Intermittently-powered Battery-free Robot

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I. Introduction

Low cost robotic platforms have been developed to tackle a variety of challenges anonymously. Miniature robots can be used for inspection in difficult to reach places, operating like mobile sensing units. Hardware modularity is a way to make the robot adapt its resources to different environments and sensing operations. By separating out power, computation, motor control and sensing a verity of capabilities can be tested [1], [2], [3]. Microrobots typically use infrared-based neighbor to neighbor distance sensing and communication [4], [2], [3]. While controlling a swarm or collective is mainly accomplished by means of active low power transceivers [1], [2], [3].

Choosing the right locomotion resource can depend on different factors, moving in the most energy efficient way on a particular surface is often the determining factor. On a flat surface, robots commonly use a two-wheeled differential drive design to not only move but allow for steering as well [1], [2]. The GRITSBot does not use conventional DC motors, requiring encoders to estimate their speed. Instead by using stepper motors the speed can be set by changing the delay between steps. Estimating it's position therefore is reduced to simply counting steps [2]. Overall cost can be a decisive factor, therefore the Kilobot uses two vibrating motors for locomotion combined with three thin legs. When the motors are activated the centripetal forces will generate a forward movement, which can be explained using the slip-stick principle [4]. Other locomotion types are biologically inspired, the HARM-VP is small scale piezoelectric driven quadrupled robot[5]. Each leg as two degrees of freedom and move up and down as well as forward and backward.

Typically the operation time is extended by regularly checking the remaining energy in the battery and move to a recharging station before the robot runs out of energy [2], [4]. As an alternative to quickly recharging, the battery can also be swapped automatically when the robot moves into the docking station [6]. Another work shows a robot that is able to swap it's primary battery using a six degree-of-freedom manipulator, used to grab the dead battery and plug it into a wireless recharging charging station [7]. Using direct wireless power to replace or supplement to a batteries energy is shown in [8], however the robot can only operate or recharge while remaining in close proximity to a transmitter. In these cases the robots are highly reliant on an infrastructure to allow for continuous autonomous operation. This can be a severe constraint if the robot moves out of reach or needs to operate in a area where this infrastructure is not present. Persistent operation can also be achieved by harvesting renewable energy, particularly solar energy to complement to the robots internal energy source. To remove weight from the robot, in [9] the solar energy is used directly without any type of energy buffer. A drawback of of this is that the incoming energy should already greater or equal to the energy required for operation.

To capture the optimal amount of solar energy along the way, a map of the expected solar power can be used to compute the optimal path. To distinguish sunny or shaded two methods are proposed in [10], one being a simple datadriven Gaussian Process and the other estimates the geometry of the environment as a latent variable. Energy aware path planning is commonly used in combination with mission planning. In [11], an analysis of the solar radiation is used to generate a time-optimized motion plan and power schedule using a cascaded particle swarm optimization algorithm. By combining maps of lighting and ground slope a solar-powered robot can be kept illuminated continuously. A connected component analysis is used to plan a optimal route on traversable slopes, as described by [12].

All the previous work assumes that a operation is only possible when there is sufficient energy to complete a task. This research will explore the feasibility of a battery-less robot, allowing persistent operation while having a very small and intermittent source of energy. Intermittently powering robots creates new challenges in control, navigation and collaboration.

II. Related Work

Comparing li-ion batteries with super-capacitors there are some big differences. Super-capacitors do not need any special charging scheme and circuity for charging, except for overcharging protection. Secondly, super-capacitors do not require any particular current profile, the energy can be stored at any rate and when the energy is required it can be extracted at any power level. Operating a li-ion battery outside of it's recommended operating conditions can severely reduce a batteries lifetime and result in overheating or even explosion of the battery. Batteries will seldom withstand more than one thousand complete charge/discharge cycles. Using super-capacitors under extreme condition's they are not likely to explode but instead rupture. While the biggest disadvantages of super-capacitors is their low energy density and high price, their lifetime is typically hundred thousands of charge/discharge cycles.

Li-Ion Battery-Supercapacitor Hybrid Storage System for a Long Lifetime, Photovoltaic-Based Wireless Sensor Network [13] Reincarnation in the Ambiance: Devices and Networks with Energy Harvesting [14]

Fully programmable RFID platforms have been developed to exploring the combination of sensing, computation and communication, while allowing battery-less operation by harvesting RF energy [15]. The amount of energy collected from RF signals is very small and decreases with the distance of the device to the transmitter. The harvested energy is typically stored in a capacitor, where larger capacitors can buffer more energy and smaller capacitors have the advantage of shorter charge times [16]. For longer, complex operations the energy budged needs to be evaluated carefully. To store the energy an appropriate size storage capacitor needs to be selected [17].

III. Design Requirements

IV. Robot Design

A. Computation and Sensing

The robot is designed around a modified WISP 5.0, utilizing the processor and backscatter communication. It's based around a Texas Instruments MSP430FR5969 ultra low power microcontroller, operating at 16 MHz and featuring 64 KB FRAM, 2 KB SRAM and 40 IO.

The mainboard is the platform that connects everything together. Most reference designs are extendable but this adds complexity, while weight and size are the main constraints of this robot design. All the sensors can be interfaced trough a I2C connection. To conserve as much power as possible each sensor can be enabled and disabled using dedicated pins.

For avoidance of obstacles, a Maxim Integrated MAX44000 proximity sensor was added of the robot facing forward. This sensor can measure the amount of ambient light as well. In addition the robot has a Bosch BMG250 Mems Gyroscope to measure yaw angle change and correct when necessary.

Because the WISP has only limited accessible GPIO ports available, an Texas Instruments TCA9538 8-Bit I2C I/O Expander is used to interface both of the H-Bridges with the motor drivers. Each Texas Instruments DRV8836 H-Bridge requires 5 input connections, one for enabling the device and four connections for control. The I/O Expander is used supply a interface to the four control connections of the H-Bridge, in turn controlling each set of output ports.

B. Locomotion

Mounted directly under the mainboard of the IPR, two stepper motors can be found in differential drive configuration. An additional single front leg acts as third point of support. The IPR is to small to install wheel encoders, while small stepper motors are commonly used in digital camera's. This design was inspired by the GRITSBot [2].

The direction of current flow through each of the coil pairs of stepper motor controls the rotation direction. The bipolar stepper motor used, requires a pulse trough each of the four connections in a fixed pattern in order to rotate it forward or backward. In this case the speed of the pulses determines the rotational speed of the stepper motor. Increasing the rotational speed of the stepper motor decreases the torque output of the motor. Therefore the speed is limited by the amount of torque required to overcome the rolling resistance of the wheels.

The wheels are laser cut from PMMA (Polymethyl methacrylate) and are press-fitted on the axles of the motors. Wire shrink is used to create a very basic tire, to give the wheels some extra grip on the flat surface.

C. Energy Harvesting

Photovoltaic cells used for indoor and outdoor energy harvesting, commonly have a different spectral sensitivity depending on the nature of their sources. Solar cells used in indoor applications need to have a high spectral sensitivity in the range of visible light (400 to 700nm). While for outdoor applications have a spectral sensitivity range can be broader, including near infrared (500 nm to 1100 nm). Triple junction solar cells harvest in some cases up to 50% of there energy out of the near infrared range.

The solar energy harvesting system is based around a Texas Instruments BQ25570. It includes a nano power boost charger with maximum power point tracking to extract the optimal amount of energy from the solar panel. This harvested energy is stored in a 22mF/4.5V supercapactor from AVX, chosen for it's low leakage current and small size. The energy stored in supercap is a function of the capacitance and voltage difference between the plates, being equal to:

$$E = \frac{1}{2}CV^2 \tag{1}$$

However, to be able to use the energy stored in the capacitor efficiently a voltage regular is required to supply a stable voltage to the connected loads. The regulated output voltage is a lower threshold of the energy that can be used from the capacitor, rewriting Equation 1 results in the following equation:

$$E = \frac{1}{2}C(V_{max} - V_{min})^2 \tag{2}$$

The Texas Insturments BQ25570 has a buck converter to efficiently regulate the capacitor voltage down to a system voltage of 2.2 Volt.

D. Software

V. Localization Algorithm

VI. Experimental Results

VII. Limitations and Future Work

VIII. Conclusions

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TABLE I

AN COMPARISON OF SMALL ROBOTIC PLATFORMS

Robot	Cost	Scalability	Odomentry	Sensors	Locomotion	Size [cm]	Weight [g]	Battery life [h]
IPR	TBD	charge, program	stepper motors	distance	wheel, 3cm/s	3	15	0.0001
mROBerTO [3]	$60[1]	program	non/external	light, range, gyro, camera, accel., compass, distance, bearing	motor shaft, 15cm/s	1.5	??	1.5
Zooids [18]	$50	??	none/external	position, touch	wheel, 50cm/s	2.6	12	1-2
GRITSBot [2]	$50[1]	charge, program, calibrate	stepper motors	distance, earing, 3d accel., 3d gyro	wheel 25cm/s	3	??	1-5
Kilobot [4]	$50[1]	charge, program	other agents	distance, ambient light	vibration, 1cm/s	3.3	??	3-24
TinyTerp [1]	$50	none	none/extrnal	3d gyro, 3d accel.	wheel, 50cm/s	1.8	??	1

[1] Cost of parts

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