Dynamic Power Sharing for Self-Reconfigurable Modular Robots

Chi-An Chen, Akiya Kamimura, Luenin Barrios and Wei-Min Shen

Polymorphic Robotics Lab, Information Sciences Institute
University of Southern California, Marina del Rey, CA 90292.

Abstract. Dynamic power sharing is used to extend the operation time of self-reconfigurable modular robots [1]. In this area of research, power and energy consumption has consistently been a critical factor in the determination of a robot's operation time. To this end, a method to dynamically share power would enable the robot to extend its operation time and allow it to function well beyond its individual energy life span. In this paper, a dynamic power sharing mechanism is proposed that provides such capabilities. It consists of five power sharing modes and is demonstrated on SuperBot, a self-reconfigurable modular robot developed at USC by the Polymorphic Robotics Laboratory at the Information Sciences Institute. The five modes include: 1) offering power 2) power bypass 3) receiving power 4) both charging the battery and receiving power and lastly 5) battery charging. The five modes that comprise the implementation will demonstrate how the self-reconfigurable modular robot SuperBot can share power dynamically. Finally, experiments were performed on SuperBot conclusively demonstrating that the operation time can be increased upwards of 30% more compared with the original hardware lacking the power sharing capabilities.

Keywords: Robot, Dynamic, Power Sharing

1 Introduction

Fig. 1: SuperBot in a rolling track configuration [2].

Module No.	1st Run (970m)	2nd Run (1142m)
Module 1	3.63	3.48
Module 2	7.41	5.19
Module 3	7.45	3.63
Module 4	7.43	7.23
Module 5	7.43	6.70
Module 6	7.44	7.63

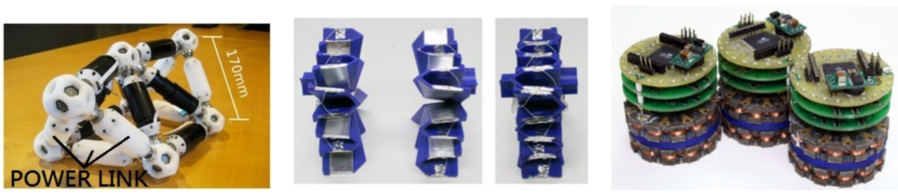
Table 1: Average remaining battery voltage (Every run was started from a fully charged battery 8.2V.) [2].

Self-reconfigurable modular robots are autonomous machines created to deal with unpredictable, dynamic and unforeseen situations in environments and tasks. They are well suited to function in environments requiring high degrees of multitasking and adaptation such as robot arm, planetary exploration, building complex structures, fixing objects in space [3], etc. Depending on the task, they can form various shapes to maximize the work efficiency of each task. Fig. 1 shows SuperBot in a rolling track configuration [2]. There are six modular robots connected together to form the shape and perform the rolling track task. In the initial design and implementation of SuperBot, each modular robot did not have a power sharing mechanism and relied solely on the energy contained within its battery pack. From Table 1, the first run (970 m) was terminated due to module 1's low battery and the second run (1142 m) was terminated by module 1's or module 3's low batteries.

Based on the experimental results, it is evident that in order to extend the operation time, it is important to solve low power issues that cause failures throughout the entire system. For example, in the above experiment, module 1's battery malfunctioned resulting in a failure that threatened to fracture the entire rolling track configuration. Therefore, if SuperBot wants to extend its operation time, it would be conducive to have modules capable of offering their power to other modules so that work and operation can proceed normally.

In this paper, a prototype of dynamic power sharing circuits was designed and implemented in two SuperBot modules. The dynamic power sharing mechanism consists of 5 operation modes. The experimental results demonstrate the power sharing functionality and confirm the improved operation time on SuperBot modules.

2 Related Work



(a) Odin [4] (b) Electrostatic Latches [5] (c) Planar Catoms [6]

Fig. 2: The related work

Power sharing is an essential problem in self-reconfigurable modular robots because the structures possible are large and diverse and require a solution that must function across all configurations. Due to the various kinds of self-reconfigurable modular robots, several kinds of power sharing structures and circuits have been developed. Fig. 2(a) shows the Odin Modular Robot [4] developed by the University of Southern Denmark where the power is transferred by the power link across the bodies of links and joints. Fig. 2(b) shows Electrostatic Latches developed by CMU [5] where the capacitors are used to transfer the power from a square wave generator. Fig. 2(c) shows Planar Catoms [6] also developed by CMU where the transformer is used to transfer the power, providing power to the connected module. The robust power sharing capabilities which are able to handle the dynamic nature of self-reconfigurable modular robots especially in unpredictable situations are not shown. For example, if one of the batteries malfunctions or has no power. In such cases, the module might cease working properly and may also affect the other modules. Because self-reconfigurable modular robots are highly versatile and dynamic, the power sharing mechanism should be also designed in a dynamic fashion to handle all kinds of tasks.

3 System Design

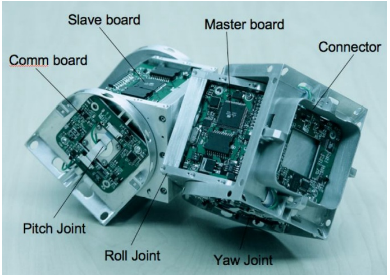
A dynamic power sharing circuit is created based on SuperBots modular structure. This section introduces the system design for the dynamic power sharing capabilities. As shown in Fig. 3(a) and Fig. 3(b), each module consists of one master board, one slave board, and six communication boards on the six faces. The modular robots can share power with each other by docking to one of the six communication boards.

3.1 Hardware Design

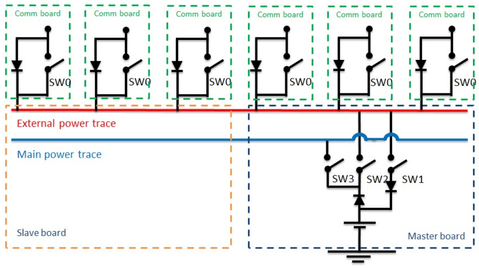
After several hardware versions [7], the power sharing circuit was created as shown in Fig. 3(b). Fig. 3(c) shows switch 1's circuit. The switch in this circuit is mainly composed of the three components: STL8NH3LL Power FET, MIC5018 High-Side MOSFET Driver and 2N7002 MOSFET. STL8NH3LL Power FET is used for passing high electric current (Max. 8A). MIC5018 High-Side MOSFET Driver is used for high output voltage (around 16V). 2N7002 MOSFET is used for controlling MIC5018 High-Side MOSFET Driver to turn on or off. MIC5018 High-Side MOSFET Driver is turned on by default so that each module is ready to receive power any time and can be turned on if other modules are willing to help. Switch 0, switch 1, switch 3 are designed based on switch 1's structure, without the MIC5018 High-Side MOSFET Driver.

3.2 Software Design

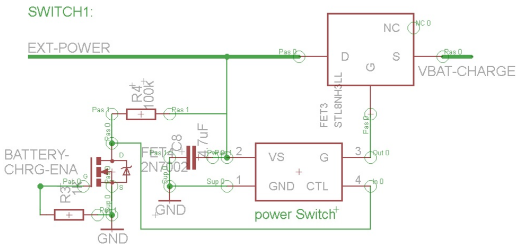
The dynamic power sharing tasks have been developed based on the previous research [8]. The two classes have been modified: system tasks and behavior tasks.



(a) SuperBot module [2].



(b) Power sharing simplified circuit in one module.



(c) Power sharing switch 1 circuit diagram.

Fig. 3: Hardware design.

1. System tasks [8]: system tasks consist of low-level programs which are used to control the hardware. For example, in power sharing mechanism, each module needs to negotiate their power needs before determining which power sharing mode they should adopt. Therefore, the power sharing signal needs to be embedded in the program, such as the "misc Task" which is used to communicate between the master and the slave boards.

2. Behavior tasks [8]: behavior tasks consist of high-level programs which are used to perform the robot's high-level behavior, such as rolling tracks, a caterpillar gait, a butterfly stroke, etc. For verifying SuperBot's dynamic power sharing capabilities, the query task has been created and used to determine which power sharing mode the modular robot should select. Behavior tasks can manipulate the functions from system tasks.

4 Dynamic Power Sharing

The SuperBot hardware shown in Fig. 3 that includes the dynamic power sharing circuit has 5 modes: 1) offering power 2) power bypass 3) receiving power 4) both charging the battery and receiving power and 5) battery charging.

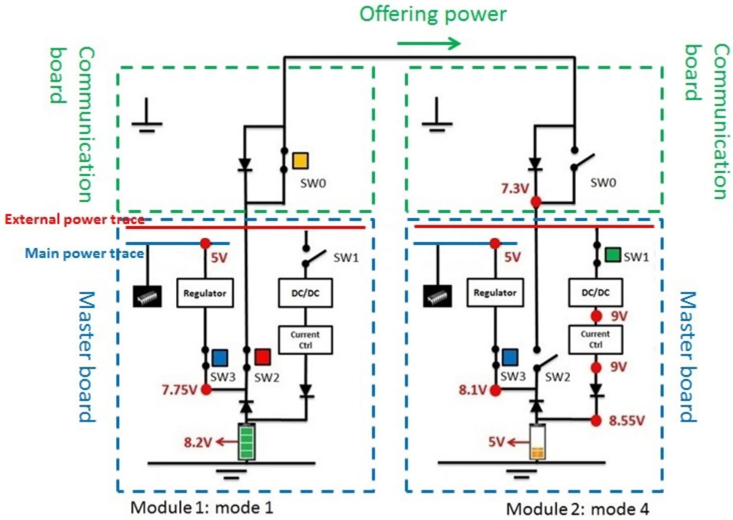


Fig. 4: Module 1, in mode 1, shares power to module 2, in mode 4.

4.1 Mode 1: Offering Power

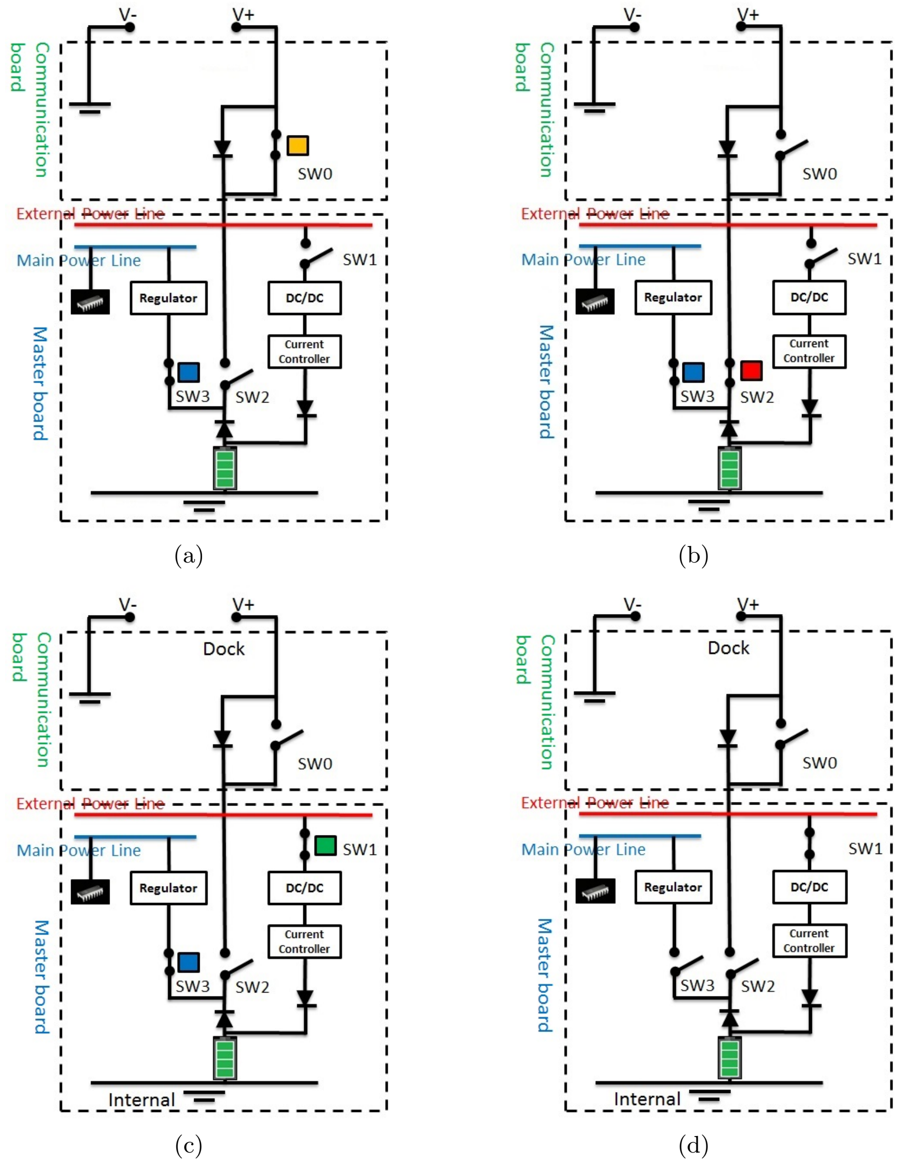
The basic function for dynamic power sharing is that one module can offer power to other modules. When module 1 offers power to module 2; the blue arrow represents offering power to module 2's system and the green arrow represents charging module 2's battery. The yellow LED, red LED and blue LED stay on, which signify that switch 0 (SW0), switch 2 (SW2), and switch 3 (SW3) are closed respectively. Fig. 4 shows the status of the offering power mode switches. The current from the battery goes through SW2, offering power to the external power path and also through SW0 to the docking board so that other modules can get power from module 1 by connecting to the docking board.

4.2 Mode 2: Power Bypass

If the module doesn't have enough power or doesn't want to offer its power to the other module(s), it enters "power bypass mode" and lets the modules which are not directly connected to the receiving power modules pass their power. Fig. 5(a) shows the power bypass mode switches status. Because SW1 and SW2 are open, the battery only offers power to its own system. SW0 is closed, so the module can pass power through the external power path and offer power to the docking board.

4.3 Mode 3: Receiving Power

If the module with insufficient battery doesn't want to charge its own battery, for example, the battery malfunctions, it can enter "only receiving power mode"



(a) (b) (c) (d)

Fig. 5: (a) Status of power bypass mode switches. (b) Status of receiving power mode switches. (c) Status of both charging the battery and receiving power mode switches. (d) Status of battery charging mode switches.

Fig. 5(b) shows how the source comes from the docking board, through SW2 and SW3, to offer the receiving module's system power.

4.4 Mode 4: Both Charging the Battery and Receiving Power

If the insufficient battery module wants to charge its own battery and also get power simultaneously from the other module(s), for example, when the module can connect to a power supply, it can enter "both charging the battery and receiving power mode". When the module is in this mode, the outside power source can pass through SW1 to charge its battery and SW3 to provide its system power simultaneously as shown in Fig. 5(c).

4.5 Mode 5: Battery Charging

If the insufficient battery module only wants to charge its own battery without receiving system power, it can enter "battery charging mode". This mode is used for SuperBot in the rest state. Fig. 5(d) shows the module in this mode. The outside power source can pass through SW1 to charge its battery but cannot go through SW3 to provide its system power because SW3 is open.

4.6 Dynamic Power Sharing Implementation

Fig. 6: Communication demonstration for two SuperBot modules.

Before each module enters the power sharing modes, they need to communicate first to determine which power sharing mode they want to adopt. Therefore, the power sharing implementation coordinates each self-reconfigurable modular robot's power needs. Fig. 6 shows two SuperBot modules exercising such communication. Fig. 7 shows the power sharing implementation diagram which handles the distributed structure, as is the case for self-reconfigurable modular robots. In Fig. 7, two modules performing dynamic power sharing are demonstrated. When module 1's voltage < Vth1, it sends "Help" signal through infrared to the surrounding modules. In Fig. 7, for example, module 2 is near module 1 and receives the "Help" signal from module 1. Module 2 checks its battery voltage first and if the voltage < Vth2, it helps module 1 broadcast the "Help" signal.

However if the voltage > Vth2, module 2 can decide whether it wants to help or not. If module 2 decides not to help, it checks the docking status, to see if they are already docked. Module 2 enters mode 2, acting as a bypass mode module and broadcasts the "Help" signal, however, if they are not docked yet, module 2 just helps module 1 broadcast the "Help" signal. From module 1's perspective, if it doesn't receive the confirmed signal from other modules, module 1 keeps sending out the "Help" signal. Once module 1 gets the confirmed signal, it checks its docking status. If module 1 isn't docked with the module which is willing to offer power to module 1, module 1 executes the docking task and then chooses one mode from mode 3, 4 or 5 after docking. If module 1 is already docked with the module, it directly chooses one mode from mode 3, 4 or 5 to share power. If module 2 decides to help, it sends out the confirmed signal to module 1 and also checks the docking status. If they are already docked, module 2 enters mode 1 to offer power to module 1. If they are not docked yet, module 2 performs the docking task and then enters mode 2 to share power after docking.

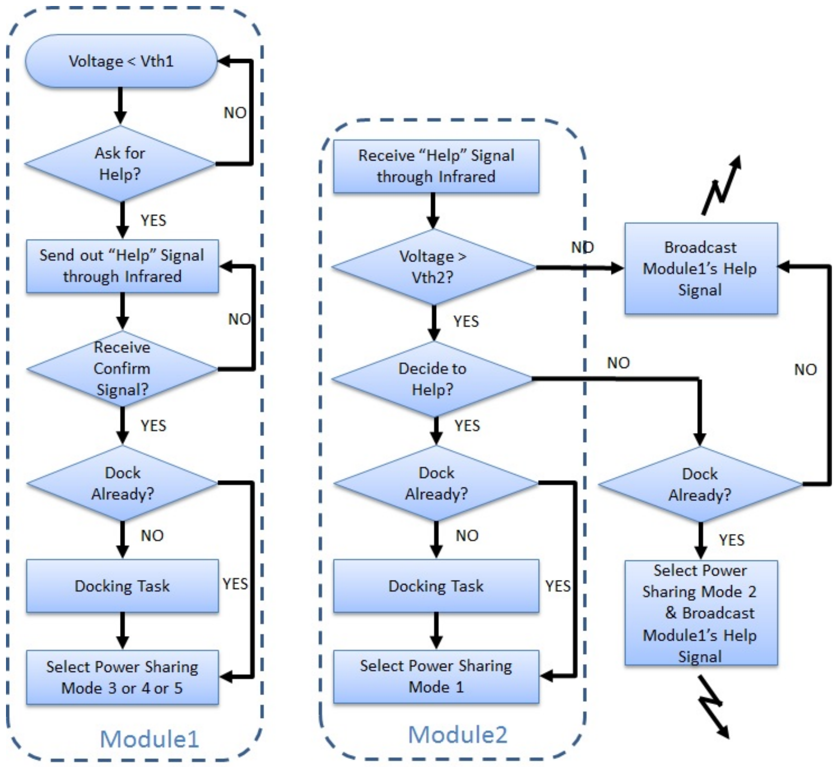
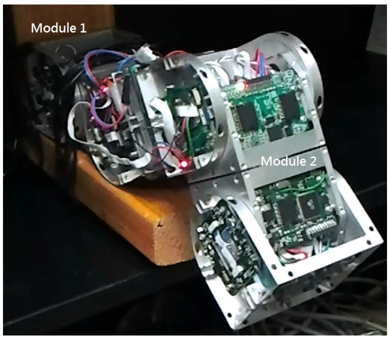
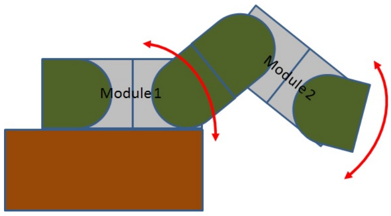


Fig. 7: Dynamic power sharing implementation

5 Experiments and Results



(a) The dynamic power sharing experiment setup.



(b) The side-view diagram of the dynamic power sharing experiment setup.

Fig. 8: Dynamic power sharing experiment.

Experiments have been conducted on SuperBot hardware to validate and demonstrate the functionalities of dynamic power sharing. The main idea for this experiment, as shown in Fig. 8, is to combine two SuperBot modules together to form a prototype of a robot joint under which various stress tests will be applied to show the improved energy performance of power sharing.

5.1 Module 1: mode 3 & Module 2: mode 1

In this experiment, module 1 carries a heavier load than module 2. Under these conditions, module 1's power consumption is greater than module 2. Two cases were taken into consideration:

Without dynamic power sharing: the two modules' batteries were independent and the result is shown in Fig. 9(a).

With dynamic power sharing: module 1 was in mode 3 (i.e., only receiving power) and module 2 was in mode 1 (i.e., offering power) and the external power paths were connected. The result is shown in Fig. 9(b).

5.2 Module 1: mode 4 & Module 2: mode 1

This experiment's configuration is the same as that described in section 5.1. Two cases were taken into consideration:

Without dynamic power sharing: the two modules' batteries were independent and the result is shown in Fig. 9(c).

With dynamic power sharing: module 1 was in mode 4 (i.e., both charging and powering simultaneously) and module 2 was in mode 1 (i.e., offering power) and the external power paths were connected. The result is shown in Fig. 9(d).

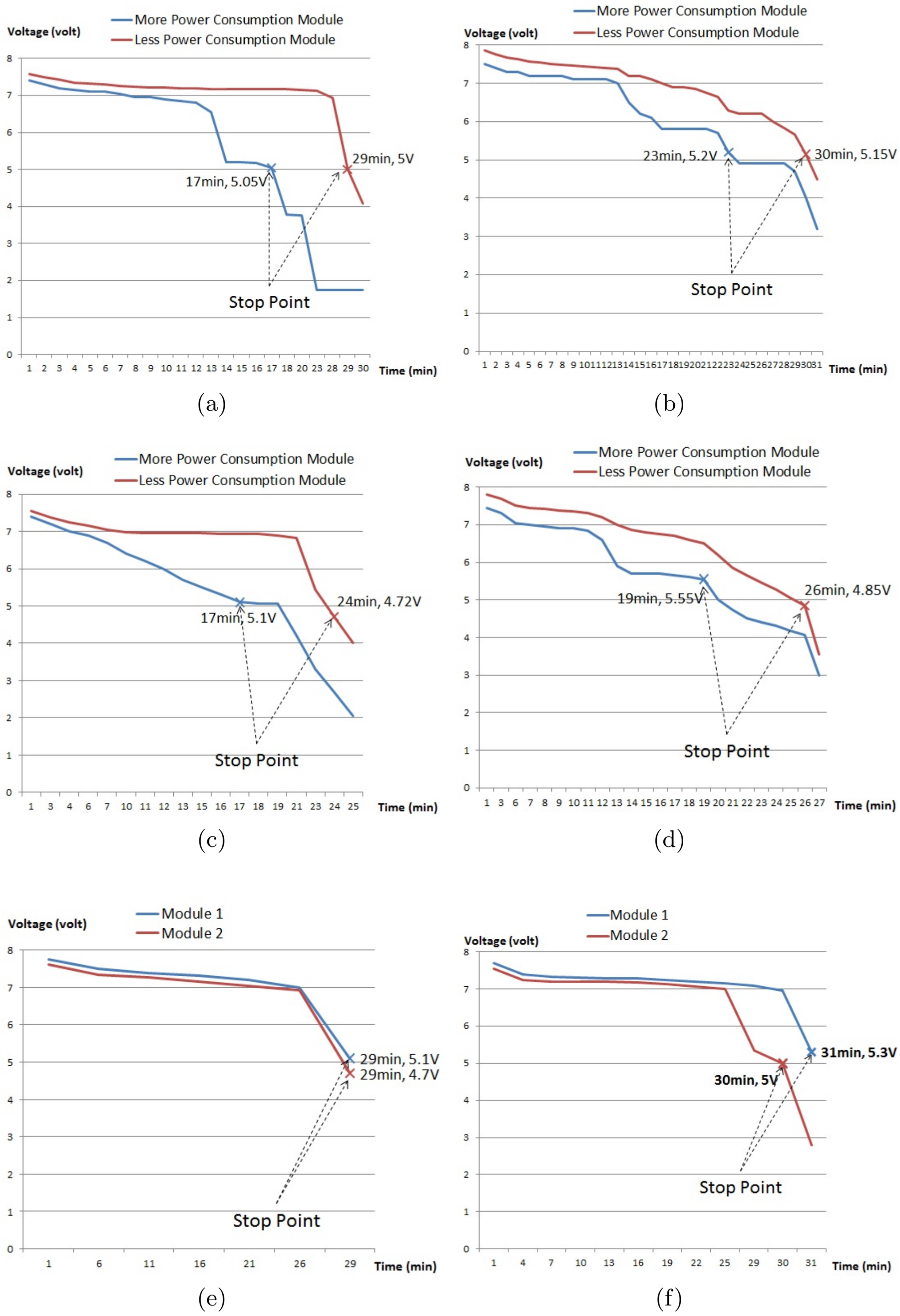


Fig. 9: Dynamic power sharing experiments results. (a) Mode 3 and mode 1 without power sharing. (b) Mode 3 and mode 1 with power sharing. (c) Mode 4 and mode 1 without power sharing. (d) Mode 4 and mode 1 with power sharing. (e) Mode 3 and mode 1 (same task) without power sharing. (f) Mode 3 and mode 1 (same task) with power sharing.

5.3 Module 1: mode 3 & Module 2: mode 1 (same task)

In this experiment, module 1 and module 2 performed the same task. Therefore, module 1 and module 2 had similar power consumption. Two cases were taken into consideration:

Without dynamic power sharing: the two modules' batteries were independent and the result is shown in Fig. 9(e).

With dynamic power sharing: module 1 was in mode 3 (i.e., only receiving power) and module 2 was in mode 1 (i.e., offering power) and the external power paths were connected. The result is shown in Fig. 9(f).

6 Discussion

6.1 Summary and contributions

According to the experimental results described in section 5.1 (module 1: mode 3 & module 2: mode 1), the operation time can be increased by around 30%. In section 5.2 (module 1: mode 4 & module 2: mode 1), when module 1 is in mode 4 and module 2 is in mode 1, the operation time can be extended by almost 12%. The difference mainly comes from charging the battery since charging the battery of the other module does not result in 100% power transfer. However, in section 5.3, if two modules do similar jobs, then the operation time with or without dynamic power sharing is almost the same. This is shown in the experimental results.

The affects of dynamic power sharing can be clearly observed when the modules have significantly different power consumption tasks because the module with higher power consumption demands can get support from other less power consumption using modules.

Through dynamic power sharing, not only do modules share power with each other, but each module can also prevent abnormal power drains from other modules, for example, in the case of a malfunctioning battery. Table 2 summarizes the results for potential battery problems. "1" means that switch is closed and "0" means the switch is open, for example, (0, 1, 0, 1) means that switch 0 is open, switch 1 is closed, switch 2 is open and switch 3 is closed.

6.2 Future Work

Power management on SuperBot: Based on the experiments carried out on SuperBot modules, the dynamic power sharing mechanism demonstrated extended operation time. However, if the scale becomes bigger, deciding the optimized power paths becomes a complex problem.

Each module might have a different task, battery condition, level of significance, configuration, etc. Depending on the various functions, each module should coordinate to decide which mode it should be in and what its level of priority for power consumption should be. In a centralized system, it might be easier to coordinate with other modules. However, SuperBot is a decentralized

Solutions	M1 (SW0, SW1, SW2, SW3)	M2 (SW0, SW1, SW2, SW3)	M1 No Battery	M2 No Battery	M1 Low Battery	M2 Low Battery	M1 Battery Damaged	M2 Battery Damaged
1	(0, 1, 0, 1) Both	(1, 0, 1, 1) Offering Power	X		X			
2	(0, 1, 0, 1) Both	(1, 0, 0, 1) Bypass Power	X		X			
3	(1, 0, 1, 1) Offering Power	(0, 1, 0, 1) Both		X		X		
4	(1, 0, 0, 1) Bypass Power	(0, 1, 0, 1) Both		X		X		
5	(0, 1, 0, 0) Charging	(1, 0, 1, 1) Offering Power			X			
6	(0, 1, 0, 0) Charging	(1, 0, 0, 1) Bypass Power			X			
7	(1, 0, 1, 1) Offering Power	(0, 1, 0, 0) Charging				X		
8	(1, 0, 0, 1) Bypass Power	(0, 1, 0, 0) Charging				X		
9	(0, 0, 1, 1) Receiving Power	(1, 0, 1, 1) Offering Power			X		X	
10	(0, 0, 1, 1) Receiving Power	(1, 0, 0, 1) Bypass Power			X		X	
11	(1, 0, 1, 1) Offering Power	(0, 0, 1, 1) Receiving Power				X		X
12	(1, 0, 0, 1) Bypass Power	(0, 0, 1, 1) Receiving Power				X		X

Table 2: Solutions to potential battery problems

system, therefore, to organize each module and determine the best configuration for optimized power consumption, further extensions will have to be made.

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Youtube video link:
http://www.youtube.com/watch?v=6F9S618jh7U&feature=youtu.be