CapBot: Enabling Battery-Free Swarm Robotics

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***Abstract*— Swarm robotics focuses on designing and coordinating large groups of relatively simple robots to perform tasks in a decentralised and collective manner. The swarm provides a resilient and flexible solution for many applications. However, contemporary swarm robots have a significant power problem in that secondary (i.e. rechargeable) batteries are slow to charge and offer lifetimes of only a few years, increasing maintenance costs and pollution due to battery replacement. We imagine a different future, wherein battery-free robots powered by supercapacitors can be recharged in seconds, offer long-life autonomous operation and can rapidly pass charge between one another using trophallaxis. In pursuit of this vision, we contribute the *CapBot,* a battery-free swarm robot equipped with Mecanum wheels, a Cortex M4F application processor and Bluetooth Low Energy networking. The CapBot fully recharges in 16 s, offers 51 min of autonomous operation at top speed, and can transfer up to 50% of its available charge to a peer via trophallaxis in under 20 s. The CapBot is fully open source and all software and hardware source is available online.**

I. Introduction

As swarm robotics moves out of the lab and into the field, power is becoming a major problem. Rechargeable batteries have an average lifetime of 3.5 years. As swarm deployments scale, the cost and complexity of swarm-wide battery replacement is becoming a major threat to the feasibility of many deployments. Furthermore, battery waste accounts for about 10% of global e-waste [1]. This is problematic when batteries are recycled at low rates, and contain toxic chemicals such as cadmium, lead, mercury and lithium, all of which pose a significant risk to the environment. Rechargeable batteries are also expensive, especially in the case of simple robots, where battery cost may be a large part of the Bill of Materials (BoM).

Recharging batteries is equally problematic. Conventional cells often take hours to recharge, resulting in low operational *duty cycles*, i.e. the proportion of time that a robot spends doing useful work, vs. being offline for recharging. Drive-in charging stations provide an infrastructure solution that can be automated to reduce manual interventions. However, the fixed position of these chargers in combination with slow charging times limits the flexibility of swarm robot behavior. Here, trophallaxis (wherein robots can recharge their peers in the field) offers an exciting alternative, but current solutions [2], [3] are either slow or complex.

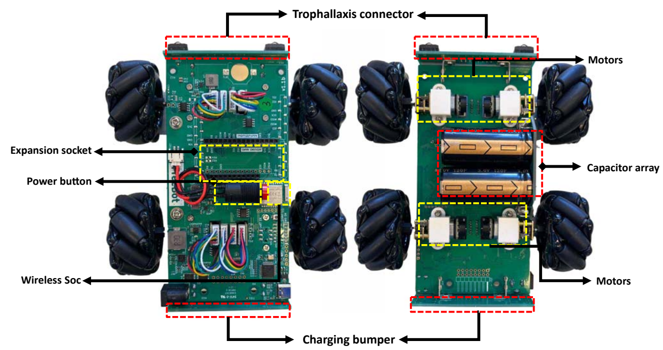

Fig. 1: The CapBot as seen from top (left) and bottom (right)

This paper introduces the CapBot [4], a prototype of which is shown in Fig. 1. The CapBot eliminates batteries as a charge storage medium in favour of supercapacitors, which can source and sink large currents. This feature enables the CapBot to recharge or perform trophallaxis in seconds, as opposed to hours. Furthermore, the lifetime of supercapacitors is not limited by charging cycles, enabling them to achieve lifespans of many decades. Notably for swarm testbeds, the operational vs charging duty-cycle of CapBots is significantly higher than battery-based platforms, at over 99%. More accurate charge metering is also possible as available energy can be measured with high accuracy based upon capacitor voltage. Finally, in contrast to batteries, capacitors can be manufactured using a wide range of non-toxic materials, thereby reducing environmental impact.

As shown in Fig. 1, we have created a prototype of the CapBot with a 240F capacitor array, four drive motors, trophallaxis charging connector, Bluetooth Low Energy networking and mecanum wheels for omni-directional movement. Evaluation of the CapBot shows 51 min of operation running at a top speed of 0.73 km/h, 2.5 kg carrying capacity, 100% recharge in 16 s from a mains charger and similar charge times via trophallaxis. All hardware and software materials are released under an open source license at: `https://github.com/openswarm-eu/ICRA2025_BatteryFreeRobot`.

The scientific contributions of this paper are twofold. Firstly, we introduce a practical battery-free swarm robotics platform that is constructed from Commercial Off The Shelf

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(COTS) components. Secondly, we demonstrate that such a design can exceed the capability of conventional battery-powered robots in terms of: recharge time, duty cycle, trophallaxis support and accuracy of charge monitoring. The reference design has a BoM cost of under €50 and is available under an open source license.

The remainder of this paper is structured as follows. Section II discusses related work. Section III describes the hardware design of CapBot. Section IV describes the software design of CapBot. Section V evaluates the platform. Finally, Section VI concludes and discusses directions for future work.

II. RELATED WORK

Farooq et al. [5] survey how mobile robots are powered and argue that their widespread application remains *"limited due to the lack of efficient power systems"*. Combustion engines provide long autonomy and rapid refuelling, though they cause pollution and cannot be used indoors. Fuel cells can also be rapidly refuelled, while reducing pollution and being safe indoors, though they are complex and expensive. In this context, batteries remain the dominant power source for swarm robots. We discuss popular battery powered swarm robotics platforms in Section II-A. In Section II-B, we discuss novel strategies to reduce charging time. This is followed by a discussion of supercapacitor based robots in Section II-C, before highlighting requirements for the design of CapBot in Section II-D.

A. Battery Powered Swarm Platforms

The Kilobot [6] is a small and low cost swarm robotics platform based around an 8-bit MicroController Unit (MCU) running at 8 MHz, short-range InfraRed (IR) communication (10 cm at 30 kbps) and vibration motors for locomotion. It is powered by a 400mW rechargeable coin-cell battery, which offers 3 hours of autonomy at a top speed of 0.04 km/h. Kilobots support manual recharging of large groups of robots in parallel, which takes 4 hours.

The e-puck [7] is based around a 32-bit MCU running at 168 MHz with Bluetooth and WiFi radios and two wheeled motors. It is powered by a 5Wh rechargeable battery, which offers an autonomy of 3 hours at max 0.9 km/h. Batteries can be recharged in 2 hours and drive-in power stations are available. e-pucks have a range of built-in sensors and can be expanded via an open expansion port.

Thymio II [8] is an educational swarm robotics platform which can be programmed in Scratch [9] and integrates with Lego Mindstorms[1]. It is based around a 16-bit MCU running at 16 MHz equipped with IEEE 802.15.4 radio, two wheeled motors and various sensors. It is powered by a 5.5 Wh rechargeable battery, offering 3 hours of autonomy at 0.72 km/h and recharges in 2 hours.

The GRITSBot is used in the Georgia Tech 'Robotarium' testbed [10].It is based around an 8-bit MCU running at 16 MHz. GRITSBots support swarm-wide WiFi communication as well as local optical communication. They are powered by a 5.5Wh rechargeable battery offering 30 min of autonomy at max. 0.9 km/h. Drive-in recharging taking around 30 min.

Considering the robotics platforms discussed above, we note that contemporary swarm robots provide sufficient autonomy, with battery lives (30 min to 3 hours) but relatively low duty-cycles (43% for the Kilobot to 60% for the e-puck).

B. Novel Charging Solutions

The MarXbot [11] is a mobile robot that reduces recharge times by automating the hot-swapping of depleted batteries for charged ones. During this process, the robots maintains power for up to 15s using supercapacitors. MarxBot's 38Wh battery enables 4 hours of autonomy at 1.26 km/h. It is based around a 32-bit processor running at 533 MHz with WiFi radio and a range of location sensors. This approach enables a very higher duty cycle (99.9%), though the cost and complexity of this charging infrastructure is higher than traditional recharging.

Arvin et al. [12] propose the use of powered surfaces with inductive charging to continually recharge swarms of battery-powered robots. The two-wheeled robot 'Mona' is based on an 8-bit microcontroller running at 16 MHz and is equipped with an inductive charging unit and an 888mW rechargeable battery. It recharges as it traverses the charging surface at speeds of up to 0.05 km/h. While this approach achieves a 100% duty cycle, it limits the speed of locomotion and requires extensive environmental modification.

Trophallaxis is a process whereby insects share nutrients in order to to enable collective goals. This idea has also been applied in the context of peer-to-peer charging for autonomous mobile robots. For example, Evo-bots [2] take over two hours to charge a peer to a level that can support 30 min of operation. Similarly, FreeBots [13] enable trophallaxis between battery powered robots which, due to a custom case design can form complex networks. However, as with the evo-bot, battery-based Trophallaxis takes hours to complete. Schioler et al. tackle this problem by introducing the CISS-bot [3], which is capable of hot-swapping batteries with peer robots. Unlike MarXbot [11] , which uses supercapacitors to provide power during battery swapping, the CISSbot uses an array of multiple batteries. As with the MarXbot, this achieves a near 100% duty cycle, though it significantly increases the cost and complexity of the robots.

C. Capacitor-based Mobile Robots

Muffoleto et al. [14] introduce a supercapacitor based mobile robot which can be recharged in 72 s, while offering an autonomy of up to 7 min. This results in a higher duty cycle than battery-powered robotics platforms (85%), however, it does so at the expense of autonomy.

Johnson et al. introduce MilliMobile [15], a 1 cm^3 mobile robot that uses supercapacitors for charge storage in combination with solar panels and wireless power transfer for energy harvesting. Through the design of a novel motor controller, MilliMobile drives down locomotion power to

[1]https://www.lego.com/en-be/themes/mindstorms

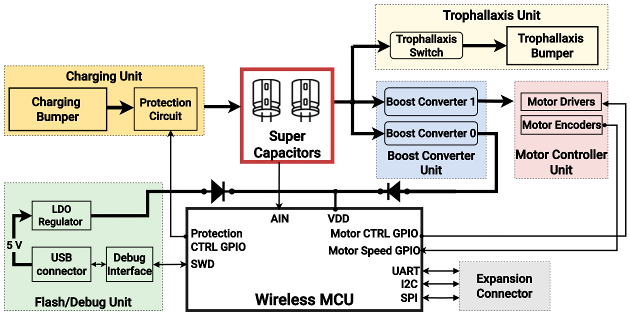


Fig. 2: High level block diagram showing the hardware components of the CapBot.

50μW, enabling the robot to move sustainably using harvested energy. Millimobile has a maximum speed of 0.020 km/h, roughly half that of the Kilobot. As with Mona [12], energy harvesting achieves 100% autonomy at low speed.

D. Requirements

Based upon our analysis of related work, we highlight the following requirements for the design of the CapBot:

1) *Enhanced duty cycle.* Exploiting the high current capability of supercapacitors, charging time can be reduced by orders of magnitude. However, system-wide power optimisation is also required to ensure that CapBots preserve comparable autonomy to today's swarm computing platforms [6], [7], [10], [8] when using a lower energy-density charge storage medium.
2) *Trophallaxis:* As demonstrated by the Evo-bot [2], trophallaxis provides a compelling mechanism to increase the flexibility of when and how robots can recharge. We aim to exploit the high current capability of supercapacitors to significantly increase the speed of trophallaxis.
3) *Energy awareness:* Given the small amount of energy that supercapacitors store in comparison to batteries, it is essential to accurately track how much energy is being consumed to inform recharging decisions and energy-adaptive behaviour.
4) *Simple COTS design:* While work such as MilliMobile [15] are inspirational, they require exotic components and advanced manufacturing techniques. A COTS design using standard manufacturing techniques is required for widespread adoption in swarm applications.

III. Hardware Design

Fig. 2 illustrates the high-level architecture of the CapBot hardware platform. Motors are mounted on the PCB. The assembled weight of the robot is 285 grams. Each element of the architecture is described below:

Wireless MCU: The nRF52840 [2] offers a Cortex M4F running at 64 MHz with 256 kB RAM, 1 MB Flash and a 2.4 GHz radio supporting Bluetooth Low Energy (BLE), IEEE 802.15.4 and ANT. This processor executes all firmware and application code; monitoring supercapacitor voltage, regulating the robot's speed and direction, managing energy transfer between robots and supporting communication.

Flash/Debug Unit: This unit allows program downloading and debugging via a standard USB connection, eliminating the need for an external debug interface.

Supercapacitor Array: Two 120F supercapacitors connected in parallel provide a reliable power supply capable of meeting high energy demands.

Trophallaxis Unit: This unit integrates a software-controlled high-current relay (Trophallaxis Switch) to enable or disable energy transfer. The Trophallaxis Bumper, equipped with spring terminals facilitates peer-to-peer energy transfer between robots while maintaining electrical and mechanical stability.

Charging Unit: The protection circuit provides over-current and over-voltage prevention during charging. The charging bumper connects to a drive-in charger or the Trophallaxis Bumper of a peer robot. The CapBot may also be charged using a standard barrel jack.

Boost Converter Unit: Consists of two TPS61021 converters, supplying up to 3 A and operating down to 0.6 V. One powers the MCU, the other supplies the motors, ensuring a stable voltage throughout the charging cycle.

Motor Controller Unit: The CapBot uses four 3 V DC motors with 1:100 gearing and rotary encoders to monitor speed, enabling omnidirectional movement through differential control of the 48 mm Mecanum wheels.

Expansion Connector: The CapBot expansion connector follows the Adafruit feather standard[3], enabling the use of 100's of compute, network, sensing and actuator 'wings'.

A. Fast Charging

The following sections discuss how CapBots rapidly recharge using infrastructure or trophallaxis.

1) Infrastructure Charging: Infrastructure charging for the CapBot is performed by a mains-connected power supply. In our experiments we used a 40 A constant voltage supply, enabling the charging of CapBots at up to 120 W. However, when charging a capacitor with a constant voltage supply set at its maximum rated voltage, charging rate decreases logarithmically as the stored charge approaches the maximum rated voltage [16], [17]. We circumvent this problem by using a supply voltage that is higher than the maximum rated voltage of the capacitor and monitoring the internal voltage of the capacitor in real time, cutting off the power supply when the measured capacitor voltage approaches its rated maximum. This maximises charging speed while minimising charger cost and complexity. The hardware protection circuit described above provides another layer of protection against over-voltage or over-current conditions.

2) Charging via Trophallaxis: Building upon the ability of the CapBot to safely source and sink high currents, we provide support for *trophallaxis* as a way to flexibly share

[2] https://infocenter.nordicsemi.com/pdf/nRF52840_PS_v1.1.pdf

[3] https://learn.adafruit.com/adafruit-feather/feather-specification

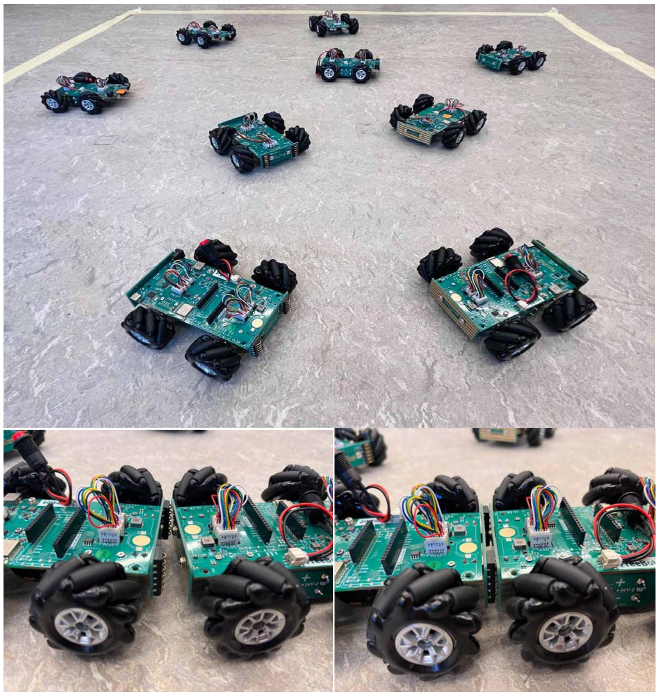


Fig. 3: A group of CapBots under test (top), two of which perform trophallaxis by connecting bumpers (bottom)

energy between CapBots. Two advantages are achieved by this system: Firstly, CapBots can share charge with a peer in order to prolong its mission or even to revive a depleted robot. Secondly, this approach enables a single CapBot to execute tasks that might outlast its individual autonomy. Both infrastructure and trophallaxis charging use the same spring-loaded bumper system that allows to CapBots to make and break a connection simply by driving up to and away from each other. The CapBot contains a simple detection circuit to sense when a connection has been made reliably and the trophallaxis switch must be explicitly closed by the firmware in order for current to flow and charging to occur. Figure 3 shows nine CapBots under test along with two robots performing trophallaxis.

IV. Software Design

Fig. 4 provides a high-level overview of the CapBot software stack which is provided as a library on top of Zephyr[4], a popular Real-Time Operating System (RTOS) for embedded devices. Zephyr provides priority-based multitasking which is useful for concurrently executing application code and background tasks such as motor control. The CapBot library API can be split in three parts based on functionality:

On-board IO: Exposes functions to interact with on-board IO like LEDs and buttons. The proof-of-concept mainly uses this to show the bot's status through the LEDs. Furthermore, some of pins on the Adafruit feather expansion connector can be controlled via this API component.

Power management: The power management API allows to monitor the the charge available on the supercapacitor by

[4]https://zephyrproject.org/

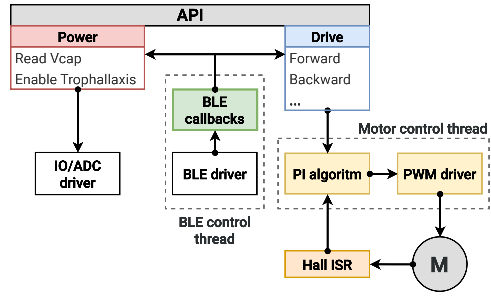


Fig. 4: High level overview of the CapBot software stack running on the Zephyr OS

measuring its voltage using the onboard Analog to Digital Converter (ADC) of the nRF52840 and converting this to charge using the formula $E = 0.5C\ V^2$, where E is energy in Joules, C is the capacitance in farads, and V is the voltage in Volts. Second, it enables the activation and deactivation of the Trophallaxis bumper using the associated switch.

Network interface: Enables a serial-port like connection implemented on top of Bluetooth Low Energy (BLE), exposing a simple management API for controlling robot actuators (e.g. motors) as well reading relevant sensors (e.g. state of charge). At the current time, CapBots cannot be programmed wirelessly and implementing scalable 'Over The Air' programming is an important element of our future work [18].

Motor control: Enables omnidirectional movement and speed control using a Proportional Integral (PI) Controller, which realises a feedback loop between the PWM motor control and hall sensor motor rotation sensor.

V. Evaluation

A. Autonomous Operation

Fig. 5 show the autonomy of the CapBot with the four motors running at different 20, 40, 60 and 80 rpm, resulting in a speed of 0.18 to 0.73 km/h. Robot behaviour becomes unpredictable once the voltage of the capacitor array falls below 0.6 V ('brown-out'), resulting in an autonomy of between 51 and 65 min. This is competitive with existing battery powered swarm robots [6], [7], [10], [8] and over four times longer than reported for previous supercapacitor based robots [14].

B. Accuracy of Energy Measurement

As described previously, the energy stored in a capacitor can be easily inferred from its measured voltage. Nevertheless, due to inaccuracies in the ADC and its associated measurement circuit some error is inevitable. Fig. 6 compares the voltage recorded by the onboard ADC against 'ground truth' as provided by a digital multimeter over one charge/discharge cycle at 80 rpm. As can be seen from the figure, the measured voltage closely tracks ground truth. Fig. 7 quantifies the accuracy of charge measurement using equation (1) and a fixed offset K that is calibrated at manufacture time.

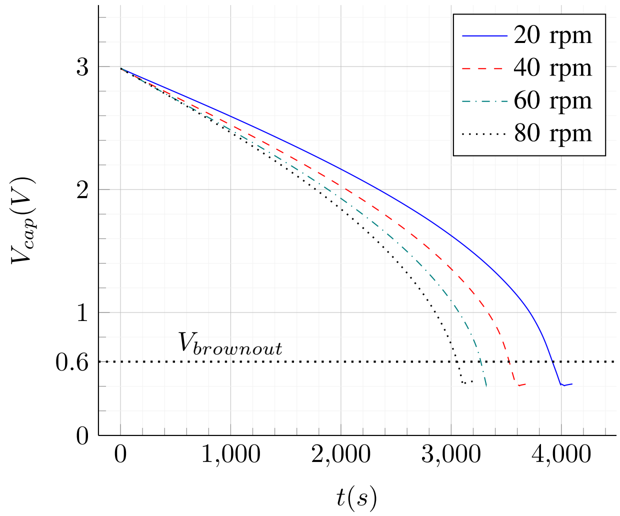


Fig. 5: CapBot operational autonomy at 20, 40, 60, and 80 rpm. The robot is fully charged at 3V and becomes inoperable at 0.6 V.

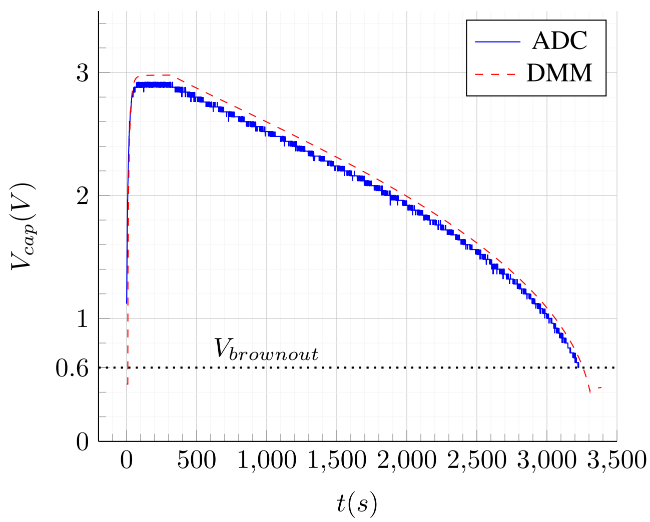


Fig. 6: Comparison between V_{cap} measured with on-board ADC and external digital multimeter at 80 rpm

$$E_{err} = \frac{\mid E_{cap,DMM} - (E_{cap,ADC} + K) \mid}{E_{cap,max}} \cdot 100 \quad (1)$$

The initial stage (I) of this graph shows charging, during which V_{cap} rapidly increases, causing an error of up to 5%. The second stage (II) starts when the capacitor is fully charged and ends when the charger is disconnected. This stage demonstrates that the error is around 1.5% whenever the voltage slope is zero. In the final stage (III), the capacitor is discharged at the maximum operational rate by running the wheels at 80 rpm. During this phase, the error climbs as capacitor voltage falls due to the limited resolution of ADC. Nevertheless, over a complete charging cycle, the error of energy measurement remains under 5%, which is considerably less than than the state of practice for lithium

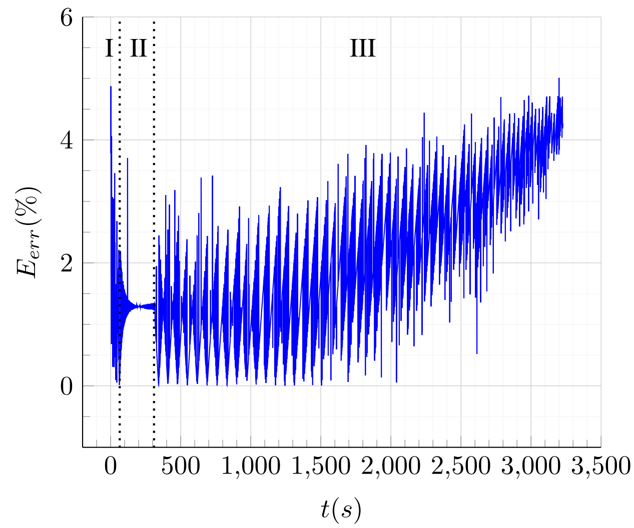


Fig. 7: Relative error for E_{cap} from the on-board ADC compared to an external multimeter (raw data in Figure 6)

batteries, which depends upon a load resistor and results in a typical error of 10-20%.

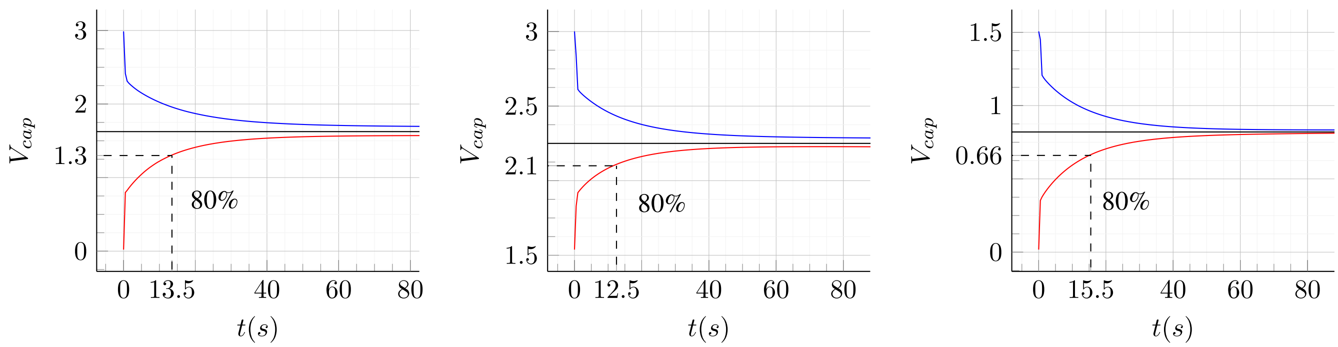
C. Infrastructure Charging

As shown in Fig. 9, charging the CapBot using a 40A power supply at the capacitor's rated voltage of 3V charges the supercapacitor to 2.9V in 64 s. Using the quick charging approach described in Section III-A, charging time is reduced to 16 s. The voltage drop that occurs at point I, when fast charging is turned off, is related to the amount of current flowing into the supercapacitors. The same drop occurs when standard charging is turned off at point II, but it is smaller due to the relatively lower current. Infrastructure charging of CapBot is significantly quicker than any of the robotics platforms discussed in Section II, including those that use supercapacitors. CapBot achieves a duty-cycle of over 99%, which is significantly higher than reported for both battery-powered robots (43-60%) or capacitor based platforms (85%).

D. Trophallaxis

Trophallaxis may occur between any two robots where a voltage differential exists and will result in charge being equally distributed across both robots. Fig. 8 shows the trophallaxis process for three voltage differentials: (a) a 3V donor charging a 0V recipient, (b) a 3V donor charging a 1.5V recipient and (c) a 1.5V donor charging a 0V recipient. As can be seen from the figure, it takes between 12.5 and 15.5 s to reach 80% of equilibrium and 80 s for charge levels to fully equalise.

As can be seen from Table I, trophallaxis is less than 50% efficient, which is fundamental to capacitor to capacitor charging. Nevertheless, CapBot's approach to trophallaxis is simple and orders of magnitude faster than prior systems [2], [13], with the exception of CISSBot which operates by physically exchange batteries [3]. In our future work, we will



(a) 3V to 0V

(b) 3V to 1.5V

(c) 1.5V to 0V

Fig. 8: Trophallaxis at multiple charge levels is faster than battery-based systems. Transferring the first 80% of charge occurs quickly (under 16 s), though reaching equilibrium is takes longer (up to 80 s).

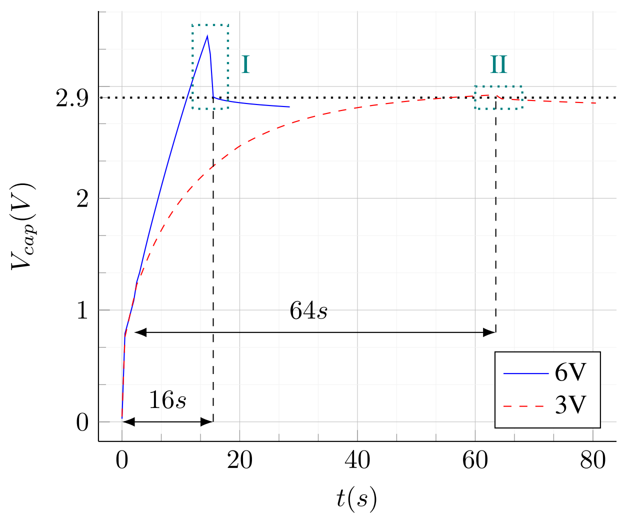


Fig. 9: Super charging the capacitors at 6 V ensures that the current stays constant and that the total charge increases linearly until the charging process is stopped.

TABLE I: Autonomy Before and After Trophalaxis

Trophalaxis Cases	Donor Change (minutes)		Recipient Change (minutes)	
	@ 80 rpm	@ 20 rpm	@ 80 rpm	@ 20 rpm
Case (a)	- 36	- 47	+ 12	+ 14
Case (b)	- 22	- 28	+ 18	+ 25
Case (c)	- 9	- 10.5	+ 1.8	+ 1.8

explore techniques to enable robots with negative voltage differentials to donate charge building on our prior work on reconfigurable capacitor arrays [19].

VI. Conclusions

This paper has presented the CapBot, a battery-free swarm robotics platform that achieves a unique performance profile, including: full recharge in under 20 s, rapid and efficient trophallaxis, 51 min of autonomy, 99% duty cycle and fine-grained charge metering with an accuracy of under 5%. Considered in sum, this feature set is very appealing in the context of large-scale swarm robotics testbeds. To date we have built 50 CapBots, which have been used to teach three masters level courses at KU Leuven (Software for Embedded Systems, Industrial Internet Infrastructure and Software for Real Time Control), each of which have approximately 50 students enrolled. The platform has proven quite reliable in an educational context. Stepping back from the specifics of the CapBot platform, this work points the way to a bright future for battery-free robots, particularly in scenarios where up-time is more important than autonomy.

Our future work is focussed on the creation of a 1000 node testbed of CapBots in the context of the EU OpenSwarm project. This testbed will be open, supporting swarm experiments for the global robotics community over the Internet. This necessitates work on a range of topics, including: cost reduction, integration of localisation technologies and support for reliable swarm-wide reprogramming.

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