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A wireless radiofrequency-powered insect-scale flapping-wing aerial vehicle

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Insect-scale aerial vehicles are useful tools for communication, environmental sensing and surveying confined spaces. However, the lack of lightweight high-power-density batteries has limited the untethered flight durations of these micro aerial vehicles. Wireless power transmission using radiofrequency electromagnetic waves could potentially offer transmissivity through obstacles, wave-targeting/focusing capabilities and non-mechanical steering of the vehicles via phased-array antennas. But the use of radiofrequency power transmission has so far been limited to larger vehicles. Here we show that a wireless radio-frequency power supply can be used to drive an insect-scale flapping-wing aerial vehicle. We use a sub-gram radiofrequency power receiver with a power-to-weight density of $4,900 \text{ W kg}^{-1}$, which is five times higher than that of off-the-shelf lithium polymer batteries of similar mass. With this system, we demonstrate the untethered take off of the flapping-wing micro aerial vehicle. Our RF-powered aircraft has a mass of 1.8 g and is more than 25 times lighter than previous radiofrequency-powered micro aerial vehicles.

Micro aerial vehicles (MAVs) are of potential use in environmental sensing¹, communication^{2,3}, indoor entertainment⁴, search and rescue⁵, and the autonomous inspection of confined or dangerous areas⁶. However, MAV regulations are being tightened due to the risk of accidents from crashing MAVs. In the USA, for example, drones weighing over 250 g must be registered, and drone flight areas are heavily restricted⁷. Japan has also recently announced that the threshold weight of MAVs subject to flight restrictions will be reduced from 200 to 100 g (ref. ⁸). These intensified requirements demand smaller and lighter MAVs. In particular, as the collision energy of a falling aerial vehicle strongly depends on the vehicle mass, the safety of MAVs can be increased by designing and developing lightweight insect-scale MAVs.

The critical components in developing a fully untethered insect-scale MAV are the actuator, drive electronics and power supply. Although larger-scale MAVs generally employ electromagnetic motors as actuators, their efficiency is notably reduced when the vehicle size is decreased due to friction and resistance losses⁹. There are several other actuation mechanisms, including electrostatic, shape memory alloy and piezoelectric mechanisms. Considering the high speed and high output required for flights, piezoelectric actuation is the most promising mechanism¹⁰ and is commonly employed. As piezoelectric actuation generates reciprocal motion, a bioinspired flapping-wing mechanism is more suitable for insect-scale MAVs than a rotating propeller^{11–15}. Lightweight, high-voltage and high-power electronics for piezoelectric actuation have also been studied^{16–18}. However, the low energy density of conventional batteries makes them unsuitable for insect-scale MAVs¹⁹.

The most successful work of a battery-powered MAV is the *DeFly*^{20,21}. *DeFly Nimble* is, for example, a bird-scale 29 g tailless vehicle capable of hovering and moving in all directions²¹. *DeFly Micro* is an insect-scale model with a mass of 3 g (ref. ²⁰). However, this vehicle can only fly forward with the help of lift during translational movement and has no hovering capability. A similar vehicle (3.2 g, battery powered) has been developed with a maximum thrust force (4 gram-force (gf)) that exceeds its mass, but it lacks the additional actuators necessary for controlled flight²². At the insect scale,

there are currently no battery-powered vehicles capable of both controlled flight and hovering by supplying enough lift to support their own weight. Thus, alternative energy sources with higher power density are required to realize insect-scale MAVs that can fly freely.

The flight time of a bird-scale battery-powered MAV is usually less than 10 min. Therefore, even if an insect-scale battery-powered MAV can be created, it would be expected to have a short flight duration. To overcome this drawback, wireless power transmission via lasers or light has been developed^{23,24}. However, for indoor applications or in confined spaces, laser/light power transmission for small MAVs has serious limitations. Laser/light power transmission is easily blocked by obstacles, and fast and robust laser steering technology (for example, phased-array lasers^{25,26}) is still not readily available off the shelf. In contrast, radiofrequency (RF) electromagnetic waves can penetrate insulating obstacles or objects smaller than their wavelength, as demonstrated by mobile phone communications. These characteristics provide considerable advantages for indoor applications. In addition, beam-steering technology implemented by a phased-array system is very practical^{27–29}. Previous research on MAVs with RF power transmission has been limited to large multirotor vehicles weighing over a few dozen grams^{30–34}, and the feasibility of RF power transmission for insect-scale MAVs is still uncharted.

Beyond MAVs, there are earlier reports on RF power transmission to insect-scale robots^{35,36}. In particular, a walking robot powered by a piezoelectric actuator with a mass of 2.1 g has been developed³⁵. The power-receiving circuit in this robot has a maximum power output of 1 W and a mass of 200 mg, which may be applicable for the flight of an MAV of equivalent weight. However, the power transmission technology used in these studies is based on near-field electromagnetic waves; the robot cannot be far away from the transmitter. To transmit power to MAVs that can fly freely, a system using radiative, far-field electromagnetic waves is desirable.

In this Article, we report a sub-gram RF power receiver for 5 GHz far-field radiative electromagnetic waves with a power density that is sufficient for flight. We install the electronics on an insect-scale flapping-wing vehicle (Fig. 1a); the piezoelectric

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Fig. 1 | Integrated MAV with RF power receiver. a, Photograph of the fabricated aircraft. **b**, Configuration of flapping-wing actuators. **c**, Flight demonstration.

flapping-wing actuators are on the upper half of the vehicle and the electronics are mounted on the lower half. The electronics consist of three sets of 5 GHz dipole power-receiving antennas/rectifiers, a high-voltage three-channel driver for the flapping-wing actuators and a microprocessor. The vehicle has six independently actuated wings that are actuated in pairs (Fig. 1b). For a configuration with the same direction of motion in actuators and wings, this paired actuation scheme results in a low vibration energy loss and high lift force efficiency^{37,38}. Level flight can be achieved by adjusting the lift forces of the three pairs of actuator, and the vehicle can be successfully launched by the RF power supply with a transmission power of 30 W (Fig. 1c and Supplementary Video 1). Our vehicle is more than 25 times lighter than the previous vehicles powered by RF (Extended Data Table 1).

Power-receiving electronic system

Photographs and system schematic of the developed high-power-density, lightweight electronics are shown in Fig. 2a,b, respectively. The circuit was fabricated using standard mass-production flexible printed circuit (FPC) technology. Thermal management is a key factor for achieving a high power density because any concentrated overheating results in high power loss as well as destruction of the microscale electrical components. To distribute the power-loss heat, a multi-antenna/rectifier configuration was employed; the 5 GHz electromagnetic wave is received by three dipole antennas and converted to direct current (d.c.) power by three rectifiers (the schematic is shown in Extended Data Fig. 1a). The dipole antennas are fabricated from the FPC wiring of Cu patterns, such that the mass of the antenna is only 4 mg. The maximum power-receiving efficiency of the rectifier was approximately 67% (Extended Data Fig. 1c).

Because the voltage of the received electrical power can exceed the maximum input voltage of the digital components, that is, the microprocessor, it should be regulated to a digital-level voltage. We separated part of the electrical power and adjusted it to 3.3 V using a voltage regulator for the microprocessor (CC2640R2F, Texas Instruments). The remaining electrical power was also regulated with an upper limit of 6.0 V, which is the maximum input voltage of the 3.3 V voltage regulator. Next, the power source was boosted to yield a constant high voltage (175 V maximum) using a d.c.–d.c. converter (the schematic is shown in Extended Data Fig. 1b), as required for the piezoelectric drive. Then, it was reshaped into three square-wave actuation signals by a three-channel high-voltage driver controlled by the microprocessor (schematic of the microprocessor and high-voltage driver are shown in Extended Data Fig. 2a,b, respectively; the driving waveform is illustrated in Extended Data Fig. 3; connection diagram of the subcircuits is shown in Extended Data Fig. 2c).

Note that the high output voltage is restricted by the limit of transistors used in the high-voltage driver (T3 and T4; Extended Data Fig. 2a) in our system. The average power consumed by the microprocessor is only 20 mW, and most of the power is supplied to the actuation system. The square-wave actuation signal was 115 Hz, which was matched with the resonant frequency of the flapping-wing actuators to maximize the wing stroke. Finally, the square waves are sent to the flapping-wing actuators. The d.c.–d.c. converter efficiency was greater than 80% over a wide range of output power with a maximum efficiency of 83.1%, as shown in Fig. 2c.

Figure 2d shows the output voltage for the continuous driving of the electronics; the electronics successfully produced a high-voltage actuation signal without thermal runaway. The maximum output power of the power-receiving circuit (antenna and rectifiers) is

Fig. 2 | Electronics and power conversion system. **a**, Photograph of the fabricated MAV circuit. **b**, System overview. **c**, Efficiency of the d.c.-d.c. converter. **d**, Continuous drive demonstration by the RF power supply.

1.2 W, which is designed to meet the required power at the d.c.-d.c. converter start up. The total weight of the power receiver was 245 mg, and the power density was $4,900 \text{ W kg}^{-1}$. This is much higher than off-the-shelf lithium polymer batteries, for example, the mass and power density of a GM300910 battery (PowerStream Technology) are 330 mg and 897 W kg^{-1} , respectively, and those of GEB201212C (PowerStream Technology) are 500 mg and $1,200 \text{ W kg}^{-1}$, respectively.

Flapping-wing actuator and its performance

The actuation mechanism is another key performance factor for MAVs. The developed vehicle employs a very simple ‘direct-drive’ mechanism for wing actuation, as shown in Fig. 3a. The 32.40-mm-long biomimetic wing is directly connected to a 16.50-mm-long piezoelectric bending actuator composed of a 0.10-mm-thick piezoelectric layer laminated to a 0.13-mm-thick titanium elastic plate. The bending actuator was designed as a trapezoid with the top and bottom sides measuring 4.4 and 8.5 mm, respectively, to avoid

stress concentration. Owing to the high piezoelectric coefficient of single-crystalline $\text{Pb}(\text{In}_{1/2}\text{Nb}_{1/2})\text{O}_3\text{-Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-PbTiO}_3$ (TRS Technologies)³⁹ used in this study (its effective piezoelectric coefficient d_{32} is $-1,156 \text{ pm V}^{-1}$ (ref. ³⁹), which is two times higher than that of typical commercial piezoelectric ceramics under large electric fields⁴⁰), large flapping motions are possible without the need for a complex transmission mechanism to amplify the motion if the strain during actuation is sufficiently smaller than the fracture strain of the piezoelectric material.

In our previous design¹⁵, we achieved 312 mgf of lift (sinusoidal drive with a peak-to-peak voltage of 100 V) per actuator with a mass of 252 mg. To obtain sufficient payload capacity even with the installed electronics, we have improved the lift by reducing the vibration energy loss of the paired-wing configuration, and we have reduced the mass without reducing the lift by downsizing the actuators; this redesign was implemented in a previous report³⁸, and the approach of the redesign is described in Supplementary Section 4. The lift force and power consumption can be controlled by the duty ratio^{18,41,42}.

Fig. 3 | Overview and performance of flapping-wing actuator. a, Photograph of the flapping wing and actuation principle (inset shows the schematic). **b**, Duty ratio versus average lift force. **c**, Duty ratio versus consumed power. **d**, Consumed power versus lift force.

Figure 3b,c shows the performance of the fabricated paired actuator with a square-wave driving signal having a voltage amplitude of 140 V and frequency of 115 Hz. Here the driving signal was generated by a combination of high-voltage driver circuit and d.c. voltage source (PMX350-0.2A, Kikusui Electronics). Thus, the consumed power includes the loss in the high-voltage driver, which is expected to be less than 1 mW (mainly due to the leakage current of the n-type metal–oxide–semiconductor field-effect transistor (nMOSFET); T3 and T4 in Extended Data Fig. 2a), which is much smaller than the handling energy. The average maximum lift force per paired actuator is 880 mgf, allowing the MAV to take off; 600 mgf per paired actuator is required to launch the MAV because its total weight is 1,810 mg. From Fig. 3d, the required power per paired actuator is approximately 130 mW, and the total power consumed by the actuators is estimated to be 390 mW. The efficiency of the d.c.–d.c. converter at an output power of 390 mW required for continuous flight was 83% (Fig. 2c). Considering this efficiency in addition to the power consumed by the microprocessor and voltage regulator (20–36 mW), the total power consumption for continuous flight is approximately 500 mW. The lift-to-power efficiency including the electronics (namely, d.c.–d.c. converter, high-voltage driver and microprocessor) was 3.6–3.7 gfW^{−1}. This value is higher than that reported for previous insect-scale flapping-wing MAVs (FWMAVs); for example, 2.4–3.0 gfW^{−1} was reported in an earlier study²⁴. Considering the efficiency of the RF receiver, a received electromagnetic-wave power of approximately 500 mW/67% $\cong$ 750 mW was required for continuous flight (the power flow diagram for continuous flight is shown in Extended Data Fig. 4).

The power consumption of the piezoelectric actuator includes the reactive power due to charging/discharging of the capacitive component. The capacitance C of the paired actuators is approximately

50 nF, and the reactive power is estimated to be $CV^2f = 113$ mW with an ideal square-wave drive at 140 V (peak to peak) and 50% duty ratio. The total power consumption was approximately 230 mW under this condition (measured with a high-voltage amplifier and a function generator for the ideal square-wave drive). Thus, the real power is about 117 mW, and the power efficiency is estimated to be 51%. Because some of the reactive power can be recovered by circuitry¹⁸, there is room for future improvement in the efficiency of this system.

The power-to-weight efficiency of the MAV was approximately 400 mW g^{−1} (including the rectifier efficiency). Therefore, the actuation system of the developed vehicle is as efficient as the metabolic performance of natural bees^{43–45}. This overall system efficiency also matches that of small quadcopters (for example, Aerix Quadrotor (10 g, 50 mm span) with an efficiency of $\sim$ 430 mW g^{−1}).

Untethered flight

The orientation of the power-receiving antennas can be freely configured by folding them like origami. In this experiment, two of the three power-receiving antennas were laid out parallel to each other, whereas the third antenna was laid out orthogonally (Fig. 4a). The orientation of the two antennas coincided with the polarization of the transmitting antenna during standby, and the two antennas received a large amount of power for circuit start up. The orthogonal antenna allows the vehicle to receive energy even when the vehicle is rotating. A horn antenna was chosen for the transmitter; because the electromagnetic waves were transmitted at a constant power (we used 30 W, which is the maximum power of our instruments), the power received by the vehicle depended on its distance from the transmitting antenna. This power characteristic limits the operating distance of the vehicle.

Fig. 4 | Configuration and actuation performance of wireless-powered flight. **a**, Antenna layout of the aircraft. **b**, Relationship between received power and distance from the transmitting antenna to the receiving horn-dipole antenna. **c**, Transition in height of the aircraft during flight demonstration. **d,e**, Flight trajectories in *y* (**d**) and *x* (**e**) directions.

The relationship between the power received at the dipole antenna and the vertical distance of the vehicle from the transmitter is shown in Fig. 4b (three-dimensional distribution of the received power is shown in Extended Data Fig. 5). The vehicle can be operated with a power that is sufficiently large for continuous actuation but not unnecessarily greater than the circuit start-up power to avoid thermal runaway. The operating vertical-distance range was 70–150 mm in the experimental setup. From this result, to maximize the flight distance, we determined the initial distance from the vehicle to the transmitting antenna and transmission power as 70 mm and 30 W, respectively.

The trajectories of three flight trials are shown in Fig. 4c–e, where the zero of the vertical position means the initial position of the vehicles. The flight performance of the vehicle had good reproducibility; the maximum altitudes showed a deviation of 18.8%. We inferred that the trajectory difference was mainly caused by the error in the initial position of the vehicle. Figure 4c shows the accelerations in altitude. These suggest that the flights were not just jumps, but flights with continuous thrust. The maximum altitude in this demonstration was 77.5 mm. The altitude at which the flapping stopped is thought to have been near the inflection point of the trajectory. We calculated the inflection point by fitting the trajectory with a quadratic curve (Extended Data Fig. 6, top). As a result, it was estimated that the actuator stopped at an altitude of 58–66 mm.

Based on the coordinates at the inflection point and the received power distribution, the received power at the inflection was estimated to be approximately 600 mW (Extended Data Fig. 6, bottom).

This coincides with the estimated power required for continuous flight (~750 mW). This is further evidence that the system was continuously powered by the RF supply. The excess lift, excluding the self-weight, during the ascent estimated from the above fitting results was 220–340 mgf. Note that we did not implement closed-loop attitude control in this experiment, because this vehicle was not equipped with any attitude estimation sensor. Instead, we carefully tuned the duty ratios of the actuation signals based on the duty ratio–lift force data (Fig. 3b) to balance the vehicle and achieve level flight; we employed duty ratios of 0.30, 0.47 and 0.49 for the right, left and back actuators, respectively. As shown in Fig. 3b, the total lift force is estimated to be about 2.4 gf at the duty ratios setting. On the other hand, the total lift force was estimated to be ~2.0–2.2 gf from the excess lift force calculated from the trajectory described above. We expect that this reduction in lift force is mainly due to the fixed state of the actuator. For the measurement shown in Fig. 3, the paired actuators were rigidly fixed. In the case of the vehicle floating in air, the lift force may have decreased due to the vibration of the entire vehicle. Another possible cause is the tilt of the vehicle. The vehicle was tilted by up to 20° during flight, potentially causing a lift loss of several percentages in the vertical direction.

The most important improvements that need to be made in the present system should be the extension of the operating range (distance) and the reduction in transmission power. To extend the operating range, a system to adjust the power supply according to the distance of the aircraft is needed. The RF power is inversely proportional to the square of the transmitter–receiver distance and

proportional to the transmitting power. Thus, if the power is increased, the distance that can be travelled should increase in proportion to the square root of the transmitting power. However, excessive reception energy leads to failure due to overheating of the circuit; therefore, the distance that can be approached by the transmitting antenna also increases. To reduce the transmitting power, a system that focuses on the electromagnetic waves, such as phased arrays, could be promising. Either way, a system that measures the current position of the aircraft and feeds it back to the transmitter will be necessary.

Conclusions

We have shown that RF power receivers can be used as sustainable power sources for insect-scale robots. Our circuit design consists of three dipole antennas/rectifiers to avoid heat concentration, and the high power density was created using a lightweight RF power receiver. We integrated it to an FWMAV³⁸ with a high lift-to-power efficiency. Key performance metrics, namely, power density and total weight of the aircraft, exceed those of existing designs. The power density of our RF power receiver is four times higher than that for off-the-shelf lithium polymer batteries. This is also 2.1 times the power density provided by the solar panel (2,300 W kg⁻¹) used for untethered flight of an insect-scale FWMAV reported previously²⁴. With regard to the total weight, previously reported motor-driven multirotor MAVs with RF power transmission weigh several tens of grams (for example, 51 g (ref. ³⁰) and 85 g); our vehicle is an order of magnitude lighter than these examples.

We believe a fully functional untethered MAV with insect-scale mass can be realized by optimizing the vehicle design and adding new features. These include integrating a flight control system in the FWMAV and using a beam-focusing/targeting system for the power transmitter. Beam focusing is also important from a regulatory point of view because the output power of the transmitting antenna is limited below a certain level. For example, according to the Federal Communications Commission (USA) and the Ministry of Internal Affairs and Communications (Japan), the output power of indoor antennas must be less than 1 W (refs. ^{46,47}). The use of square waves has the advantage of lower peak-to-peak voltage and a simpler drive circuit compared with those required to generate a sinusoidal actuation signal. On the other hand, the steep drive may increase the risk of actuator damage. The verification of the long-term reliability of this system will be another important future step. Furthermore, a closed-loop flight control system could also be implemented and an altitude-sensing system, such as an inertial measurement unit, could be included in the electronics. An additional antenna for wireless communication is also desirable for practical applications. We note that the developed vehicle has sufficient payload capacity to carry such sensors: the maximum total lift force and payload were 2,620 and 810 mgf, respectively; the typical mass of a commercial inertial measurement unit or communication antenna (such as Bluetooth) is several tens of milligrams only.

Methods

Vehicle fabrication. The body and legs of the vehicle were fabricated from glass-fibre-reinforced plastic (GFRP) plates with a thickness of 0.38 mm (FS-10, ACP Composites) and GFRP rods with a diameter of 0.5 mm (Featherfield), respectively. The GFRP parts, flapping-wing actuators and circuit board were joined using an ultraviolet-curable adhesive (LOCTITE 4310). Enamel wire with a diameter of 70 μ m was used to wire the actuator to the circuit; the circuit-side and actuator-side ends were connected using a solder and conductive adhesive (CW2400, Chemtronics), respectively. In our earlier reports, we have comprehensively described the fabrication processes for the vehicle (without electronics)³⁸ and the wings⁴⁸. The mass of the six wings, six actuators, body and three legs before assembly was 107, 696, 340 and 71 mg, respectively. The weight of the assembled vehicle without electronics and wiring was 1,264 mg; 50 mg was added by the adhesive. The image of the vehicle assembly is shown in Supplementary Section 2.

Circuit. The schematic of the power-receiving and converting circuits is shown in Extended Data Fig. 1. The circuit board was manufactured by Cir-Tech (Hamamatsu). The FPC comprises resist lamination, Cu pattern, polyimide, and Cu pattern layers; their thicknesses are 20 μ m, 9 μ m (with 7 μ m Cu plating), 50 μ m and 9 μ m (with 7 μ m Cu plating), respectively. The power-receiving circuit (Extended Data Fig. 1a) consists of rectifiers, voltage-limiting diodes (D2), power storage capacitors (C2) and a voltage regulator (IC1). The voltage-limiting diode protects the d.c.–d.c. converter and limits the output voltage below 6 V (any input beyond this voltage is dissipated as heat loss). The power storage capacitors are used to smooth the output voltage and absorb fluctuations due to the instantaneous load power. A voltage regulator is used to supply power to the digital circuits (for example, microcontroller), and the output is 3.3 V. We employed a combination of boost converter and charge pump for the d.c.–d.c. converter; the input voltage (<6 V) is boosted to a maximum of 35 V and then multiplied by five (Extended Data Fig. 1b): $35 \times 5 = 175$ V. The boost converter is controlled by XC9104D095DR-G (Torex Semiconductor) with an operation frequency of 500 kHz. The high-voltage driving circuit is based on the one developed by us in an earlier study¹⁸ (the full schematic is shown in Extended Data Fig. 2a); note that the charge recovery reported in ref. ¹⁸ was not used in this experiment. This high-voltage driver is composed of a combination of bipolar transistor and nMOSFET. We selected the components among the available ones along with focusing on withstanding the voltage and mass (the breakdown of the circuit mass is summarized in Extended Data Table 2 and the complete electrical component list is shown in Extended Data Table 3). The schematic of the rectifier and the simulated performance using electronic design automation software (advanced design system, Keysight Technologies) are shown in Extended Data Fig. 1c–e. There are four types of power entering and leaving the rectifier: input power (P_i ; Extended Data Fig. 1c), output power (P_o ; Extended Data Fig. 1c), internal losses (diodes and wires) and reflections back to the input port. Extended Data Fig. 1d shows the internal loss against the input power at a constant P_o . When P_i increases, the internal loss increases almost proportionally. Since the increase in internal losses leads to the risk of thermal runaway, it is important to appropriately adjust P_i . As shown in Extended Data Fig. 1e, the maximum efficiency of the rectifier (P_o/P_i) was approximately 67% with an optimized input power at $P_o = 500$ mW, which is required for continuous flight. This efficiency is comparable to larger rectifiers^{49,50}.

The d.c.–d.c. conversion efficiency. To determine the d.c.–d.c. conversion efficiency (Fig. 2c), the circuit was powered by a d.c. voltage source (E3631A, Agilent Technologies) and the input and output powers were evaluated by power analysers (PA1000, Tektronix). The input voltage was set to 3.7 V in this evaluation. The output voltage was set to 140 V. Using the fabricated high-voltage driver, we drive a pseudo-load with a duty ratio of 50%. Here we used an equivalent pseudo-load composed of resistor–capacitor parallel circuits (resistance, $R = 133$ k Ω ; capacitance, $C = 50$ nF) instead of real actuators to prevent the breakage of the actuator caused by excessive drive power. The electrical characteristics of piezoelectric actuators can be modelled as a parallel circuit of a capacitor and a resistor–inductor–capacitor (RLC) series in a simplistic form^{51,52}. The capacitance and resistance values are estimated based on the power consumption characteristics around the resonance frequency (the fitting method and result are shown in Extended Data Fig. 7). With a voltage amplitude of 140 V and a duty ratio of 50%, the power consumptions of the pseudo-load circuit and real actuator were 204 and 186 mW, respectively (the error was 8.6%). We adjusted the output power by changing the resistance and capacitance.

Continuous driving test of circuit. In the continuous driving test (Fig. 2d), we used the equivalent pseudo-load employed in the measurement of the d.c.–d.c. converter. The RF wave was generated by a system composed of a programmable voltage source (2461, Keithley), 5.8 GHz RF amplifier (OSGM50-5.7G5.9G, Plasma Applications) and horn antenna (1424-15, Flann Microwave). The output RF power was 30 W. The output signal was recorded by an oscilloscope (DPO4034B, Tektronix).

Actuator performance. The driving signal was generated by a combination of the high-voltage driver circuit and a d.c. voltage source (PMX350-0.2A, Kikusui Electronics). Here the input voltage was set to 140 V. The control signal for the high-voltage driver was generated by the microprocessor circuit, where the voltage and frequency of the control signal were set to 3.3 V and 115 Hz, respectively. The lift force was measured by a precision electrical balance (HR-100A, A&D Company); the experimental layout is the same as reported earlier¹⁸.

Distance dependency of received power by dipole antenna. The RF wave was generated by the same instruments as used in the continuous driving test. The received power was measured by a combination of our fabricated FPC dipole antenna and an attenuator (–30 dB) (E9301B, Keysight Technologies) in series with a power sensor (E9304A or N1913A, Keysight Technologies).

Flight demonstration. The RF wave was generated by the same instruments that were used in the continuous driving test. The output RF power was 30 W. The

flight trajectory was captured by a motion-tracking system (Prime[®] 41, OptiTrack) and its image was recorded by a colour camera included with the system. The vehicle was placed on a 160 mm square acrylic plate above the transmitting horn antenna with an initial distance of 70 mm from the transmitting antenna to the receiving dipole antenna.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

T.O. designed, fabricated and evaluated the mechanical part of the vehicle. He also assembled the whole vehicle. N.O. designed, fabricated and evaluated the electronics of the vehicle. T.O. and N.O. conducted the flight demonstration experiment. T.J. and K.H. analysed the system performance. T.O. wrote the paper. All the authors provided critical feedback.

Competing interests

The authors declare no competing interests.

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Extended Data Fig. 1 | Schematics of power-receiving and conversion circuit. Schematics of power-receiving and conversion circuit. a, Schematics of RF power receiver. b, Schematics of high-voltage DC-DC converter. c, Schematic of rectifier circuit. d, Input power-loss characteristics. e, Input power-efficiency characteristics.

Extended Data Fig. 3 | Driving waveform of high voltage driver. Driving waveform of high voltage driver. Here, as an example, we show the drive waveform for one channel. The square waves Q and QB are generated from PWM0 by FF (LC1) with double period. The logical NOR of PWM1 and Q creates the gate voltage of T3 that drives the high-side switch. The gate voltage of T4, which drives the low-side switch, is generated by the logical NOR of PWM1 and QB. When the switch timing of T3 and T4 overlaps, a large loss occurs due to the through current flow from the high voltage side to GND. Therefore, a high impedance period (the period when both T3 and T4 are low) is provided for the transition from the high voltage side to the GND side of VO1.

Extended Data Fig. 4 | Power flow diagram in continuous flight. Power flow diagram in continuous flight.

Extended Data Fig. 5 | Three-dimensional distribution of received power. The measurement setup and condition are same as in Fig. 4b. The numbers labelled to the contour map show the received power in mW.

Extended Data Fig. 6 | Fitting result of flight trajectory and estimated received power along the trajectory. Fitting result of flight trajectory and estimated received power along the trajectory. We considered the trajectory to be a quadratic curve both during the ascent and after the actuator stops, and the two quadratic curves that are continuously connected are considered to switch at a certain time T_i . In other words, the following functions were used to fit the three trajectories using the least-squares method: $z = \begin{cases} \frac{1}{2}at^2 & : t < T_i \\ \frac{1}{2}gt^2 + (a - g)T_it - \frac{1}{2}(a - g)T_i^2 & : t \geq T_i \end{cases}$ where a and T are the acceleration during ascending and time of the inflection point; they are the fitted parameters. g is the gravitational acceleration: -9.8 m/s^2 . As a result, we obtained the fitting parameters of $(a, T_i) = (1.86 \text{ m/s}^2, 0.26 \text{ s})$, $(1.62 \text{ m/s}^2, 0.26 \text{ s})$ and $(1.18 \text{ m/s}^2, 0.33 \text{ s})$ for the three takes, respectively. The fitting was performed using the 'curve_fit' function in the Python module Scipy. The upper graphs in the figure show the trajectory measurement results superimposed on the fitting results. The red circles are the inflection point: that is, the moment the circuit was estimated to have stopped. Here, we use light blue bands to represent the confidence interval of the shutdown time. In our system, it takes up to 52 ms to shut down due to the energy stored in the capacitor (C2) and the decay time of the actuator when the receiver power becomes insufficient low. The total capacitance is $400 \mu\text{F}$, the maximum receiving voltage is 6 V, the minimum operating voltage of the microprocessor is 1.8 V, and the steady-state consumed power is 500 mW. Therefore, a maximum margin of $400 \mu\text{F} \times ((6 \text{ V})^2 - (1.8 \text{ V})^2) / 500 \text{ mW} = 26 \text{ ms}$ can be expected. The Q-factor of the actuator is approximately 3. Therefore, the amplitude decay time is roughly $(115 \text{ Hz})^{-1} \times 3 = 26 \text{ ms}$, and intervals of 52 ms centered on the estimated inflection point are indicated in the graph. From this interval, the confident shutdown altitudes are 53.9–74.5 mm, 48.0–63.2 mm, and 49.5–67.8 mm for takes 1–3, respectively. By linear interpolating the distribution of the received RF power data shown in Extended Data Fig. 5, we estimate the received power along the trajectory. The results were shown in the lower graphs in the figure. The estimated received powers at the inflection points were 549, 589, and 652 mW. Similar to the above, considering the confidence interval of 52 ms, the received power at shutdown for takes 1–3 are 390–741 mW, 351–743 mW, and 507–724 mW, respectively.

Extended Data Fig. 7 | Frequency-consumed power characteristic of paired-actuator. Frequency-consumed power characteristic of paired-actuator.

The parameters of the pseudo-load were estimated from the frequency vs. power consumption characteristics at 50% duty cycle, 100 V square wave drive (without charge recovery). The power consumption $P(\omega)$ can be obtained from the Fourier transform of the square wave as follows.

$$P(\omega) = C_0 V^2 \frac{\omega}{2\pi} + \sum_{k=0}^{\infty} P_{\text{act}} \left((2k+1) \omega, \frac{\sqrt{2}}{(2k+1)\pi} V \right), P_{\text{act}}(\omega, V) = \frac{V^2 R \omega^2}{R^2 \omega^2 + L^2 (\omega^2 - (LC)^{-2})^2},$$

where R , L and C are the RLC circuit parameters for simulating the mechanical characteristics of the actuator. C_0 is the capacitive component of the actuator. ω and V are the frequency and voltage amplitude of the drive signal. By fitting this function to the measurement results, the following parameters were obtained: $(R, L, C, C_0) = (127 \text{ k}\Omega, 1215 \text{ H}, 1.61 \text{ nF}, 48.8 \text{ nF})$.

Extended Data Table 1 | Comparison of RF-powered MAVs

Ref.	Field region	Receiver	Based MAV product	Total mass
30	Near-field	Inductive coupling coil	H107L X4 (Hubsan)	50 g*
31	Near-field	Inductive coupling coil	JJRC-H98 (Jianjian Technology)	85 g*
32	Near-field	Inductive coupling coil	H107L X4 (Hubsan)	50 g*
33	Near-field	Inductive coupling coil	X525 (hobbypower)	1.337 kg
34	Near-field	Inductive coupling coil	Phantom 3 (DJI)	1.28 kg*
This work	Far-field	Dipole antenna	–	1.8 g

* Estimated from the based MAV products

Extended Data Table 2 | Mass of fabricated circuit

Subcircuit		Mass (mg)
Power receiver	Components	60
	Substrate and solder*	185
	Total	245
DC-DC converter	Components	51
	Substrate and solder*	38
	Total	89
3-ch high voltage driver	Components	70
	Substrate and solder*	28
	Total	98
Microprocessor	Components	28
	Substrate and solder*	50
	Total	78
Total		510

* The masses of “substrate and solder” are derived by subtracting the mass of the components from the total mass.

Extended Data Table 3 | Components of fabricated circuit

Subcircuit	Component	Part ID	Manufacturer/Product No.	Mass (mg)	Main Parameter
Power receiver	Balan	B1	TDK / HHM1907B1	0.70	4.90-5.95 GHz
	SBD	D1	AVAGO / HSMS-282E	5.8	-
	Zener diode	D2	DIODES / GDZ6V0LP3-7	0.20	-
	SBD	D3	STMicroelectronics / BAT30F4	0.12	-
	Voltage regulator	IC1	TOSHIBA / TCR3UG33B	0.26	-
	Capacitor	C1	SAMSUNG / CL03C100JA3GNNC	0.10	10 pF
	Capacitor	C2	AVX / F980J107MMAAXE	7.9	100 μ F
	Capacitor	C3	Vishay / 298W107X0004M2T	6.3	100 μ F
DC-DC converter	SBD	D4a-i	NXP / PMEG4005AESF	0.7	-
	Capacitor	C4	Murata / GRJ155R60J106ME11D	3.0	10 μ F
	Capacitor	C5a-i	Murata / GRM155R61H105KE05D	1.6	1 μ F
	Resister	R1	ROHM / KTR03EZPF1005	1.8	10 M Ω
	Resister	R2	Vishay / CRCW020152K3FKED	0.17	52.3 k Ω
	Inductor	L1	Murata / DFE201612E-2R2MP2	18.8	2.2 μ H
	nMOSFET	T1	Toshiba / SSM3K59CTB	0.75	Max. 40V
	DC-DC controller	IC2	TOREX / XC9104D095DR-G	6.0	-
3-ch high voltage driver	Resister	R4	ROHM / KTR03EZPF1004	1.8	1 M Ω
	Resistor	R5	Panasonic / ERJ-1GNJ1ROC	0.15	1 Ω
	Bipolar transistor	T2	NXP / PMSTA92	5.5	Max. 300 V
	nMOSFET	T3	Vishay / SiB452DK	6.0	Max. 190 V
	nMOSFET	T4	Vishay / SiB452DK	6.0	Max. 190 V
	NOR	LC1	Texas Instruments / SN74AUP2G02YFPR	1.4	-
	Flip-flop	LC2	Texas Instruments / SN74AUP1G74YFPR	1.4	-
Microprocessor	Capacitor	C6a-b	Murata / GRJ155R60J106ME11D	3.0	10 μ F
	Capacitor	C7a-c	Murata / GRM033R60J104KE19	0.33	100 nF
	Capacitor	C8a-b	Murata / GRM0335C1E9R0CA01D	0.33	9 pF
	Capacitor	C9a-b	Murata / GRM0335C1E8R0BA01D	0.33	8 pF
	Capacitor	C10	Murata / GRM032R60J105ME05D	0.20	1 μ F
	Resister	R6	KOA / RK73B1HTTC104J	0.15	100 k Ω
	Ferrite beads	L2	Murata / BLM03HD152FN1D	0.30	1.5 k Ω
	Inductor	L3	Murata / LQM18FN100M00D	5.0	10 μ H
	Quartz oscillator	Y1	ECS / ECS-240-8-47-JTN-TR	2.5	24 MHz
	Quartz oscillator	Y2	ECS / ECS-.327-9-16-TR	2.5	32.768 kHz
	Microprocessor	IC3	Texas Instruments / CC2640R2FYFVR	8.7	-