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Delivering Electricity to Home Appliances by Mobile Robots

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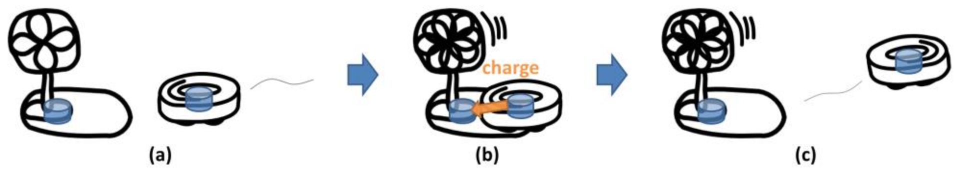

Figure 1. Cable-Free Operation with a Battery Charging Mobile Robot. (a) The robot autonomously finds an appliance dock connected with a fan. (b) The robot transfers its battery power to the appliance dock. (c) The fan operates using the received battery power.

Abstract— **In this paper, we propose an electric power management system for delivering power to home appliances with mobile robots. With our system, the user places an appliance without power cables freely within the home, and a robot provides the appliance with the electric power required for its operation. In addition to providing explanations of a usage scenario and a theoretical analysis, we demonstrate a prototype implementation. The robot of the prototype autonomously locates the target appliance, transfers its battery power to the appliance, and returns to the home position to recharge its battery. The validation study showed our proof-of-concept prototype worked as expected by the theory.**

I. Introduction

Our living and working environments are full of electronic appliances such as lamps, fans, and TVs. Most of these appliances run with power from outlets, and thus appliances are often deployed near outlets. If the user wishes to deploy an appliance in the middle of a room, a power cable must be extended across the room. However, such cables can interfere with our activities. We may get caught in a cable while walking, and home robots may be unable to cross cables. Consequently, deploying appliances near outlets is the first choice in current home environments.

In this paper, we reconsider the issue of appliance deployment. Some appliances work more efficiently or conveniently if they are operated at arbitrary locations in a room. For example, an electric fan deployed near a person can work in an energy–efficient manner. As another example, the ability to freely use battery-charging equipment for mobile devices such as computers, phones, and cameras at many locations (e.g., sofa, table, kitchen) would be highly convenient. Recently, mobile work practice as known as flexiwork [1] or nomadic work [2] is attracting attention and also becoming popular within the office and living environment. Therefore, the ability to use appliances in places is worth realizing because it supports this new style of living and working.

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One solution to the cabling problem above is to use batteries. Some of the aforementioned commercial home appliances (e.g., TVs, fans, electric lamps) can be used for a while without connecting cables because they already have batteries. This inspired us to conceive of robots that autonomously charge the batteries of appliances to free them of cables. Building on this idea, we propose a cable-less power management system consisting of power-delivering mobile robots and batteries. A key component of our system is the "remote dock," which is an appliance-side robot dock that contains a battery and a power inverter to provide AC output. Hence, each appliance operates on battery power from a remote dock, the battery of which in turn is charged by a mobile robot.

Fig. 1 illustrates a usage example. A fan is connected to a remote dock. The robot searches for the to-be-charged remote dock. After docking, it transfers its battery power to the battery in the remote dock, thereby allowing the fan to operate subsequently using the battery power. Thus, freed of cables, appliances can be used anywhere in the home. If the power consumption of an appliance is below a certain value as described later, it can be continuously operated as if it were connected to an outlet.

In this paper, we first describe a usage scenario of our system and provide a theoretical analysis of the system performance. The equations derived from the theoretical analysis are useful for selecting appropriate components to replicate similar systems. We then describe the implementation of our prototype and a validation study. Our main focus is not on any specific algorithm or mechanism of robot navigation or scouting, but on the application of a home mobile robot. Our contribution includes the idea of using mobile home robots as cable-less electric-power suppliers, a theoretical analysis of the proposed system and a proof-of-concept demonstration.

II. Related Work

The battery issue is a crucial topic in the field of robotics. The idea of autonomous robot recharging has been explored [3]. A robot can autonomously recharge its battery for permanent robot activities. Current commercial domestic robots basically have this feature to achieve sufficient autonomy in the home. In addition to the use of special docking stations, recent studies have addressed the self-feeding problem with common outlets [4-6]. The robots in these studies autonomously detect outlets on walls and recharge their batteries by plugging in their own power cables.

In other studies related to swarm robotics, the idea of robots delivering electric power to other robots for continuous operation of the robot team has been proposed [7-9]. In these studies, simulation results showed that energy-transporting robots successfully transferred battery power to other robots. With the technique presented in [10], the robots in [9] are expected to be physically implemented. Our approach is similar in that a robot is used to transfer battery power. However, our concept is unique in targeting regular home appliances in our living environment. Unlike in [9], we employ a domestic robot that can move in a home environment. We also model the use of home appliances and demonstrate a reproducible implementation that has not been shown in previous energy-transporting studies.

III. Usage Scenario

We envision that users of the system move appliances and their remote docks (Fig. 2 left) while the robot autonomously finds these repositioned remote docks. One or more robots cooperatively provide electric power to one or more home appliances (Fig. 2 right). We consider three power-supply strategies: greedy, optimistic, and scheduled. The greedy strategy, in which a robot delivers its battery power whenever available, provides maximum availability for appliances and is suitable for devices used sporadically (e.g., mobile TVs). The optimistic strategy, in which a robot delivers its battery-power when the battery of an appliance is running out, provides maximum availability for the robot and is suitable for continuously used devices (e.g., floor lamps). The scheduled strategy, in which the user provides the desired time and duration for a to-be-used device, allows the system to plan an efficient trip and is useful for devices regularly used at the same time of day (e.g., music players for enjoyment after returning home, electric kettles for preparing breakfast). In accord with the usage of each appliance, the appropriate strategy should be selected by the user.

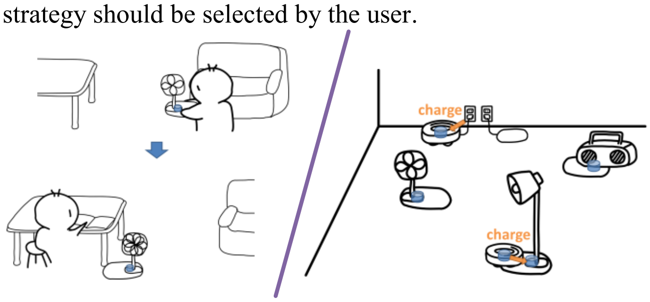

Figure 2. Usage Scenario. The user moves an appliance to the desired location. The robots distribute their battery power to the appliances.

The aforementioned strategies are not mutually exclusive. A robot can reserve its time slots for charging a scheduled appliance while it starts charging for the optimistic strategy during unreserved time. The system sends idle robots on a trip for greedy charging of an appliance with a reduced battery level. In addition, robot tasks other than charging can be incorporated into the schedule. For example, a room cleaning robot that performs on average a daily one-hour cleaning for a room can use its 23 hours of idle time for charging appliances.

IV. Theoretical Analysis

In this section, we present a theoretical analysis of the system. Several issues require consideration because the behavior or performance of the system depends on the target appliance and each component of the system. Therefore, theoretical analyses and deliberations are useful for considering the components to instantiate our concept. In the following subsections, we specifically describe each of the following topics: energy loss rates, relation between charging and operating times, continuous operating time limit, availability, and output power limit.

The system involves base units where the robots are recharged and appliance-side devices where the robots transfer their battery power. We call these the home and remote docks, respectively. Fig. 3 shows the key symbols used in the theoretical analyses below. There are three kinds of energy transfer: electric power from the home dock to the robot, battery power from the robot to the remote dock, and electric power from the remote dock to the appliance. Each type of energy transfer is characterized by the following parameters: energy transferred, transfer speed, and transfer time. In the following expressions, we use uppercase subscript letters to indicate devices (e.g., R for robot, A for appliance) and lowercase subscript letters to indicate the channels of a device (e.g., c for charge, o for output). Note that all energy transfers in the system are performed under DC battery voltage and not the AC power from an outlet (e.g., 220V AC).

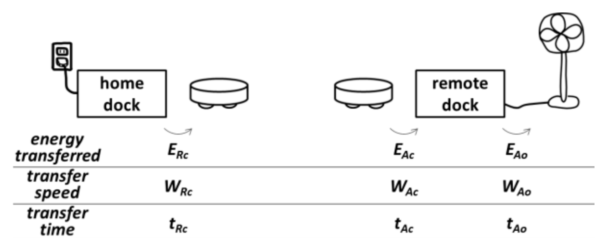

Figure 3. Key Symbols in Energy Transfer.

A. Energy Loss Rates in Remote Dock

We assume that each remote dock has a battery pack that stores electric power for certain duration. This requires the consideration of energy losses. A battery pack has internal charging and protection circuits that may cause energy loss. In addition, a voltage converter is required to consistently provide an input voltage to the battery in the appliance-side component because the output voltage from the robot battery depends on the battery level. Optionally, the battery output can be connected to an inverter to generate alternating current (AC) for general appliances. Fig. 4 shows a block diagram of the energy flow from a robot to an output outlet. The energy losses of the converter, battery pack, and inverter should be considered; the energy loss rates for these components are denoted by L_C, L_B, and L_I, respectively. L_I in the following equations can be regarded as 1 if the user does not employ an inverter.

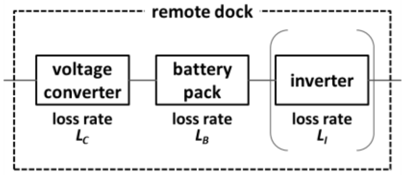

Figure 4. Energy Losses in Remote Dock.

B. Relation between Charging and Operating Times

Next, we consider the charging time for a battery in a remote dock. In general, a charging circuit controls the input current to be constant for most of the charging time. We assume that the battery in a remote dock is charged by a constant current. We then obtain the following expression:

$$E_{Ac} = W_{Ac} * t_{Ac}, \tag{1}$$

where E_{Ac} is the total energy charged, W_{Ac} is the power to be charged per time unit (i.e., charging speed), and t_{Ac} is the charging time of the appliance battery.

Note that we confirmed that a battery used for the remote dock of our prototype has a constant current characteristic for most of the charging time. Fig. 5 plots the accumulation of input power during charging with a power cable until the battery pack is fully charged. The blue circle in Fig. 5 indicates the time and level at which the system detected the end of constant current charging. After almost two hours of constant current charging, the battery level reached 93%. For simplification, we decided to use constant current charging only and terminated the charging process when the end of this charging mode was detected.

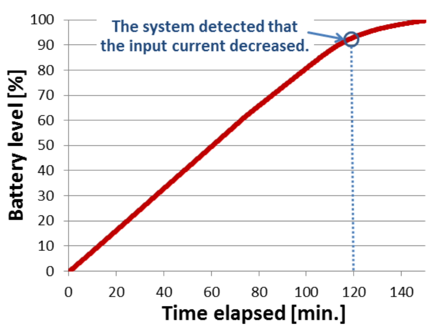

Figure 5. Constant Current Characteristic of the Appliance Battery.

Next, we model the output from the remote dock. The average power consumption is usually provided for appliances. By using this value, we obtain the following expression:

$$E_{Ao} = W_{Ao} * t_{Ao}, \tag{2}$$

where E_{Ao} is the total energy consumed, W_{Ao} is the average power consumption, and t_{Ao} is the time of use of the appliance. The charged energy and output energy are related as follows using the loss rates modeled in the previous subsection:

$$E_{Ao} = E_{Ac} * L_C * L_B * L_I. \tag{3}$$

Therefore, we obtain the following expression

$$t_{Ac} = (1/W_{Ac}) * (1/L_C L_B L_I) * W_{Ao} * t_{Ao}. \tag{4}$$

We can measure W_{Ac} once the battery is determined. Therefore, we can estimate the sufficient charging time by using (4), given the average consumption power and time of use. This is useful for planning a scheduled trip.

C. Continuous Operating Time

By viewing (4) from a different perspective, we can obtain the following expression:

$$t_{Ao\_single} = (W_{Ac}/W_{Ao}) * L_C L_B L_I * t_{Ac\_single}, \tag{5}$$

where t_{Ao_single} denotes the continuous operating time with the energy stored by single power transfer from a fully charged robot to a remote dock, and t_{Ac_single} denotes the time required for single power transfer from a fully charged robot to a remote dock. We can empirically measure the charging speed W_{Ac} and the time required by the robot to charge the remote dock t_{Ac_single}. Hence, we can calculate the operating time of the appliance after a robot trip.

We also consider a further operating time limit. From the specifications of the appliance battery, we obtain the capacity of the battery and calculate the operating time by using the fully charged remote dock battery as follows:

$$t_{Ao\_max} = E_{Ab\_max} * L_I \ / \ W_{Ao}, \tag{6}$$

where t_{Ao_max} denotes the continuous operating time using the fully charged appliance battery, and E_{Ab_max} denotes the total energy that the battery can store. Equation (6) is useful for determining how long the appliance can operate with a greedy charging strategy.

D. Availability

As shown for t_{Ac_single}, we can also measure the time required to fully charge the robot t_{Rc_single}. By using these values, we can derive the availability of the appliance A_A, which we define as the time of operation (as a ratio of the total unit time) during which the system attempts to provide maximum energy to the appliance. For example, if A_A is 0.5, the appliance can be used for a maximum of 12 h/day. If A_A is 1, the user can continuously use the appliance all the time.

We first treat the input and output factors of the remote dock separately to consider availability. The input factor is related to how much the system can assign the robots to charge the remote dock. In the case of a single robot, the robot maximally provides electric power when it repeatedly charges the remote dock battery and recharges its own battery. Therefore, the input factor is determined by the ratio of the charging time of the remote dock to the cycle time of one round trip made by the robot as follows:

$$input\ factor\ single = t_{Ac\_single} \ / \ (t_{Rc\_single} + t_{Ac\_single}). \tag{7}$$

In the case of two or more robots, after one robot finishes charging, another can start charging. Hence, the numerator of the input factor is multiplied by the number of robots. However, the input factor cannot exceed 1. Therefore, we can derive the following expression:

$$input\ factor = \min(1, t_{Ac\_single} * n / (t_{Rc\_single} + t_{Ac\_single})), \quad (8)$$

where n denotes the number of robots. For example, for robots whose t_{Rc_single} is 3 and t_{Ac_single} is 2, the input factor is 0.4 with a single robot, 0.8 with two robots, and 1 with three or more robots. The output factor is related to how long the remote dock can operate the appliance, and determined by the ratio of the operating time to the charging time.

$$output\ factor = t_{Ao\_single} / t_{Ac\_single}. \quad (9)$$

Again, by considering that availability cannot exceed 1, we finally derive the following expression to calculate availability A_A by multiplying the input and output factors:

$$A_A = \min\left(1, \min\left(1, \frac{t_{Ac\_single} * n}{t_{Rc\_single} + t_{Ac\_single}}\right) * \frac{t_{Ao\_single}}{t_{Ac\_single}}\right). \quad (10)$$

Using (5), (10) is expanded to

$$A_A = \min\left(1, \min\left(1, \frac{t_{Ac\_single} * n}{t_{Rc\_single} + t_{Ac\_single}}\right) * (W_{Ac}/W_{Ao}) * L_C L_B L_I\right). \quad (11)$$

All symbols except W_{Ao} in (11) are constants for certain batteries in the robots and remote docks. Hence, the availability is determined by the power consumption of the appliance once the user determines the robots and remote docks.

E. Output Power Limit

Another limit concerns power consumption. Given that a typical battery pack has an output current limit for safety considerations, the final output from the inverter is also limited as follows:

$$W_{Ao\_max} = W_{Ab\_max} * L_I, \quad (12)$$

where W_{Ao_max} is the limit of the final output from the inverter and W_{Ab_max} is the limit specification of the battery output from the inverter. To use high-power appliances, the user must select a high-performance battery for the appliance battery.

V. Implementation

We implement a proof-of-concept system that employs one robot and one appliance dock. The robot finds the appliance dock completely autonomously. We also design the dock-finding method in a way that makes it extendable to multiple robots and appliances.

A. Hardware

The user-visible parts of the system are mainly divided into three components: a battery-charging robot, a home dock, and a remote dock (Fig. 6). All three components are wirelessly connected to a host computer through Wi-Fi infrastructure. For the battery-charging robot, we employ an iRobot Roomba [11] modified to bypass its battery terminals to outside the robot. The battery terminals, which are attached to the front of the robot, make contact with the terminals on the remote dock (Fig. 7). The robot also has a circuit board to monitor the output current and voltage of the battery and to switch the bypass line for safety during exploration.

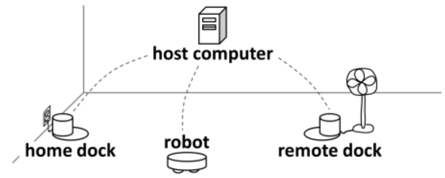

Figure 6. System Configuration.

Figure 7. Battery-Charging Robot.

We use Roomba charging docks for the home and remote docks. A charging dock has a set of beacon transmitters used by a Roomba to find its location. We use this beacon mechanism to enable the robot to explore and find the target dock autonomously. To move the robot to a dock in the environment, the system turns on the target dock, turns off the other docks, and has the robot search for the target dock with its preprogrammed behavior (Fig. 8).

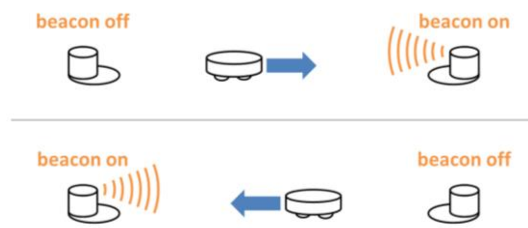

Figure 8. Time Division Switching of Robot Docks.

The home dock is connected to an outlet to provide electric power to the robot, and comes with a circuit board that switches the power of the dock (Fig. 9). The remote dock contains a battery to store electric power for driving an appliance as described earlier, a circuit board with current sensors to monitor the input/output of electric power, and a relay to switch the power of the dock (Fig. 10). Fig. 11 shows the parts on the circuit board. A microcontroller on the circuit board estimates the battery level on the basis of the values from the current sensors. The microcontroller also controls the dock power for robot navigation.

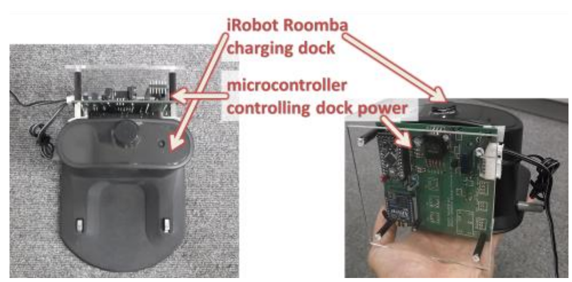

Figure 9. Home Dock for Recharging the Robot.

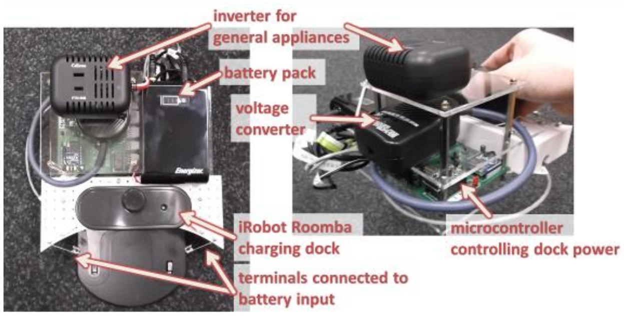

Figure 10. Remote Dock to Store Battery Power for Appliance.

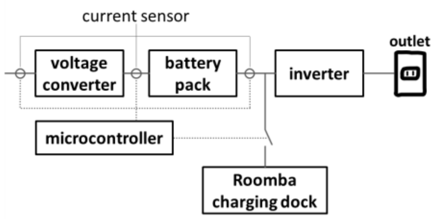

Figure 11. Parts on the Circuit Board of the Remote Dock.

B. Parameters

In this section, we describe the specifications of the prototype implementation. We also derive specific formulas by using the parameters obtained from measurements or specifications in the expressions of Section IV.

We first measured the energy loss rates. For that of the voltage converter (L_C), we measured its typical input/output voltage and current and obtained an input of 14.4 V, 1250 mA and an output of 19.0 V, 900 mA. Therefore, L_C is given as

$$L_C = (19.0 \text{ V} * 900 \text{ mA}) / (14.4 \text{ V} * 1250 \text{ mA})$$

$$= 17.1 \text{ W} / 18.0 \text{ W} = 0.95. \quad (13)$$

For the energy loss rate of the battery pack (L_B), we measured its typical input/output voltage and current and the time required for its full charge/discharge. For the input and output, we obtained 19.0 V, 900 mA, 2.0 h and 12 V, 574 mA, 4.5 h, respectively. Therefore, L_B is given as

$$L_B = (12 \text{ V} * 574 \text{ mA} * 4.5 \text{ h}) / (19 \text{ V} * 900 \text{ mA} * 2.0 \text{ h})$$

$$= 30.1 \text{ Wh} / 34.2 \text{ Wh} = 0.88. \quad (14)$$

For the energy loss rate of the inverter (L_I), the typical output currents of the battery pack for driving an appliance (fan) with and without the inverter were 574 and 331 mA, respectively. Therefore, L_I is given as

$$L_I = 331 \text{ mA} / 574 \text{ mA} = 0.58. \quad (15)$$

The battery-charging speed for the remote dock (W_{Ac}) is calculated by the input voltage and current to the remote dock. As described earlier, we obtain W_{Ac} as

$$W_{Ac} = 14.4 \text{ V} * 1250 \text{ mA} = 18.0 \text{ W}. \quad (16)$$

We next measured the time required by a fully charged robot battery to charge a remote dock (t_{Ac_single}). We manually placed the fully charged robot on the empty remote dock and found that the robot battery was depleted after two hours. Given the discharge required for a robot to make a single round trip, we set the charging time to 1.8 h.

$$t_{Ac\_single} = 1.8 \text{ h} \quad (17)$$

We also measured the time required to fully charge the robot battery t_{Rc_single}. Fig. 12 plots the accumulation of the input power until the robot was fully charged. We confirmed that 2.8 h was required to fully charge the robot battery.

$$t_{Rc\_single} = 2.8 \text{ h} \quad (18)$$

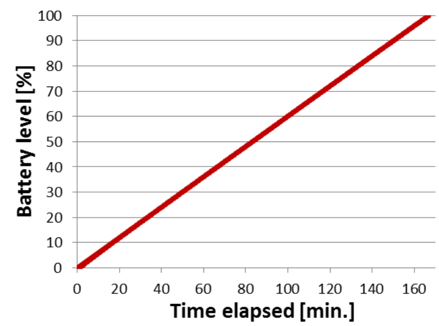

Figure 12. Constant Current Characteristic of the Robot Battery.

Note that the robot battery used has a constant current characteristic throughout the course of charging. The battery level reached 100% by constant current charging.

Next, we examined the specifications of the battery pack to find its capacity E_{Ab_max}. Given that charging is terminated at 93% of the battery level (Section IV.B), the capacity is multiplied by 0.93 to calculate E_{Ab_max} as

$$E_{Ab\_max} = 3.7 \text{ V} * 8000 \text{ mAh} * 0.93 = 27.5 \text{ Wh}. \quad (19)$$

Finally, we examined the battery specifications to find the battery output limit W_{Ab_max} as

$$W_{Ab\_max} = 12 \text{ V} * 2000 \text{ mA} = 24.0 \text{ W}. \quad (20)$$

Applying the parameters in (13)–(20) to (4), (5), (6), (11), and (12), we obtain the following specific expressions for our prototype implementation.

$$t_{Ac} = 0.115 * W_{Ao} * t_{Ao} \text{ [h]} \quad (21)$$

$$t_{Ao\_single} = 15.71 / W_{Ao} \text{ [h]} \quad (22)$$

$$t_{Ao\_max} = 15.95 / W_{Ao} \text{ [h]} \quad (23)$$

$$A_A = 3.42 / W_{Ao} \quad (24)$$

$$W_{Ao\_max} = 13.92 \text{ [W]} \quad (25)$$

C. Scheduling Control

We additionally implemented a smartphone application to register strategies and schedules. Fig. 13 shows screenshots of

TABLE I. SUMMARY OF VALIDATION OF FOMULAS

Condition		W_{Ao}	t_{Ac} for 30-min t_{Ao}	t_{Ao} for left t_{Ac}		t_{Ao_single}		t_{Ao_max}		A_A
Weak	theoretical	-	0.16	30 min		5.80		5.89		1.00
	mesured	2.71	-	31 min	29 min	5.85	5.77	6.03	6.01	1.00
Strong	theoretical	-	0.59	30 min		1.53		1.56		0.33
	mesured	10.24	-	34 min	37 min	1.70	1.73	1.59	1.65	0.33
Strong+Motion	theoretical	-	0.76	30 min		1.19		1.21		0.26
	mesured	13.15	-	35 min	32 min	1.28	1.17	1.28	1.24	0.26

the application. The top level of the interface shows a list of remote docks (Fig. 13 left). Tapping an item in the list leads to a setting screen (Fig. 13 right), in which the user enters a name, a strategy, and optional start/end times. The name is an alias for the user to distinguish the remote dock. The strategy is the charging strategy for the remote dock. Selecting a scheduled strategy enables forms for the start and end times, which are used to plan a scheduled trip. When the user taps the "Save" button, the application sends this information to the host computer controlling the system, and the scheduled trip is reserved. In particular, the system calculates the charging time (t_{Ac}) according to (21) with the required use time (t_{Ao}) and last power consumption (W_{Ao}). The system adds 15% of the theoretically estimated charging time as a buffer charging time. The system also adds further 10 minutes for a round trip to the buffered charging time. Hence, the trip begins at a time that precedes the start time by 115% of the theoretically estimated charging time + 10 minutes.

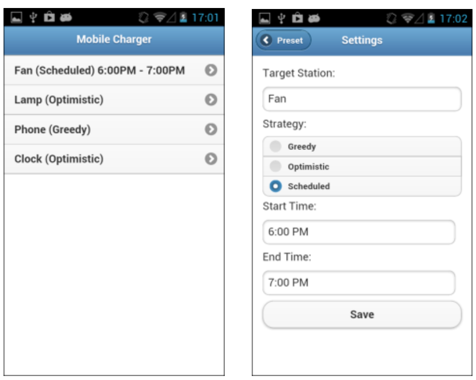

Figure 13. Smartphone Application for Strategy and Schedule Registration.

VI. VALIDATION STUDY

We empirically investigated the prototype implementation to validate the theoretical analysis. The experiment was conducted from three perspectives: expressions, scheduled trips, and reliability. As a baseline, we first measured the output load by using an off-the-shelf fan as the output device. The wind strength could be adjusted to one of eight levels, and the direction of the head could be periodically changed. We used the fan in three conditions: weak (level 3) wind (Weak condition), strong (level 8) wind (Strong condition), and strong (level 8) wind with head motion (Strong+Motion condition). We connected its original power cable and measured the input voltage and current. With a 12 V input, the currents were 226, 853, and 1096 mA in the Weak, Strong, and Strong+Motion conditions, respectively. Hence, the required power (W_{Ao}) values for each condition were 2.71, 10.24, and 13.15 W, respectively. These values were used in the evaluations below.

A. Validation of Formulas

We tested whether the prototype worked as expected by theoretically derived formulas (Table I).

We first checked the relation between the charging and output times. For each operating condition, we operated the fan until the battery was depleted after the robot had charged the remote dock battery for 30 minutes of use (t_{Ao}). The theoretical charging times (t_{Ac}) were calculated by (21) as 0.16, 0.59, and 0.76 h for the corresponding conditions. Two tests were conducted for each condition in this and all subsequent experiments except availability.

The fan was operated for 31 and 29 min on each trial in the Weak condition, 34 and 37 min on each trial in the Strong condition, 35 and 32 min on each trial in the Strong+Motion condition.

Similarly, we checked the continuous operating time. For each operating condition, we operated the fan until the battery was depleted after the fully charged robot had transferred all of its power to the remote dock. The theoretical operating times (t_{Ao_single}) were calculated by (22) as 5.80, 1.53, and 1.19 h for the corresponding conditions.

The fan was operated for 5.85 and 5.77 h on each trial in the Weak condition, 1.70 and 1.73 h on each trial in the Strong condition, and 1.28 and 1.17 h on each trial in the Strong+Motion condition.

We also checked the continuous operating time after full charging of the remote dock. For each operating condition, we operated the fan until the battery was depleted after the robot completed charging of the remote dock. Two trips were required to fully charge the remote dock battery. The theoretical operating times (t_{Ao_max}) were calculated by (23) as 5.89, 1.56, and 1.21 h for the corresponding conditions.

The fan was operated for 6.03 and 6.01 h on each trial in the Weak condition, 1.59 and 1.65 h on each trial in the Strong condition, and 1.28 and 1.24 h on each trial in the Strong+Motion condition.

We next tested the availability as given by (24). The system was run for three rounds of charging the remote dock. We prepared an empty remote dock and turned on the fan at the beginning of the first charging. Each time the robot completed charging during this test, we turned on the fan again if the fan was not operating due to depletion. We measured the total operating time to calculate the availability (A_A). The expected values of availability were 1.00, 0.33, and 0.26 for the corresponding conditions.

The total operating times for corresponding conditions were 9.8, 4.5, and 3.5 h. The total times elapsed were 9.8, 13.8, and 13.8 h, and hence the measured availability values were 1.00, 0.33, and 0.26, respectively. We note that the second and third charge in the Weak condition finished earlier than usual (1.0 h each). As a special case, we additionally operated the fan in the Weak condition for three days to test whether it could operate continuously. The fan continued to operate successfully for 29 rounds of charging as if connected to a power cable.

In the previous experiment, the fan was shown to consume 13.15 W in the Strong+Motion condition. With a Wi-Fi router connected to the remote dock by an inverter, the router failed to start. With the router connected directly to the remote dock without an inverter, the fan correctly functioned with an average output current of 1375 mA (i.e., power consumption of 16.50 W). These results indicate that the prototype has an output limitation described in (25).

B. *Validation of Scheduled Trips*

We tested the behavior of the system during scheduled trips. For three days, we registered the fan to operate in the Strong condition for one hour begging at 6 pm each day. Given that the required charging time was 1.18 h (i.e., 71 min) from (21), the robot was expected to begin a trip 92 min (71 min (theoretical) + 11 min (15% buffer) + 10 min (round trip)) before 6 pm, i.e., at 4:28pm (Section V.C).

As expected, the robot began the trip at 4:28 pm each day. The times at which the robot returned to the home dock varied slightly (5:53, 5:51, and 5:54 pm). This is because the navigation time between the home and the remote dock was not fixed. The battery of the remote dock was thus sufficiently charged because the fan could be operated until 7 pm each day.

C. *Reliability*

In the previous two experiments, the robot was moved a total of 118 times to the other dock in a 5 m × 5 m environment. On each trial, the robot successfully reached the other dock. It required 104 seconds on average and a maximum of 195 seconds to complete a trip.

VII. Discussion and Limitations

The maximum output power of our current implementation is only 13.92 W, in which case the operation time is only 1.15 h. This means that the current prototype can serve only limited low-power consumption devices such as fans, lamps, and certain low-power computers for a relatively short time. To reduce this limitation, batteries with higher capacity and charging speed can be used. This battery change is unlikely to require a change in the configuration of the system. In addition, the robot may have a powerful battery separate from its internal battery. Although this requires a slight change in configuration (i.e., a home dock requires two charging circuits), we can independently select the additional battery regardless of the internal battery and avoid the ad hoc discharge adjustment for robot navigation (2.0 h to 1.8 h in (17)). A further possible change in the future is that each appliance will have a battery and a charging dock. This will eliminate the need for the inverter and allow the appliance to use a higher output from the appliance battery.

Although we focused on presenting the concept and a feasible implementation in this paper, the system can be extended or optimized to suit the user's preferences. For example, the user may want the robot to move only when the user is outside. A potential extension for this is to provide a user interface that registers the preferred time or directly notifies the system if the robot can move. As future work, we also plan to conduct a user study with the implemented system to investigate such user preferences. We hope to obtain insights for practical use and discover further avenues of research.

VIII. Conclusion

In this paper, we proposed the concept of a power-delivering mobile robot and a battery management system for home appliances. We demonstrated a proof-of-concept implementation by using an off-the-shelf robot, battery, and appliance, and showed that the proposed concept was feasible in a typical environment. By considering the parameters described (Section IV), developers can select components of the system according to appliance usage.

The demonstrated technique may change how the deployment of appliances is determined. If appliances that contain a battery and docking terminals increase, we can expect to see more cable-less appliances that are freely placed in the future. We believe that the demonstrated technique offers an opportunity to reconsider daily life in future home environments with mobile home robots.

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