

Motion Control by Wireless Transmission of Power Packets: Experimental Verification with Multi-finger Robot Hand

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Abstract—Wireless power transmission (WPT) is promising technology allowing robot hand to increase mobility and improve robustness of joints. However, there are two challenges for its full utilization. First, for articulated robot powering, multi-channel WPT is required for independent power supply to each joint. Second, additional communication wires are required for conveying control commands to each joint, which spoils the advantage of WPT. Addressing the challenges, we apply power packetization to WPT. Power packetization integrates power and information transmission on the physical layer. This paper demonstrates that power packet can wirelessly deliver to each finger of robot hand both a displacement command and electric power to be used for the control.

Index Terms—robot hand, power packet, wireless power transmission

I. INTRODUCTION

In recent years, wireless power transmission (WPT) has been actively studied [1], [2]. One of the promising applications of WPT technology is a power supply to a robot arm [3]–[5]. Replacing wires at a movable part of a robot with WPT contributes to better robustness and mobility, e.g. extension of motion range, contact protection, and reduction of volume and weight.

Especially for articulated robot arms, WPT needs to accommodate multiple channels for independent power supply to multiple actuators at each joint. There have been several approaches for this purpose, including multiplexing in frequency domain [3], [6] and time domain [5].

Another remaining challenge in the robotic applications is the integration of WPT and transmission of information such as control commands of actuators. The use of separate wires for communication spoils the advantage provided by the introduction of WPT. Besides, simply making the communication channel wireless also has a problem; the simultaneity of power and information transmission is not ensured. Their discrepancy can cause a breakdown of power management due to the imbalance of supply and demand. Recently, several approaches have been proposed to integrate them on the same wireless channel [7], [8], but making them multi-channel is not a straightforward task.

This study addresses the challenge by introducing the concept of power packetization [9]–[12]. The concept has recently been realized in the physical layer as a power packet dispatching system [13]–[15]. A power packet is a unit of power and information transmission. The time-divided power pulses are transmitted with information tags attached as voltage waveforms. The physical tag attachment guarantees the simultaneity of information and power transmission. The power transmission is then controlled via a network of power packet routers based on the tag information. A one-to-one relationship between multiple sources and loads is ensured by the time-division multiplexing (TDM) of power transmission with the support of tag-based routing.

The authors' group fabricated the router circuit and demonstrated the power packet routing on wired power networks [13]. There are also an application of the wired network to motion control [15], [16]. In addition, we recently proposed an extension of the router circuit that can accommodate WPT while keeping the packetization of power [17].

This paper presents the application of wireless power packet routing to robot motion control. We consider a robot hand shown in Fig. 1. The robot is equipped with a power source and multiple servo motors, between which power is supplied through a wireless channel. The novelty of this approach is that both power and a control command are transmitted to the servo motors by means of wireless power packets. Simultaneous transmission of information and power in an associated fashion provides immediate drive based on the information. We demonstrate the experiments of the robot hand control by packet-based power and information management.

II. CONCEPT AND CONFIGURATION OF POWER PACKET DISPATCHING SYSTEM

In this study, a power packet dispatching system is applied to manage power transmission. Here, we describe the basics of the power packet dispatching system.

As shown in Fig. 2, a power packet is a unit of pulsed power with an information tag attached by means of a voltage waveform. In this system, power is not treated as a continuous flow, but is divided into a train of time-domain segments called

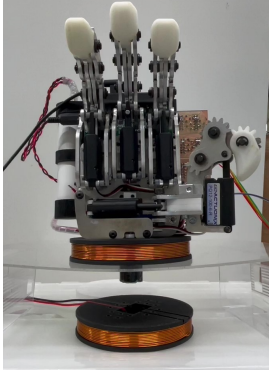


Fig. 1: Robot hand with wireless power-supply circuit.

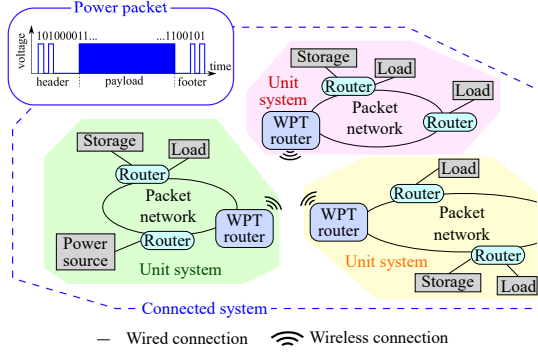


Fig. 2: Power packet dispatching system [13], [17].

payloads. The information tag represents logic signals such as destination address of a load and its control command. The physical attachment of the information tag enables time-division multiplexing of power packet transmission. In this way, the system can accommodate power transmission between different pairs of power sources and destination loads on the same path while keeping them distinguishable from each other.

An example network configuration is also shown in Fig. 2. In a power packet transmission network, a power packet router is installed as a network node where multiple transmission paths are connected. Not only the power supplies, storage, and loads but also networks themselves are connected to each other through the routers. The router forwards a power packet to its addressed path according to the information in its tag [13].

The function of the router and its corresponding circuit configuration can be divided into two sections: output and input. The output section generates power packets from the power source and outputs them to the adjacent routers. The input section, on receiving a power packet from adjacent routers, outputs the power packet to the desired storage or load according to the information tag. It is also possible to forward the power packet to the next hop by sharing temporal-storage between input and output sections.

In order to read the logic signals of power packets, the clocks corresponding to one bit width of the power packet

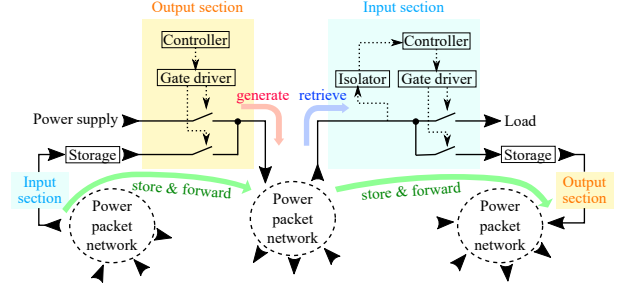


Fig. 3: Configuration of the router and its connection [13].

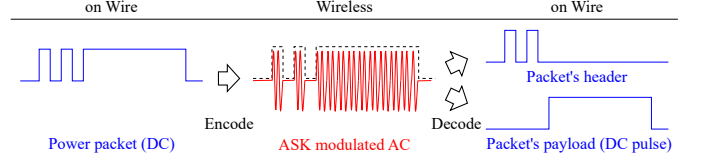


Fig. 4: A waveform concept during wireless transmission of power packets [17].

must be synchronized among neighboring routers. This can be achieved by providing common clock wiring for synchronization, or by adding a signal for autonomous clock synchronization to the header [18]. In this study, we adopt a simple autonomous clock synchronization scheme as follows. First, the clock period is fixed and its value is shared by all the routers. Then, the first few bits of the header are preserved for phase correction. The receiving router alters its clock phase if the detection bits are not recognized correctly within a certain time.

III. ROUTER DESIGN FOR WIRELESS TRANSMISSION OF POWER PACKETS

In this study, we use the router capable of wireless transmission of power packets that we have recently developed in [17]. The original router shown in Fig. 3 is modified to accommodate wireless transmission by adding extra circuits described below.

The wireless channel adopts magnetic resonant coupling, which can transmit large power in a large gap with high efficiency [19]. Since this method is based on AC coupling, power conversion is required when it is incorporated into the DC-based power packet dispatching system. For this purpose, the input and output parts of the wireless router are equipped with a rectifier and an inverter, respectively. In addition to the power conversion, they also integrate and separate power and information at the output and input parts, respectively, for packetization. Fig. 4 shows a conceptual diagram of the voltage and magnetic flux density for wireless transmission of power packets. The payload power and information tag are integrated with amplitude-shift (ASK) modulation at the sending router, and then separated by demodulation at the receiving router. The following subsections describe the details of the router output/input design to realize the above functions.

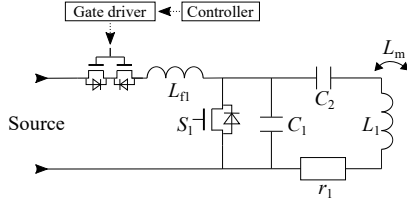


Fig. 5: Wireless transmitter of power packet [17].

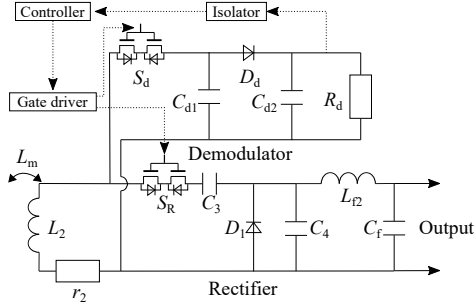


Fig. 6: Wireless receiver of power packet [17].

A. Wireless output feature of power packet

Fig. 5 shows the output part of the router for wireless power packet transmission. This circuit consists of a class E inverter [20] connected to the output side switching circuit of the original router. By driving the inverter with carrier frequency higher than the bit length of a power packet, the current in the coil and magnetic flux density is ASK modulated to the approximate shape of the power packet.

B. Wireless input feature of power packet

In order to receive a wirelessly transmitted power packet, it is necessary to demodulate the ASK modulated header signal and to perform a highly efficient AC/DC conversion of the payload at the same time. For this purpose, the receiver part of the router shown in Fig. 5 employs two independent circuits for reading the header signal by the demodulation circuit and a class E rectifier to receive the payload. The operation of the two circuits is controlled by switches placed at their input side. The detailed behavior is shown below. Initially, the switches S_d connected to the demodulation circuit is turned on and S_R to the rectifier circuit is turned off. In order to decode the logic signal of the power packet, the envelope of the voltage generated in the resonant capacitor is separated by an RC low-pass filter. The filtered signal is converted into a logic value by sampling at a preset clock cycle by the controller of the router. When the router recognizes that the incoming power packet is addressed to itself, its controller switches S_d to off and S_R to on, and converts the payload to DC power using the rectifier. If the power packet is addressed to other routers, both S_d and S_R are turned off, and the coil is left open. This is to avoid an unintended coupling of receiver coils of systems that are not subject to transmission, which can result in a decrease in the intended power transfer. At the end of the previous power packet, the controller turns on the switch to the demodulation

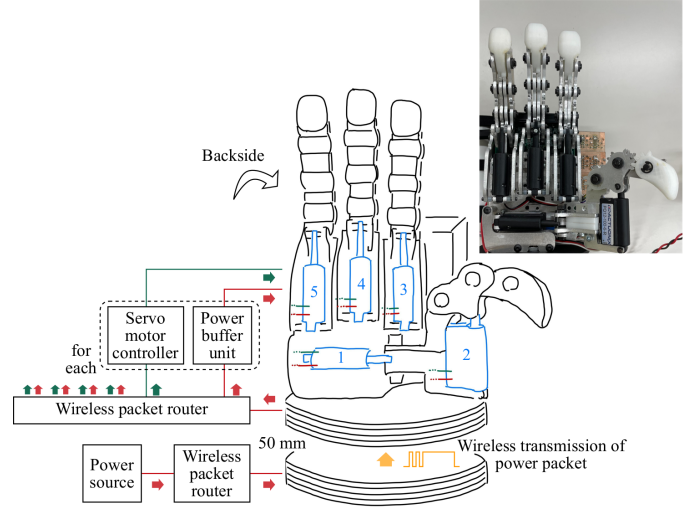


Fig. 7: Robot hand operated by power packet.

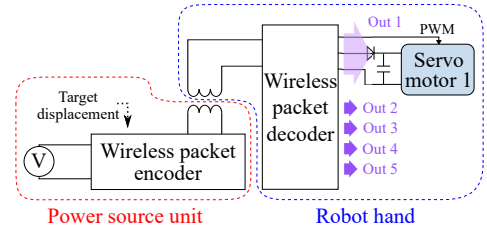


Fig. 8: Circuit configuration of the power packet dispatching system.

circuit to prepare for the next power packet. The end of a power packet is detected by counting the length of the payload.

IV. CONFIGURATION OF ROBOT HAND AND CONTROL SCHEMES OF POWER PACKET TRANSMISSION

In this section, we describe the configuration of the robot hand, the power packet dispatching system to feed the hand, and its control schemes.

A. Robot hand configuration

We use the robot hand BioGripp manufactured by Protogene Factory shown in Fig. 1. The hand is equipped with five linear servo motors to regulate the flexion and extension of the four inner fingers and the angle of the outer finger. The fingers and corresponding motors are indexed as 1 to 5 in the order shown in Fig. 7. The servo motors contain a built-in power converter that regulates the displacement according to the external command. The command is applied by means of a PWM signal, where the pulse width corresponds to the target displacement.

B. Configuration of power packet dispatching system

Fig. 8 shows the circuit configuration of the power packet dispatching system applied to the robot hand. The circuit is divided into two subsystems connected by a wireless channel. The power unit is considered to be a cutout of a general

power packet dispatching system including a source and a router. The router shown in Fig. 5 generates power packets and outputs them wirelessly. The robot hand unit then receives the power packet with the router shown in Fig. 6, and then outputs the power to the specified servo motor. Capacitor C_{bi} ($i = 1, 2, \dots, 5$) is placed in parallel with the power input of the servo motor of index i as a temporal buffer of power packet. We denote the combination of a capacitor and a servo motor of index i by simply a load i hereafter.

The header tag of a power packet conveys the destination finger of the packet and its target displacement value. When the receiving router recognizes the tag information, it forwards the payload power to the addressed load as well as generates the PWM signal for servo motor corresponding to the target displacement. This PWM signal keeps the same value until the next power packet is input. With the stored power in the capacitor and the PWM signal, the servo motor can drive for a while after receiving the power packet.

C. Control of power packet transmission

In this paper, we attribute motion control to maintaining the capacitors' state of charge (SoC) by the wireless power packet supply. When the power packet is not fed to a specific load for a long time, the stored power in the capacitor is consumed as the servo motor drives, and eventually the servo motor stops. To keep the SoC of all the motors, TDM supply of power packets is introduced. Specifically, as its simplest realization, we adopt a demand-independent TDM scheme. That is, power packets are output for five fingers in TDM manner according to a predetermined priority. Although the way to determine the priority is not unique, we will set uniform weight and fixed order for supplies to all the motors according to the finger indices. In more detail, the destination will first be 1 and then transition in order of 2,3,4,5,1,2,... for each power packet. In this way, the role of the power supply control is consolidated to the power source unit away from the robot hand side for its weight reduction and miniaturization.

Note that excessive transmission of power packets does not overcharge the capacitors. As the capacitor is charged, its voltage increases and the potential difference between it and the output of the receiving router decreases. This results in a smaller current and less power per packet. Thus, power packets transmitted to a well-charged capacitor have a small amount of power and do not affect the operation of the circuit. On the other hand, there are still challenges in terms of effective use of time slots. One solution would be on-demand transmission of power packets, as realized on a wired supply in [21], to dynamically change the weight of the fingers' supply.

V. EXPERIMENT OF ROBOT HAND OPERATION

In this section, we show the results of driving the robot hand according to the setup in Section IV.

A. Experimental setup

In this section, we show the setup we used in the experiment. The frequency of the carrier wave used for magnetic resonant coupling is 1 MHz. The parameters of power conversion

circuit in Figs. 5 and 6 are designed to achieve high efficiency under power supply of 1 MHz, 12 V, regarding [20]. The circuit parameters are set the same as in the previous report [17], so please refer to it for their specific values. The coil has a diameter of 100 mm, a wire diameter of 1 mm, several turns of 10, and a thickness of 12 mm. The transmission circuit's rise time was measured to be 25 μ s. The rise time is defined as the time required for the output voltage to attain 90 % of its steady-state value. The steady-state value was obtained under the test condition where the load was 47 Ω resistor and the vertical distance between the coils was 50 mm. Based on this, we determined that the bit width of the power packet should be 100 μ s, which is sufficiently larger than the rise time. That is, the modulation frequency is 10 kHz. The demodulation circuit is designed to demodulate signals with a cutoff frequency of about 100 kHz.

The configuration of the information tag is as follows: Bits 1–3 are 010, used for clock synchronization. Bits 4–6 and the 7–9 indicate the destination address and the target value, respectively. Bits 10–140 correspond to the payload. For simplicity, we fixed the packet length to 140 bits and shared it among all routers, thus omitting the footer.

The target displacement is quantized into 8 levels to be represented in 3 bits. Allocating more digits allows finer control, but it is enough for this paper's demonstration. In order not to impair finger movement, the longest and shortest displacements are not used.

B. Results of experiment

Now we show and discuss the results of the experiment conducted with the setups explained above. It should be noted that the time reference (0 s) in different figures does not coincide with each other.

First, we confirm the achievement of the robot hand control. Fig. 9 shows the movement of the robot hand every 1.5 seconds. Robot hand was given a target trajectory for the motion of the fingers in rock-paper-scissors. The picture at 0 s, 4.5 s and 7.5 s represents scissors, paper and rock, respectively. From this result, we found visually that it achieves the manipulation of the robot hand as intended.

Then, we evaluated the robot hand movements quantitatively. Here, the servo motor was extracted from the robot hand and a slide resistor was attached to sense the position via voltage. Fig. 10 shows the trajectories of the target and measured displacement of the finger 1: Φ_{T1} is the target displacement given to the router at the power unit; Φ_{R1} is the target displacement detected through the tag of power packets at the receiving router; Φ_{A1} is the actual displacement measured at the servo motor 1. Note that the step-like shape of the trajectory is due to the quantization of the target value. The detected target Φ_{R1} was approximately consistent with the change of the original target trajectory Φ_{T1} . This result indicates that the tag information was correctly delivered to the receiving router via wireless transmission of power packets. At several points, Φ_{R1} shows 17.5 which is corresponding to 111 in header's logic. This means that there were some

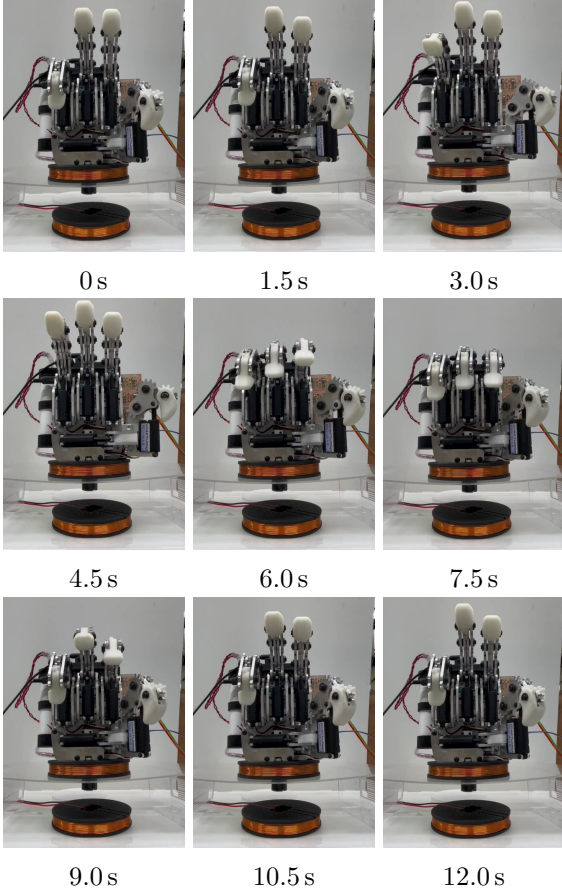


Fig. 9: Robot hand representing rock-paper-scissors.

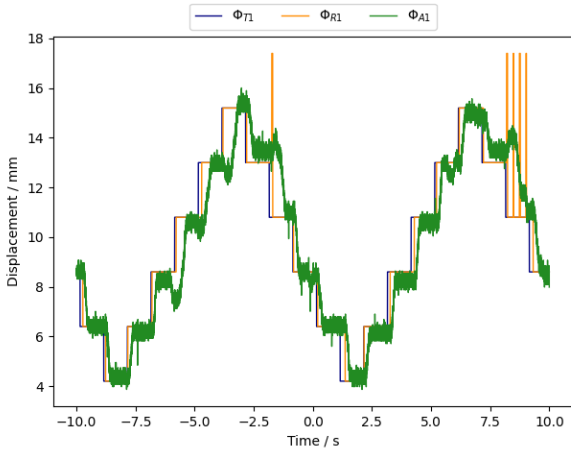


Fig. 10: Trajectory of the displacement of the finger 1.

errors in logic value recognition, misidentifying low as high, probably due to noise on the channel. However, the next packet transmitted in sequence corrected this error. The measured trajectory Φ_{A1} also shows good accordance with the Φ_{R1} . At -2 s and $8-9$ s, where Φ_{R1} 's error often occurred, Φ_{A1} rapidly increased to follow the value. For increasing displacement,

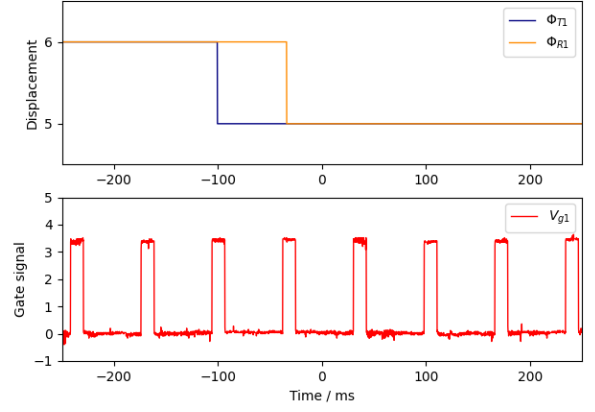


Fig. 11: Feedforward transmission of power packets.

the steady value of Φ_{A1} tended to be smaller than Φ_{R1} , and for decreasing displacement, the steady state of Φ_{A1} tended to be larger than Φ_{R1} . This misalignment is thought to come from backlash in the servomotor and its connection to the slide sensor. From these comparisons of Φ_{T1} , Φ_{A1} and Φ_{R1} , it can be said that the actual displacement tracked the target well. We also confirmed similar results for all the other fingers. The results above demonstrated the successful operation of the robot hand using wireless transmission of both power and information via power packetization and its routing.

Second, we take a closer look at the process in which displacement information is transmitted by power packets. Fig. 11 shows the Φ_{T1} , Φ_{R1} and gate signal V_{g1} for rectifier circuit's switch when the target displacement of the finger 1 changes. Power packets destined for finger 1 were transmitted once every 75 ms. The update of Φ_{R1} to the value of Φ_{T1} occurred at the reception of the power packet that follows the change of Φ_{T1} . This result also confirms that changes in displacement can be transmitted by power packets. In addition, by transmitting power simultaneously with a control command, the system distributes power in a feed-forward manner.

Lastly, we check the result of power packet forwarding by the receiving router. Fig. 12 shows the transition of power packet destination and resulting supply waveforms. The top figure represents the destination index of power packets: Addr_T is the destination address set by the router at the power unit; Addr_R is the destination address recognized by the receiving router. The bottom figure shows the output voltage of the receiving router directed to load 1 to 5, namely V_1 to V_5 . The top figure shows that Addr_R matches well with Addr_T . This result indicates that the router designed in Section III read the information tag of the power packet correctly. Comparing the top and bottom figures reveals that the router at the robot hand side correctly forwarded payloads according to the destination Addr_R . The bottom figure also shows the multiplexed power supply to the five loads as

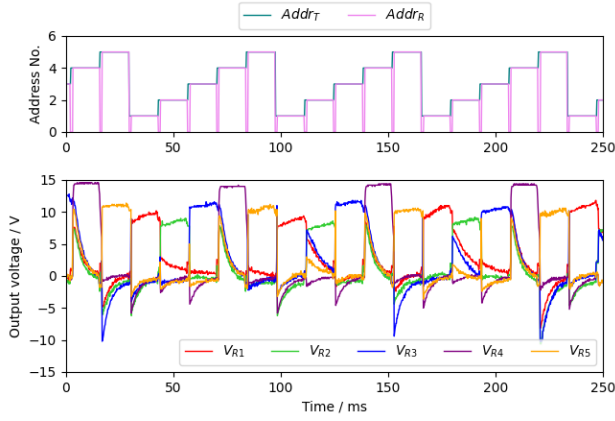


Fig. 12: Transition of power packet destinations.

specified in the tag. The results indicate the achievement of the TDM transmission in wireless power packet transmission. The magnitude of load voltage varied from packet to packet and also across each finger. The difference corresponds to the time-varying driving status of the motor; when it is running, the voltage is low as it consumes power, and vice versa.

VI. CONCLUSION

This paper presented the robot hand control based on packet-based wireless power transmission. The main achievements of the proposed scheme are:

- Multi-channel WPT for selective power supply to each finger of the robot.
- Simultaneous transmission of the finger control commands and power over the same wireless channel.

We demonstrated them through displacement trajectory control of the robot fingers.

The distinct features of power packetization, namely the TDM nature and the physical integration of information and power transmission, ensure the one-to-one handshake between sources and loads, while keeping the advantages of WPT such as better maneuverability and maintainability. It should be noted that, although we set a common power source for all the loads as proof of principle, the proposed scheme can easily be applied to general many-to-many power supply management. In this sense, the presented technology has the potential to be applied to a broad range of cyber-physical systems [22] including the Internet of Things, providing flexibility as well as eliminating the gap between the cyber and physical quantities.

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