Millimeter Wave Power Transfer to an Autonomously Controlled Micro Aerial Vehicle*

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The present paper is the first report of an experimental study on the energy efficiencies in the millimeter wave power transfer to an autonomously-controlled micro aerial vehicle (MAV). A tight beam of millimeter wave at 28 GHz was transmitted vertically upward, and a quad-rotor type MAV was autonomously controlled using the iterative feedback tuning method to hover over the beam and receive the millimeter wave power. The maximum value of the receiver efficiency was (1±2) × 10⁻³ and its duty ratio was 0.29±0.08, for which the distance between the MAV and the millimeter wave transmitter was 800 mm. The energy loss and the low duty ratio were both due mostly to the loss in the capture efficiency due to the location scattering of the MAV.

Key Words: Autonomous Flight Control, Multicopter, Iterative Method, Wireless Power Transmission

Nomenclature

\( d \): distance between drone and horn antenna [mm]
\( h \): altitude above ground [m]
\( I \): power density of millimeter wave [W/m²]
\( K_y \): yaw controller gain
\( K_u \): \( u \) controller gain
\( K_v \): \( v \) controller gain
\( K_z \): altitude controller gain
\( K_{\phi} \): roll controller gain
\( K_{\psi} \): pitch controller gain
\( r \): yaw rate
\( u \): translational velocity along \( x_b \) body frame [m/s]
\( v \): translational velocity along \( y_b \) body frame [m/s]
\( w \): beam radius of millimeter wave [m]
\( x, X \): \( x \) coordinate in inertial frame/on E-plane
\( y, Y \): \( y \) coordinate in inertial frame/on H-plane
\( z \): \( z \) coordinate in inertial frame
\( \phi \): roll angle [deg]
\( \eta \): energy conversion efficiency
\( \lambda \): wavelength [m]
\( \theta \): pitch angle [deg]
\( \psi \): yaw angle [deg]

Superscripts

ref: reference

1. Introduction

Today, electric-powered micro aerial vehicles (MAVs) are being implemented in real societies. Their applications cover a broad range of fields, including observation, data acquisition, disaster monitoring, couriers, and so on.1) Nevertheless, limited flight duration restricts their applicability. Typical flight duration is 10 min, depending on the size, payload, flight conditions, and battery capacity. Along with progress in battery technology, wireless power transfer (WPT) technology will be useful for extending flight duration.

WPT via magnetic resonant coupling has been studied mainly for charging electric ground-vehicles at near field.2) An inductively-coupled WPT for MAVs has been demonstrated. The MAV was a 24 cm reference size and 27 g in weight. The MAV received electric power of 8 W at 10 cm above a power source of 30 W/430 MHz.3) For such magnetic resonant WPTs to operate efficiently, an MAV carrying a receiver must stay in close proximity to a transmitter, and therefore it is not feasible to apply this method for in-flight charging.

In contrast, microwave power transfer (MPT) enables power supply to aircrafts at far field. A rectenna (rectifier + antenna) positioned underneath the aircraft fuselage and wings receives the microwave transmitted from the ground, and rectifies the microwave power into direct current (DC) power for charging onboard batteries. MPT-to-aircraft was first exploited by Brown, who is the pioneering researcher of rectenna-based MPT systems. He demonstrated a microwave-powered helicopter flight in the 1960s.4–6) A 2.3 kg (5 lb) single-rotor helicopter received electric power from a 5 kW magnetron operated at a frequency of 2.45 GHz. Continuous flight at an altitude of 15 m (50 ft) for 10 h was demonstrated, while the attitude and position of the helicopter were maintained by wires. Vitale demonstrated an MPT system to power a small propeller fixed on a table using a 1.3 GHz microwave generator.7) Dunber et al. developed a 5.9 GHz lightweight flexible rectenna array and power management circuit. They proposed a charging method for a fixed-wing MAV after landing, fixed on the ground.8) While the target objects were fixed in the experiments mentioned above, “free-flight” demonstrations of MPT-to-aircraft have
been performed by a few research groups. The Stationary High Altitude Relay Platform (SHARP) experiment was performed by the Communication Research Centre in Canada in 1987.9) A 2.45 GHz/10 kW microwave was transmitted to a fixed-wing airplane model flying at approximately 150 m above the ground. Energy Transmission toward High-altitude long endurance airship ExpeRiment (ETHER) was conducted by Kobe University in 1995.10) A 2.45 GHz/10 kW microwave beam was transmitted to an airship flying approximately 45 m above the ground. In these two demonstrations, movable parabolic antennas were used to direct the microwave beam to the flying target. In the MILAX project conducted by Kyoto University, a phased array retro-directive system was first demonstrated to direct a microwave beam to a flying object.11) A 2.4 GHz/1.25 kW microwave beam was formed using a phased array consisted of 288 antennas, with a diameter of approximately 1.3 m, and was directed from the roof of a car toward a fixed-wing airplane, whose position was identified using images from two charge coupled device (CCD) cameras mounted on the roof of the car, flying over the car approximately 10 m above the ground. The maximum DC power obtained on the airplane was approximately 88 W, which was sufficient for the fuel-free flight of the airplane, but means that only 7% of the transmitted power could be utilized.

The overall energy efficiency of an MPT system is the product of the efficiency of the microwave transmitter system and the efficiency of the receiver system. Then, the overall efficiency of a receiver system, \( \eta_{\text{rec}} \), is the product of \( \eta_{\text{cap}} \), \( \eta_{\text{int}} \), and \( \eta_{\text{conv}} \), where \( \eta_{\text{cap}} \) is the capture efficiency, defined as the fraction of the power of transmitted microwave beam that is received over the area of rectenna surface; \( \eta_{\text{int}} \) is the aperture efficiency, defined as the fraction of the received microwave power that is collected as RF power in a single unit of rectenna circuit; \( \eta_{\text{int}} \) is the integration efficiency, defined as the ratio of \( \eta_{\text{a}} \) for arrayed rectenna to that for a single unit of rectenna; and \( \eta_{\text{conv}} \) is the rectification efficiency or the RF-DC conversion efficiency, defined as the fraction of the collected radio frequency (RF) power in a unit of rectenna circuit that is rectified and converted to the DC power.

The present paper focuses on the capture efficiency, which is strongly dependent on the microwave frequency. In all the free-flight demonstrations mentioned above, the microwave frequency used was 2.4 GHz. The minimum spot diameter of a microwave beam has the same order as the wavelength of microwave, \( \lambda \), due to the diffraction limit. \( \lambda \) is defined as \( c/f \), where \( c \) is the speed of light and \( f \) is the frequency. The wavelength of the microwave at \( f = 2.4 \) GHz is approximately 120 mm, whereas it is 10 mm at \( f = 28 \) GHz, which corresponds to the millimeter wave. In order to attain high capture efficiency, the beam spot diameter should be kept smaller than the surface area size of the receiving surface. Because the typical size of MAVs is several tens of millimeters, millimeter waves are more suitable for MPT-to-MAV in terms of the capture efficiency than the conventional microwave frequencies. In our previous study, an MPT system of a 5.8 GHz phased array transmitter was tested as a preliminary study prior to extending the frequency to the millimeter wave range.12) In the present study, we report the first free flight test of an MPT-to-MAV system using a 28 GHz millimeter transmitter.

Another feature of the present study is the autonomous control of the MAV in accordance with the MPT system. A strong linkage between transmitter and receiver must be maintained to attain a high level of capture efficiency. In real situations, the linkage must be maintained automatically through the cooperative control of the beam direction and the MAV motion. In the previous free-flight experiments mentioned so far, the aircraft has been controlled manually, while the beam direction was controlled automatically. In such a system, it is difficult to analyze theoretically the balance of the energy efficiency quantitatively. Here, as an intermediate step in constructing a fully cooperatively-controlled system, we decided to test autonomous control of only the position and attitude of the MAV, while the beam direction is fixed vertically.

To the best of the authors’ knowledge, such an experiment of millimeter wave power transmission to an autonomously-controlled MAV is performed here for the first time. The authors believe that the results provide a valuable reference of the energy efficiencies in such an autonomously-controlled MPT-to-aircraft system.

2. Experimental Setup

2.1. Millimeter wave transmitter

The millimeter wave transmitter consists of a dielectric resonance oscillator (DRO, VG14-28G, Vega Technology Inc.), an amplifier (WPAC172PG, Advanced Microwave Inc.), an isolator, a 20 dB directional coupler with a power meter (R8466A, E4419B, Keysight Technologies Inc.), and a 25 dBi horn antenna (7A-67/25, Baytron), as illustrated in Fig. 1. The frequency of the transmitted millimeter wave was 28 GHz. The transmitted power was fixed at 2.04 W. The cross-section of the horn antenna exit was a square of 65 mm \( \times \) 50 mm. For \( d > 2L_b^2/\lambda \), where \( L_b \) is the diagonal length of the horn antenna exit, the electromagnetic wave can be considered far-field and the beam profile can be approximated as Gaussian. However, in the present case, the critical value of \( d \) was 1260 mm because \( L_b = 65 \) mm, and all the experiments were performed at \( d = 300 \) mm and 800 mm within the near-field.

In the experiments, an MAV was autonomously controlled to maintain the horizontal and the vertical location as illustrated in Fig. 1. The hovering test was done at two different altitudes, at \( d = 300 \) mm and 800 mm, both of which correspond to the near field of the millimeter wave. The power density profiles were measured using a power meter both on the E-plane and H-plane as shown in Fig. 2. The power density profile is approximated by the following function:

\[
I(x, y) = I_0 \exp(-2x^2/w_E^2 - 2y^2/w_H^2)
\]

\( w_E \) corresponds to the beam radius on the E-plane and \( w_H \), H-plane, both of which are estimated by fitting Eq. (1) on the
measured beam profile for each \(d\), as shown in Fig. 2. For \(d = 300\) mm, \(w_E = 45\) mm and \(w_H = 50\) mm. For \(d = 800\) mm, \(w_E = 131\) mm and \(w_H = 110\) mm.

### 2.2. Rectenna

The detailed design of the rectenna has been described in our previous paper.\(^{13}\) A four-element micro-strip patch antenna with F-class load rectifier was used. The size of a unit rectenna was \(18\) mm \(\times\) \(15\) mm. In the experiment, a \(2 \times 2\) rectenna array connecting four unit rectennas in parallel was used. Its surface area was \(36\) mm \(\times\) \(30\) mm, which was smaller than the millimeter wave beam spot size.

In the hovering test, the energy balance of \(\eta_{\text{rec}}\) consisting of \(\eta_{\text{cap}}, \eta_{\text{a}}, \eta_{\text{int}},\) and \(\eta_{\text{conv}}\) was estimated on the basis of the time-series data of the positions and the attitudes of the MAV to clarify the effect of the dynamics of the autonomously-controlled MAV on the energy balance. \(\eta_{\text{cap}}\) was estimated by integrating the beam profile over the surface area of the rectenna array, whose position relative to the millimeter wave beam spot was estimated from the data of the indoor GPS unit. The reflection coefficient of the four-element antenna, \(S_{11}\) was \(-19.4\) dB at \(28\) GHz. The gain of the antenna, \(G\), was measured using the comparison method, as shown in Fig. 3. The maximum value was 10.7 dBi and the half-gain width was from \(-12\) to \(21\) deg on the E-plane (that is, the plane containing the electric field vector), along the roll angle, \(\phi\), and from \(-20\) to \(10\) deg on the H-plane along the pitch angle, \(\theta\). The maximum antenna gain has been formulated as \(G = 32000/(\theta_E \theta_H)\) where \(\theta_E\) is the beam power half width on the E-plane in degrees, and \(\theta_H\) is that on the H-plane.\(^{14}\) From this formula, the maximum value of \(G\) is calculated to be 18 dBi, as we assume that \(\theta_E = 21\) deg and \(\theta_H = 20\) deg. However, as is pointed out in the literature,\(^{15}\) the formula tends to overestimate the gain for such an antenna of large sidelobe as in the present case. Numerical simulation results determined using the software EMPro are also shown in the figure. The simulated results agree reasonably well with the measured results both on the E-plane and the H-plane. The difference should be due to manufacturing errors. The aperture efficiency, \(\eta_{\text{a}}\), for a single unit of rectenna is estimated using the formula.
where $A_a$ is the aperture area of a unit rectenna.\(^{15}\) The maximum value of $\eta_a$ was approximately 0.4 for $\phi = \theta = 0$ deg. For estimating $\eta_a$, $G$ was estimated as a function of $\phi$ and $\theta$ on the basis of the measured results.

$\eta_{int}$ is equal to the ratio of $\eta_a$ for arrayed rectenna to that for a single unit rectenna. $\eta_a$ for arrayed rectenna is affected by the spacing between every single unit of rectenna. $\eta_a$ drops sharply when the spacing becomes larger than the wavelength of the transmitted electromagnetic wave.\(^{16}\) In the present paper, we leave the influence of the array spacing on $\eta_a$ for future works, and we assume here a constant value of $\eta_{int}$ to investigate the energy balance of the receiving system.

$\eta_{conv}$ for a unit rectenna is plotted as a function of the input RF power in Fig. 4. The maximum value was 55.5% for input RF power at 245 mW and 132 $\Omega$ load. The major energy loss was due to the line loss at approximately 44.3%. $\eta_{conv}$ is a nonlinear function of the input RF power. $\eta_{conv}$ of a unit rectenna circuit was measured changing the input RF power from 1.95 mW to 368 mW, and its trend was fitted to a polynomial functions of the input RF power to estimate $\eta_{conv}$ of the parallel connected four-element array of rectenna used in the flight tests.

### 2.3. MPS-to-MAV system

An AR.Drone\(^{2.0}\) (Parrot Inc.) was used as the MAV. The AR.Drone\(^{2.0}\) is equipped with an autopilot system for sensing, controlling, and communicating as illustrated in Fig. 5. The centerpiece of the autopilot hosts a 32-bit ARM Cortex A8 processor with 800 MHz video DSP TMS320DMC64x.\(^{21}\) It has an embedded Linux 2.6.32 operating system and has 1 GB DDR2 RAM running at 200 MHz. The navigation system contains all the sensors necessary for the state estimation of the quadcopter.

A 6-degree of freedom (dof) inertia measurement unit (IMU) is installed to measure roll, pitch, and yaw angles. A three-axis gyro, a three-axis accelerometer, and a three-axis magnetometer are included in the IMU. For the altitude measurement, a couple of ultrasonic sensors are used at altitudes lower than 5 m from the ground, and a pressure sensor at higher altitudes. The communication between the MAV and the ground computer is through wifi. The ARM processor simultaneously manages the wireless communications, state estimation, and control algorithms. The horizontal location of the MAV was identified using an additionally-installed indoor navigation system (Marvelmind HW v4.9). Four stationary beacons were located at the top corners of the room. A mobile beacon was installed on the top of the MAV body.

The error of the location data is approximately 20 mm. In the flight experiment, the $2 \times 2$ rectenna array was placed underneath the body of the AR.Drone as shown in Fig. 6. In the flight experiment, the rectenna array was connected to a 132 $\Omega$ load to measure the received DC power. The flight test was performed inside a room (2.0 m $\times$ 2.3 m $\times$ 2.5 m), which was electrically shielded using wire gauze. The horn antenna was directed vertically, and its exit was located 250 mm above the ground.

### 2.4. Method of autonomous flight control

The IFT algorithm was implemented for the position control of the vehicle. IFT is a model-free approach appropriate for tuning parameters of high-level controllers in multistage structure as is the case for the autonomous flight controller.\(^{17-19}\) The IFT method has been implemented in a wide range of applications.\(^{20-25}\) A cascade IFT has been implemented in the attitude control of a quadcopter.\(^{26}\)
The goal of the autonomous flight controller design task is to ensure that the drone follows a given trajectory specified by a sequence of waypoints. The 2-dof feedback loop of the autonomous controller, illustrated in Fig. 7, consists of a high-level position controller that tracks the drone position relative to the desired path and calculates velocity references for mid-level velocity controllers. The output of the velocity controller will be fed to the low-level attitude controller.

For the AR.Drone used in the present study, the transfer functions from $\theta^{\text{ref}}$ to $u$, $\phi^{\text{ref}}$ to $v$, $\psi^{\text{ref}}$ to $h$, and $r^{\text{ref}}$ to $\psi$ have been specified through identification processes.\(^2\)

\[
\begin{align*}
u(t) &= \frac{-15.47s - 29.95}{s^3 + 4.64s^2 + 14.56s + 7.93} \\
v(t) &= \frac{7.08s - 16.82}{s^3 + 4.73s^2 + 14.65s + 5.83} \\
\psi(t) &= \frac{1.265}{s + 0.0059} \\
h(t) &= \frac{0.153s + 5.153}{s^2 + 5.82s}
\end{align*}
\]

The cost functions corresponding to $x, y, h$, and yaw controller are defined as

\[
\begin{align*}
J_x(K_u, K_\phi) &= \frac{1}{2N} \sum_{t=1}^{N} [x^{\text{ref}}(t) - x(t, K_u, K_\phi)]^2 \\
J_y(K_v, K_\psi) &= \frac{1}{2N} \sum_{t=1}^{N} [y^{\text{ref}}(t) - y(t, K_v, K_\psi)]^2 \\
J_h(K_u) &= \frac{1}{2N} \sum_{t=1}^{N} [h^{\text{ref}}(t) - h(t, K_u)]^2 \\
J_\psi(K_\psi) &= \frac{1}{2N} \sum_{t=1}^{N} [\psi^{\text{ref}}(t) - \psi(t, K_\psi)]^2
\end{align*}
\]

The evaluation of these cost functions with respect to controller parameters is shown in Fig. 8. The $x$ controller and $y$ controller execute 60 iterations, while the $h$ controller and yaw controller execute 30 iterations. It is shown that these cost functions tend to converge to the minimum values. These results demonstrate that the controller gains are tuned in such a way that good tracking properties are achieved after each iteration. The optimal values of controller parameters are tabulated in Table 1.

![Fig. 7. Architecture of the feedback controller.](image)

![Fig. 8. Convergence of cost functions of $x$, $y$, $h$, and $\psi$ controllers.](image)

| $K_v$ | $K_u$ | $K_\phi$ | $K_\psi$ | $K_r$ | $K_w$ |
|-------|-------|---------|---------|-------|-------|
| 0.8   | -0.5  | 0.7     | 0.7     | 1.5   | 1.2   |

3. Results

Figure 9 shows the receiver efficiency of the $2 \times 2$ rectenna array measured changing its position along the X-axis/E-plane. $\eta_{\text{rec}}$ was calculated from the measured voltage of the load resistor, and $\eta_{\text{cap}}\eta_{\text{a}\text{int}}\eta_{\text{conv}}$ was calculated by multiplying the estimated components: $\eta_{\text{cap}}$, $\eta_{\text{a}}$, $\eta_{\text{conv}}$, and $\eta_{\text{int}}$. Although $\eta_{\text{rec}}$ and $\eta_{\text{cap}}\eta_{\text{a}\text{int}}\eta_{\text{conv}}$ coincide with each other in principle, there is a difference due to an assumption in estimating $\eta_{\text{cap}}$, $\eta_{\text{rec}}$ and $\eta_{\text{cap}}\eta_{\text{a}\text{int}}\eta_{\text{conv}}$ are quite close, especially near the center, at $X = 0$. At $X = 0$, the peak value is approximately 0.004 for $d = 300$ mm, and it is 0.0012 for $d = 800$ mm. Estimated values of $\eta_{\text{cap}}$, $\eta_{\text{a}}$, $\eta_{\text{int}}$, and $\eta_{\text{conv}}$ are also shown in Fig. 9. As is evident from the figure, the relation between $\eta_{\text{rec}}$ and $X$ is dominated by $\eta_{\text{cap}}$, whereas $\eta_{\text{a}}$ and $\eta_{\text{int}}$ are mostly constant, and $\eta_{\text{conv}}$ just yields to the change in the input RF power determined by $\eta_{\text{a}}$. The $\eta_{\text{cap}}$ rose sometimes when the MAV could stay near the Z-axis equal to the beam. The maximum value is around 0.2 in this case, and the duty ratio of the $\eta_{\text{cap}}$ signal was around 20%. Because $\eta_{\text{conv}}$ increases with increasing input power, $\eta_{\text{conv}}$ rose only when $\eta_{\text{cap}}$ rose. Time-series data of $\eta_{\text{rec}}$ and $\eta_{\text{cap}}\eta_{\text{a}\text{int}}\eta_{\text{conv}}$ rose at slightly different timing. Moreover, the peak values of $\eta_{\text{rec}}$ and $\eta_{\text{cap}}\eta_{\text{a}\text{int}}\eta_{\text{conv}}$ are quite different from each other at each timing. The main cause of these differences in the peak values originates from the error in the GPS data. Figures 12 and 13 show the data...
for $d = 800$ mm. The trends appear similar as for $d = 300$ mm.

The hovering test was performed several times for each condition. As a result, for $d = 800$ mm, the mean value of the duty ratio of $\eta_{\text{rec}}$ was $0.3 \pm 0.1$, which was consistent with that of $\eta_{\text{cap}}$ and $\eta_{\text{int}}$ and $\eta_{\text{conv}}$. The maximum value of $\eta_{\text{rec}}$ was $(1 \pm 2) \times 10^{-3}$ as an average over several tests, and that of $\eta_{\text{cap}}$, $\eta_{\text{int}}$, and $\eta_{\text{conv}}$ was $(1.0 \pm 0.2) \times 10^{-3}$. The differences between these averaged values of $\eta_{\text{rec}}$ and $\eta_{\text{cap}}$, $\eta_{\text{int}}$, and $\eta_{\text{conv}}$ are within the error. Further studies are necessary to understand the mechanisms of MAV’s location scattering, and to find a method to suppress it. We shall leave them for the following studies.
4. Summary

Energy efficiencies in the millimeter wave power transmission to an autonomously-controlled MAV were investigated experimentally for the first time. A beam of millimeter wave at 28 GHz was transmitted vertically, and a quad-rotor type MAV was autonomously controlled to hover over the beam. The results of the hovering experiments showed that the maximum value of $\eta_{\text{rec}}$ was $(1 \pm 2) \times 10^{-3}$ and the duty ratio of $\eta_{\text{rec}}$ was $0.3 \pm 0.1$, for which the distance between the MAV and the millimeter wave transmitter was 800 mm. The rough estimate of the balance in the maximum value of $\eta_{\text{rec}}$ consists of $\eta_a$ at 0.4, $\eta_{\text{int}}$ at 0.8, $\eta_{\text{cap}}$ at 0.05, $\eta_{\text{conv}}$ at 0.1. $\eta_a$ depends on the antenna gain, which can be enhanced by the antenna design. $\eta_{\text{conv}}$ can be enhanced by the circuit design. In order to enhance $\eta_{\text{cap}}$, it is necessary to suppress the location-scattering of the MAV, which originates from the characteristics of the autonomously-controlled system coupled with flight dynamics.

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References

1) Indago USA. [Online] Available: http://www.lockheedmartin.com/us/products/procerus/indago-us.html (accessed 14-Sep-2017).
2) Campi, T., Cruciani, S., and Feliziani, M.: Wireless Power Transfer Technology Applied to an Autonomous Electric UAV with a Small Secondary Coil, Energies, 11 (2018), p. 352. https://doi.org/10.3390/en11020352
3) Nishikawa, H., Kitai, Y., Furukoshi, T., Yamaguchi, H., Tanaka, A., and Douseki, T.: UHF Power Transmission System for Multiple Small Self-rotating Targets and Verification with Batteryless Quadcopter Having Rotors with Embedded Rectenna, 2015 IEEE Wireless Power Transfer Conference (WPTC), Boulder, CO, 2015, pp. 1–4. https://doi.org/10.1109/WPT.2015.7140153
4) Brown, W. C.: Experiments Involving a Microwave Beam to Power and Position a Helicopter, IEEE Trans. Aerospace Electronic Syst., AES-5, 5 (1969), pp. 692–702. https://doi.org/10.1109/TAES.1969.309867
5) Brown, W., Mims, J., and Heenan, N.: An Experimental Microwave-powered Helicopter, IRE International Convention Record, Vol. 13, Part 5, March 1966, pp. 225–235. https://doi.org/10.1109/IRECON.1965.1147518
6) Brown, W. C., George, R. H., Heenan, N. I., and Wonson, R. C.: Microwave to dc Converter, U.S. Patent 3434678, March 25, 1969.
7) Vitale, R. L.: Design and Prototype Development of a Wireless Power Transmission System for a Micro Air Vehicle (MAV), Master’s Thesis, Naval Postgraduate School, Monterey, CA, USA, 1999.
8) Dunbar, S., Wenzl, F., Hack, C., Hafeza, R., Eisfer, H., Defay, F., Proth, S., Bajon, D., and Popovic, Z.: Wireless Far-field Charging of a Micro-UV, Proceedings of the IEEE Wireless Power Transfer Conference (WPTC), T1.2, May 2015. https://doi.org/10.1109/WPT.2015.7140154
9) Schlesak, J. J., Alden, A., and Ohno, T.: A Microwave Powered High Altitude Platform, Proceedings of the IEEE MTT-S International Microwave Symposium Digest, May 1988. https://doi.org/10.1109/MWSYM.1988.22031
10) Kaya, N., Ida, S., Fujino, Y., and Fujita, M.: Transmitting Antenna System for ETHER Air-ship Demonstration, Space Energy Transportation, 1, 4 (1996), pp. 237–245.
11) Shinohara, N.: Beam Control Technologies with a High-efficiency Phased Array for Microwave Power Transmission in Japan. *Proc. IEEE*, 101, 6 (2013), pp. 1448–1463.

12) Shimamura, K., Sawahara, H., Oda, A., Minagawa, S., Mizojiri, S., Suganuma, S., Mori, K., and Komurasaki, K.: Feasibility Study of Microwave Wireless Powered Flight for Micro Air Vehicles, *Wireless Power Transfer*, 4, 2 (2017), pp. 146–159. https://doi.org/10.1017/wpt.2017.9

13) Matsukura, M., Shimamura, K., Suzuki, M., Mizojiri, Yokota, S., Minami, R., Kariya, T., and Imai, T.: Instantaneous Measurement of High-power Millimeter-wave Beam for 28 GHz Gyrotron, *Rev. Sci. Instruments*, 90 (2019), 024703. https://doi.org/10.1063/1.5050957

14) IECE Japan: *Antenna Engineering Handbook*, Ohmsha, Tokyo, 1980, p. 154.

15) Balanis, C. A.: *Antenna Theory: Analysis and Design*, 3rd ed., Wiley-Interscience, New Jersey, 2005, Section 2, pp. 50–52.

16) Shinohara, N., ed.: *Solar Power Satellite/Station*, Ohmsha, Tokyo, 2012 (in Japanese).

17) Hjalmarsson, H., Gunarsson, S., and Gevers, M.: A Convergent Iterative Restricted Complexity Control Design Scheme, Proceedings of the 33rd IEEE Conference on Decision and Control, Orlando, FL, 1994, pp. 1735–1740.

18) Hjalmarsson, H., Gevers, M., Gunarsson, S., and Lequin, O.: Iterative Feedback Tuning: Theory and Application, *IEEE Control Syst. Mag.*, 18, 4 (1998), pp. 26–41. https://doi.org/10.1109/37.710876

19) Lequin, O., Gevers, M., Mossberg, M., Bosmans, E., and Triest, L.: Iterative Feedback Tuning of PID Parameters: Comparison with Classical Tuning Rules, *Control Eng. Practice*, 11, 9 (2003), pp. 1023–1033. https://doi.org/10.1016/S0967-0661(02)00303-9

20) Gevers, M.: A Decade of Progress in Iterative Process Control Design: From Theory to Practice, *J. Process Control*, 12, 4 (2002), pp. 519–531. https://doi.org/10.1016/S0959-1524(01)00018-X

21) Yang, P. H. and Koo, S. L.: Control Systems and Methods Applying Iterative Feedback Tuning for Feed-forward and Synchronization Control of Microlithography Stages and the Like, U.S. Patent 8,451,431 B2, May 28, 2013.

22) Kissling, S., Blanc, Ph., Myszkorowski, P., and Vaclavik, I.: Application of Iterative Feedback Tuning (IFT) to Speed and Position Control of a Servo Drive, *Control Eng. Practice*, 17, 7 (2009), pp. 834–840. https://doi.org/10.1016/j.conengprac.2009.02.005

23) Prochazka, H., Gevers, M., Anderson, B. D. O., and Ferrera, C.: Iterative Feedback Tuning for Robust Controller Design and Optimization, Proceedings of the Conference on Decision and Control, and the European Control Conference, Seville, Spain, 2005, pp. 3602–3607.

24) Veres, S. and Hjalmarsson, H.: Tuning for Robustness and Performance Using Iterative Feedback Tuning, Proceedings of the 41st IEEE Conference on Decision and Control, Las Vegas, Nevada, 2002, pp. 4682–4687. https://doi.org/10.1109/CDC.2002.1185117

25) Haussom, J. K., Poulsen, N. K., and Jørgensen, S. B.: Improving Convergence of Iterative Feedback Tuning, *J. Process Control*, 19, 4 (2009), pp. 570–578. https://doi.org/10.1016/j.jprocont.2008.09.004

26) Tesch, D. A., Eckhard, D., and Guarienti, W. C.: Pitch and Roll Control of a Quadcopter Using Cascade Iterative Feedback Tuning, *IFAC-PapersOnLine*, 49, 30 (2016), pp. 30–35. https://doi.org/10.1016/j.ifacol.2016.11.118

27) Lugo, J. J. and Zell, A.: Framework for Autonomous On-board Navigation with the AR.Drone, *J. Intelligent Robotic Syst.*, 73, 1–4 (2014), pp. 401–412. https://doi.org/10.1007/s10846-013-9969-5

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