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.

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 [9], 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 [10], 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 [11].

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 [12] Reincarnation in the Ambiance: Devices and Networks with Energy Harvesting [13]

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 [14]. 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 [15]. 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 [16].

III. Design Requirements

IV. Robot Design

A. *Computation and Sensing*

B. *Locomotion*

C. *Energy Harvesting*

D. *Software*

V. Localization Algorithm

VI. Experimental Results

VII. Limitations and Future Work

VIII. Conclusions

References

[1] A. P. Sabelhaus, D. Mirsky, L. M. Hill, N. C. Martins, and S. Bergbreiter, "TinyTeRP: A tiny terrestrial robotic platform with modular sensing," in *Proc. IEEE ICRA*, Karlsruhe, Germany, May 6–10, 2013, pp. 2600–2605.

[2] D. Pickem, M. Lee, and M. Egerstedt, "The GRITSBot in its natural habitat - a multi-robot testbed," in *Proc. IEEE ICRA*, Seattle, WA, USA, May 26–30, 2015, pp. 4062–4067.

[3] J. Y. Kim, T. Colaco, Z. Kashino, G. Nejat, and B. Benhabib, "mROBerTO: A modular millirobot for swarm-behavior studies," in *Proc. IEEE/RSJ IROS*, Daejeon, Korea, Oct. 9–14, 2016, pp. 2109–2114.

[4] M. Rubenstein, C. Ahler, and R. Nagpal, "Kilobot: A low cost scalable robot system for collective behaviors," in *Proc. IEEE ICRA*, Saint Paul, MN, USA, May 14–18, 2012, pp. 3293–3298.

[5] A. T. Baisch and R. J. Wood, "Pop-up assembly of a quadrupedal ambulatory microrobot," in *Proc. IEEE/RSJ IROS*, Tokyo, Japan, Nov. 3–7, 2013, pp. 1518–1524.

[13] R. V. Prasad, S. Devasenapathy, V. S. Rao, and J. Vazifehdan, "Reincarnation in the ambiance: Devices and networks with energy harvesting," *IEEE Commun. Surveys Tuts.*, vol. 11, no. 1, pp. 195–213, First Quarter 2014.

[6] N. K. Ure, G. Chowdhary, T. Toksoz, J. P. How, M. A. Vavrina, and J. Vian, "An automated battery management system to enable persistent missions with multiple aerial vehicles," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 1, pp. 275–286, Feb. 2015.

[7] J. Zhang, G. Song, Y. Li, G. Qiao, and Z. Li, "Battery swapping and wireless charging for a home robot system with remote human assistance," *IEEE Trans. Consum. Electron.*, vol. 59, no. 4, pp. 747–755, Nov. 2013.

[8] M. Karpelson, B. H. Waters, B. Goldberg, B. Mahoney, O. Ozcan, A. Baisch, P.-M. Meyitang, J. R. Smith, and R. J. Wood, "A wirelessly powered, biologically inspired ambulatory microrobot," in *Proc. IEEE International Conference on Robotics and Automation*, Hong Kong, China, May 31 – Nov. 4 2014, pp. 2384–2391.

[9] P. A. Plonski, J. Vander Hook, and V. Isler, "Environment and solar map construction for solar-powered mobile systems," *IEEE Trans. Robot.*, vol. 32, no. 1, pp. 70–82, Feb. 2016.

[10] A. Kaplan, N. Kingry, J. Van Den Top, K. Patel, R. Dai, and D. Grymin, "Motion planning for persistent traveling solar-powered unmanned ground vehicles," in *Proc. IEEE/RSJ IROS*, Daejeon, Korea, Oct. 9–14, 2016, pp. 3212–3218.

[11] N. D. Otten, H. L. Jones, D. S. Wettergreen, and W. L. Whittaker, "Planning routes of continuous illumination and traversable slope using connected component analysis," in *Proc. IEEE ICRA*, Seattle, WA, USA, May 26–30, 2015, pp. 3953–3958.

[12] F. Ongaro, S. Saggini, and P. Mattavelli, "Li-ion battery-supercapacitor hybrid storage system for a long lifetime, photovoltaic-based wireless sensor network," *IEEE Trans. Power Electron.*, vol. 27, no. 9, pp. 3944–3952, Sep. 2012.

[14] A. P. Sample, D. J. Yeager, P. S. Powledge, A. V. Mamishev, and J. R. Smith, "Design of an rfid-based battery-free programmable sensing platform," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 11, pp. 2608–2615, Nov. 2008.

[15] J. Gummeson, S. S. Clark, K. Fu, and D. Ganesan, "On the limits of effective hybrid micro-energy harvesting on mobile CRFID sensors," in *Proc. ACM MobiSys*, San Francisco, CA, USA, Jun. 15–18, 2010, pp. 195–208.

[16] S. Naderiparizi, A. N. Parks, Z. Kapetanovic, B. Ransford, and J. R. Smith, "Wispcam: A battery-free rfid camera," in *Proc. IEEE RFID*, San Diego, CA, USA, Apr. 15–17, 2015, pp. 166–173.

[17] M. Le Goc, L. H. Kim, A. Parsaei, J.-D. Fekete, P. Dragicevic, and S. Follmer, "Zooids: Building blocks for swarm user interfaces," in *Proc. ACM UIST*, Tokyo, Japan, Oct. 16–19, 2016, pp. 97–109.

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 [17]	$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