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Microwave Power Transmission to a MAV using a Software Retro-Directive System

Eri Shimane,[1] Alseny Diallo,[1] Takashi Komaru,[2] Kimiya Komurasaki[3]
The University of Tokyo, Kashiwa, Chiba 277-8561, Japan

and

Yoshihiro Arakawa[4]
The University of Tokyo, Bunkyo, Tokyo 113-8656, Japan

Microwave power transmission system for a Micro Aerial Vehicle using a software retro-directive system has been studied. Power transmission demonstrated while the MAV model was circling over the transmitter antenna at the altitude of 60cm. The output voltage from the rectenna array was measured while the microwave beam was synchronized the motion of the MAV model. The out put voltages were higher than 0.2V which means the minimum requirement for operation of the electric motor on the MAV model.

Nomenclature

d	=	array pitch
D	=	array antenna diameter
M	=	beam quality factor
R	=	external load resistance
V	=	detector output
x, y	=	coordinates
α	=	incident angle of the pilot signal to the antenna
δ, φ	=	phase difference
η	=	conversion efficiency
λ	=	wavelength
θ_{str}	=	steering angle

I. Introduction

Wireless Power Transmission (WPT) for an Micro Aerial Vehicle (MAV) using a microwave beam has been studied. WPT has been intensively studied as the technology for Solar Power Satellite (SPS) systems, in which microwave is transmitted from a satellite to the ground. [1,2] As its spin-off, a phased array transmitter system for MAV power supply has been developed. The concept of our MAV WPT system is following. A MAV, working over the area struck by a disaster, for example, comes back to a power station to charge its battery when the battery becomes low. The battery is charged by receiving a microwave beam transmitted from the power station while the vehicle is circling over the station. Thereby, this system enables the MAV to charge semi-automatically without landings and take-offs. Figure1 shows a schematic of the system. [3, 4] It can steer the beam by tracking a MAV model while it is flying over the antenna and an electric motor on the MAV model is driven by transmitted power.

Our WPT system consists of three subsystems; the transmitter system, the rectenna system, and the tracking system. A microwave beam is formed and its steering angle is controlled in the transmitter system. The transmitted microwave is received and rectified (converted from AC into DC) in the rectenna system on a MAV. In the tracking

[1] Graduate student, Department of Advanced Energy, Kashiwanoha 5-1-5, Kashiwa, Chiba, Student member.
[2] Graduate student, Department of Aeronautics and Astronautics, Hongo 7-3-1, Bunkyo, Tokyo, Student member.
[3] Associate professor, Department of Advanced Energy, Kashiwanoha 5-1-5, Kashiwa, Chiba, Senior member.
[4] Professor, Department of Aeronautics and Astronautics, Hongo 7-3-1, Bunkyo, Tokyo, Senior member.

system, the position of MAV is computed by analyzing the MAV's pilot signal and the information is send to the phase controllers in the transmitter system. Details of each sub-system are described in the following sections. By integrating these systems, power is supplied to the MAV circling over the transmitter.

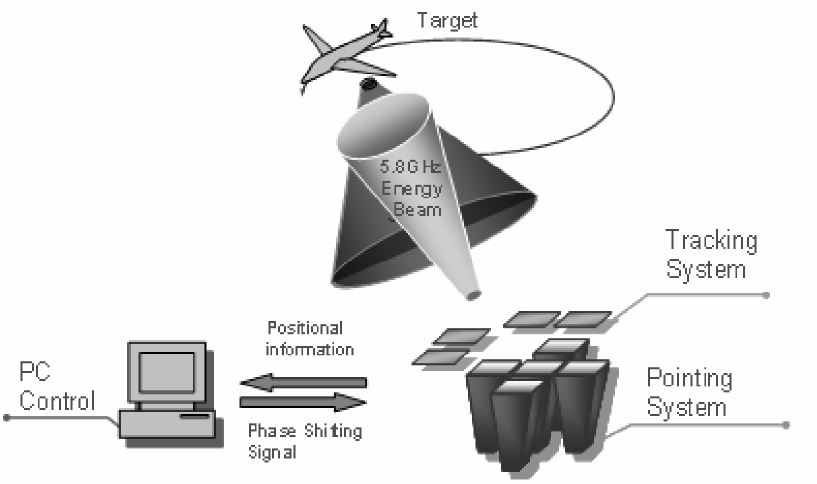


Figure 1. Schematic of the microwave power supply system to MAV.

II. Development of Subsystems

A. Transmitter System

Pointing and steering of a 5.8GHz microwave beam was achieved by controlling the phase of microwaves emitted from a five-element antenna called a phased array, not by mechanical control of the antenna's attitude.

Figures 2 and 3 show the pictures of the microwave circuits and the five-element arrayed antenna, respectively. Five horn antennas were arranged to form one large beam aperture and to steer the beam in the *x-y* directions. Each horn antenna transmits 0.7W power and phase of microwaves was controlled by the 6-bit digital phase shifter controlled by a PC. The beam divergence was about 9deg, which corresponds to the beam quality factor M^2=1.6. The range of beam steering θ_{str} was from -9deg to +9deg. Specifications of the transmitter are listed in Table 1.

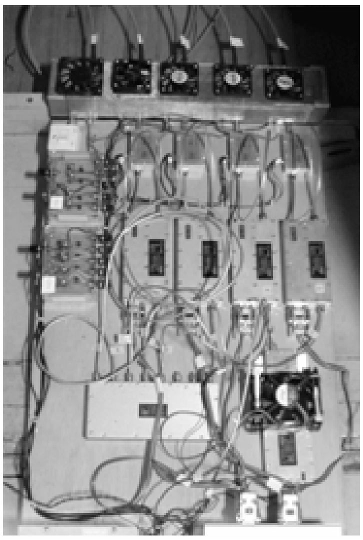


Fig. 2. The picture of the antenna array system.

Fig. 3. The picture of the five arrayed antenna elements.

Table 1. Specifications of the five-element phased array antenna.

Parameters	values
microwave frequency	5.8GHz
wavelength, λ	51.7mm
total transmission power, P	3.5W
array pitch, d	110mm (d/λ=2)
diameter of the array, D	330 mm

B. Rectenna System

The rectenna system consists of a receiver antenna on the front side and a rectifier circuit on the back side (Fig.4). The patch antenna for circular polarization was used as a receiver antenna for constant power conversion at various MAV's yaw angle with respect to the polarization axis of the transmitted wave. Measured rectification efficiency of our in-house rectenna is shown in Fig. 5. Optimum load impedance is about 240Ω and the efficiency at 1mW level is 20% at maximum.

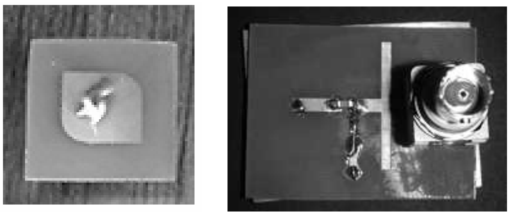


Fig. 4 A patch antennas for circular polarization (left) and rectifier circuit (right).

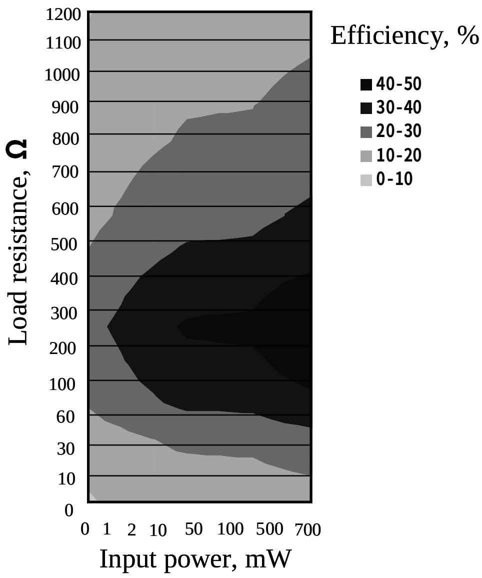
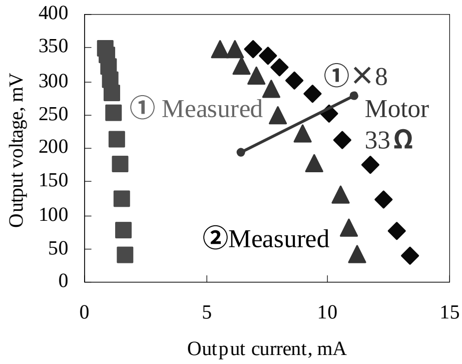


Fig. 5 Rectification efficiency.

To obtain electric power enough to drive an electric motor on an MAV, eight rectennas was connected in parallel as shown in Fig.6. Because the rectifier circuit size became bigger than the antenna size, the rectifier circuit was set vertical to the antenna surface to achieve high antenna density and high reception efficiency.

Figure 7 shows the rectifying characteristic of single and eight-rectenna arrays at 60cm from the transmission antenna. The measured output current of the eight-element array was slightly lower than the current of eight times of the single rectenna output. The electric motor can operated at optimum rectenna efficiency in power. As a result, the electric motor driving was demonstrated at the altitude of 60cm from the transmitter emitting 3.5W power in total.

Fig. 6. Eight-rectenna array.



(a) ① Measurement efficiency of 1 rectenna
(b) ② Measurement efficiency of 8 renctennas

Fig. 7. I-V characteristics of single and eight-rectenna arrays.

C. Tracking System

In the tracking system, the software retro-directive function is applied. Multiple antennas on the ground receive a pilot signal of 5.8 GHz microwave sent from the MAV and its position is analyzed using the phase difference in the signals received by these antennas. Figure 8 shows the block diagram tracking system.

For tracking a MAV in 2-Dimension space while it is circling (despite of the MAV yaw angle) one patch antenna for circular polarization was set for transmitter of the pilot signal and two patch antennas with same pattern were aligned as a receiver for each axis. The cable which makes π/2 of phase difference was inserted in one line. Divided and combined microwave signals are rectified using a commercially available detectors. Finally three DC outputs V_0, V_{com0}, V_{com1}, V_1 are read in the PC. The incident angle of a pilot signal α is computed by a LabVIEW program.

Figure 8 shows expected relationship between incident angle α for x axis and output signal V_{com1} / V_1 by following equation Eqs. (1) and (2).

$$\phi = (d/\lambda)\sin\alpha \tag{1}$$

$$V_{com1}/V_1 = 2 + 2\cos(\pi/2 - \phi) \tag{2}$$

As plotted in Fig. 9, α can be uniquely determined from the measured V_{com1} / V_1. Also, the incident angle for *y* axis can be determined using the same method.

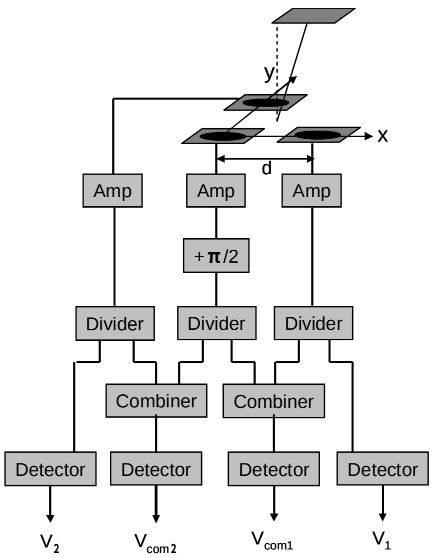


Fig. 8. The block diagram of tracking system.

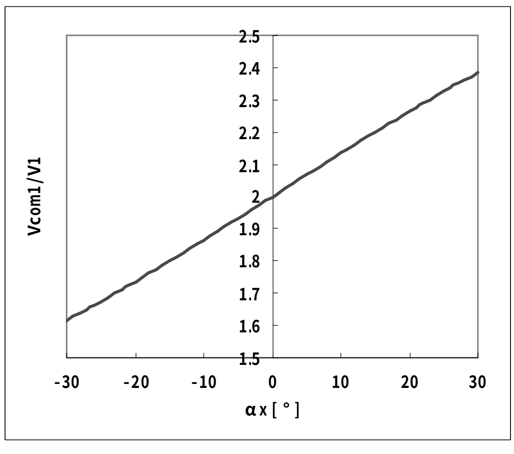


Fig. 9. Expected relationship between incident angle α and output signal V_{com1} / V_1.

III. Power Transmission Demonstration

Figure 10 shows the installation of equipment for power transmission demonstration. The MAV model circles over the transmitter antenna at the altitude of 60cm using another electric motor. An electric motor with a propeller of 6cm in diameter was mounted on the MAV model and the output voltage from the rectenna array was measured while the MAV model is circling.

Moreover the output voltage which was measured while the point of the microwave beam and the point of the MAV model were synchronizing was plotted in Fig.11. (The tracking system was not integrated yet.) The output voltage was always higher than the minimum condition for operation of 0.2V.

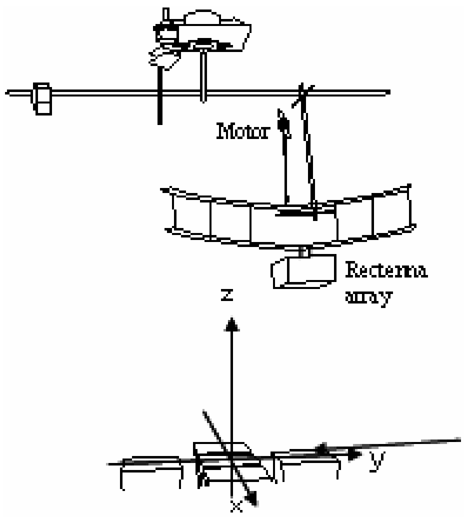


Fig. 10. Installation of equipment for power transmission demonstration.

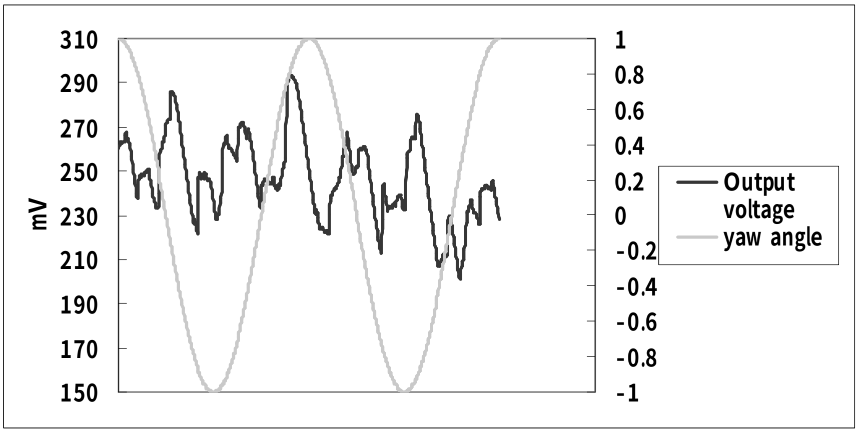


Fig.11. Rectenna output voltage and difference between yaw angle and direction of linearly-polarized wave while the microwave beam synchronized the MAV

IV. Experiment of the Tracking system

The output voltage of V_{com} for x axis was measured in two different moving of the transmitter antenna. Figure 12 shows the output voltage while the transmitter antenna was moved toward x axis with y=0. The value of V_{com} showed an upward tendency as expected though some points were deviated from the line. It is inferred that fabrication accuracy of antennas caused these points.

The output voltage reaction to change of yaw angle was measured in Figure 11. As long as MAV was at one point the output voltage V_{com1} / V_1 was constant at various yaw angles. Therefore this system can detect the MAV's position despite of the change of yaw angle.

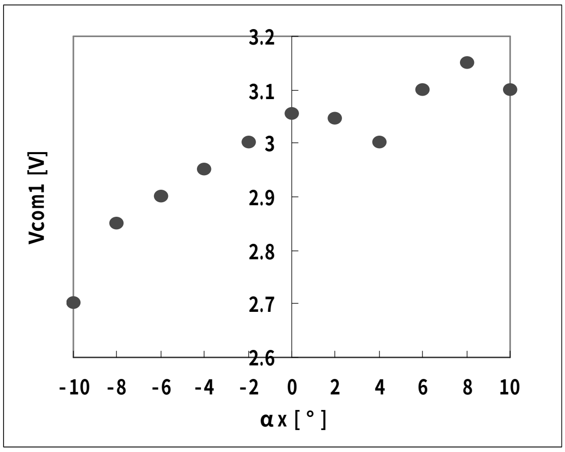


Fig.12. The output voltage while the transmitter antenna was shifted in x axis. (y=0)

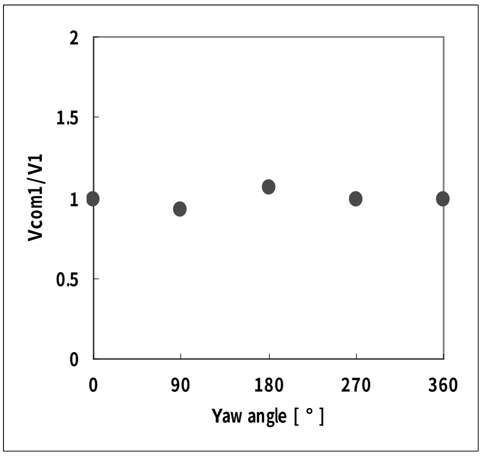


Fig.13. The output voltage reaction to change of yaw angle.

V. Conclusions

Wireless Power Transmission system to a MAV model was developed. A phased array transmitter, and rectenna array receiver with patch antennas for circular polarization were integrated.

Although the transmitted power from the phased array was only 3.5W, an electric motor mounted on a MAV model flying at the altitude of 60cm was successfully driven by the transmitted microwave power.

Software retro-directive tracking system is still under development.

Acknowledgments

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