Wireless Charging System for KILOBOTs Using Inductive Power Transfer with Management System

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ABSTRACT

One of the emerging platforms for swarm robotics research today is the KILOBOTs robot. Studying swarm behavior usually takes place over extended periods of time. One drawback of using KILOBOTs or any other robot in this case, is the limited on board power supply it can carry through its batteries. This would be compounded by the fact that doing swarm research would typically involve multiple robots meaning that multiple robots could also require charging within a certain time. Using the current charging scheme for KILOBOTs it would be tedious as one has to manually check battery voltage reading, locate the actual KILOBOT that needs charging and actually pick and place the KILOBOT to the charging rack provided for the KILOBOTs.

The study aims to lessen the need for human intervention during the charging phase of the KILOBOT. This was done through the design and implementation of a wireless charging platform for nine KILOBOTs to charge. A management system was also implemented for the KILOBOTs which cover the queuing process for the use of the charging platform.

There were a total of nine wireless charging transmitters in the study. There were 10 wireless charging receivers created for the study, one for each KILOBOT. The management algorithm was implemented in the KILOBOTs code to allow an orderly charging process as well as manage the limited slots in the charging platform. Actual battery voltage gains were measured for every KILOBOT used in the study to confirm that the platform works. Output voltage and current were measured and platform efficiency was also measured.

***Key Words** – Algorithm, inductive power transfer, KILOBOT, wireless charging platform.*

I.INTRODUCTION

In the technology today, almost all devices, gadgets, or even robots use batteries to perform a certain operation. For example, robots are used in many different areas of research, it can be just a simple line follower robot or, more complex swarm robotics whichever task it does its life always depend on the battery's capacity. If the stored power in the battery runs out, the person will connect it to the charger and plug it to the wall socket. The problems with this method: (1) it limits the robot's capacity to fully perform its operation, (2) the human intervention, a person always needs to check on the robot if it is running out of power, and (3) the cable, wires, and cords are needed to be attached in the robot just to be able to recharge it. Imagine a swarm of robots that are performing a certain task without even worrying about the power running out. It can charge itself by going to a specified charging area and to able to share it with other robots that also needed to be recharged.

The study deals with the wireless charging of multiple robot or also known as swarm robots. Several theses from De La Salle University, which deals with power transfer using microwaves [1], and Sri Eshwar College, which deals with the power transfer by utilizing inductive power transfer [2] both study deals with the study of power transfer. The theoretical considerations behind these studies are being integrated in the study of swarm robotics. The swarm robots that will be used in this study are called KILOBOTs. KILOBOTs are tiny robot about 3.3cm tall that is invented by a research group in Harvard University [3]. A KILOBOT can be programmed to be able communicate with other KILOBOTs surrounding it.

The study is composed of two major areas: (1) wireless charging system which is composed of the arena, transmitter circuit, and receiver circuits, (2) Algorithm that will be programmed into the KILOBOTs that will serve as the management system of the wireless charging platform.

II. DESIGN CONSIDERATIONS

A. Wireless Power Transfer Overview

Inductive Power Transfer is a process where the output of power is caused by the transmitting of energy from the transmitter circuit to the receiver circuit through an oscillating magnetic field. Ampere's Law and Faraday Induction are the two main theories that explain how the power transfer would work.

Wireless power transfer starts with the oscillating driver which drives the primary coil. The primary coil would only produce a changing magnetic field if the driver is oscillating. In the study, this would be achieved by using a Hartley Oscillator and the primary coil would be the inductive elements of the Hartley Oscillator. The magnetic field produced by the primary coil would then induce a voltage in the secondary coil, the receiver. The magnitude of this voltage would be dependent on the amount of magnetic field lines the secondary coil would be able to cut through. The more enclosed the secondary receiver is with the magnetic field of the primary coil, the higher the induced voltage and power would be available in the receiver circuit.

B. Transmitter Circuit

The transmitter circuit in the study is a Hartley Oscillator circuit Fig. 1. *L1* and *L2* are made up of A.W.G. # 33 enamel coated magnetic wire. #33 was selected because it was small enough that skin effect in the operating frequency is negligible as well as light enough for use as receiver coil for the KILOBOT receiver circuit. The wire was hand wound to be a center-tap inductor with a 14 + 16 configuration. Inductance values can be seen in the table I and were measured using an LCR meter.

The values of the inductance would be used in determining the operating frequency of the oscillator circuit which is given in equation 1. With a known value of *L* and a desired operating frequency of 100 kHz, the value for *C* could then be solved which would be 173.495 nF.

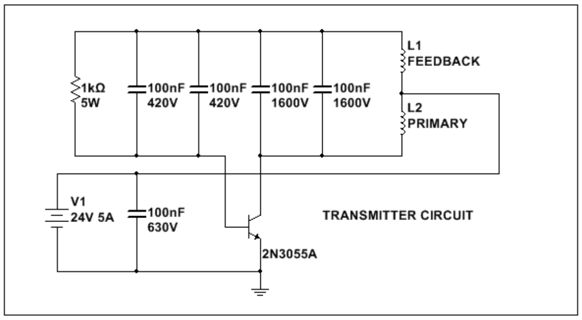

Fig. 1 Hartley Oscillator Circuit used as the primary coil driver for the study

TABLE I
LCR Measurements of Transmitter Coils

Transmitter Coil		
Configuration	Measuring Points	Measured Inductance
Single Coil	L1 (Primary)	21.66 μH
Single Coil	L2 (Feedback)	21.75 μH
3 Coil Array	End to End (Primary + Feedback)	14.6 μH

$$freq = \frac{1}{2\pi\sqrt{LC}}$$ Equation 1

Where:
freq. = Operating Frequency
L = Total Inductance
C = Tuning Capacitance

C. Receiver Circuit

The receiver circuit would be used for the charging of the KILOBOT. The receiver coil is also made up of the same wire used for the transmitter and also the same number of total turns which would be 30 turns. The receiver coil was wound on a 1” diameter pipe nipple. For the receiver coil, equation 1 would still apply. The measured value of the coil was 30.66 μH. The solved value for the capacitor of the receiver was 95.52 nF.

D. Charging Platform and Circuit Box

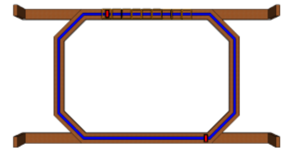

Figure 2(a)

Figure 2(b)
Figure 2a Underside view of proposed wooden canopy Figure 2b Proposed circuit box for transmitter

Figure 2 shows the charging platform canopy and Circuit box for the study. Figure 2a shows the underside of the canopy where the transmitting coils would be placed. Figure 2b shows the proposed circuit box of the study where all the components of the transmitter, except the coils, would be housed. The charging platform would include a canopy that would be placed above the arena. The canopy would serve as a mounting point for the transmitter coils of the circuit which needs to be above the KILOBOTs. The LED strips which serve as guide lights for the KILOBOTs would also be placed under the canopy.

III. Circuit Implementation and Setup

A. Transmitter Circuit

Fig. 3. Wooden canopy with LED strips and Transmitter Coils mounted.

Figure 3 shows the underside view of the Canopy where transmitter coils were mounted. The transmitter coils are the ones in the bottom center of the image. The LED strips are the white lines that follow the outline of the canopy. The canopy would be placed above the glass arena where the KILOBOTs would roam. Fig. 4 shows the transmitter coils arranged in a line before placement in the canopy. The nine coils are grouped together by threes. The coils in each group are connected in parallel to each other.

Fig. 4. Transmitter Coils in Array forming a line.

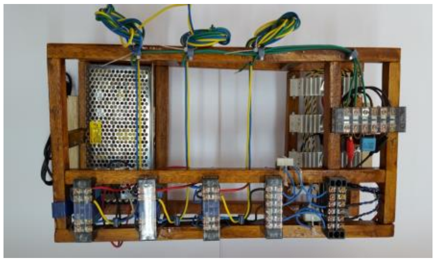

Fig. 5. Circuit Box with transmitter components mounted.

The transmitter coils are wounded in the guidepost in the shape of a square with the guidepost in the four corner 3 cm apart. A Hartley Oscillator requires a center-tap configuration for the inductive component. The number of turns was a total of 30 based on the number of turns used in the receiver circuit using 14+16 configurations

Figure 5 shows the second part of the transmitter circuit. The Circuit box is located outside the arena because of the weight limitations of the Canopy. This is where the power supply, transistors mounted on heat sinks, capacitors, and terminal blocks are mounted. The 3 coiled wires near the top of the image are the stranded wires used to connect the circuitry box to the transmitter coils in the canopy. It is connected to transmitter coils via #18 stranded wires which is also color coded depending on their function. Both of the Canopy and the Circuit box should be connected with each other in the transmitter circuit to function.

B. Receiver Circuit

The reciever circuit is made up of tuned tank circuit, rectifier, and a voltage regulator. The tuned tank circuit is composed of inductor and capacitor which is parallel to each other. The value of the inductor and capacitor was computed based on the desired frequency. The rectifier used a 1N4148 diode because of it acts as a fast switching diode. The voltage regulator used in the circuit was LM7806. Figure 6 shows a sample receiver circuit with coverings removed. The receiver circuit contains the receiver coil, LM7806 voltage regulator, tuning capacitor (blue component in the left). The middle of the receiver circuit board is reserved for the LDR module which is used for the KILOBOT management algorithm.

Fig. 6. Sample receiver module with coverings removed.

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Fig. 7. KILOBOT with receiver module attached compared to original KILOBOT.

Figure 7 shows a comparison of a KILOBOT with receiver module attached (right KILOBOT) and a regular KILOBOT (left KILOBOT). The receiver module on the KILOBOT has the same components as shown in Figure 6, the black covering is added to provide support for the transmitter coil placed above. A construction paper was wrapped around the receiver circuit to provide structural support for the receiver coil and to to help block ambient light of the surroundings out of the LDR sensor in the receiver. Although not shown, the bottom of the receiver module has a folder – alluminum foil – folder sandwich. This serves as an RF sheild to prevent the electromagnetic field from disrupting the ICs in the KILOBOTs.

One of the objectives of this study was to have a 6V and 350mA output rating for the reciever. A dummy load module was made to measure the voltage and current ratings of the receiver. The components are similar to the receiver circuit the only difference between the KILOBOT receiver circuit and dummy load is that load resistors are connected to the output of LM7806.

Shown in Fig 8 is the actual circuit of the dummy load which is used to measure the output of the transmitter circuit. The actual dummy load is composed of three 50Ω parallel resistor and 0.1Ω shunt resistor. The connectors to the receiver coils are not yet attached. Heat sink was attached and high wattage resistors were used due to the relatively high expected current draw.

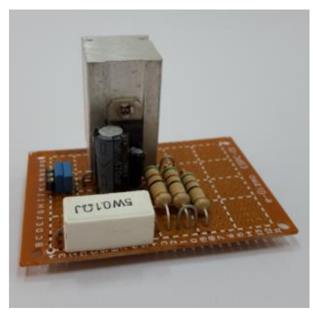

Fig. 8. Dummy Load module used for the 6V 350mA test

C. Management System

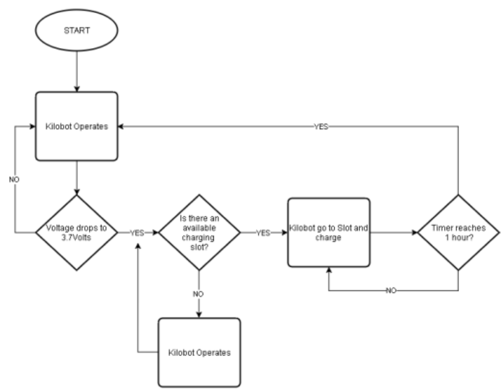

Fig. 9. Flow diagram of the Charging Algorithm of the KILOBOTs

As shown in Fig 9, the process of the algorithm is first the KILOBOT will check its voltage level, if it is below 3.7V. If it is below the voltage trigger, 3.7V, the KILOBOT will then proceed to the charging area, and check if there is still an available slot to charge. If there is none, the KILOBOT will then enter into sleep mode until a signal is transmitted by the other KILOBOTs that there is an available slot in the charging area. The charging of a KILOBOT will take about one hour before it resumes its operation.

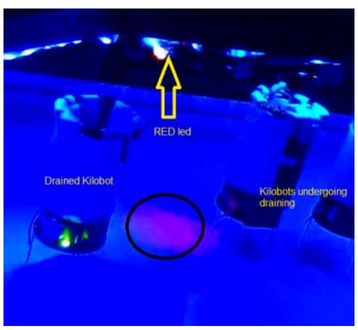

Fig. 10. KILOBOTs Queuing

Shown in Fig 10 the queuing part of the algorithm. The black circle shows the area where the KILOBOT needs to proceed if its voltage level reaches 3.7V or below. Also, only one KILOBOT will be allowed under the red LED area at any given time. If all the slots in the charging area are occupied, and one KILOBOT reaches the voltage trigger, 3.7V, it will enter to sleep mode until there is a slot available.

Fig. 11. KILOBOTs Charging

Fig 11 shows that the drained KILOBOTs from the algorithm will then proceed to the charging area. As shown above, the first KILOBOT and the second KILOBOT is the only ones recharging. The third KILOBOT will wait for the fourth KILOBOT before it recharges itself. The reason behind this is that when the KILOBOT begin to charge itself, it will turn off any communication to other KILOBOT. The last KILOBOT in the charging pad will serves as a beacon for other KILOBOTs.

IV. DATA AND RESULTS

TABLE II shows that during all three trials, all the KILOBOTs are charging. It can be seen that after an hour of charging the voltage level increase in a range of 100mV to 300mV. Fig 12 shows that some of the area of the charging area have different output with each other. It should be taken to consideartions that all the coils are hand-wounded, meaning all the coils are different from each other. Also shown in the Fig 12 a relatively small voltage gain. The reasons that the researches could think that causes this are: (1) KILOBOTs have internal limiting circuitry which reduces the maximum draw of the charging current, and (2) choice of initial voltage. Since the KILOBOTs are programmed to proceed to the charging area when the voltage level reaches 3.7V which is still close to the 4.2V full charge level and Lithium-ion batteries follows charging principle that the current drawn would be proportional to the difference in the full voltage and initial voltage. Therefore the lower the initial battery voltage the higher the charge rate would be. That is the reason for the spike seen in Fig 12 which was KILOBOT 2053/4 charging from 3.03V instead of 3.7V which causes it to draw more current. The same could also be said for KILOBOT 2243/6 which started from 3.14V instead of 3.7V.

TABLE III shows the load current, transmitter current, and calculated efficiency of the platform with a seperation distance of 1cm between the transmitter coils and the receiver coils. One objective of this study is to have an efficiency of at least 60%. As seen in TABLE III all coils have an efficiency above 60%. The table also shows that there is a slight deviation in terms of efficiency percentage among all the coils and again due to the fact that all coils are hand wound and would never be exactly same with each other.

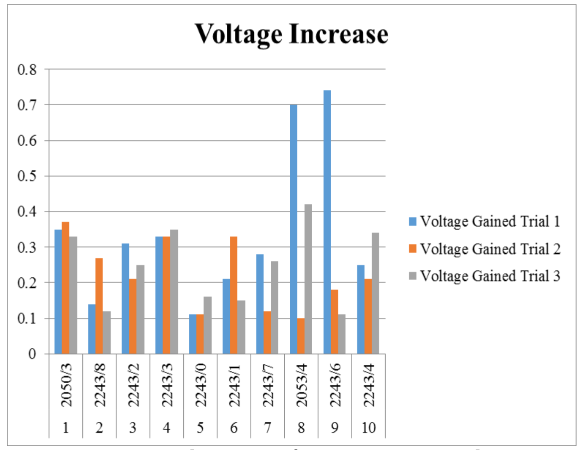

Fig. 12. Voltage gain of KILOBOTs in 3 trials

TABLE II
Result of KILOBOTs Charging

		Trial 1		Trial 2		Trial 3	
Coil #	Kilobot Tag	V(initial)	V(final)	V(initial)	V(final)	V(initial)	V(final)
1	2050/3	3.77	4.12	3.79	4.16	3.78	4.11
2	2243/8	3.75	3.89	3.77	4.04	3.76	3.88
3	2243/2	3.71	4.02	3.78	3.99	3.75	4
4	2243/3	3.72	4.05	3.76	4.09	3.73	4.08
5	2243/0	3.74	3.85	3.76	3.87	3.76	3.92
6	2243/1	3.72	3.93	3.79	4.12	3.79	3.94
7	2243/7	3.71	3.99	3.75	3.87	3.7	3.96
8	2053/4	3.03	3.73	3.78	3.88	3.56	3.98
9	2243/6	3.14	3.88	3.76	3.94	3.73	3.84
10	2243/4	3.76	4.01	3.8	4.01	3.71	4.05

Fig 13 and Fig 14 shows the V_{out} values obtained during the 6V 350mA dummy load test. The results show that the values are mostly within the tolerated values of LM7806. The specified output voltage tolerance of an LM7806CT that was used in this study is ±4%, which would be ±0.24V and therefore a projected output voltage of 5.76V to 6.24V. One probable reason as to why the results have value less than the projected tolerance is due to loading effect where the voltage regulator drops the output voltage to provide the current being drawn.

TABLE III
Efficiency of Different Transmitter Coils

coil	Load current (mA)	Transmitter current (mA)	Efficiency @ 1cm
1	373	590	63.22033898
2	373	620	60.16129032
3	373	610	61.14754098
4	373	580	64.31034483
5	373	570	65.43859649
6	373	600	62.16666667
7	373	600	62.16666667
8	373	610	61.14754098
9	373	580	64.31034483

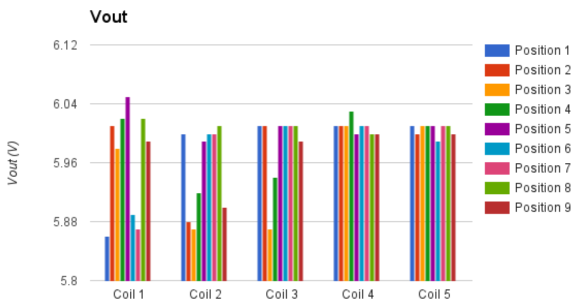

Fig. 13. Different V_{out} values obtained during the study (Coils 1 – 5)

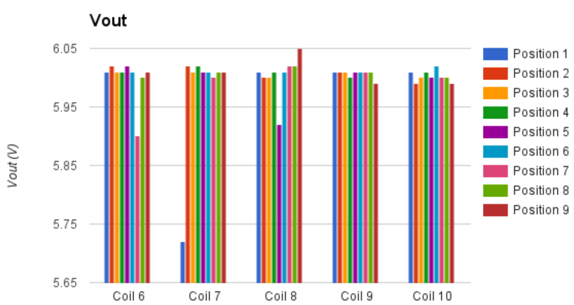

Fig. 14. Different V_{out} values obtained during the study (Coils 6 – 10)

Fig 15 and Fig 16 shows the chart of all the I_{out} values obtained during the study. The average I_{out} value is 359.62 mA, the lowest obtained value is 341mA and the highest is 377mA. Looking at the figures below, there are only six values that fall below the 350mA level out of the total 90 values. Figure 15 shows the histogram of I_{out} values for coils 1 to 5 under positions 1 through 9. Fig 16 shows the histogram of I_{out} values for coils 6 to 10. Figure 15 contains the 6 measurements that fall below the 350 mA value. All of the measurements for coils 6 – 10, Fig 16, fall above the 350 mA. It can be noticed that the values of the current measurements tend to vary without a pattern and it can also be seen that most of the measurements tend to be near the 360mA line.

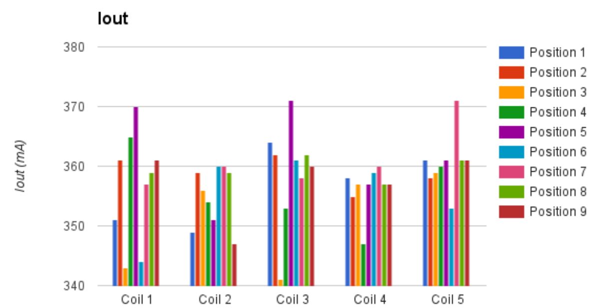

Fig. 15. Different I_{out} values obtained during the study (Coils 1 to 5)

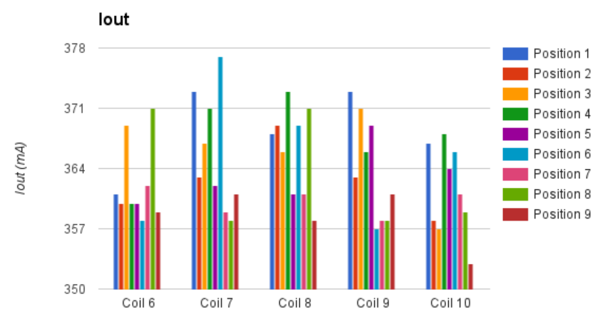

Fig. 16. Different I_{out} values obtained during the study (Coils 6 to 10)

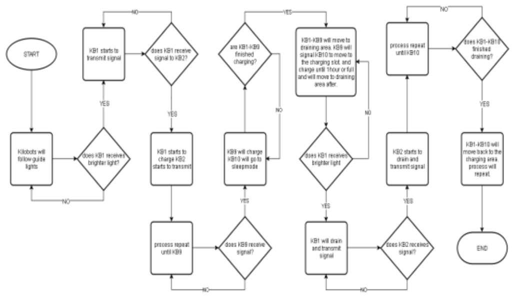

Fig. 17. Algorithm of the 1st KILOBOT to the 10th KILOBOT

In the algorithm, the KILOBOTs are programmed individually. The KILOBOTs to have their own unique ID named Tx. The ID Tx that is assigned to the KILOBOT and it will be the order of the KILOBOTs. The study uses 10 KILOBOTs, the first KILOBOT will have an ID of Tx=1 up to the tenth KILOBOT which will have an ID Tx=10. In the charging part of the algorithm, the KILOBOT will either charge for 1 hour or until the battery of the KILOBOT is full. Let the first KILOBOT be KB1 and the tenth KILOBOT be KB10. KB1 will move to the first slot and when KB1 is in the first slot, it will start to transmit until KB2 will receive the transmitted signal. The behavior is the same to other KILOBOTs in the charging part of the algorithm. The reason why the KILOBOTs wait for the other KILOBOTs is that when the KILOBOTs start to charge, the KILOBOT cannot transmit signals. When the other KILOBOTs has finished charging because they are fully charge, the KILOBOT will have to wait for the KILOBOT next to it to finished charging e.g. when KB1 is not yet finished while KB2 is finished. KB2 will have to wait until KB1 is finished. When KB1 is finished charging KB1 will now move to the to the drain area. The other KILOBOTs that are still charging will continue to charge even if KB1 left the charging area. KB2 to KB8 has the same behavior of when the charging is done. The KILOBOTs will now move to the draining pad. KB9 has an additional function because KB9 will signal KB10 if KB9 is done charging. KB9 will transmit a signal to KB10 that is on sleep mode to wake up and move towards the first slot of the charging area. Because there are only 9 slots in the charging area KB10 will have to wait for the other KILOBOTs to finish charging. KB10 will go into sleep mode while KB9 is not yet finished charging. When KB9 is finished charging, KB9 will transmit a signal to KB10 and will now move to the charging area. Unlike the charging part of the algorithm where the KILOBOTs will have to wait for the other KILOBOTs, the KILOBOTs in the draining area does not need to wait for the other KILOBOTs before draining. The KILOBOTs will continue draining until the KILOBOT reaches 3.7 volts (Note: The battery of the KILOBOT is 4.2V as opposed to the 3.7V stated in the KILOBOT User Manual). When the KILOBOTs reach 3.7 volts the KILOBOTs will now move back to the charging area. When other KILOBOTs has finished draining. The KILOBOTs will have to wait for the next KILOBOT to finished draining. When KB1 is not yet finished draining KB2 will wait for KB1 to finished draining before moving. The behavior is the same to other KILOBOTs in the draining part of the Algorithm. Block diagram is presented in Figure 5.30.

V. CONCLUSION

In the paper it was shown that the KILOBOTs could charge themselves autonomously, without human intervention, with the use of the wireless charging platform designed in the study. The paper shows that by providing slight modifications to the robot, wireless charging can be achieved. The results also show that not all KILOBOTs charge uniformly. This is to be expected as even using the conventional charging of KILOBOTs there are KILOBOTs that charge slower than others. The charging platform was able to deliver enough power to wirelessly charge up to nine KILOBOTs simultaneously.

Applying the circuit designed in the study to other robot platforms could be done with slight modifications depending on the power requirements of the desired platform. The main limitation in the study was the physical size of the KILOBOTs as well as the weight restriction for the KILOBOTs. The circuit in the study, when applied to bigger more capable robots, should be modified to achieve better results in terms of efficiency and output power.

For future studies, the researchers would recommend testing the degree of scalability wireless charging platforms. Studies involving increased charging pad capacity and distributed charging pad locations could be used as future study parameters to fully maximize the autonomy that wireless charging systems could give to the study of swarm robotics.

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