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Research Article

Design and Characterization of a Small-Scale Solar Sail Prototype by Integrating NiTi SMA and Carbon Fibre Composite

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Solar sails are propellantless systems where the propulsive force is given by the momentum exchange of reflecting photons. In this study, a self-deploying system based on NiTi shape memory wires and sheets has been designed and manufactured. A small-scale prototype of solar sail with carbon fibre loom has been developed. Different configurations have been tested to optimize material and structure design of the small-scale solar sail. In particular the attention has been focused on the surface/weight ratio and the deployment of the solar sail. By reducing weight and enlarging the surface, it is possible to obtain high values of characteristic acceleration that is one of the main parameters for a successful use of the solar sail as propulsion system. Thanks to the use of shape memory alloys for self-actuation of the system, complexity of the structure itself decreases. Moreover, sail deployment is simpler.

1. Introduction

Solar sails use sunlight as propulsion system. The continuous photonic pressure provides propellantless thrust to hover in the space. Therefore no active propulsion system or any chemical propellant is required for primary propulsion. Solar sail accelerates slowly but surely, reaching very high speeds which may be applied to interstellar exploration. Solar sails are generally deployable and lightweight spacecraft structures, unfolding large areas of highly reflective thin film, thus being able to transform the momentum of solar photons into propulsive force (Figure 1). The concept was proposed in 1920 by Tsiolkowsky and Tsander [1, 2]. Missions to the outer solar system may be enhanced by using solar sails. The solar pressure decreases by the square of the distance from the sun; then the solar sail gains a large amount of energy when approaching the sun. The solar radiation pressure is very low, about 6.7 N/GW [3] that equals $9.12 \times 10^{-6}\,\mathrm{N/m^2}$ at Earth's orbit. If the spacecraft is close to Mercury the light pressure can be an order of magnitude higher. Then two parameters are decisive: the size of the sail must be as large as possible so that the pressure of photons would result in nonnegligible driving force; the overall mass must be as small as possible to efficiently convert the driving force into a nonnegligible acceleration [4].

Solar sail performance is significantly affected by four main factors: sail surface/mass ratio; optical properties of the sail film; mechanical properties of the sail film; and sail geometry. In the end of the 20th century and beginning of the 21st century, solar sail propulsion has been proposed for a manifold range of mission applications such as planet or small body centred trajectories, escape manoeuvres (i.e., orbit inclination change), and rendezvous missions. Several space missions have been devoted to this aim. In 1973, Mariner 10 (NASA) used radiation pressure for the attitude control [5]. In 1999, Odyssee project (DLR-ESA) proposed a laboratory deployment test [6]. In 2010, Ikaros (JAXA) was the first space probe successfully tested [7, 8]. In 2011, Nanosail-D2 (NASA) showed the applicability of the solar sail propulsion to small satellites [9]. In 2015, Lightsail-1 (Planetary Society) was a solar sail totally deployed without reaching the orbit [10].

Unfolding of sails requires rigid structures such as booms [11]. Many different booms have been designed as pantographic or inflatable structures. In the case of inflatable booms, the structure is stabilized by internal gas pressure. Generally, booms are morphing structures which exist in

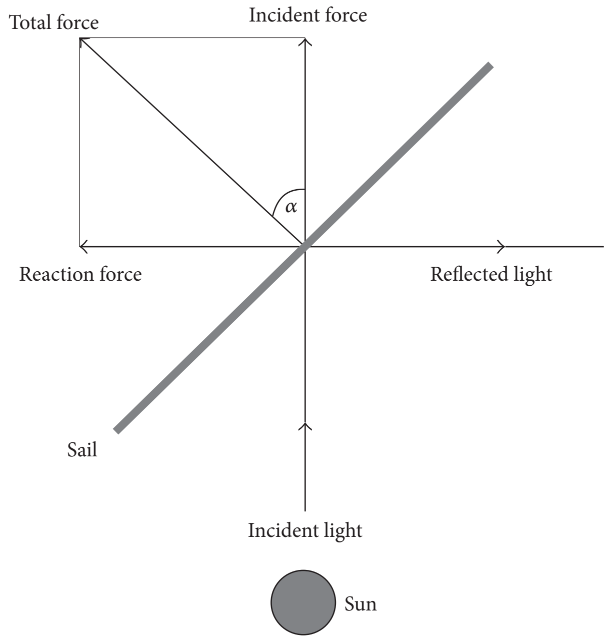
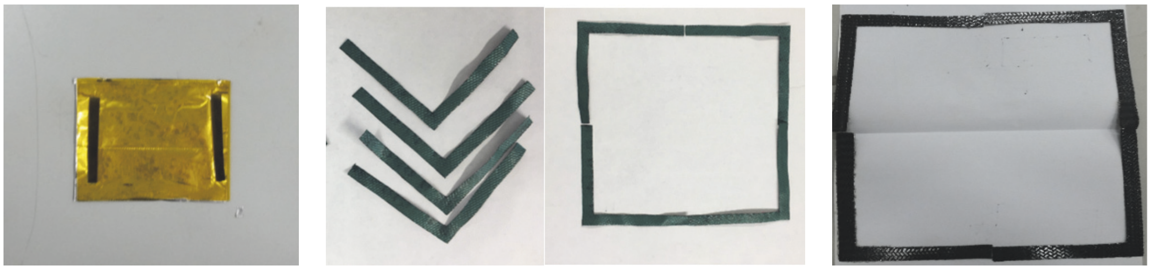


Figure 1: A sketch of the interaction of the solar photons with the sail.

two stable geometrical states, one for the stowed and one for the deployed configuration. Apart from the deployment of the sail system, the sail structure involves the use of guide rollers which are electromechanical actuation devices [12]. First generation sails should vary in size from 100 to 200 m depending on mission destination. Solar sails are composed of a flat smooth material, covered with a reflective coating or film and supported by a lightweight structure. They are compacted and stowed for launch and the main limitation of the current deployment technology is the overall mass of the system and the complexity of the deploying mechanism of such huge surfaces. The main goal of this study is to build up and test an innovative miniaturized self-deploying system actuated by shape memory alloy elements which are integrated with carbon fibre loom. The small-scale prototype of the sail self-deployment system has been designed and manufactured to reach a low surface/weight ratio in order to take advantage from this kind of space propulsion.

2. Solar Sail Materials and Shape Memory Alloys

The correct choice of materials is fundamental to achieving the best performance in terms of active surface, number of possible folding passes, and lightness of the structure [13, 14]. In our experiments, commercial pure Al thin sheets and adhesive Kapton films have been used to prototype the sail structure. The adhesive film thickness is 2,5 μm and has been applied on 12 μm thick Al film. Kapton (density of 1.4 g/cm^3) is chemically inert and shows a high radiation resistance. It is stable also at high temperatures. Aluminium has been chosen for the high reflectivity in the whole solar spectrum and the relatively high melting point. These two choices were motivated in a previous work [15] and the structure has been improved in this study by adding the carbon fibre loom. Carbon fibre composites have good stiffness and strength and are suitable to produce low weight structures. The Al reflective surface can be maximised as well. Composite loom was manufactured by using thermosetting prepregs according to modern technologies in Aerospace applications. Self-deployment of the sail has been achieved due to the activation of the shape memory alloys elements inserted perpendicularly to the bending line in the composite loom. Shape memory alloys are a class of functional materials able to recover the preset shape just upon heating above a critical transformation temperature [16]. The shape recovery is based on the thermos-elastic martensitic transformation occurring in such kind of alloys. The characteristic transformation temperature is function of the composition of the alloy, and the thermal and mechanical history of the material [17]. Typical transformation temperatures are 45–65°C (alloy H) and 65–95°C (alloy M) according to the nomenclature used by the supplier of the alloys. These materials are used as sensors, sensor/actuators, or only actuators. Shape memory alloys are able to bear also high number of activation cycles [18]. In the current application, no cycling is required to the alloys as the self-deployment of the sail must occur just once. As active materials, wires of 0.41 and 0.60 mm diameter have been acquired as well as 1 mm thick foils. In the first experiments, silicone was used in order to fix the shape memory wires onto the aluminium sail. Nevertheless, an undesirable twisting of the wires was noticed. As a consequence, the deformed wire could damage the aluminium foil during recovery. Subsequently, it was decided to replace the shape memory wires with ribbons. The use of the rolled ribbon with thickness of 0.36 mm led to an improvement in the solar sail performances in terms of deployment but not in weight. In



(a) (b) (c)

Figure 2: From (a) to (c) SMA foils applied on the solar sail surface, the composite prepregs, and the composite loom.

the end, the best solution both in terms of deployment and weight was found by using the rolled wire with a thickness reduction down to 0.15 mm. Thereafter, to set the shape, different thermal treatments, called shape-setting, have been tested on the ribbon in order to ensure the recovery of the desired shape during the deployment. The best result consists in heating up to 500°C the foil in the oven, maintaining this temperature for 5 min, and finally quenching in cold water. After this thermal treatment, the cold ribbon is bent in the desired shape. At this point, the ribbon is able to recover the preset straight shape just upon heating above the activation temperature (65–95°C), whichever is the heating method. On the aluminium surface, the shape memory foil was bonded by using the sticky part of the Kapton. The composite loom has been produced by a moulding process at 150°C for 15 min. Two prepreg sheets where used to obtain a multilayer structure. Figure 2 shows the first step of the sail production. In the same figure there the composite loom is also shown before and after moulding.

3. Characteristic Parameters

In this work the main parameters which have been taken into account are the overall weight of the solar sail, the reflecting surface, and the maximum number of available bending. These parameters are fundamental in order to achieve the best performance of the solar sail and the experimental tests are principally aimed at defining the optimum among these parameters. After several attempts, the optimum for the active element has been found in the rolled wires, due to the advantages resumed from the foil configuration and the wire configuration such as monodirectional shape recovery and the lightness. In Table 1 the advantages and disadvantages of the different configurations are reported.

Table 1: Advantages and disadvantages of wires and foils.

	Wires	Foils
Advantages	(i) Lightness (ii) Low dimensions	Monodirectional shape recovery; no requirements of sticky elements.
Disadvantages	(i) Torsion (ii) Requirements of sticky elements	High weight

4. Experimental Results

In the first experiment the attention was focused on the study of the behaviour of the shape memory alloy and its reaction to bending. For this reason the first configuration, shown in Figure 2(a), was manufactured without the loom. Bending experiments performed on many different radii of curvature show that there exists a critical minimum radius. If the alloy is bent beneath this value, the alloy is no more able to recover its shape due to a spring back effect which cannot be considered negligible.

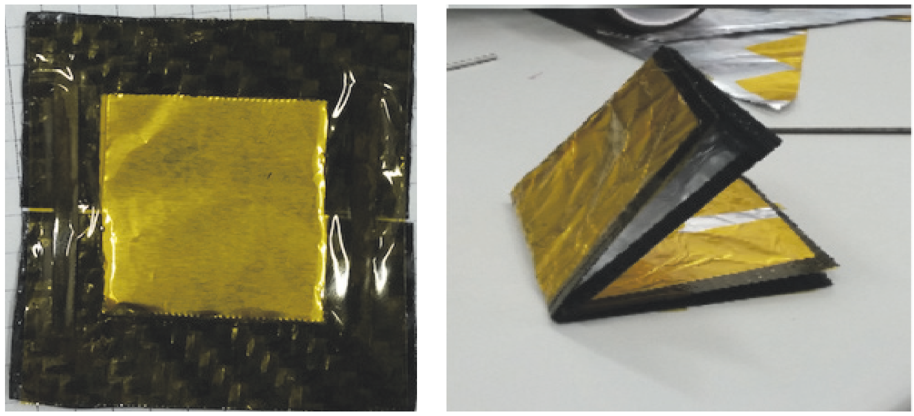
For this reason in the successive attempt the radius of curvature was fixed at 2 mm. In Figure 2(a) an example of this configuration with foil as SMA elements is shown.

Next developing step has been the prepreg loom manufacturing and its insertion on the external side of the solar sail. With the insertion of the prepreg loom a problem arose: the stiffening of the sail system and consequently some folding difficulties. Furthermore the prepreg material has high insulating properties which could cause problems and delay in the activation of the SMA elements and consequently to the self-deployment of the sail. Finally the loom has been cut alongside the bending lines in order to allow a better folding of the whole solar sail structure. This configuration is shown in Figure 3.

Thanks to the shape recovery of the SMA foil it has been observed that this configuration recovered its shape perfectly without any spring back phenomenon. The analysis on the surface/weight ratio taking into account all the experimental data obtained in these configurations showed that the best value has been achieved with a small-scale model $20 \times 20\ \mathrm{cm}^2$. This model is very easy to be bent alongside the bending lines while the shape recovery is almost perfect.

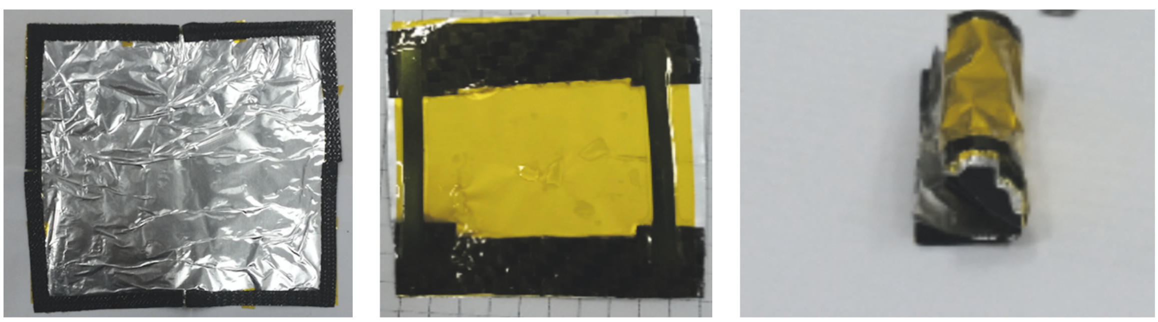
Further weight reduction can be achieved by decreasing the loom width in order to eliminate the loom in one direction and to allow a cylindrical bend of the solar sail. In this configuration the rolled wires replace the loom in one direction (Figure 4).

Another important parameter is the opening time required in the different configurations adopted for the solar sail, mainly due to the insulating properties of the prepreg. In the experiments performed in the atmospheric condition of the laboratory the opening times have been



(a) (b)

Figure 3: From (a) to (b) an example of the second configuration of solar sail with loom deployed and its folded state.



(a) (b) (c)

Figure 4: From (a) to (c) a 20 × 20 cm^2 small-scale solar sail without Kapton, the configuration of solar sail without loom in one direction and its cylindrical bending.

Table 2: Different opening times under different configuration and number of foldings.

	Opening times (s)
Configuration 1, folding 1	5
Configuration 2, folding 2	14
Configuration 2, cylindrical folding	24

fully influenced by the number of foldings. Considering only the full deployment of the sail, the solution with rolled wire and the cylindrical deployment are both to be considered optimal starting from smaller folded configuration. The full deployment of the sail has been obtained also in the case of cylindrical configuration, without particular drawback in the opening times.

In Table 2 the opening times required in the different configurations and number of foldings are reported under the same experimental heating condition imposed.

5. Discussion and Conclusion

The main objective of this work was to demonstrate the feasibility of a new self-deployment system of solar sail by means of shape memory alloy active elements and at the same time to maximise the surface/weight ratio of the manufacture small-scale solar sail. In our experiments shape memory alloys replace the electromechanic actuators; thus the design and the characterization of the solar sails can be simplified. Also the costs and the weight of the structure can be drastically reduced. Prepreg employed for the manufacturing of the loom played an important role due to the weight reduction of the structure and the increase of the stiffness of the solar sail. However, nowadays the main solar sails projects are totally realized using carbon fibre material (Solar Sail L'Garde).

The small-scale prototype designed and manufactured in this work has highlighted the following results:

(i) It is impossible to bend over a certain curvature radius.

(ii) Employing light components like prepreg loom and rolled wires as active elements, high values of surface/weight ratio can be achieved.

A summary of the surface/weight ratio values for each configuration of solar sail is shown in Table 3 and in Figure 5

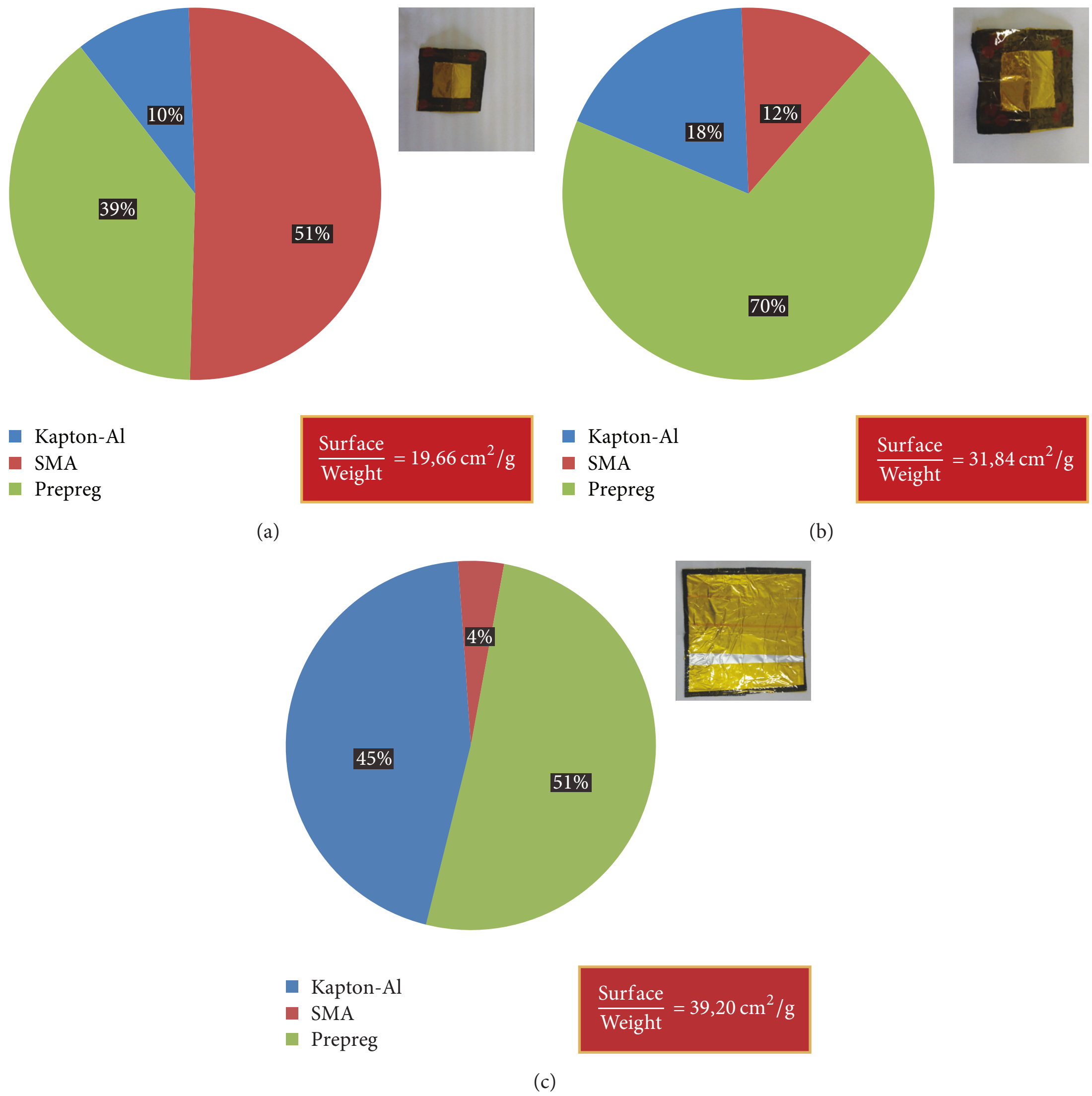


Figure 5: (a) Configuration 1, (b) Configuration 2, and (c) Configuration 3: contribution of the components (SMA, Kapton-Al, and prepreg) to the surface/weight ratio of the sails.

Table 3: Example of surface/weight ratio for different configurations of the solar sail.

Solar sail	Surface/weight
Configuration 1	19.66 cm^2/g
Configuration 2	31.84 cm^2/g
Configuration 3	39.20 cm^2/g

the single contribution of the components (SMA, Kapton-Al, and prepreg) to the surface/weight ratio of the sails is reported.

As a term of reference Configuration 3 has shown a ratio twice that reached by Nanosail-D. Carrying on this work with greater solar sails could be very useful for future realizations of new model as well as inspiration for new bending configuration. However the scale-effect dealing with bigger solar sail must be fully understood and tested both in laboratory and in near to orbit conditions.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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