Multi-Functional Rectenna for a Lunar Rover

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Abstract— **Current and previous lunar rovers are powered solely by batteries. These batteries are charged up during the lunar day and the rover is powered down during the lunar night to conserve energy. The rover can be made operational at all times by powering the rover wirelessly using a microwave beam. This microwave beam being transmitted to the rover can also be used to navigate the rover. The theory of a multi-functional rectenna array is presented in this article. 8 symmetrical nodes on the circumference of the rectenna and one node in the center of the rectenna are fitted with sensors which calculate the power density constantly. The central node communicates with the other 8 nodes calculating the relative power density. The central node is assigned to send movement commands such as faster speed in the direction of movement, slower speed in the direction of movement, forward, reverse, left turn, right turn, start and stop to the rover. These commands are triggered when the microwave beam is moved to focus one of the 8 nodes. For example, when the microwave beam is focused towards node 1 which is programmed to trigger the 'stop' command, the central node detects that node 1 has the highest relative power density and send the 'stop' command to the rover. Similarly, the microwave beam can be focused on other nodes to trigger the respective movement commands. While the beam is required to be returned back to the center before a new command is used, a return to center policy is employed, that sends data signals back to the transmitter so that the beam is moved back to the center of the rectenna after a movement has been triggered. The data signal contains the delta x and delta y of the beam position from the center of the rectenna. This data signal can also be used to relay other information collected by the rover to the ground station. Thus, the proposed multi-functional rectenna can power the rover at all times increasing its operational time, can be used to navigate the rover and also relay information collected by the rover to the ground station, all at once.**

I. INTRODUCTION

A 'rectenna' is a rectifying antenna that receives an RF signal from the transmitter and rectifies it into a DC signal for the load. Heinrich Hertz was the first to send and receive electromagnetic signals, while Nikola Tesla is credited with the concept of wireless transmission of power [1]. With the advent of radar, and in particular, the phased array antenna, interest in wireless power transmission (WPT) surged in the 1960s in Japan [2] and the U.S. [3].

With demonstrations of increasing scale, Raytheon employee William C. Brown conducted a series of WPT experiments that culminated in conversion efficiencies of 90.6%. which have not been exceeded as of 2020 [4]. Brown invented the shunt diode rectifying receiving antenna ("rectenna") which uses a platinum-contacted gallium arsenide Schottky barrier diode (SBD) in parallel with a load resistor across the rails of a dipole antenna. In 1982, Brown designed a 2.45 GHz thin-film etched-circuit flexible rectenna. An efficiency of 85% was reported [5].

II. RECTENNA

Figure 1 shows the block diagram representing the elements and sequence of a rectenna converting radio frequency (RF) energy into a direct current (DC) load. In modern phased array antennas, a patch-type antenna element receives energy across free space from a suitable transmitter. The patch design is tuned to a specific frequency. Higher frequencies have shorter wavelengths and therefore antenna area scales as the inverse square of frequency. While terrestrial WPT typically uses 2.45 or 5.8 GHz, these being "windows" of relatively low attenuation through atmospheric moisture (fog, humidity, precipitation, clouds), on the lunar surface there are no such restrictions, so the frequency can be chosen based on trades between size, mass, and power density.

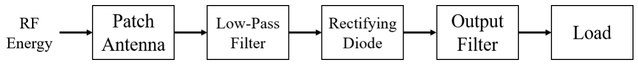

Fig. 1. Block diagram of a rectenna element

The low-pass filter removes the higher harmonics created by the rectifying diode. While traditional rectifiers use either a full-bridge with four diodes or a half-bridge with a single diode in series, the rectifying diode is in parallel in the Brown design [6]. the output filter is used to minimize alternating current (AC) ripple on the rectified DC power delivered to the resistive load. Such ripples can experience destructive interference when combined with other antenna elements, and reduce overall conversion efficiency thereby. In some applications, a DC-DC converter may be used to modify the output voltage or current to meet the demands of a particular load.

Dipole antennas can be very low in mass. Although traditional dipole antenna design includes a contiguous conductive backplane spaced 1/2 wavelength behind the antenna element, Brown's work suggests that a backplane may not be required [8]. On the other hand, patch antennas consist of a three-layer structure of metal-insulator-metal, and therefore have a built-in backplane, and can also be quite low in mass. Patch antennas are easily fabricated with modern lithography, and are readily compatible with the microstrip or coplanar waveguide (CPW) designs of RF printed circuit boards and planar connector technology [7]. Surface-mount shunt SBDs can be readily soldered between adjacent conductors in a CPW assembly.

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This is the author's manuscript of the article published in final edited form as:
Schubert, P. J., & Saket Suri, R. (2020). Multi-Functional Rectenna for a Lunar Rover. International Astronautical Conference.
https://iafastro.directory/iac/paper/id/57815/summary/

An array of patch antenna elements can be connected in series to increase the voltage to the load, or they can be connected in parallel to sum the load current. The patch array is a thin membrane which may be rolled up to converse launch volume with suitable care in design and selection of materials. When deployed on a lunar rover or other asset, the antenna array membrane can be unfurled and mounted on a suitable frame, and electrically connected to the load.

III. CONTROL STRATEGY

A. *Control nodes*

Figure 2 shows how the layout of rectenna elements (blue) and control components (red) on a circular array. Nine positions implement the closed-loop control functions, with one node in the center and eight equally spaced around the periphery. These nodes serve two functions, first, they measure the power level of the WPT beam, and second, they illuminate a light-emitting diode (LED) which provides optical feedback to the transmit system. A simple processor at the central node compares signals from the peripheral RF detectors to determine the alignment of the incoming WPT energy beam.

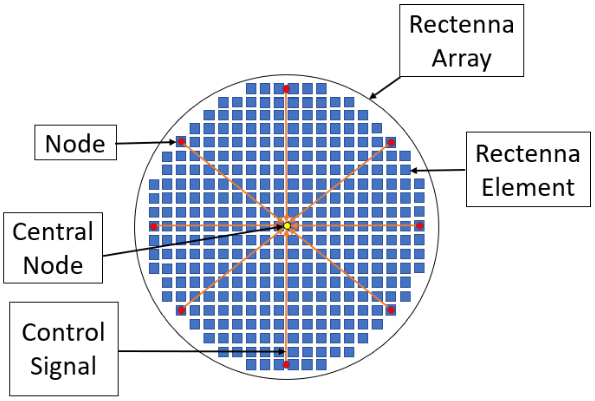

Fig. 2. Rectenna layout

A perfectly-aligned transmit beam arriving broadside to the rectenna array will be symmetric around the periphery. LED illumination lumens correspond to local power density, such that a slightly misaligned beam will cause one edge to be brighter and one edge to be more dim. This can be used to advantage in delivering low bandwidth signals to the target rover. Assuming for a moment that the beam can be held in near-perfect alignment, then deliberate movements of the transmit beam can be used to deliver eight bits of command to the rover. For instance, an excursion of the transmit beam to the upper edge might signal the rover to steer right. Table 1 describes how the eight peripheral nodes (N1-N8) can be activated to effect navigation commands to a lunar rover.

Such a simple approach is clearly error-prone, so a more robust system is now described, and illustrated in figure 3. The feedback for beam steering is via optical pattern recognition of the LED illumination level or color. The lunar horizon is 2.4 km, so there is negligible time delay and sufficiently mature optics hardware available to make detection straightforward. Optical frequencies are several orders of magnitude removed from RF so as to avoid desensitization ("desense"), which is the over-saturation and interference of a communications signal in proximity to a power beam. Detecting direction optically, once calibrated, is simpler than using a retrodirective beam, which requires phase-sensitive detectors on the transmit antenna, and which can experience aliasing when the angle is large between transmit and receiver, as seen in fig. 3(a). Optical devices can zoom in magnification to account for different fields of view, as depicted in the three rovers of fig. 3.

TABLE I

MOVEMENT COMMANDS ASSIGNED TO THE PERIPHERAL NODES

Node ID	Command
N1	Stop
N2	Start
N3	Forward
N4	Reverse
N5	Left Turn
N6	Right Turn
N7	Move faster
N8	Move slower

Fig. 3(b) illustrates a carrier wave manifesting as a minor wobble in the precise boresight direction of the transmitted radiation pattern. A sinusoidal "heartbeat" in the y and z directions is sufficiently small so as to sacrifice only a tiny fraction of efficiency in return for establishing a carrier wave for a matched filter to extract a deliberate variation. Whereas the movement of the rover, including roll and yaw, will modulate the orientation angles ϕ and θ such that the beam traces a tight, circular pattern on the rectenna. Variations from rover movement can be subtracted by on-board inertial sensors, so that deliberate movements to the 8 points of the compass can be robustly detected as remote control commands. For example, a steady dwell in the vertical (+z) direction for a duration three times longer than the heartbeat period may signal to turn right. For even greater error reduction, the LED feedback lights can blink a "command received" confirmation pattern discernible to the optical tracking apparatus. In addition, the same command can be repeated twice more at a pre-set time interval such that even if only two of the 1-bit information packets occur, the command can be confidently executed by the rover navigation system.

B. *Control logic*

Figure 4 illustrates the outline of the command routine implemented at the rover. Detection of the heartbeat signal is important for beam steering because various environmental factors and detector sensitivities can conspire to confound information to the command routine. For remote distances, or with intervening dust plumes occluding a portion of the signal, a static power profile at the rectenna may be a noisy means of detecting direction. The heartbeat beam

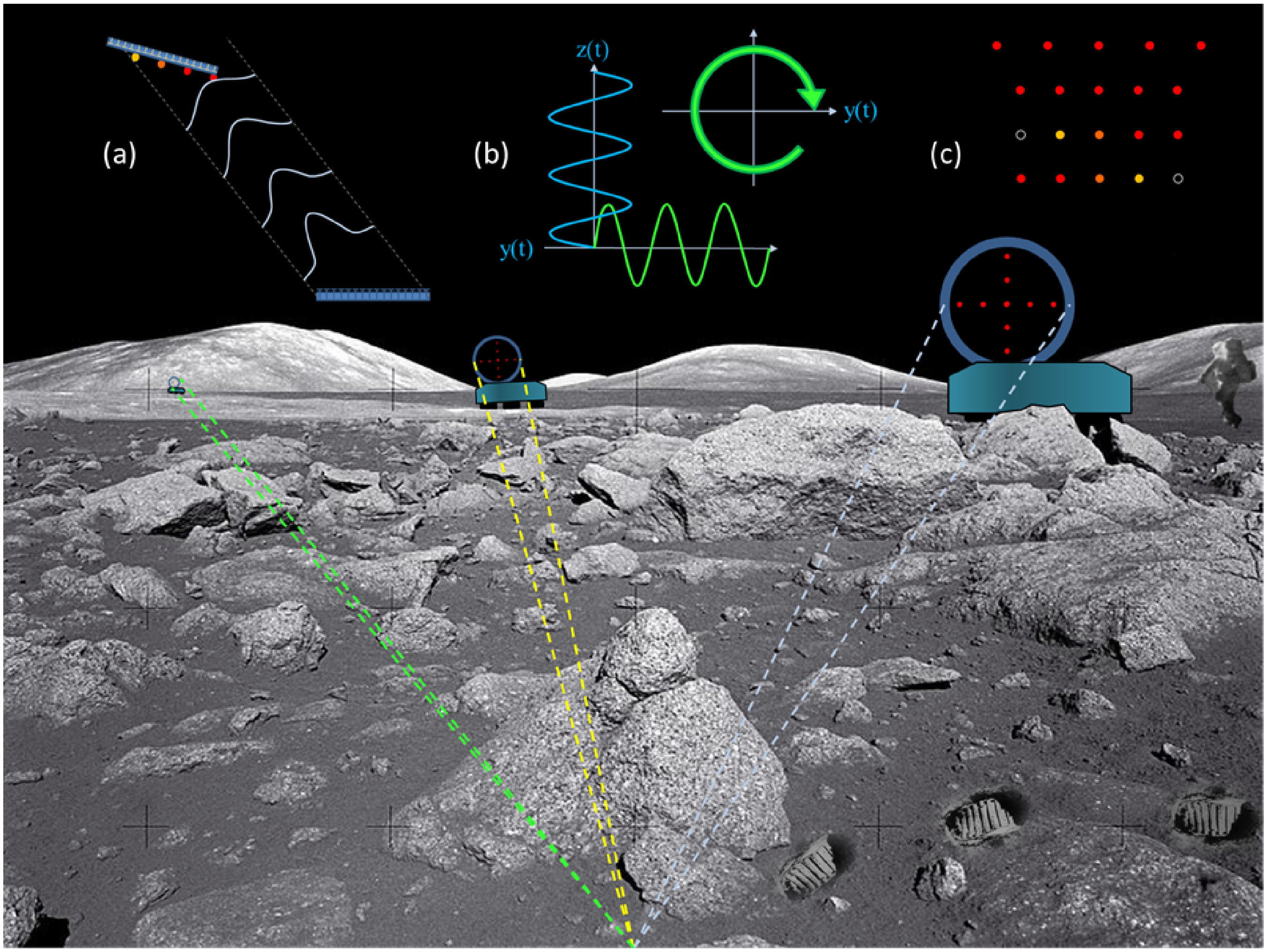

Fig. 3. Power beaming to multiple targets on lunar surface. Embedded images: (a) beam development towards angled rectenna; (b) beam wobble "heartbeat"; (c) LED patterns for, respectively, top-to-bottom broadside aligned beam, aligned/angles, angled/offset-right, angled/offset-left.

wobble illustrated in fig. 3(b) provides a spatial and temporal reference against which to discern between deliberate and unintended beam power density fluctuations across the rectenna. A matched filter is a technique of digital signal processing in which the carrier wave is selectively filtered out to achieve a higher signal-to-noise ratio (SNR) for command signals. If the carrier wave is not present, the matched filter output becomes large, such that loss-of-power can be readily detected. This may occur if a rover moves behind an boulder, in which case, using short-duration energy storage, on-board inertial navigation can either continue past the obstacle, or reverse course to re-acquire the power beam.

Peripheral LEDs viewed by an optical tracking camera can guard against the conflation of distance and yaw angle of the rover relative to the transmit station. The top two scenarios in fig. 3(c) show a horizontal array of five LEDs across the face of the rectenna, the spacing between which indicates either rover distance or angle. A similar array in the vertical (z) direction may resolve this, for example, if the vertical spacing remains fixed while the horizontal spacing diminishes, this is a clear indication of yaw alone. If the rover experiences both yaw (about the z axis) and roll (about the y axis), this can be confounded with an indication of greater distance. Because distance does not change suddenly, this double-confounding scenario can be identified by comparison with recent confirmed distances together with inertial movement relative to such way-points. It is also possible for the transmit station to issue commands for the rover to move such that any remaining distinction between yaw, roll, and distance can be quickly resolved.

C. *Feedback mechanism*

Several methods have been explored by which electronically-steered WPT beams are kept in alignment with a moving rectenna. These are compared in Table II, along with an evaluation of their relative merits in fragility/robustness, cost, and likelihood of unwanted interference. A score for each is computed, along with a judgement as to which scenarios most favor each such method. On the lunar surface realistic scenarios range from meters-long recharging, to 100 meter distribution by a fission reactor to a habitat, to single-kilometer distances for

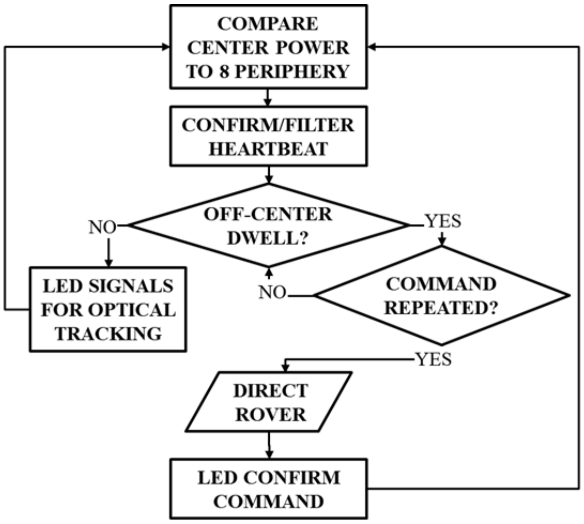

Fig. 4. Flowchart of the rover command process

exploration and construction, to 10 kilometer distances for mining operations in permanently-shadowed regions (PSR). For these applications, the optical tracking is found to be superior.

TABLE II
FEEDBACK IMPLEMENTATION TECHNIQUES

Method	Fragility	Cost	Interference	Total score	Operation Range
Retrodirective rectenna array	1	2	1	4	Long range
RADAR on transmitter	1	3	1	5	Long range
RFID	1	1	1	3	Short range
Electro-active material	2	5	0	7	Long range
Optical tracking	1	1	0	1	Medium range

D. *Cyber-security*

Deliberate hacking attempts of a semi-autonomous rover are to be expected eventually, whether for sport or malice or theft. Some degree of protection is offered by the geometry and physics of the transmit antenna, which is at least as large as the rectenna, and which must be on a line-of-sight. The same adjustable-magnification, steerable optics used for beam steering feedback to the rovers can be periodically, or episodically employed to panoramically scan the horizon to identify threats. If a potential bad actor is detected, the transmit beam can be spatially and temporally modulated so as to direct the rover(s) to enter a safe mode, until such time as they receive a pre-programmed unlock command. Or, as additional safeguard, the transmit beam steer pattern can deliver a meta-message according to the schedule of a one-time programming (OTP) sequence initiated at the start of service. Such a "keep-alive" signal assures the rover that the authorized transmit station remains in control; and the lack of which causes the rover to automatically enter safe mode.Additional security measures can be implemented which serve a dual purpose with resolving yaw/roll/range confounding. The use of a Kalman filter between rover internal navigation and transmit station history of the rover position can provide a robust ground truth against spoofing of steering commands. Furthermore, if the rover is surreptitiously moved or taken, a sudden deviation can raise alarms calling for additional investigation or intervention. Rovers can be pre-programmed to shut down, or even to self-disable, in order to prevent bad actors from using them for nefarious purposes.

IV. CONCLUSIONS

Power distribution on the lunar surface via WPT is superior to cables because of the lower mass, simultaneously serving multiple moving loads by time-sharing, and by avoiding tangling of long wires. WPT power delivery is adaptive and flexible, and lower in mass when compared to a battery-driven system. A WPT-powered rover will still need limited on-board energy storage for brief passages behind occluding outcrops, and also for continuity of power when a single transmit station is serving multiple rovers in a rotating sequence (see fig. 3). Optical tracking as a feedback control method for electronic beam steering is found to be the optimal method for all anticipated lunar surface operations where line-of-sight transmission is available. Optical feedback is simple and mature, resistant to desense, and provides valuable confirmation and state-of-health information to the transmit station. Relatively simple and robust control methods are available by which to resist erroneous or spoofed command signals, thereby safeguarding people and their valuable hardware assets on the Moon. These methods dovetail with other recent WPT advances, such as pencil beam radiation patterns, high efficiency power delivery, and self-adaptive power summing among rectenna elements. Operated in the manner described herein, a single transmit station can operate multiple rovers conducting scientific, commercial, or recreational activities.

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