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Research Paper

Coupled optic-thermodynamic analysis of a novel wireless power transfer system using concentrated sunlight for space applications

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HIGHLIGHTS

- A novel space wireless power transfer system is proposed.
- Concentrated sunlight is used as the medium to avoid multiple conversions.
- Fresnel lens and optical fiber bundle make the system compact and space-qualified.
- Coupled optic-thermodynamic model is developed to analyze link efficiencies.
- End-to-end efficiency achieved is as twice as that of microwave or laser system.

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ABSTRACT

The energy generation and supply for in-orbit spacecraft have become an urgent problem concerning efficient and economical utilization of spacecraft formation flying. To fill the gap between the requirement of inter-spacecraft energy transfer and the development of wireless power transfer, this paper presents a novel wireless power transfer system whose transmission medium is concentrated sunlight. The system concentrates sunlight using a Fresnel lens, and changes the direction of concentrated sunlight beam with optical fibers. The light energy is converted to thermal form by a heat collector, and then it is utilized to generate electricity by a Stirling engine integrated with linear alternator. Equipments employed on fractionated spacecraft shall be supported by this electric energy. A coupled optic-thermodynamic model was developed to analyze system link efficiencies. This system offers characteristics such as high flexibility, relatively low cost for launch and maintenance, and most importantly, high end-to-end efficiency. Simulation results show that the geometric concentration ratio and the temperature ratio of expansion and compression spaces are two key parameters of this system. Output power of 234.3 W was achieved on the distance of 100 m, and the end-to-end efficiency of the system was above 20%.

1. Introduction

Efficient as well as economical methods of supplying energy to micro spacecraft have increasingly become a key technology of Spacecraft Formation Flying (SFF). The SFF is a concept that distributes the functionality of a monolithic, single spacecraft to a cluster of smaller and closely flying spacecraft to increase performance and reliability [1–3] (Fig. 1a). The concept promises a great application prospect in space industry, such as monitoring the Earth and its surrounding atmosphere, geodesy, deep space imaging and exploration, and in-orbit servicing and maintenance of spacecraft [4]. Compared with a monolithic single spacecraft, the SFF approach has several advantages, including flexibility and modularity, strong robustness and reliability [5,6]. The most challenging technique of the SFF lies with energy supply to each spacecraft in formation. For conventional spacecraft, energy supply is implemented by photovoltaic power generation through solar arrays. However, as for the SFF, the cost increment due to replication of hardware and increased number of interfaces make it impractical to employ solar arrays on each fractionated spacecraft. Resource Centralization (RC) and Wireless Power Transfer (WPT) have been proposed as enabling solutions to balance the conflicting requirements that SFF with superior performance while at an acceptable cost level [7,8]. In this methodology, high-cost equipment, especially power system, is supposed to concentrate on a uniform platform to support other Mission Spacecraft (MS) via

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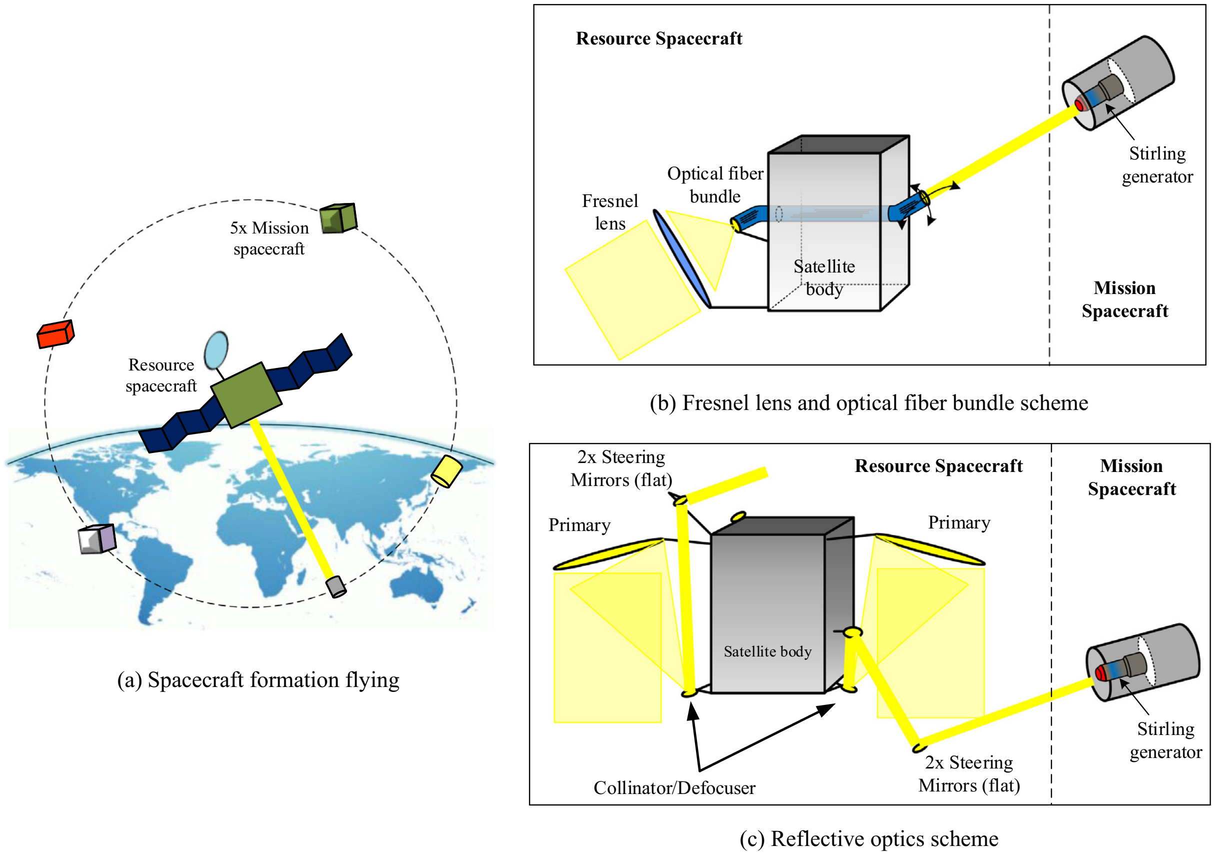

Fig. 1. Comparison of the system scheme from [7] with that of the CS-WPT system.

WPT, which could greatly alleviate the cost for design, manufacture and launch of formation flying spacecraft.

Plenty efforts have been made in the past to investigate several relatively efficient methods of WPT such as microwave, laser and concentrated sunlight [9–11]. For microwave and laser approaches, solar energy is firstly converted to electric energy by crystalline silicon solar cells with an efficiency of 18% [12], then it is converted to Radio Frequency (RF) or laser beam with an efficiency of less than 80% according to Bergsrud and Straub [13] and Nayfeh et al. [14]. The invertible course (RF-to-DC or laser-to-DC) is conducted at a similar efficiency after receiving by a MS. Synthesizing the above three procedures and attendant heat loss, the end-to-end (sunlight-to-DC) efficiency of both approaches can hardly exceed 12%.

In order to improve the WPT efficiency, a novel concept using unconverted concentrated sunlight to transfer power was proposed [7]. In this scheme, sunlight pass through reflective optics for concentration, collimation and emission, which avoids multiple conversions of energy, namely sunlight-to-DC, DC-to-RF or DC-to-laser, RF-to-DC or laser-to-DC in microwave or laser scheme. Energy conversion only happens at the receiving spacecraft where sunlight is converted to electricity. The end-to-end efficiency of this approach is expected to exceed 20%. Though this scheme presents advantages on efficiency over conventional microwave and laser approaches, there are still some difficulties in introducing it to space applications. Firstly, the use of reflective optics would sharply enlarge the launch cost because of increment in weight and size caused by optical parts. Secondly, little research has been done on either the specific implementation method of receive and transform (RT) subsystem aboard the mission spacecraft or the efficiency evaluation of the concentrated sunlight approach of WPT.

To address aforementioned issues, the Concentrated Sunlight Wireless Power Transfer (CS-WPT) system was constructed in this paper, which utilizes a Fresnel lens as a concentrator, an optical fiber bundle to change beam direction, and a Stirling generator as the receive device aboard a MS. Compared with the reflective scheme referred to in [7], Fresnel lens offers higher optical performance along with minimized weight, smaller volume and lower cost [15]. Additionally, optical fiber bundle further enlarges the illumination zone under limited range of weight and volume owing to its superior flexibility. The main novelty of this system is the combination of a Fresnel lens and an optical fiber bundle, which achieves the functionality of reflective optics with a highly compact, flexible and light-weight structure, thus making the CS-WPT system more space-qualified. Stirling generator, guarantees a high heat-to-electricity convention efficiency. Fig. 1b and c compare the system scheme from [7] with that of the CS-WPT system.

There are already many previous references that support the study in this paper. Concerning the Fresnel lens, Leutz et al. [16] designed a Fresnel lens for the application of a thermal solar collector intended to provide heat source for a sorption heat pump cycle. A concentrator comprising a line-focus Fresnel lens was used to collect and focus sunlight onto high-efficiency multi-junction photovoltaic cells by O'Neill et al. [17]. Rosell et al. [18] studied the thermal behavior of the combination of a Fresnel lens concentrator with a channel PV/T collector. Concerning the optical fiber bundle, Jaramillo et al. [19] developed a model to determine the non-linear absorption in SiO_2 optical fibers, whose results indicated that optical fiber can be an alternative form to transmit concentrated solar