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Condition Monitoring and Cloud-based Energy Analysis for Autonomous Mobile Manipulation - Smart Factory Concept with LUHbots

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Abstract

In this paper, a smart factory concept for autonomous mobile robots is presented. The main purpose is to increase productivity of the transport in machine-floor. It is based on advanced methods for failure handling and prevention, leading to increased robustness, less downtime and less effort in maintenance [1], [2]. Therefore, condition data and states of the robot are collected by Robot Operation System (ROS) and transferred to a factory hub (server). The collected data, e.g. voltages, currents, set points, velocities and accelerations are used to identify important system parameters, e.g. moving masses and friction parameters to enable the proposed smart factory concept. Further aim is to let the factory hub control a group of mobile robots using a self-organizing algorithm for different tasks.

Due to the increasing customization of products causing smaller lot sizes [3], manufacturers of mobile robotic production systems have developed a diversity of flexible robots [4], [5], [6], [7], [8]. Mobile robots inside the production line allow for collecting and evaluation of system-inherent data e.g. handling and transportation time, wheel friction, workpieces mass, center of gravity and energy consumption during trajectory execution.

In general, mobile robots are electrically driven. Hence, an estimation of the battery state is essential in order to automatically plan charging cycles and to organize and optimize the cooperation behavior of a group of mobile robots. In this proposed approach, mobile robots are equipped with a measurement system and connected via Bluetooth to a factory hub, providing monitoring, analyzing and planning tools. The battery states of all robots are considered in the process planning.

The robots are based on the KUKA youBot, equipped with a soft gripper and a RealSense camera. A condition monitoring system measures the energy consumption of all components and transfers the information to the factory hub. The state of charge limits the number of executable operations. Therefore, in a first step the power consumption of all individual consumers is captured, e.g. EC-Maxxon base motors, PC, gripper, camera and five-axis arm. Experimental results show, that the youBot requires 46 W in standstill plus the drive power depending on the movement. Here, the results for mobile manipulation in industrial scenarios during preparation for the RoboCup@Work 2016 will be presented. The transfer of raw measurement data to the hub is shown, as well as

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the proposed algorithms allowing for range prediction and optimized set point generation. The concept provides excellent capability in data collection, analysis of existing production and production planning.

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Keywords: Mobile Robotics; Condition Monitoring; Cloud-based Energy Analysis; Logistic Handling

1. Introduction

For mobile robots, energy is the determinative factor of every action. The variation of actions is considerably greater and it is not only necessary to optimize the trajectories of the arm and the base, but also to regard the current battery state in the planning of next actions. With the combination of energy, position, velocity and acceleration values, it is possible to identify parameters for the robot model. Deviations from the model can be indicators, which show that a robot component diverges from its specification, or may be in faulty operation. Measuring these deviations cannot only help to optimize the movement, but also help protecting the hardware from damage. In autonomous robotics, these indicators are eminently important to reduce necessary human interference.

This paper presents the implemented state machine with condition monitoring to achieve increased robustness against e.g. grasping failures of workpieces. In the RoboCup, the LUHBots team started using an energy model of the arm movement to prevent hardware damage. If the electric current exceeds the calculated value during the movement, the arms stops and enters a gravity compensation mode. This is a new approach to collect the raw data from several robots at the same time and analyze the behavior in the background during a competition. The main goal is to improve pre-maintaining, save time and money by intelligent data analysis and to transfer the new knowledge to industrial robots for the integrated industry. The first section describes the scenario in the RoboCup competition and the team's current approaches. In the second part of the paper, a newly developed energy measurement system is introduced and the measured results are presented. Finally, the paper describes possibilities how to use the obtained data for optimized robot operation and task planning.

1.1. KUKA youBot

The robot is based on the KUKA youBot mobile robot [9]. It consists of a platform with four Mecanum wheels and a five-degrees-of-freedom (DoF) manipulator. Commutated DC motors (EC-Motors) are integrated into the joints and

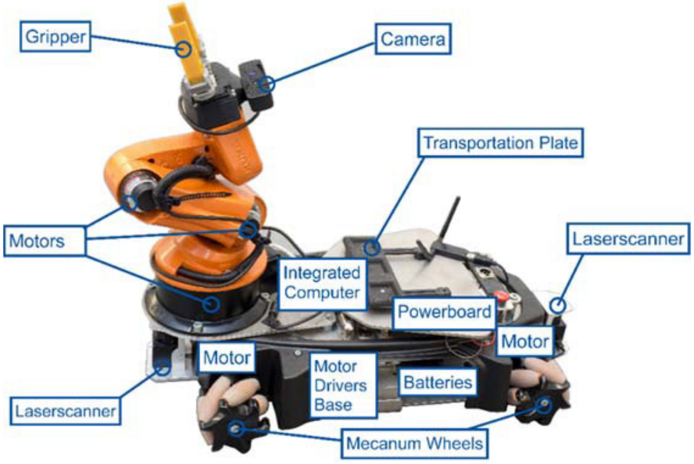


Fig. 1 The modified KUKA youBot used by LUHbots for mobile manipulation tasks.

wheels. Additionally, a gripper is attached at the end of the manipulator (see Fig. 1). Furthermore, the robot is equipped with two commercial laser range finders (Hokuyo URG-04LX-UG01) at the platform's front and back. An RGB-D camera is mounted on the wrist of the manipulator. The standard internal computer of the youBot has been replaced by a faster system with an Intel Core i7 processor. In addition, the robot is equipped with an emergency stop.

1.2. Particular Tasks in RoboCup@Work

The RoboCup@Work League was founded in 2012 [10] to boost development and integration of mobile robots into the industrial environment. The LUHbots team of the Hannover Centre of Mechatronics was one of the founding members. Until now, the team became twice world champion and three-time German champion. During the competitions, a variety of industry-related tasks such as precision placement (PPT) have to be solved. In this challenging task, standard industrial parts such as screws, nuts or workpieces have to be placed precisely into the appropriate holes. Besides Precision Placement a series of advanced manipulation tests are performed. Workpieces need to be grasped from a linear conveyor belt or a rotating table. The transportation test combines the tasks of both domains navigation and manipulation. During each test the successful manipulation actions are scored. Collision or incorrect actions are penalized. If a test is completed with all finished tasks and without penalties, then bonus points will be awarded based on the remaining time.

For the successful completion of a task, it is advantageous to know the state of all individual robot parts. The additional information allows for the detection of failures during a complete run. In this way, it is possible to react to the current situation and possible errors in order to avoid damages. Another advantage is the ability to re-schedule task solutions in order to achieve the best score despite the presence of errors. An exemplary scenario is shown in figure 2. Here, it can be seen that after a successful navigation to area point S1, the pickup of object one failed (B, PickUp and PutDown). As a remedy action, the task is re-planned (shown in C) to pick up the object again in a new order.

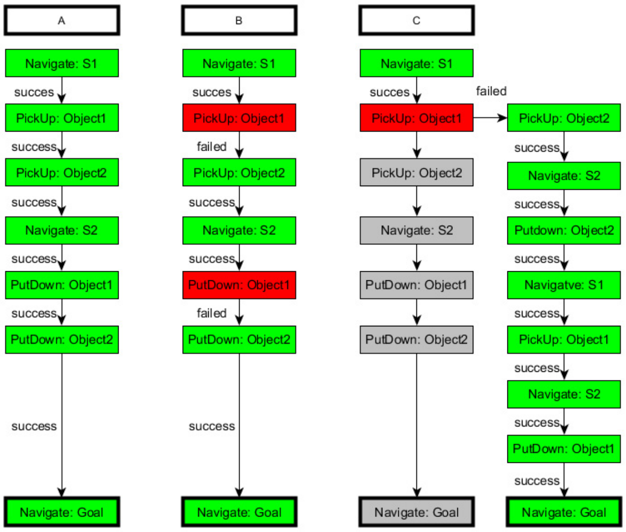


Fig. 2 Illustration of the advantages of re-planning and re-scheduling of tasks. In A with a complete run, B with no re-planning and C with re-planning and re-scheduling

1.3. State Machine

The state machine is based on SMACH [11], which is a Python library for building hierarchical state machines in ROS [12]. Due to the capabilities of SMACH the state machine is modular and consists of the main components, such as task planning, task execution, navigation and manipulation (see Fig. 3). The state machine acts as an action client, which sets the goals in navigation and manipulation to accomplish the tasks and receives feedback in case of issues. The state machine is designed for recovery. A watchdog monitors each action. The watchdog will interrupt the execution as soon as an unexpected event appears and interrupt a sub-state-machine on a failure. Depending on the failure, different recoveries are available and might be executed consecutively. If recovery does not succeed, the action will be marked as failed. The task execution will request a new plan and the failed actions will be scheduled as the last action in the task list (Fig. 3).

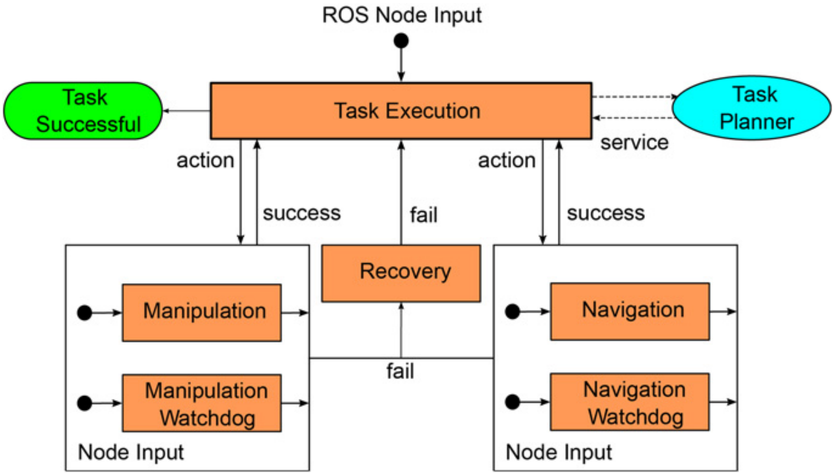


Fig. 3 The state machine used for mobile manipulation. The task planner first plans each task. Afterwards, the actions are sequentially executed by either the manipulation or the navigation sub-state-machine. A watchdog monitors each executing action. If a failure is detected, a sequence of recovery behaviors will be executed. If the task fails completely, the action will be marked as failed and the whole task will be re-planned.

1.4. Condition Monitoring

As one of the main components of the state machine, the watchdog is used for condition monitoring. During manipulation, different conditions are monitored. For instance, force feedback is used to validate the grasping level of the grips and to detect possible failures with the gripper. The force is estimated by the electrical current of the gripper servo. Motion of the manipulator can be monitored by the integrated sensors, which provide information about the actual position, velocity and electrical current of each servo drive. These data are checked with an internal robot- and gripper-model to verify the actual states. A deviation above a defined threshold will abort the ongoing manipulation action and start a recovery. Approaches for monitoring of classical industrial robots have already been developed [13], [14], [15]. For navigation improvement, the current of each servo drive is used to validate the robots motion according to the navigation algorithm. It is compared to the estimated position from the Adaptive Monte Carlo Localization (AMCL [16]) based localization.

1.5. *Task planning*

The task planning is based on a graph search algorithm [17]. At first, the robot is moving inside an unexpected terrain and it systematically builds up its own service area map. In each step, all known map information is used to calculate possible navigation tasks. All workpieces on the back of the robot (Fig. 1, up to three allowed) are used for possible positioning tasks. The workpieces in the service area are used for grasping tasks. A greedy search algorithm [18] is used to a definable maximum depth and repeated in a loop until a complete task-plan (Fig. 2) is produced. The greedy approach was chosen because it provides good performance for online planning while still delivering near-optimal results in the given scenarios. The algorithm uses an objective function considering the time to perform the task, the probability to fail and the expected output. For the navigation tasks, the distances are precomputed based on the known map. Following, expected time costs are computed from the distances. The manipulation time costs are estimated based on previously benchmarked manipulation actions. When the state machine is not able to recover a failure successfully, the task is re-scheduled and re-planned. The following equation (Equ. 1) describes how to calculate the score in the area. A score value from a predefined table multiplied by a chance factor from the task planning scores the actual action. This result is added to the value from the previous step and divided by the costs (time per test plus penalties). The goal is to obtain a maximum score for the whole competition.

$$\mathrm{Score}_{n+1} = \frac{\mathrm{Value}_n + \mathrm{Value}_{\mathrm{Action}} \cdot \prod \mathrm{Chance}_i}{\sum \mathrm{Cost}_i} \tag{1}$$

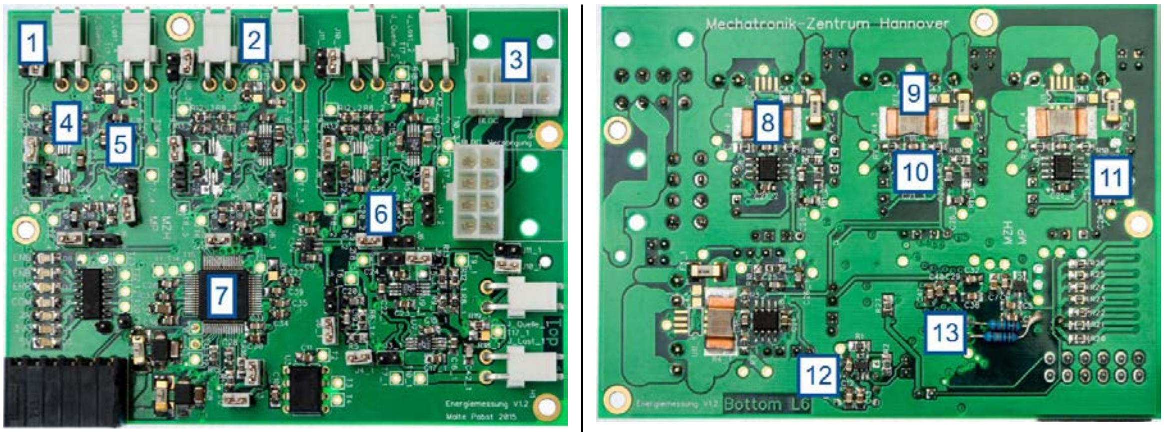
The greedy algorithm approach is optimized for maximum points at the competition. Expected points (value) per action are multiplied by all prior probability, resulting in risky tasks to be executed last. In RoboCup@Work, time is the fundamental limiting resource.

1.6. *Stability*

One major goal in the design of any robot control system is stability. Robots have learned to cope with uncertain information as for example with dynamic obstacles. It is not possible to predict all possible occurring events. The control system must be capable to handle blind spot situations. A major problem is the interpretation of sensor data, e.g. laser scanner errors due to reflective or transparent surface properties. In addition, the structured-light-sensor generates some erroneous data due to the reflectance or the lighting of the workspace. These uncertainties need to be considered within a control system. If an unexpected situation occurs, it is often preferred to stop the operation instead to proceed with unknown outcomes. Defined recovery behaviors and re-planning (Fig. 3) are used to allow the robot to proceed. The mobile robot has no hardware redundancies. Therefore, failure handling is only capable by software at this moment.

2. Energy measurement device

An energy measurement device was developed to monitor the electric energy flows in a mobile robot. The main benefit of the system is the possibility to identify the load distribution and to enable condition monitoring. The device measures voltage and current to calculate power, which allows the determination of the energy. To facilitate adaption to different mobile robotic systems, the device employs a modular approach. A mainboard distributes the signals from the central microcontroller to up to five measurement boards. Each measurement board, displayed in Fig. 4, is able to observe four electric components. The measuring chain uses a shunt and a bidirectional current shunt amplifier to transform the current into voltage. A low-pass filter is used to prevent aliasing and reduce noise. An analog to digital converter (ADC) with a delta sigma topology (see [19]) is used for signal processing. The configuration of the measurement chain can be adjusted to generate true RMS signals up to 400 kHz. The tested measuring range is ± 25 V and ± 10 A with nominal loads.



Top Side: 1 – Reference Configuration, 2/3 - Connectors to sources and loads, 4 – Voltage Divider, 5 – RMS-to-DC Converter, 6 – Low pass Filter, 7 – ADC

Bottom Side: 8 – Shunt, 9 – Hall Effect Sensor (Assembly variant), 10 – Current Shunt Amplifier, 11 – Low pass Filter, 12 – Negative Voltage Supply, 13 – Buffer-Capacitors

Fig. 4 Measurement board for monitoring of four electric components.

The core components of the electric system of the youBot are shown in Fig. 5. The robot runs on two lead acid batteries, which are connected to the power board. The power board provides the fixed voltage power rails for the internal electronics. The 12 V rail supplies the internal computer while the drivetrain uses the 24 V rail. In Fig. 5, taps mark the detailed energy measurement locations. The marks show the nominal voltage and maximum current limited by internal fuses. The implementation of this concept identifies the major loads within the robotic system. The typical measurement accuracy for voltage and current is lower than 1 %, comparable to a typical multimeter but with a modular number of channels.

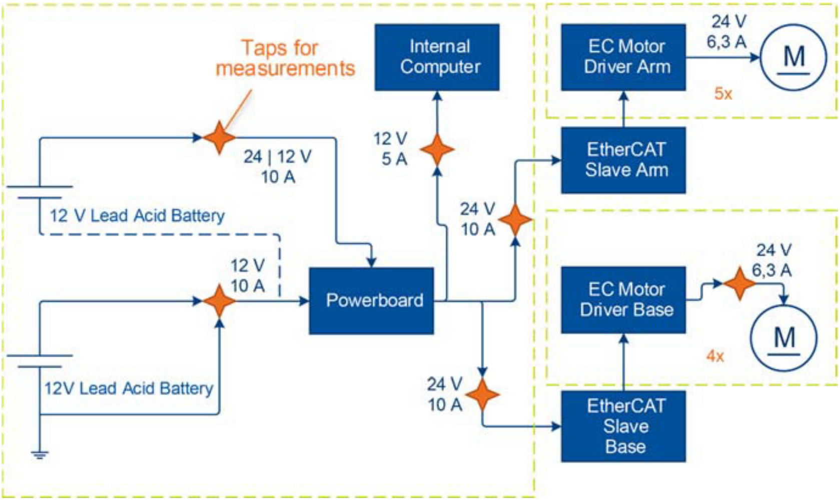


Fig. 5 Power distribution of the youBot core components.

The measurement device is able to monitor the batteries state. By using the Peukert equation and the average of the current, the state of charge (SOC) as well as the remaining operating time can be estimated [20]. A measurement chain for temperature measurement (PT100) is available on the mainboard. This allows expanding the battery model with temperature dependency factors (cf. [21]).

3. Results of the energy analysis

After equipping the youBot with the measurement device, a series of experiments was made. When the robot stands still, while all systems are enabled, the youBot consumes an average power of 28.93 W. The measurement is made on one of two parallel 12 V batteries, thus the data must multiplied by two. The base load is nearly steady, having a standard deviation of only 1.04 W. The average current from the battery is 2.53 A with a standard deviation of 0.1 A. Total values of energy, power and current values were estimated by doubling the presented results. For measurements of the active load, the youBot was programmed with a cyclic procedure as displayed in Fig. 6. Within a time of 30 minutes, the robot finished 62 cycles. The activity was filmed, allowing for the mapping of different movement phases to the measurements by synchronization on a key signal. During the phases one (Fig. 6) and five, only the base is moved. Whereas the arm is actuated in the phases two, three and seven. The phases two and six feature concurrent movement of the base and the arm (Fig. 6).

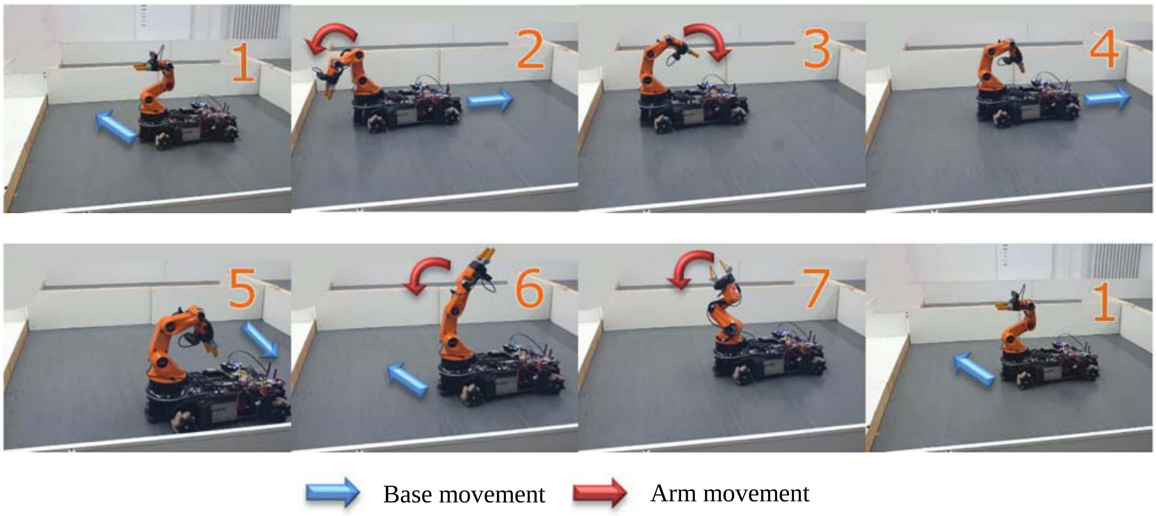


Fig. 6 Movement phases during series of measurement.

The integral of energy over the total time resulted in 61.4 kJ leading to an average power of 32.0 W. With an average discharge current of 2.88 A, a total charge of 1.49 Ah was discharged from the battery. In Fig. 7, the power over three cycles (approx. 28 s) is shown.

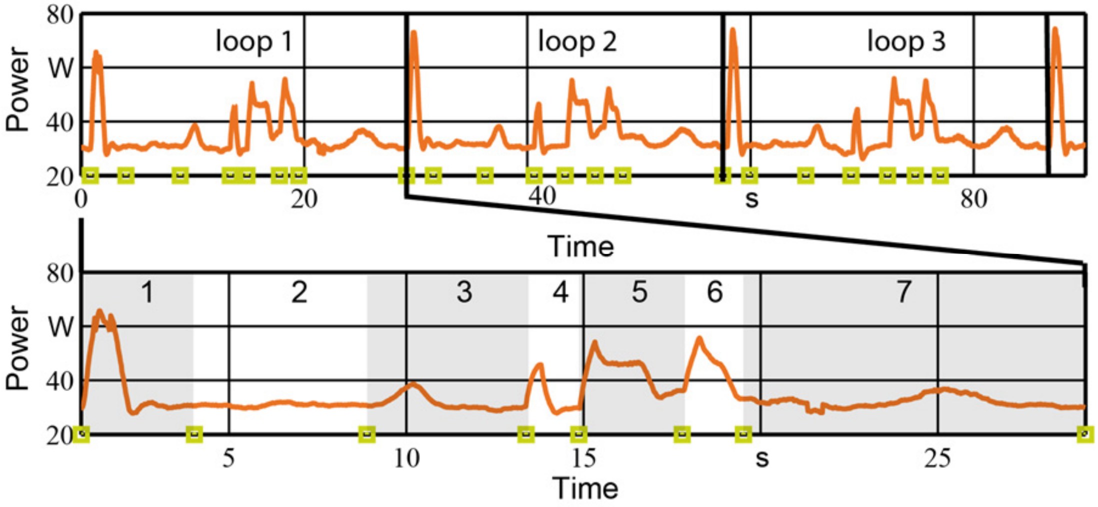


Fig. 7. Power and current over three cycles (Top) and close up of the first cycle (Bottom).

The movement phases result in characteristic and repetitive shapes. The first phase shows the largest power spike with peaks up to 78.8 W and current up to 6.97 A due to the unfavorable energy consumption when moving diagonal with mecanum wheels [22]. Further large spikes are bound to the phases where the base moves. The smaller peaks in the phases three and seven are most likely consequences of the arm moving against the direction of gravity.

Integration of the power during each phase yields the corresponding energy consumption seen in Table 1. By calculating the average power for each phase, the base increases the power intake by at least 12.46 W. In addition, the arm increases the power consumption up to 3.6 W on average. In this particular setup, the time period for arm movements was longer than for base movements. Thus, phases with arm movements show a larger total energy exchange due to the integrated constant base load.

Table 1. Integrals of energy during the movement phases.

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	base only			base only	base only		
Duration [s]	2.67	4.85	4.32	2.51	2.69	2.15	9.42
Energy Integral [J]	110.4	151.3	137.8	81.7	116.7	90.6	306.6
Average Power [W]	41.39	31.22	31.92	32.51	41.38	42.08	32.53

Based on the presented measurements, the power consumption of the youBot in power-on mode is a major factor for the total energy distribution. The movement of the base consumes less power. Global arm-actuation consumes the lowest power but during a longer time. To improve the energy efficiency of the youBot, work should focus on reducing the base load as well as increasing the efficiency of the base movement. Options include increasing the energy efficiency of the integrated computer, reducing computing time for path and trajectory planning, task shifting and trajectory re-planning.

4. Integration and Application

Measurement results are transmitted to a connected factory hub via Bluetooth. With this connection, the measurement device can also be remote controlled. In one mode, results (e.g. charging energy or cycle state) are computed in the device and transmitted to the hub. Another mode sends voltage and current with timestamps to the hub for external processing. A developed Matlab application enables live data representation.

By capturing reference movements as seen in the previous section, the youBot is able to utilize the required energy as basis for task planning. As described in sections 1.3 and 1.5, the task is planned with respect to the objective function, where all tasks have an associated value, an occurrence probability and a cost. By using the expected energy as cost, an energy-optimized task can be planned. The robot could e.g. avoid areas with unfavorable floor conditions or minimize the distance traveled with heavy loads. The battery capacity can also be used as an additional constraint for the optimization algorithm.

Using the Matlab Robotic System Toolbox [23], the factory hub is able to connect with ROS, running on the youBot, and stream the robot's internal data to a larger database on the hub.

Measurement of energy consumption in combination with planned tasks and reference movements enables the prediction of the remaining time until the battery charge is too low for further movements. A larger factory can therefore schedule a replacement or react upon this information well in advance. The recorded data can also be used to verify the energy efficiency of motion planning. Condition monitoring and failure detection can be implemented by comparing the average power consumption and peak currents for matching with a robot energy model.

5. Conclusion and Outlook

The initially described condition monitoring has been successfully tested at the RoboCup 2015 in China. For further improvement, an energy measurement device with connection to a factory hub was developed and successfully used to analyze the energy consumption of the youBot. With this setup, energy can be used as a new key factor for optimized task planning. To further improve the condition monitoring, energy consumption profiles of individual actions can be learned from the collected data and then be compared to the actual measurement. In future, the RoboCup is able to implement a new test scenario for energy and time optimized task planning. Further goal is to connect all youBots to the factory hub and collect all available information in a common database. Then, data-mining technologies can be used to research into possible process-structure interactions and environment recognition. Future work will focus on cooperative work of robot groups and cloud-based data mining for example. Further aim is to let the factory hub control a group of mobile robots using a self-optimizing energy algorithm for different tasks. Usage of mobile agents and further improvements in real-time ROS may allow for data pre-processing in every robot system or for distributing calculations over a swarm of robots to decentralize the computation and to reduce data traffic.

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