed a battery charging system for long-term operation of mobile robots, using infrared sensors and a reflective tape on the floor to reach the docking station. Oh. Zelinsky and Taylor [26] proposed a docking system similar to an aircraft landing, the robot approached the dock using a long-range infrared beacon and a sonar; when the robot was in proximity to the station, a Sick laser range finder was used to align the robot to a grid with a pattern designed to distinguish it from the surrounding environment.

Silvermann et al. [27] developed a docking system which allowed a high angular and displacement error during the docking process. A combination of vision and laser beacons was then deployed to perform the autonomous recharging of a Pioneer 2DX robot. They further enhanced their approach in [28] by adding circuitry that shuts down all systems upon identification of a successful dock. This results in a faster and more efficient recharging cycle time, and allows for a full recharge. Cassinis, R et al. [29] proposed a docking algorithm, inspired by an ancient navigation aid Bowditch [30] proposed the use of range lights, the light pairs indicate a specific line of position when they are in line. The higher rear light is placed behind the front light which aids the navigation depending on the position from where the light pairs are seen. Some researchers have also investigated continual charging from electrified floor in robot arena to provide power to the robots [31], [32]. Some commercially available auto-docking mechanisms provided by the manufacturers of robots [33], [34], [35] are also available.

IV. POWER MANAGEMENT

In this section we look at one important approach specifically dealing with power management using a variety of energy saving techniques.

A. Energy Conservation Techniques

In an important case study carried out on energy consumption and conservation techniques on a robot Pioneer 3DX [36], Yongguo Mei et al. analysed the energy consumers on a mobile robot and built power models for motion, sonar sensing and control, based on experimental results. The results showed that motors during motion consumed less than 50% power on average. Thus, it is important to consider the other power consuming components in energy-efficient designs. They calculated the maximum and minimum range of power consumption and the percentage attributable to each component such as motion, sensing, microcontroller, embedded computer (see Table I). Their analysis showed that motion accounted for at most 44.6% of the total power. This also implies that other power consumers like computation have a big impact on power consumption.

TABLE I
POWER CONSUMPTION BREAKDOWN [36]

Component	Power (Watts)	Percentage
Motion	2.8W - 10.6W	12.1% - 44.6%
Sensing (sonar)	0.58W - 0.82W	1.9% - 5.1%
Microcontroller	4.6W	14.8% - 28.8%
Embedded Computer	8W - 15W	33.3% - 65.3%

They proposed two main energy-conservation techniques, dynamic power management and real-time scheduling. 1) Dynamic power management (DPM) [37], [38] dynamically adjusts the power states of components in relation to task requirements. The purpose is to reduce the power consumption without compromising system performance. A simple DPM method shuts down a component when it is idle. 2) Real-Time Scheduling: Real-time scheduling (RTS) schedules multiple tasks in order to meet the deadlines. The two often used scheduling algorithms are rate monotonic (RM) and earliest deadline first (EDF) [43].

They also suggested several ways of improving energy efficiency using RTS and DPM, for example, (a) Shutdown of Unused Components in order to avoid waste during static power in idle states [39], (b) Scaling sensing frequency: scale frequency of sensing in accordance with the speed of robot. The sensing frequency needs to be higher when the speed is higher. (c) Dynamic Voltage Scaling: dynamically changing voltage and clock frequency of a processor to save power [40], (d) Trade-off between Motion and Communication: A team of robots may move and cooperatively execute a task, such as exploring an unknown area. Robots need to send sensing data through wireless communication when the other robot is too far. (e) Energy-Efficient Real-Time Scheduling for Robots [41], [42]: RTS can work with DPM to effectively reduce the power consumption. For example, if a scheduler can cluster tasks, creating longer idle periods, shutdown techniques can be more effective. The deadlines are different at different traveling speeds; at a higher speed, the periodic tasks have shorter periods. All of these approaches can be taken into consideration in order to conserve electrical energy for a mobile robot at different layers of design.

B. *Biologically Inspired*

For advances in the energy autonomy, robots will need to extract energy from the environment [44], [45]. In many ways robots will face the same problems as animals. Examples include the Mars rover Sojourner [46], which used solar panels to collect sunlight for conversion to energy (non-chargeable batteries were used as a back- up); and the SlugBot [47], which tried to establish a cycle of catching slugs and using them to generate power via a bio-gas generator. A later work on EcoBot II [48] investigated raw foodstuffs such as flies or rotten apples for energy.

Yet another bio-inspired approach was presented by David McFarland and Luc Steels at AI lab [49], VUB at Brussels, involving an artificial ecosystem in which robots cooperated in maintaining both their short-term and long-term energy supply. The approach focused on mutualism, which requires co-operation between robots, whereby one robot aids another out of self-interest. Further work with robotic ecosystems was carried out by Birk et al. [50], [51]. Zebrowski and R. Vaughan [52], discuss a simulated robot acting as a tanker that moves in an environment to seek out robots in need of refuelling. This system resembles an aerial tanker during in-flight refuel, only able to service a single robotic system at one time.

An interesting alternative to recharging is proposed in [53], where the robots in the team can physically exchange batteries. This system is unique with respect to the rate of energy transfer between team members, though it requires a high degree of precision to be successful. In [54] the authors explore the idea of robot ‘trophallaxis’, whereby one robot can donate an amount of its own internal energy reserve to another. This brought about improvements in terms of collective task performance by a swarm of robots.

V. TOWARDS SOCIALLY CONSTRAINED POWER MANAGEMENT

In our future research, we aim to develop a power management system for a mobile robot for long-term operation. To carry out this research we need a test bed scenario where experiments can be conducted and the developed system can be evaluated. This research will be conducted as part of EU project LIREC [55] (LIving with Robots and intEractive Companions). In this project, we aim to create interactive, emotionally intelligent companions which are capable of establishing long-term relationships with humans in social environments. The project research focuses on both virtual companions and physical embodiments such as robots. We will develop the power management system specifically for the “Spirit of the Building” showcase at Heriot-Watt University, Edinburgh, in which one overall aim is to produce a social helper robot that can share a lab with human researchers and act as a “Team Buddy”- an assistant to facilitate long-term relationship with users. The “Team Buddy” aka SARAH (Social Agent Robot to Aid Humans, Figure 1) would act as a workplace buddy within a lab inhabited by a small group of people, performing tasks such as carrying the phone, carry printed material, giving reminders, provide a lab tour to visitors, approaching and greeting the users, whilst a collective memory about user preferences such as lunch breaks, entry/exit time.

Fig. 1. “Team Buddy” SARAH, Pioneer P3AT Robot with enhanced superstructure and Graphical face, Height 1.2 meters

SARAH is deployed on a Pioneer P3AT [17] with an enhanced custom built super structure to make it more interactive with users in the lab. We also have a tablet laptop on the top with a static graphical face to demonstrate simple emotions like joy, anger and neutral. We have currently developed some capabilities for SARAH such face detection, navigation, greeting the users by approaching by maintaining a comfortable physical distance them [61]. We are currently working on developing the auto-docking mechanism for the robot taking into consideration the related auto-docking work mentioned before (Section III. C). Furthermore we need an architecture to support our power management system, which will carry out planning tasks, action selection and higher level goal management. In the first stage of the project we have developed skeleton three-layer architecture for the long-term interaction system. (Figure 2)

- Layer 3: FAtiMA (FearNot Affective Mind Architecture) [56] is an extension of BDI (Beliefs, Desires, Intentions) deliberative architecture [57] that contains a reactive component mainly responsible for emotional expressiveness and it also employs the OCC [58] emo-

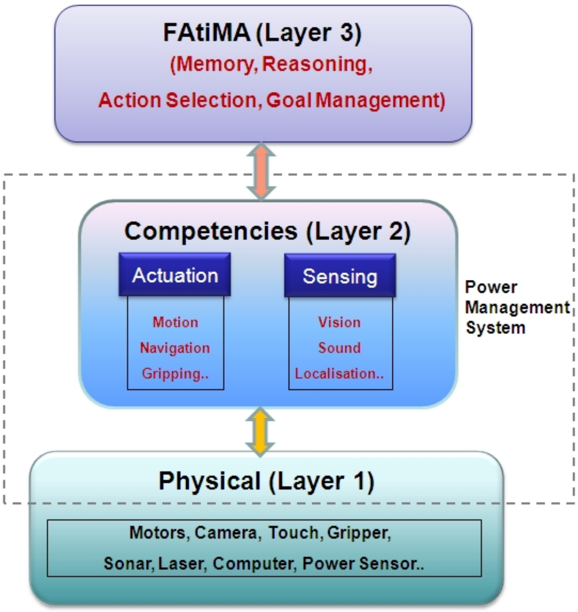

Fig. 2. Three-layered architecture and Power management system (dashed box)

tional influences on decision-making processes. FAtiMA maintains high-level memory; carries out cognitive appraisal; manages goals; generates plans (action sequences); monitors plan outcomes

- Layer 2: Competencies are programs that abstract physical sensors and actuators to logical ones; runs sensor and actuator-related programs; maintains low-level memory; passes information to layer 3 and accepts goal-directed constraints on competences from layer 3
- Layer 1: Contains the physical sensors and actuators

From the relevant work (Section II, III) described earlier, power management systems until now have primarily been considered at layer 1, monitoring and managing the power consumption at the physical layer. We believe that a more pragmatic approach is necessary to monitor and manage the power consumptions at all layers. As mentioned in section IV. A, power consumption is affected at various layers in a robotic system and not just by the physical sensors or actuators, but also at computational level. For instance SLAM (Simultaneous Localisation and Mapping) requires a high end obstacle detection using sensors such as laser range finders and sonar and it is computationally quite expensive [59].

We plan to develop the power management system to monitor the power consumption on the layers 2 and 1 (dashed box in Figure 2: Power Management System). For example a task of carrying a phone to user's desk involves competencies running at layer 2 such as navigation, localisation and motion, monitoring power consumption at the physical layer as well as computational level. We can assess, also at the computational level, which can give us a better estimate of the power cost for a particular task. This information can be updated and passed to Layer 3, which can carry out a plan taking into consideration the power cost involved for a particular task and select an appropriate action. The system can also learn the power consumption of various tasks over a long-term operation [60]. We believe the context of power cost associated with decision making at layer 3 is important and requires reliable and accurate estimate of power consumption cost perceived from layer 2, 1.

Our aim is to develop the power management system as a generic tool and used by any planing mechanism at layer 3. We hence anticipate most of our development work on power management system to be focused on layer 1 & 2. Although we want to evaluate the system with a specific goal of power management under social constrains which will involve some planning at layer 3. We will take into consideration some of the approaches mentioned in related work to develop the power management system. A method to evaluate the performance of the system could be implemented by measuring the number of social errors caused by the system. An example of a social error could be the non-performance of a task due to occupation while recharging or the battery dries up due to starvation and human has to plug in the robot for recharging can be considered as bad planning by the robot.

The key idea is to develop an autonomous system on the mobile robot which can perform the tasks in a power efficient way and is also able to reason when best to recharge its batteries, taking into account social considerations. One example of social constrains can be, the robot should not try to help accomplish a specific task when the user is not in a good mood or is planning to engage in some other activity (conversely the robot should be able to perform tasks when user expects and not be pre-occupied in recharging activity at that time). For example SARAH can plan to perform the most important and power demanding tasks at the beginning of the working day, when the users in the lab are available and more likely to be serviced. SARAH can use the time in the lunch breaks of users and night to autonomously recharge its batteries when the users in the lab have left after work. We will evaluate our system performance over a long-term period for weeks and investigate power consumption issues in relation to performance of tasks.

VI. CONCLUSIONS

In this paper we discussed the significance of power management for long-term operation of mobile robots. We described our motivation in context of autonomy and future socio-economic impact on the global energy usage, which seems to have been hitherto overlooked by robotics research until now. We gave an overview of immediate challenges for true energy autonomy in mobile robots with regards to battery technology, power estimation and auto recharging. We also discussed some approaches related to power management for mobile robots, which can be considered when designing future autonomous mobile robotic systems. The state-of-the-art power management approaches have addressed the power management primarily at the physical layer in their design. In our future work will address the challenge of power management with more elaborate power monitoring for long-term operation of mobile robots, taking into account social considerations. Hence, we advocate that a prudent power management design approach taking into consideration social constrains is necessary in designing future robotic applications, which can lead towards power efficient long-term operation of mobile robots and a green social robotics future.

VII. ACKNOWLEDGMENTS

This work is partially supported by European Community (EC) and is currently funded by the EU FP7 ICT-215554 project LIREC (LIving with Robots and IntEractive Companions). The authors are solely responsible for the content of this publication. It does not represent the opinion of the EC, and the EC is not responsible for any use that might be made of data appearing therein.

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