

INTEGRATED PIEZOELECTRIC AND FLEXIBLE SOLAR SYSTEMS FOR ENHANCING INFLIGHT OPERATION TIME OF SMALL UAV

Veena Phunpeng^{1,*} and Thongchart Kerdphol²

Received: October 25, 2021; Revised: February 08, 2022; Accepted: February 23, 2022

Abstract

This paper proposes the design of an inflight power generation system applicable to small unmanned aerial vehicles (UAVs). To extend the flight range and battery usage, the alternative power supply should be produced by multiple sources during flight, including bending movement, air pressure, vibration, and sunlight. Such sources of renewable energy can be summed and used during flight operations. The air pressure and vibration experiencing the UAV surface are captured by piezoelectric devices installed at the leading edge. This is a suitable location where the most air pressure/strain occurs. A flexible solar panel is installed at the top of the UAV wing to increase the capability of energy harvesting. A maximum power point tracking (MPPT) board is applied to adjust the input voltage and transform the harvested power to the battery voltage requirement under various load conditions. Subsequently, the power from renewable sources is summed together to help the battery for powering the operation of the UAV propeller. The flight test results have shown the effectiveness of the designed strategy that the small UAV can power itself during the flight, resulting in a longer flight operation time of about 35%.

Keywords: Power generation, piezoelectric, solar panel, renewable energy, unmanned air vehicles

Introduction

From the past up to now, unmanned aerial vehicles (UAVs) or drones have been rapidly developed as they could perform remarkable tasks in both military and civil services (e.g., disaster management and detection, environmental monitoring, and weather forecasting) due to their abilities of strong mobility and low communication overhead. In such situations, manned flight vehicles may not be applicable, and UAVs are more suitable for completing dangerous and dull missions (Khalid *et al.*, 2020). Compared

with large UAVs, small UAVs are implemented widely in several fields as they have features of flexibility, low cost, easy updating, short maintenance, and large quantities. In the near future, through multi UAV cooperation, small UAVs may have the potential to complete difficult missions, which are conventionally succeeded by large UAVs or manned airplanes (Yanying *et al.*, 2007). In the meantime, it still remains several issues in small UAV research, such as communication, obstacles,

¹ Suranaree University of Technology, Faculty of Engineering, Department of Mechanical Engineering, 111, Maha Witthayalai Rd., Suranari, Mueang Nakhon Ratchasima District, Nakhon Ratchasima, 30000, Thailand. E-mail: veenap@g.sut.ac.th

² Kyushu Institute of Technology, Faculty of Engineering, Department of Electrical Engineering and Electronics, 1-1, Sensui-cho, Tobata-ku, Kitakyushu-shi, Fukuoka, 804-8550, Japan.

* Corresponding author

lifetime, and energy consumption. Lack of energy in the power generation system could cause a serious shortcoming of small UAVs as the mission failures. In the worst case, the small UAV may crash if the battery or inflight generation system cannot support to accomplish the mission. Alternatively, by reducing communication and flight overhead during the operation, energy consumption can be reserved for accomplishing the mission. Thus, the power generation system must be carefully designed to match with the mission objective, preventing severe consequences.

Currently, the small UAV missions mainly depend on pre-planning, which may be difficult to adapt to the complex mission environment in the near future. The inflight power generation system has become one of the restrictive factors to accomplish the mission. As the current employments of UAV payload equipment and flight communication are more complex than ever, they could cause a significant reduction in inflight operation time. To increase the flight range, operation time, and battery usage, the power supply should be produced by multiple sources during the flight. Many published works (Meyer *et al.*, 2007; Shiau *et al.*, 2009; Morton *et al.*, 2015; Rajendran and Smith 2015; Ruben *et al.*, 2017; Karthik Reddy and Poondla 2017) have designed the large UAV powered by renewable solar energy, which could significantly lead to longer flight operation time. Furthermore, some of the research work (Meyer *et al.*, 2007) focused on the design of a low attitude with long endurance for solar-powered UAVs. The performance analysis of solar-powered UAVs was fully investigated (Karthik Reddy and Poondla 2017). Then, the impacts of longitude and latitude of solar-powered UAVs were analyzed (Rajendran and Smith 2015). Many designs of solar-powered UAVs with experimental tests were reported in several publications (Shiau *et al.*, 2009; Morton *et al.*, 2015; Ruben *et al.*, 2017). However, it still remains many solutions to harvest energy during the inflight UAV. One of those solutions is to generate power from the air pressure and vibration. The pressure and vibration are captured by piezoelectric devices installed at the aircraft surface. Up to now, a few research works have used piezoelectric devices for powering aircraft or increasing flight ranges. The main reason is that the piezoelectric devices could generate a small amount of energy compared to the high energy consumption in large UAVs or aircraft. Thus, it may not be sufficient to apply piezoelectric devices for energy harvesting during the flight. By deploying the small UAVs, the ability to harvest energy using piezoelectric devices becomes possible due to the lower energy consumption driven by less complex/advanced

equipment. Until now, the piezoelectric devices have been utilized as sensors, actuators, and health monitoring for UAV and aircraft applications as follows. In 2018, Cheng *et al.* applied the piezoelectric devices for attitude adjustment of high-speed rotation aircraft (Cheng *et al.*, 2017), and in 2013 Goenaga *et al.* used the piezoelectric actuators for frequency contactless power transfer in their communication system (Goenaga *et al.*, 2013). The aircraft shape control detecting by piezoelectric actuators was designed by Agrawal and Treanor (Agrawal and Treanor, 1999). In many publications (Giurgiutiu, 2006; Liberatore *et al.*, 2006; Mo and Davidson, 2013; Qing *et al.*, 2019), the applications of piezoelectric sensors were used for health monitoring in aircraft and aerospace. In 2003, piezoelectric devices were used as a sensor for determining aircraft ages (Giurgiutiu *et al.*, 2000). In 2007, the piezoelectric devices were applied as active sensors in the aircraft brake system (Rongyuan *et al.*, 2006). In 2013, piezoelectric devices were applied in aircraft wings for thermal detection and monitoring (Yue *et al.*, 2013). In 2018, the piezoelectric devices were utilized with the modal shear wave system for de-icing the aircraft wing (Shi and Jia, 2018). To the best of the author's knowledge, there is no research combining the piezoelectric and solar systems for energy harvesting in small UAVs. Thus, it remains challenging to develop the small UAV energy-efficient technology based on the employments of solar and piezoelectric systems.

To fill in this gap, this work presents the design of an inflight power generation system applicable to small UAVs. The power from the proposed design system is generated by three sources; that is the battery, solar panels, and piezoelectric devices. The battery is considered as the main source in powering the UAV propeller, and it is fully charged power before a flight. During the flight, the piezoelectric and solar systems help the battery to generate power and recharge the battery, leading to the increasing flight operation time. As a result of air pressure and vibration, the occurred force at the wing leading-edge of UAV is captured by piezoelectric devices and transformed into energy. This is a suitable location where the most air pressure/strain occurs. A flexible solar panel is installed at the top of the UAV wing to increase the capability of energy harvesting. The flight test results are performed to evaluate the effectiveness of the designed strategy. The rest of this paper is organized as follows. Initially, this paper starts with an overview of power generation systems for small UAVs. Later, the design of piezoelectric and solar systems for inflight operation is proposed. Then, the results and discussion are revealed. Finally, it ends with some conclusions.

Power Generation System for Small UAV

This section briefly describes the power generation system to power the small UAV. The power for driving the UAV is generated by three sources; that is the battery energy storage system, solar panels, and piezoelectric devices. The battery system is considered as the main source in powering the UAV propeller, and it is fully charged power before a flight. During the flight, the piezoelectric and solar systems help the battery to generate power and recharge the battery, leading to the increasing flight range and time.

Battery Energy Storage System

The battery energy storage system is an equipment of electrochemical cells for powering electrical devices (Kerdphol *et al.*, 2016). In principle, the battery changes the chemical energy to electrical energy. A brief literature review of batteries used in aerospace is reviewed and reported (Alfonso *et al.*, 2018). Various battery energy storage systems can be used as the main power source for driving a UAV propeller. In this work, the lithium-ion polymer battery is used due to the high capacitance/power to weight ratio compared with traditional batteries. Considering Kirchhoff's law, the dynamic equation of the battery can be defined as (Alfonso *et al.*, 2018):

$$V_B = V_{OC} - R_S I_B - V_C \quad (1)$$

Figure 1(a) shows the equivalent model of the studied battery. It consists of three parts; that is 1) the internal ohmic resistor (R_S); 2) the resistor-capacitor parallel part, where C_p is the equivalent polarization capacitance, and R_p is the equivalent polarization resistance; 3) the open-circuit voltage. This model considers the current as the model input and the terminal voltage as the measured output.

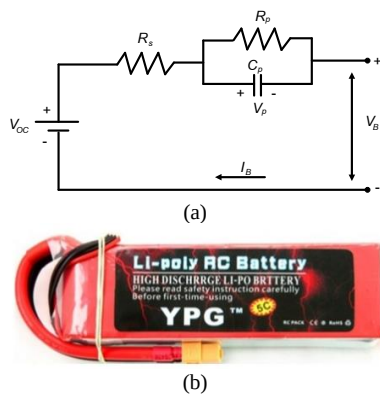


Figure 1. Battery structure; (a) equivalent circuit model; (b) commercial model used in this project

Figure 1(b) shows the commercial battery energy storage system used in this project. It is a three-cell battery, which has a capacity of 5,200 mAh, 14.8 V.

Piezoelectric Generation System

Piezoelectric devices generate electricity in certain solid materials (e.g., crystals, ceramics, polymers, and biological matter) in response to applied mechanical stress. The piezoelectric effect is a result of the linear electromechanical interaction between the electrical and mechanical states. A brief review of several piezoelectric types for energy harvesting is reported (Howells 2009; Kim *et al.*, 2011; Calìo *et al.*, 2014). Figure 2(a) describes a basic block diagram of piezoelectric for energy harvesting. It consists of a full bridge AC/DC converter, which rectifies the AC signal from the piezoelectric. The capacitor is applied for controlling the output of the full-bridge converter. Based on research work (Kim *et al.*, 2011), the maximum power transfer can be obtained when the voltage (V_{cc}) corresponding to the voltage across the rectifier capacitor is half of the open-circuit voltage across the piezoelectric (V_{PZT}). Thus, the dynamic equation of the piezoelectric can be defined as (Kim *et al.*, 2011):

$$V_{PZT} = \frac{V_{OC}}{2} \quad (2)$$

In this study, the piezoelectric is integrated into an aircraft skin, which could generate power during flight according to air pressure and vibration caused by thrust, drag, lift, and weight. Figure 2(b) shows the piezoelectric polymer type used in this project. For one piezoelectric plate, it can produce a nominal voltage (V_{PZT}) of about 1.1 V/g. The charge sensitivity is about 260 pC/g.

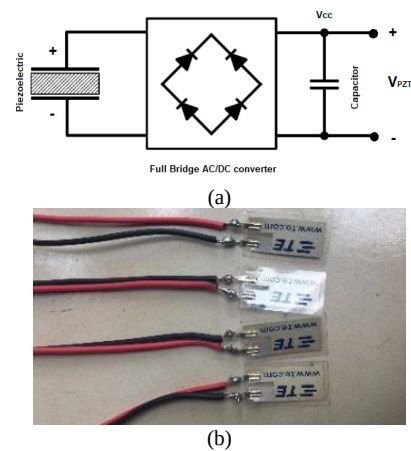


Figure 2. Piezoelectric structure; (a) equivalent circuit model; (b) piezoelectric polymer

Solar Generation System

A solar or photovoltaic generation system (solar cell) is electric equipment that changes the energy of light directly into electricity using the photovoltaic phenomenon (i.e., physical and chemical effects) (Sharma *et al.*, 2015). The solar system is represented in the form of a photoelectric cell, which consists of electrical characteristics (voltage, current, and resistance), changing when exposed to sunlight. Each solar cell can be formed as modules called solar panels or systems. To understand the dynamic behavior of the solar system, the equivalent circuit model is described in Figure 3(a). The model represents the current-voltage (I-V) curve of one solar cell/array as a continuous function for a set of operating conditions. Figure 3(b) shows the commercial solar panel used in this project. One solar panel has a dimension of 7.5×5.2 cm, which can generate the nominal voltage of 0.55 V and nominal current of 1.32 A, resulting in the maximum power of 0.66 W. Using Kirchoff's current law, the current control equation for a solar panel is defined as (Gray 2011; Sharma *et al.*, 2015):

$$I_s = I_L - I_D - I_{SH} \quad (3)$$

where I_s is the output current of the solar system, I_L is the photogenerated current, I_{SH} is the shunt current, and R_{SH} is the shunt resistance.

Then, the control voltage equation for a solar panel can be expressed as (Gray 2011):

$$V_{Solar} = V_T + I_s R_s \quad (4)$$

where V_{Solar} is the output voltage of the solar system, V_T is the voltage across the terminals, and R_s is the series resistance.

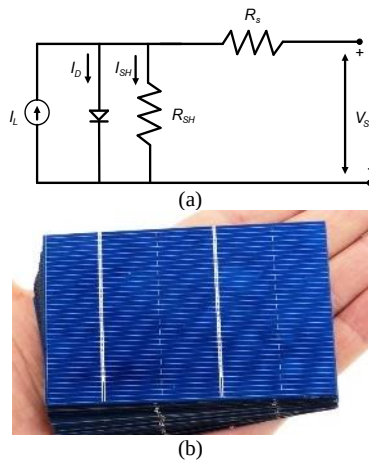


Figure 3. Solar structure; (a) equivalent circuit model for one panel; (b) commercial panel model used in this project

Design of Piezoelectric and Solar Systems for Inflight Operation Improvement

In this section, the proposed solar and piezoelectric structures are designed with respect to maximum energy harvesting during a flight. Regarding the stable power generation during flight, the solar system is used as the primary renewable source compared with the piezoelectric. The piezoelectric source may be vulnerable as the generated power depends on air pressure or vibration (changing within seconds), resulting in an intermittent or unstable power supply. Thus, the piezoelectric is used as the auxiliary source for energy harvesting.

Design of Solar Panels

Based on research works (Meyer *et al.*, 2007; Morton *et al.*, 2015; Rajendran and Smith 2015; Ruben *et al.*, 2017; Karthik Reddy and Poondla 2017), the suitable location for generating the maximum solar power is over the top of the UAV wing. Thus, the equivalent solar circuit of the UAV wing for harvesting energy is shown in Figure 4(a). The solar panels are mounted on the wing, as shown in Figure 4(b). This project used 102 solar panels, resulting in a maximum power of 70 W. In addition to the circuit connection, each UAV wing is installed with 51 solar panels connecting in the series to increase the maximum output voltage up to 28.05 V with an output current of 1.32 A. This configuration is suitable for increasing the capability of fast charging of the battery. To properly prevent malfunctioning, each solar wing is merged by the parallel, which produces the maximum output current of 2.64 A with a similar voltage level of 28.05 V. The overall area of the installed solar system is about 40.5 cm².

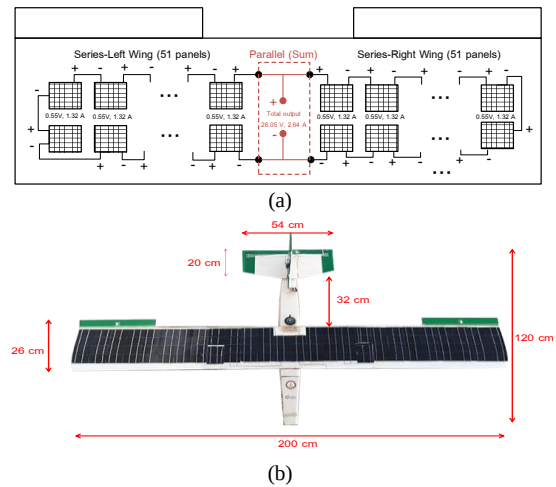


Figure 4. Solar-powered UAV analysis; (a) proposed panel circuit; (b) installed location

Design of Piezoelectric Device

To determine the suitable location for mounting the piezoelectric generator, the computational fluid dynamics (CFD) simulation is performed using the ANSYS software at the UAV wing. The primary objective of CFD in aerodynamics is to predict air pressure distortions (e.g., drag, lift, and moment coefficient) around the wing. As a result, in Figure 5(a), it is obvious that the maximum pressure occurs at the leading-edge stagnation point (i.e., red area) of the UAV. Evidentially, the piezoelectric generates the maximum energy when installed at such high air pressure areas. Therefore, this work has installed five piezoelectric generators at the leading edge of the left and right wings (the total is ten piezoelectric plates), as shown in Figure 5(b). Each piezoelectric is connected in parallel to avoid malfunctioning. By experiencing the air pressure, the accumulated voltage (energy) will be stored at the battery in enhancing flight time.

The detail of the power management system is briefly described in Figure 6. The main electrical loads of the UAV are the propeller (motor) and servos for directional and attitude control. The generation (i.e., solar and piezoelectric) and storage (i.e., battery) mechanisms are connected with the power management circuit (i.e., Pixhawk flight controller), which is capable of collecting electrical power inputs from renewable sources to charge the battery. The maximum power point tracking (MPPT)-charger board is used to adjust input voltages from different sources and store the harvested power in the battery for driving the UAV. In addition to the applied MPPT, it is based on the constant voltage technique, where its output voltage is controlled to a constant value/ratio under all conditions (Leedy *et al.*, 2012). The overview of

various MPPT methods can be found in (Ko *et al.*, 2020). Then, the stored power is used to drive the UAV propeller, increasing flight operation time.

Finally, the total voltage (V_{Total}) of the designed system that expresses the generation of piezoelectric and solar systems for the UAV can be defined as:

$$V_{Total} = V_{PZT} + V_{Solar} \quad (5)$$

Results and Discussions

In this section, the experimental and flight test results are depicted, showing the effectiveness of the proposed energy-efficient design under no payload condition. Firstly, the inflight study of the piezoelectric circuit connection over airspeed is analyzed to determine a suitable connection for the small UAV. Figure 7 shows the generated output voltage of the piezoelectric against the increasing airspeed. It is obvious that both connections of series and parallel yield almost the same pattern of the output voltage. This indicates that both circuit connections could produce similar power against the variation of airspeed. During the flight, when 15-20 m/s, the series circuit tended to generate the higher output voltage. Clearly, the piezoelectric generates a higher voltage after passing the airspeed of 30 m/s.

Secondly, the inflight analysis of solar-wing power generation is presented. During the flight test, it was a cloudy day (i.e., low solar irradiation). Consequently, the UAV solar system could generate less power (about 25 W), which is only 40% of its maximum power generation. The flight operation time of the proposed energy-efficient design is

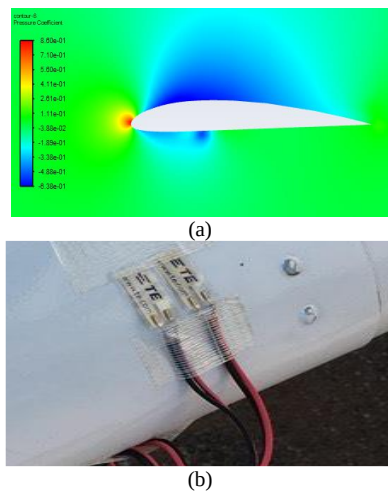


Figure 5. Piezoelectric-powered UAV analysis; (a) wing pressure contour; (b) installed location

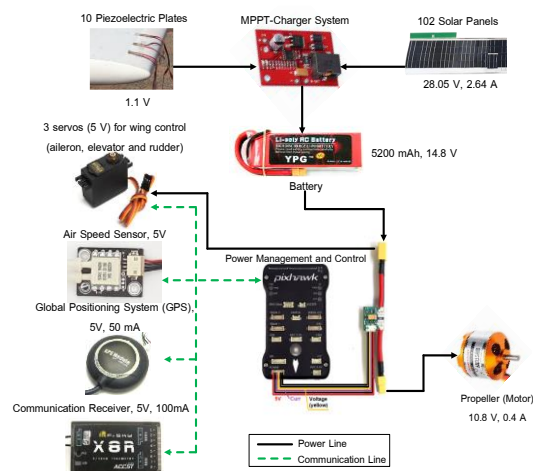


Figure 6. Power management architecture of the UAV

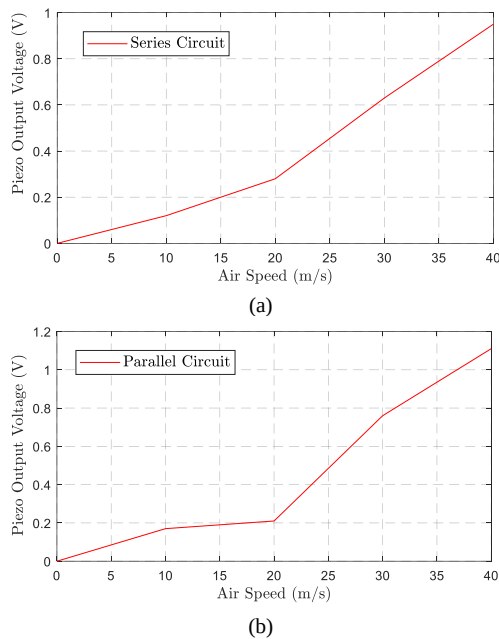


Figure 7. Piezoelectric output voltage over airspeed; (a) series connection; (b) parallel connection

revealed in Figure 8. It is clearly seen that the employment of solar and piezoelectric systems could generate more power. Consequently, by using the proposed system, the UAV could be able to recharge itself during the flight. Notably, the UAV can fly with only the solar and piezoelectric systems for more than 5 min under cloudy conditions (i.e., about 35% improvement of flight operation time). The proposed strategy significantly indicates the energy efficiency improvement of the small UAV.

Conclusions

This paper presents the design of the power generation system for small UAVs. To improve the flight range and battery usage, renewable power sources are used during flight to generate alternative energy from bending movement, air pressure/vibration (e.g., drag force, thrust force, lift force, weight force, wind flutter, and wind gusts), and sunlight. Such sources of renewable energy can be summed and used during flight operations. The air pressure and vibration from the UAV wing are captured by piezoelectric devices installed at the wing leading edge. The solar panel is installed at the top of the UAV wing to increase the capability of energy harvesting. Subsequently, the power from two renewable sources is summed together to help the battery for powering the UAV propeller. The flight test results confirm that the UAV could

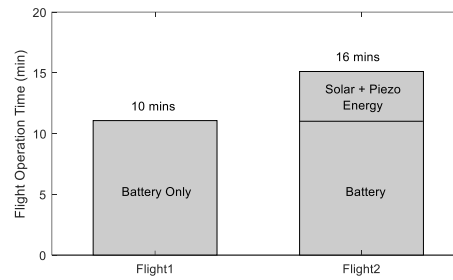


Figure 8. Improvement of the UAV flight operation time

recharge itself during the flight by using the proposed system. Moreover, the UAV could fly with only the solar and piezoelectric systems for more than 5 min, leading to an increasing flight operation time of about 35%. Future work will be focused on the flight test of the proposed solution under various weather, temperature, and payload conditions.

Acknowledgments

The authors are grateful for the financial support from the National Science and Technology Development Agency (NSTDA-Thailand), Contract No. FDA-CO-2562-9853-TH. Special thank goes to staff and students who participated in this project

References

- Agrawal, B.N. and Treanor, K.E. (1999). Shape Control of a Beam Using Piezoelectric Actuators. *Smart Mater. Struct.*, 8(6):729.
- Caliò, R., Rongala, U.B., Camboni, D., Milazzo, M., Stefanini, C., De Petris, G., and Oddo, C. (2014). Piezoelectric energy harvesting solutions. *Sensors (Switzerland)*, 14(3):4,755-4,790.
- Gang, C., Chen, C., Chen, H., and Liu, S.X. (2017). Application of piezoelectric bimorphs in attitude adjustment of high speed rotation aircraft. In: *Proceedings of the 2017 Symposium on Piezoelectricity, Acoustic Waves, and Device Applications*. 27-30 October 2017; Chengdu, China, p. 1-6.
- Ruben, D., Henderson, T., Jenson, D., Calvert, M., Heller, T., Schulz, B. (2017). Design and experiments for a transformable solar-UAV. In: *Proceedings of IEEE International Conference on Robotics and Automation*, 29 May-3 June 2017; Singapore, p. 1-5.
- Alfonso, D., Porru, M., Salimbeni, A., Serpi, A., Castiglia, V., and Tommaso, A.O.D. (2018). Batteries for aerospace: a brief review. In: *Proceedings of 2018, 110th AEIT International Annual Conference*. 3-5 October 2018; Bari, Italy, p. 1-6.
- Giurgiutiu, V., Redmond, J., Roach, D., and Rackow, K. (2000). Active sensors for health monitoring of aging aerospace structures. In: *Proceedings of International Journal of COMADEM*, 8-9 June 2000, Californai, USA, p. 1-6.

- Giurgiutiu, V. (2006). Structural health monitoring with piezoelectric wafer active sensors. In: Proceedings of 16th International Conference on Adaptive Structures and Technologies. 9-12 October 2005; Paris, France, p. 1-5.
- Goenaga, E., Ferrieux, J.P., Barbaroux, J., and Kwimang, G. (2013). Low and medium frequency contactless power transfer system for piezoelectric actuators in aeronautical applications. In: Proceeding of 2013-15th European Conference on Power Electronics and Applications, 3-5 September 2020; Lille, France, p. 1-6.
- Gray, J.L. (2011). The Physics of the Solar Cell. In: Handbook of Photovoltaic Science and Engineering. Luque, A. and Hegedus, S. (eds)., Wiley, USA, 202p.
- Howells, C.A. (2009). Piezoelectric energy harvesting. *Energy Conversion and Management*, 50(7):1,847-1,850.
- Karthik Reddy, B.S. and Poondla, A. (2017). Performance analysis of solar powered unmanned aerial vehicle. *Renewable Energy*, 104(1):20-29.
- Kerdphol, T., Qudaih, Y.S., Hongesombut, K., Watanabe, M., and Mitani, Y. (2016). Intelligent determination of a battery energy storage system size and location based on rbf neural networks for microgrids. *International Review of Electrical Engineering (IREE)*, 11(1):78.
- Khalid, W., Yu, H., and Noh, S. (2020). Residual energy analysis in cognitive radios with energy harvesting uav under reliability and secrecy constraints. *Sensors (Switzerland)*, 20(10):2,998.
- Kim, H.S., Kim, J.H., and Kim, J. (2011). A review of piezoelectric energy harvesting based on vibration. *Int. J. Précis. Eng. Manufac.*, 12(6):1,129-1,141.
- Ko, J.-S., Huh, J.-H., and Kim, J.-C. (2020). Overview of maximum power point tracking methods for pv systems in micro grid. *Electronics*, 9(5):816.
- Leedy, A., Guo, L., and Aganah, K. (2012). A constant voltage mppt method for a solar powered boost converter with dc motor load. In: Proceeding of IEEE Southeastcon. 15-18 March 2012; FL, USA, p. 1-6.
- Liberatore, S., Speyer, J.L., and Hsu, A.C. (2006). Application of a fault detection filter to structural health monitoring. *Automatica*, 42(7):1,199-1,209.
- Meyer, J., Du Plessis, J.A.F., Ellis, P., and Clark, W. (2007). Design considerations for a low altitude long endurance solar powered unmanned aerial vehicle. In: Proceedings of IEEE AFRICON Conference, 26-28 September 2007, South Africa, p. 1-5.
- Mo, C. and Joseph, D. (2013). Energy harvesting technologies for structural health monitoring applications. In: Proceedings of IEEE Conference on Technologies for Sustainability, 1-2 August 2013, Oregon, USA, p. 1-6.
- Morton, S., Ruben, D., and Papanikolopoulos, N. (2015). Solar powered UAV: design and experiments. In: Proceedings of IEEE International Conference on Intelligent Robots and Systems. 28 September 2015, Hamberg, Germany, p. 1-6.
- Qing, X., Li, W., Wang, Y.-S., and Sun, H. (2019). Piezoelectric transducer-based structural health monitoring for aircraft applications. *Sensors (Switzerland)*, 19(3):545.
- Rajendran, P. and Smith, H. (2015). Implications of longitude and latitude on the size of solar-powered UAV. *Energy Conversion and Management*, 98(1):107-114.
- Rongyuan, L., Fröhleke, N., Wetzel, H., and Böcker, J. (2006). Investigation of power supplies for a piezoelectric brake actuator in aircrafts. In: Proceedings of International Power Electronics and Motion Control Conference. 14-16 August 2006, Shanghai, China, p. 1-6.
- Sharma, S., Jain, K.K., and Sharma, A. (2015). Solar cells: in research and applications-a review. *Mat. Sci. App.*, 6(12):1,145-1,155.
- Shi, Y. and Jia, Y. (2018). Multimodal shear wave deicing using fibre piezoelectric actuator on composite for aircraft wings. *IEEE/ASME Transactions on Mechatronics*, 23(5):2,090-2,098.
- Shiau, J.K., Ma, D.M., Yang, P.Y., Wang, G.F., and Gong, J.H. (2009). Design of a solar power management system for an experimental UAV. *IEEE Transactions on Aerospace and Electronic Systems*. 45(4):1,350-1,360.
- Yanying, T., Rongchun, Z., Xiaoping, Z., and Zhang, B. (2007). The design and implementation of autonomous mission manager for small UAVs. In: Proceedings of IEEE International Conference on Control and Automation. 30 May 2007, Guangzhou, China, p. 1-6.
- Yue, H.H., Wang, L., Jiang, J., Song, X.T., and Yu, Z.W. (2013). Dynamics modeling of piezoelectric control for the aircraft wings in aerodynamic thermal environment. In: Proceedings of the 2013 Symposium on Piezoelectricity, Acoustic Waves and Device Applications. 25 October 2013, Changsha, China, p. 1-5.