The 2015 World Congress on
Aeronautics, Nano, Bio, Robotics, and Energy (ANBRE15)
Incheon, Korea, August 25-28, 2015

Development of Laser-powered Wireless Sensing System for Aircraft Structures

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ABSTRACT

Structural health monitoring (SHM) is required in the in the aerospace industry to monitor structural integrity. The conventional wired SHM method uses coaxial wires which provide a very reliable communication link, their installation in structures can be expensive and labor-intensive. Therefore, introduction of a wireless structural health monitoring system could help to reduce the maintenance costs. However, the powering method to these wireless sensing systems is still one of technical challenge for their practical applications. Conventional power source for wireless sensor nodes is batteries. However, replacing batteries is labor intensive and costly job. Therefore, it is preferred to make the sensor nodes have the ability to generate energy from artificial energy source, for example, wireless power transmission (WPT) from RF or laser. In this study, we propose a promising solution to this challenge by collecting energy from a laser beam to power a wireless sensor. The delivered light is captured by a GaInP photovoltaic cell which has high spectral responsivity at 532 nm of laser wavelength and collected inside a supercapacitor to supply power to the sensor. We also suggest a laser-powered wireless sensing system is called wireless strain gauge device (WSGD) for aircraft structural health monitoring. The wireless sensing system is developed using a MSP430 evaluation board and a CC2500 radio and designed to include a Wheatstone bridge circuit. The applicability of the proposed system to monitoring strain is experimentally investigated. The results show that the proposed wireless sensing system can provide measurement of the voltage induced strain and transmission data back to a base station successfully.

KEYWORDS: *Wireless power transmission, Wireless sensor, Structural health monitoring, Laser-powered wireless sensor, Laser power transmission*

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1. INTRODUCTION

Autonomous wireless sensor nodes powered by wireless power transmission (WPT) are essential for the realization of wireless structural health monitoring system due to two main reasons. First, the WPT reduces the payload as well as the complexity of whole system as no conventional cabling for data and power transmission is needed. Secondly, this approach makes replacing depleted batteries obsolete. The goal of this research is to develop a laser-powered wireless sensing system included strain gauge device (WSGD) for aircraft structural health monitoring (SHM). In this study, we propose a continuous-wave (CW) laser powered WSGD for inaccessible aircraft structures as shown in Figure 1. To deliver laser beam to inaccessible regions of aircraft, we excogitate a fiber optic bolt as waveguide. The delivered laser beam is captured by a photovoltaic (PV) cell and the generated electricity is collected in a storage medium to the required power to the wireless sensor.

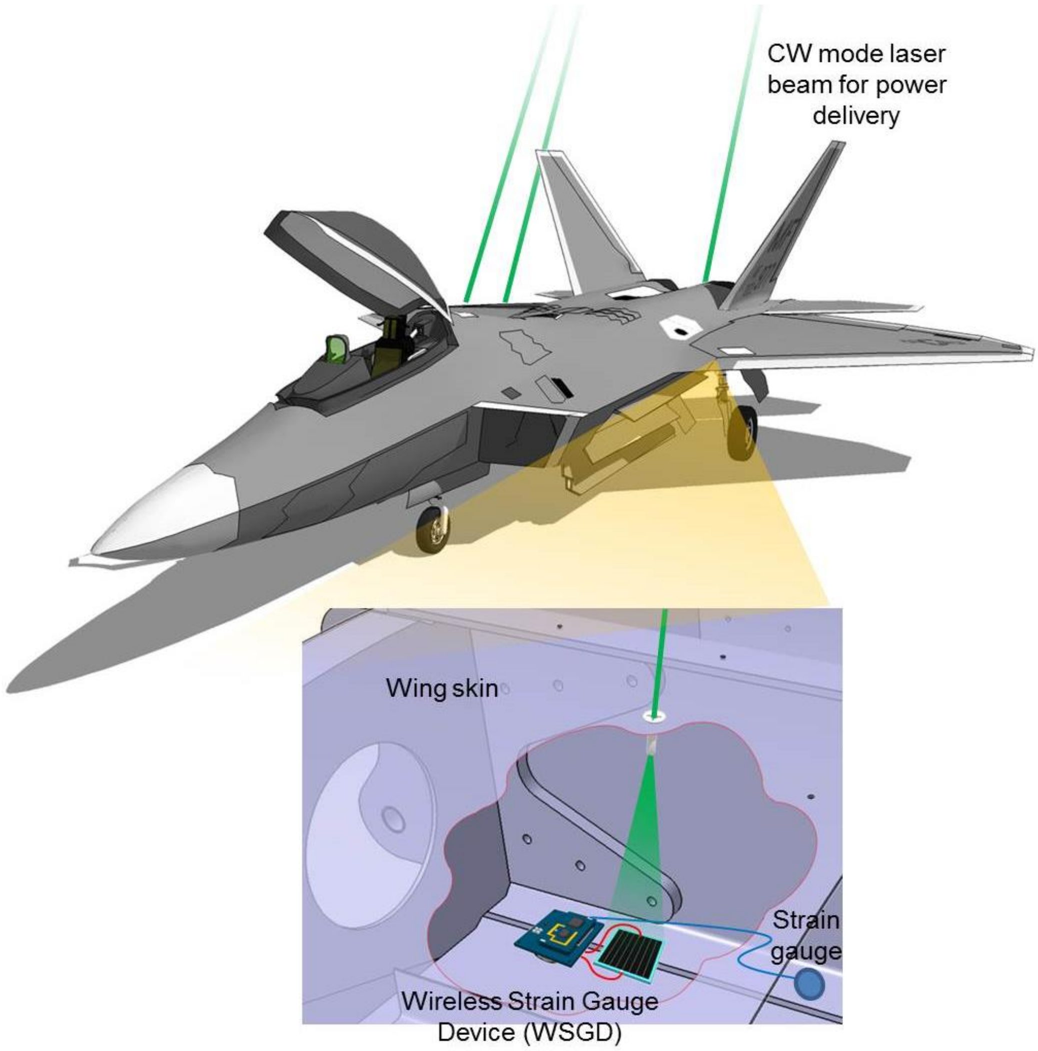

Figure 1. Laser-powered wireless sensing system for aircraft SHM.

2. LASER-POWERED WIRELESS SENSING SYSTEM

A laser-powered wireless sensing system consists of two key components: the laser source and the laser-powered wireless sensor unit as shown in Figure 2.

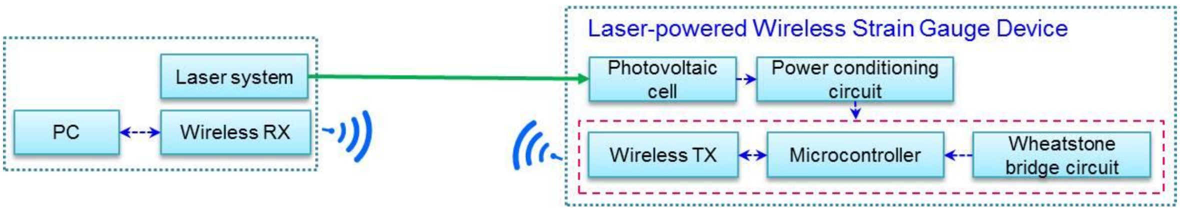

Figure 2. Overall block diagram of the laser-powered WSGD.

2.1 LASER POWER TRANSMISSION SYSTEM

Laser is a device that generates and amplifies coherent beam that is very nearly single wavelength, is highly directional, and has high intensity [1]. There are many different types of lasers, roughly classified by the type of gain medium. The laser gain medium can be a solid (Nd:YAG), gas (He-Ne), or something else. Among them, the advantages of solid-state laser results from its high efficiency and compact size, which leads for efficient delivery of power to a receiver. In this study, we selected a frequency doubled Nd:YAG solid-sate laser at 532 nm and Table 1 shows its specification. The choice of 532 nm was done due to safety reasons (visible green laser) and easily aiming. For further experiments, the original wavelength of 1064 nm would be choose (non-visible infrared light) for gaining high power.

Table 1. The specification of the selected laser

Characteristics	532 nm Frequency doubled Nd:YAG laser
Wavelength	532 nm
Laser power	0.4 W at CW mode
Beam divergence	1.6 mrad
Beam size at the exit port	0.7 mm

Currently, the best devices for converting CW (continuous wave) laser beams to electric power are PV cells. The photovoltaic effect refers to photon exciting free electrons into a higher energy level, allowing them to act as charge carriers for an electric current. The minimum energy required to be an excited electron state is called the ‘band gap’. Since the photon energy is proportional to its frequency, PV cells are responsive to particular frequencies of light corresponding to the cell’s bandgap energies [2]. Photons at too low frequency do not generate electric current, whereas high-frequency photons waste energy in excess of the bandgap energy. Thus, it is important to select a wavelength near the optimum value for efficient laser power transmission (LPT). The best device for converting CW laser beams to electric power is a PV cell. In this study, we have selected a GaInP PV cell by SPECTROLAB which has a bandgap of 1.85 eV which is the closed to the photon energy of 532 nm laser.

Figure 2 shows a system diagram of the proposed LPT which consists of a laser generator, a beam collimator, and a laser mirror positioner (LMP) acts as a transmitter and delivers a laser beam to a PV cell. Consequently, a PV cell converts the laser light into DC current and supplies power to the connected sensor node. Given the nature of divergence of the laser beam, a beam expander is necessary to adjust the laser beam size to the aperture of the PV cell.

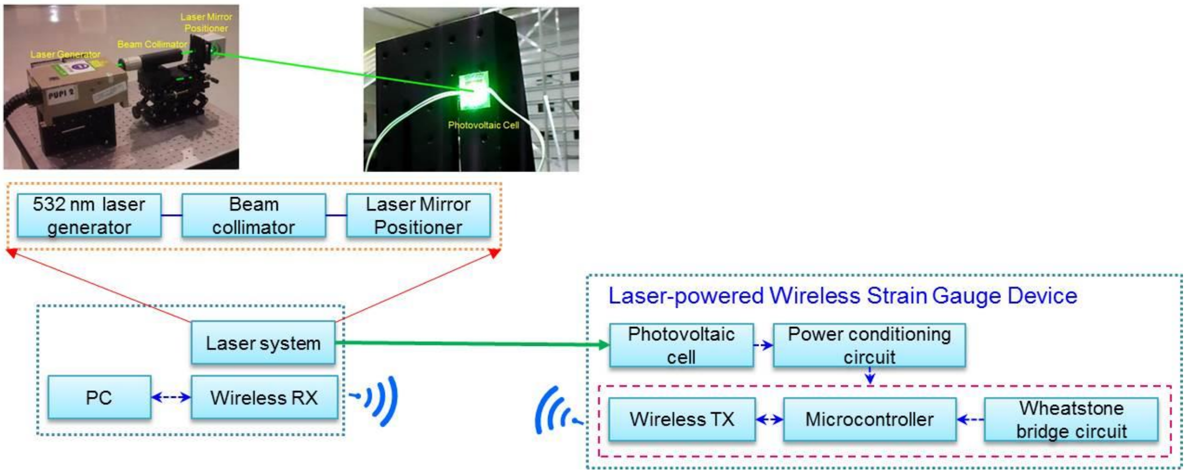

Figure 3. Laser power transmission system.

2.2 LASER-POWERED WSGD

OVERALL DESIGN OF THE WSGD

Strain gauges are often used in SHM applications to monitor strain of structures. Strain measurement is a very useful and general method to evaluate integrity. Strain gauges are usually connected to their signal conditioning and data acquisition system using long and costly electrical wires. Given these limitations of conventionally wired strain gauges, efforts are ongoing to integrate the strain gauge to a wireless sensing unit. However, one of the main challenges is to obtain the energy necessary to operate the wireless sensors. To overcome this problem, we propose energy-efficient wireless sensing gauge powered by LPT. This devices features wireless and battery-free operation, and utilizes conventional strain gauge as a measurement sensor. In this study, we selected Texas Instruments MSP430 series microcontroller and a 2.4 GHz IEEE 802.15.4 RF transceiver (Texas Instruments CC2500). Table 2 outlines the power

Table 2. Power requirement of the laser-powered WSGD.

Laser-powered WSGD				
Subsystem		Nominal Voltage (V)	Nominal Current (mA)	Power (mW)
Microcontroller	MSP430FG 4618	3.3	0.33	1.1
Wireless modem	CC2500		Tx: 21.6, Rx: 12.8	Tx: 71.3, Rx: 42.2
Amplifier	AD620		1.3	4.3
Power conditioning circuit	NCP1402		3	9.9
	D24V6F3		2	6.6
Total Power (mW)				Tx: 93.2 Rx: 64.1

requirement of the component on the WSGD based on the datasheet estimates. From the table it is clear that the wireless modem CC2500 is by far the greater single power consumer in the WSGD, accounting for nearly 77% (Tx) and 66%(Rx) for the total power.

WHEATSTONE BRIDE CIRCUIT

For digitization of measurement data from the sensor, the MSP430 internal analog-to-digital converter (ADC) was employed. The 12-bit ADC(Analog-to-Digital Converter) interface comprising a Wheatstone bridge and an amplifier was developed for gauge-resistance measurement and signal amplification, respectively. In this study, a uniaxial general-purpose strain gauge (062LW from Vishay Precision Group, Inc.) with a 350-Ω resistance and a gage factor (GF) of 2.115 was connected to the interface circuit. This resistance value was chosen for trade-off between the SNR and power consumption. To measure strain, quarter bridge circuit was designed as shown in the Figure 4.

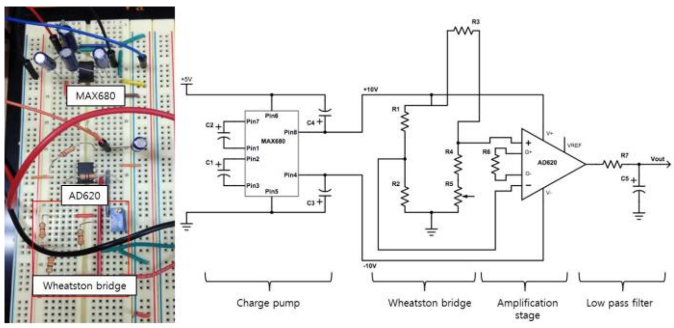

Figure 4. Wheatstone bridge circuit of the WSGD.

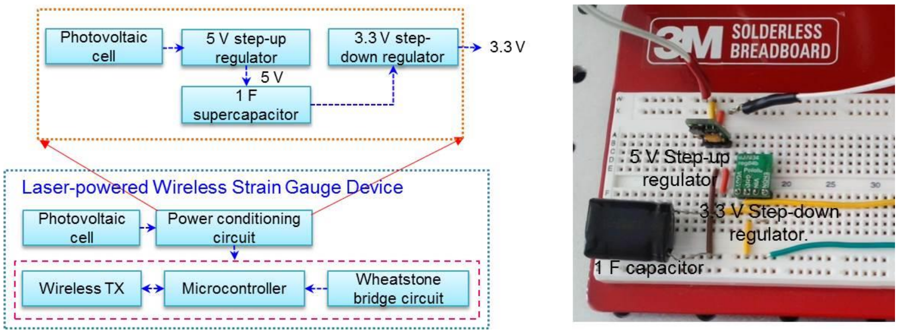

Figure 5. Power conditioning circuit.

POWER CONITIONING CIRCUIT

A power conditioning circuit is necessary to convert low voltage input from the PV to a constant voltage level of 3.3 V used by the sensor. Figure 5 details the circuit diagram of the power conditioning circuit. The laser power transmission function is quite similar to that of a battery, which provides power to the WSGD. The generated laser beam is absorbed by the PV cell then it converts the absorbed laser beam into electricity and the converted electricity goes to the energy conditioning circuit which comprises two voltage regulators and a super capacitor. The output voltage of the PV cell is approximately 1.4 V ant this voltage level is lower than the minimum required voltage

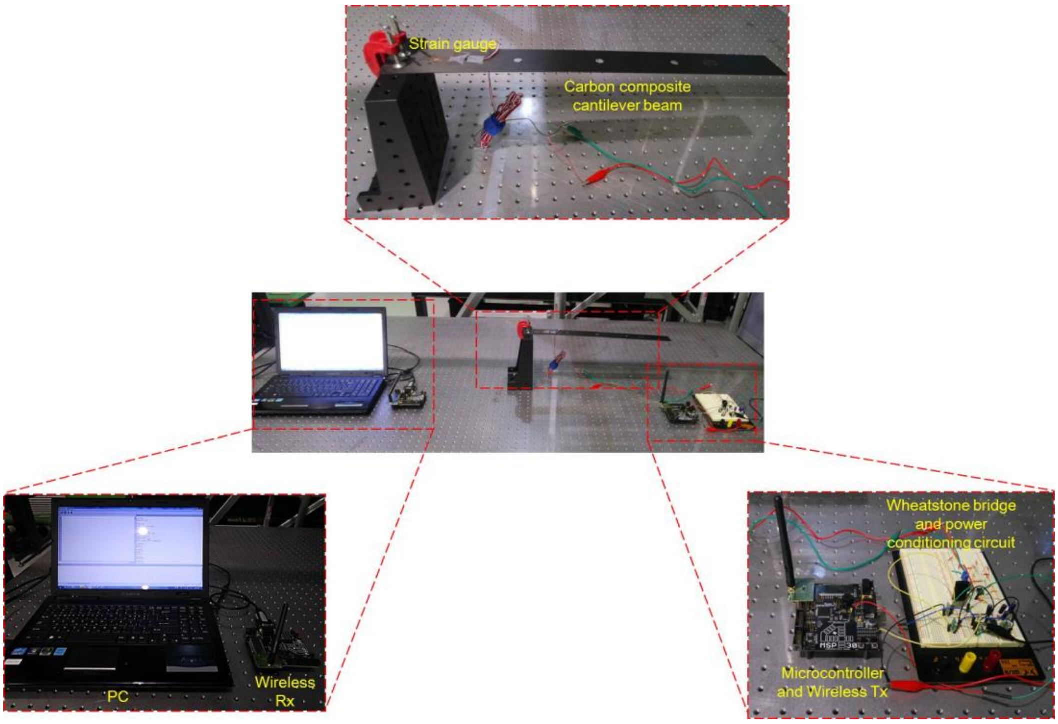

Figure 6. Test setup of strain measurement.

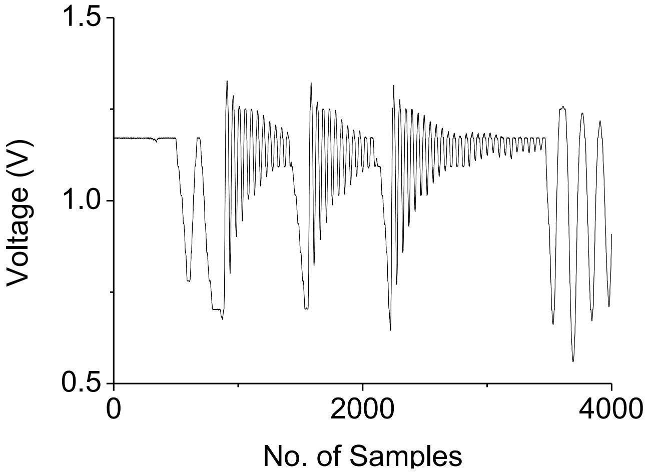

Figure 7. Voltage response to structural load of the WSGD.

level of the WSGD. For this reason, a step-up voltage regulator was placed before the 1 F capacitor and we selected 5 V voltage booster in this study. In addition, another regulator is needed to maintain the voltage level of the capacitor for accurate strain measurement. Therefore, we placed a 3.3 V voltage regulator after the capacitor.

3. EXPERIMENTAL RESULTS

Figure 6 shows test setup of response measurement of the WSD to structural load.

A carbon composite cantilever beam was used for strain measurement. The strain gauge was bonded onto the specimen using conventional methods. The WSGD connected to the strain gauge measured the voltage of the strain gauge and transmitted the acquired voltage data to the wireless receiver. The transmitted data can be converted to strain using excitation voltage and gauge factor. Figure 7 shows one example of voltage representative of induced strain at the WSGD which are transmitted to the base station via wireless communication.

4. CONCLUSION

In this paper, we proposed a laser-powered WSGD for deployment of potential aircraft structural health monitoring system which features low power consumption. The WSGD was developed based on a MSP430 evaluation board and a CC2500 radio module and designed an interface circuit with a conventional strain gauge using a Wheatstone bridge and an amplifier. Demonstration of the proposed system was provided measurement of the voltage induced strain at the WSGD and transmission data back to a base station successfully.

ACKNOWLEDGMENT

This research was supported by Leading Foreign Research Institute Recruitment Program through the National Research Foundation of Korea funded by the Ministry of Science, ICT and Future Planning (2011-0030065) and by the research grants (UD130058JD) of the Agency for Defense Development of the Korean government.

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