

Design and Development of a Sun Tracking mechanism using the Direct SMA actuation

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ABSTRACT

In recent years, the growing global interest in the conservation of environment has provided a fresh impetus for research in the area of solar energy utilization. Already, installation of solar energy extraction devices such as solar panels, solar water heaters, solar cookers etc. is becoming popular in urban buildings. Most of these devices consist of a solar receptor that is kept facing the sun during the day with the help of a sun tracking mechanism operated by an electrically driven unit consisting of a sensor, an actuator and a controller. It is obvious that an external power source is necessary for energizing the sun tracking unit. If one could dispense with this extra energy source then the efficiency of the solar panel would be increased. A tracking mechanism directly activated by the sun would go a long way towards achieving this aim.

An attempt has been made to develop a simple yet efficient sun tracking mechanism (SSTM) using smart Shape Memory Alloy (SMA). The SMA element incorporated in the SSTM device performs the dual functions of sensing and actuating in such a way as to position the solar receptor tilted appropriately to face the sun directly at all times during the day. The mechanism has been designed such that the thermal stimulus needed to activate the SMA element is provided by the concentration and direct focusing of the incident sun rays on to the SMA element. This paper presents, in detail, the design and construction adopted to develop the functional model that was fabricated and tested for performance.

Keywords: sun tracking mechanism, Shape Memory Alloy (SMA)

1 Introduction:

This paper describes an attempt that has been made to develop a simple yet efficient smart sun tracking mechanism (SSTM) using SMA actuators. The efficiency of solar receptors depends on the incident angle (i.e. the output energy is ideally proportional to the cosine of the incident angle) [1]. This objective can be realized by the incorporation of a sun tracking mechanism in the solar receptor, increasing the efficiency up to 75% compared to a non-rotating solar receptor [2].

Finster [3], in 1962, was the first one to construct a purely mechanical device that tracked the sun. Later, Saavedra [4] realized the same objective by employing an automatic electronic control to orient an Eppley pyro heliometer. Since then, significant amount of work has been carried out on the design of sun tracking systems using electromechanical actuators. Abdallah and Nijmeh (2004) [5] developed the two-axis sun tracking system with an open loop Programmable Logic Controller (PLC). Roth et al (2004) [6] designed and constructed a system for sun-tracking which operates automatically, guided by a closed loop servo system. A four-quadrant photo detector is used for sensing the position of the sun and two small DC motors are

used for moving the instrument platform keeping the sun's image at the center of the four-quadrant photo detectors. Recently, Alata et al [7] have developed a multipurpose sun tracking system using fuzzy logic control. Rizk and Chaiko [8] have recently introduced a simple solar system tracker using a stepper motor and a light sensor. A recent review of the existing systems can be found in [2].

Fig.1 shows the conceptual diagram of a typical existing sun tracking mechanism. In the closed-loop system the sensor senses the position of the sun and sends a signal to the controlling unit, whereas in an open-loop system control algorithms are preloaded in the controlling unit, which determines the amount of actuation required and sends an appropriate signal to the motor which tilts the solar device towards the sun.

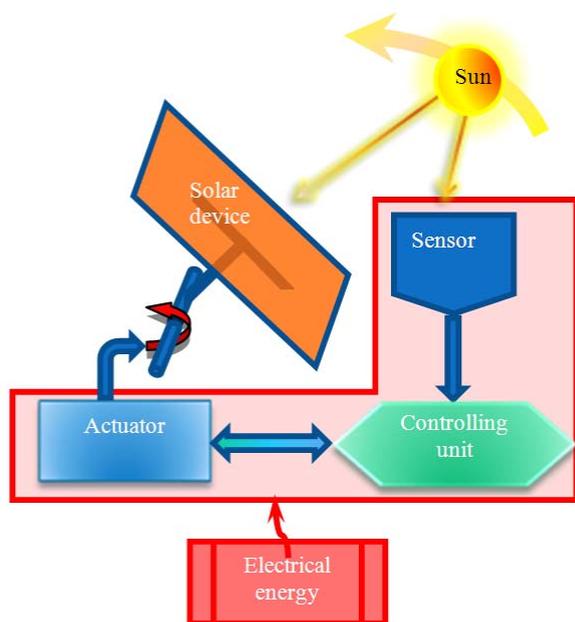


Fig.1 Working elements of a typical currently existing sun tracking mechanism

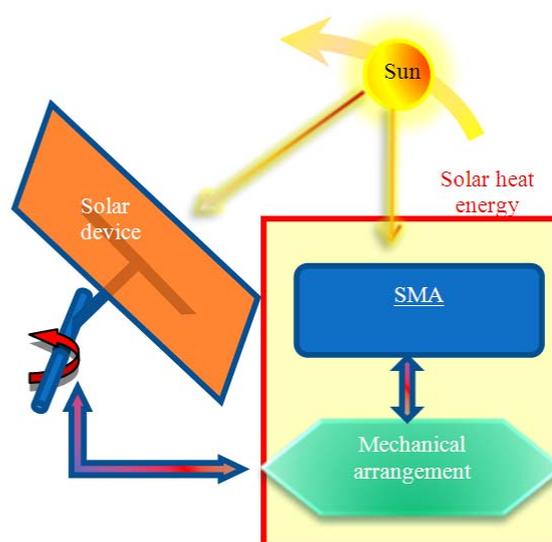


Fig.2 Working elements of the proposed smart sun tracking mechanism (SSTM)

In all the above, the sun tracking mechanisms there is a requirement for a certain amount of electrical energy input for the controlling units(PLC, micro-controller, electronic circuit), for the actuators (electrical motor),and, for the sensors (Photo Detector, Light Dependent Resistors). Since electrical energy is needed as an external source to energize the motor, the employability of such mechanisms is restricted only to areas where electrical energy is easily and continuously available or when the unit itself is an electricity generator.

However, the need for an electrical energy source could be dispensed with, if one could replace the electric motor by a tilting device that can be activated directly by solar heating. Some tracking mechanisms for solar collectors were proposed in the early 1980s which required no electric power supply and no electronic control devices for simplifying their mechanisms [9-11]. These devices included heat responsive elements that could exert a thrust when they were heated by the radiant energy from the sun and become limp in its absence. But the tracking mechanisms based on these could change their position to only two or three positions of the movement of the sun over the entire day.

It is well known that Shape Memory Alloy (SMA) based actuators can respond to a thermal stimulus in such a way as to induce a movement by exerting a significant force on a movable element. It is being used in a variety of applications such as military, medical, safety, and

robotic applications. Nitinol (an SMA material) couplers are in use in F-14 fighter planes since the late 1960s [12]. Thus, it appears possible to design an SMA based device that can be energized by solar heating to achieve the appropriate tilting of the solar receptor. A patent for a tracking mechanism using shape memory alloys (SMAs) as heat responsive elements had been taken initially by Hashizume [13, 14]. The system outlined in the patent requires a number of parabolic trough reflectors or compound parabolic concentrators and SMA springs and pulleys depending on the number of positions of the movement sought. The returning of the solar receptor after completing one day is not addressed. The SMA functional degradation and cyclic behavior of the SMA are not considered in the design, and therefore, may be difficult to achieve controlled, repeatable movement in the system.

The objective was to fabricate a mechanism in which the SMA element performed the dual functions of sensing and actuating in such a way as to position the solar receptor tilted appropriately to face the sun directly at all times during the day. The thermal stimulus needed to activate the SMA element sufficiently, was to be provided by concentrating and direct focusing of the incident sun rays on to the SMA element by suitable lenses (Fig.2 shows the essential elements of the device). The key innovation of this approach is to use a single set of movable focusing mechanisms rather than a fixed array of them with these basic aims, a functional table-top model was fabricated and tested for performance. This paper presents, in detail, the design methodology and construction adopted to develop the functional model.

The layout of the paper is as follows: In the section that follows, the conceptual design of the functional model of SSTM is presented. In the next section, the construction and working principle of SSTM are explained. The subsequent section describes the design and preparation of the SMA spring actuator element, the most important component of this device. Characterization tests conducted on the spring actuator and the design decisions made on the basis of the same are discussed in the section that follows ending with the final section on conclusions.

2 Functional model

2.1 Conceptualization of a Functional model:

In the present case, the core function of the proposed smart sun tracking mechanism would be to keep the solar receptor always facing the sun directly from sunrise to sunset. To accomplish this, a tilting device consisting of an SMA actuator would be fitted into the solar receptor assembly. This device would be activated by the sun's heat, whenever the solar receptor gets out of alignment with the sun, causing a tilting of the solar receptor such that it is brought face to face with the sun. Once the alignment of the solar receptor with the sun is accomplished, the actuator would cease to act until the receptor again registers a misalignment with the sun to a degree detectable by the SMA device.

The first step towards realizing this goal is the fabrication and assemblage of a table-top functional model that could be scaled up later to an actual working device in the site. In the present design, a closed-loop control system is envisaged where the SMA element is able to sense the position of the sun provided there is no interruption. One needs also to take into account the fact that in a real situation, the sunlight may not be incident on the sensor- actuator because of interruption by clouds. Further modifications (that are not addressed here) may be necessary to accommodate such interruptions to the incidence of sunlight on the SM element.

The design of the open-loop functional model needs to be based on the following parameters: 1) the incidence angle of sun's rays and 2) the response time interval between actuations. The incident angle depends on the hour angle and the declination angle. The hour

angle is an angular measure of time and is equivalent to 15° per hour and it varies from -90° to 90° . The declination angle is the angle made by the line joining the centers of the sun and the earth with its projection on the equatorial plane and it varies from -23.45° to 23.45° [1]. Since the variation of the declination angle in time is generally very small, it is ignored in the current design and the incidence angle can be assumed to be the hour angle for the design of the present functional model and the spinning axis of the solar receptor is perpendicular to the equatorial plane. For the current design, the error likely to be introduced by ignoring the declination angle maybe rectified by carrying out a manual weekly correction for increasing the efficiency further more.

2.2 Construction / Fabrication of the functional model:

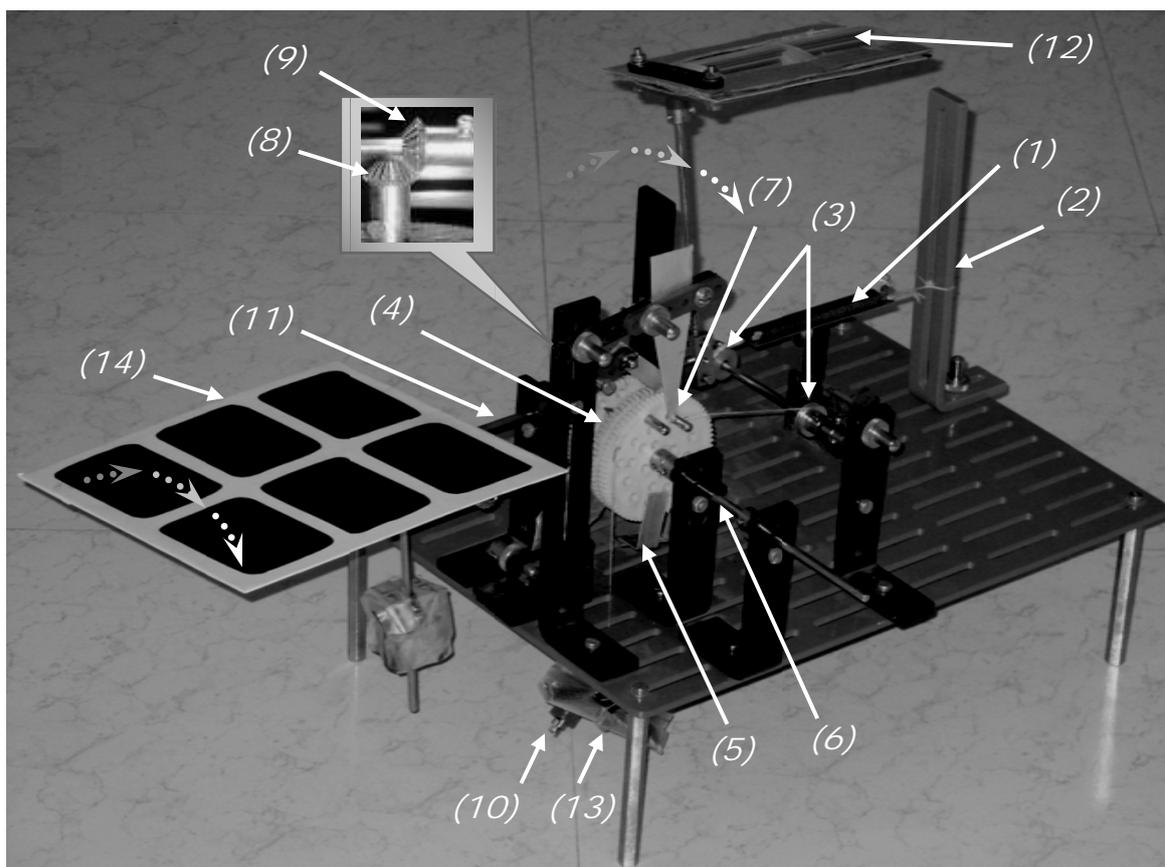


Fig.3 Functional model of the proposed smart sun tracking mechanism (SSTM) working elements are:

1. SMA spring; 2. Fixed frame X; 3. Pulley A&B; 4. Wheel C,D&E; 5. Pawl and Ratchet; 6. The main shaft; 7. Stopper arrangement; 8. Driving bevel gear; 9. Driven bevel gear; 10. The mechanism dead weight; 11. Solar receptor shaft; 12. Lens; 13. The actuator dead weight and 14. Solar receptor

Initially a brief description of the mechanism and its component parts are given below, to be followed by a more detailed explanation of their individual functions in a subsequent section.

Fig. 3 shows the arrangement of the model of the sun tracking solar energy receptor mechanism. The SMA spring (1), the design of which is described in section 2, is suspended horizontally by two connecting cables. One cable connects one end of the SMA spring to the fixed frame X (2) and the other cable connects the other end of the spring to the pulley A. Pulley A and pulley B are mounted on the same shaft so that when A moves B also moves by the same amount. A cable is connected between the pulley B and the wheel C to transmit the motion from

the pulley B to the wheel C. Wheels C, D, and E are mounted on a main shaft (6) as shown in Fig.3. Wheels C and D are mounted freely such that their rotation will not be transmitted to the main shaft, while Wheel E is fixed integrally to the main shaft.

A bevel gear (8) is provided at the end of main shaft near wheel E. A tapered stopper (7) is provided between the two rods projecting from the wheel C to control the amount of stroke of the SMA spring. The tapering of the stopper allows for vertical movement of its position, enabling controlling adjustments to the magnitude of the stroke. A pawl and ratchet mechanism is provided in between the wheels C and D to restrict the rotation of the wheel D to one direction. A lever clutch arrangement is provided in between the wheels D and E to restrict the motion of wheel E to 120° , beyond which the lever gets disengaged from wheel D. The function of the mechanism dead weight (10) hanging from wheel E is to drive this wheel in the reverse direction by 120° to reengage with wheel D. The bevel gear mounted on main shaft to transmit motion to the solar receptor shaft is in turn engaged with another bevel gear (9) which is mounted on the solar receptor shaft.

The elevated frame platform supporting the focusing lenses is attached to the solar receptor shaft (11) in such a way that a constant radial phase angle is maintained between the lens and solar receptor. These lenses (12) are appropriately positioned and fitted on the elevated platform so as to focus the sunlight on to the SMA spring. Since the design enables the platform to rotate with respect to the axis of the spring it is ensured that the spring is at all times receiving the concentrated beam of sunlight focused by the lenses. The two cylindrical lenses (Item #14.0300, Rolyn Optics Company, CA) with 150mm focal length, 50mm width and 60mm length are used to concentrate the sunlight. It is placed one after the other to make a concentrated light beam length of 120mm.

The important specifications that were to be taken into account in designing the SMA spring and the appropriate design parameters used in the actual designing the SSTM are given in Tables I and II .

2.3 Working principle of the model:

The smart sun tracking mechanism described in this paper is designed and constructed to enable the solar receptor to track the sun for 120° hour angle (roughly from 8am to 4pm) and the spinning axis of the solar receptor and lens are kept perpendicular to the equatorial plane. The solar receptor and the focusing lens arrangement are mounted on the same shaft such that a constant angular difference exists between the normal of the solar receptor and the lens arrangement. This angular difference is to provide enough time for SMA actuator to get actuated by the sun and for it to cool in still air.

At the start of the day, the solar receptor is in a position such that the solar receptor normal is approximately normal to the sun at 8am. When the sun moves away from the solar receptor and approaches the maximum value of the angular deviation, the rays begin to get focused towards the SMA spring by the lenses. The focused rays start heating the SMA spring causing it to contract. This action pulls the cable connected to the SMA spring, causing the cable to rotate the pulley A. This rotation sets in motion a series of rotational movements by pulleys, B, C and D and the beveled gears, culminating in the movement of the solar receptor, which gets tilted forward such that it faces the sun.

As indicated earlier, the stroke of the SMA is controlled by the tapered stopper to restrict the tilt in such way that the solar receptor gets correctly aligned towards the sun's rays. This tilt would simultaneously cause the lens platform also to move away, since both the lens platform and the solar receptor are mounted on the same shaft, such that the sun rays are not any more

focused on the SMA spring. In the absence of any heating, the SMA spring would start to cool and elongate due to the pull exerted by the weight attached to the wheel C. The wheel D will also try to rotate back, but would be prevented from doing so by the ratchet pawl mechanism that would arrest such movement, allowing only wheel C to rotate, preventing the reverse rotation of the solar receptor. As regards the SMA actuator it would have been restored to its initial status and would be once again ready to execute the actuation cycle when the sun again reaches the maximum of the angular deviation mentioned earlier.

At the end of the day, after 120° rotation of the sun, the lever clutch arrangement restores the solar receptor back to the initial position i.e. to the position of the solar receptor at the time of the first actuation of the day.

2.4 Design and construction of the SMA spring actuator:

The most important element of this sun tracker is the SMA actuator (part (1) as shown in Fig.3). This actuator is made up of a Ni-Ti alloy that exhibits the phenomenon called 'shape memory effect'. Information is abundant in literature that describes this phenomenon in detail and how it could be put to use in the design of smart actuators that respond to a thermal stimulus (see ref. [12,15&16] for example). Of all the different shapes of actuators that are possible, a spring shaped actuator seemed to be the most appropriate shape for incorporation in the SSTM mechanism, mainly because it's stroke capability. Moreover, standard design procedures have been also been formulated for such SMA spring actuators that could readily be applied to design a spring for the SSTM (see for example, ref [17-18]). In this section, the logic of how a SMA spring was designed and used as the principal actuating element in driving the SSTM mechanism is described.

The SMA spring actuator could be either a tension spring or a compression spring. A tension spring that would be open-coiled in the low temperature under the load and would show the memory contraction in the high temperature was chosen as the SMA spring actuator for incorporation in the SSTM. The extended spring at low temperature would contract and exert a tensile force on heating by the sunlight focused onto it by the appropriately positioned cylindrical lenses in the SSTM mechanism. After the completion of the actuation event, the spring would need to be brought back to a predefined configuration as it cools down to the ambient low temperature, so that it is ready for the next stroke. Since the SMA spring is not expected to automatically come to this required low temperature position, a load is needed for this restoration of configuration at low temperature. In this design, as stated earlier in the construction of the SSTM mechanism, a dead weight hung from wheel E is used to bring the spring back at ambient temperature to a configuration suitable for the next activation.

It should be noted here that the ambient temperature really matters and therefore, picking the right SMA element is important depending on the region the device is used in. For example, in the fabricated model, we used an element which could operate well if the ambient temperature is below 35 degree Celsius suiting to conditions in Chennai, India. The heating is required from the sun to take the SMA temperature to above 30 degrees from the ambient to realize the full transformation. Very low ambient temperatures would mean bringing the transformation temperatures down to accommodate for being able to heat to austenite for transformation. High ambient temperatures would mean pushing the transformation temperatures up to accommodate for obtaining a fully martensite condition at the ambient temperature. Seasonal changes have to be accommodated for. There is, however, a challenge in terms of wide variations in temperature in certain parts of the world. The current design does not account for this kind of situation.

In order for the sun tracking mechanism to successfully operate using the SMA spring, it is necessary to ensure that the SMA material properties are such that thermal stimulus provided by

the focusing lenses in the device is adequate to raise the temperature of the actuator to the required level for optimum force and stroke outputs. In addition, the spring should be designed such that the actuation force and the stroke that needs to be generated by the spring in this application should be achievable without the spring undergoing excessive accumulation of unwanted irreversible plastic deformations on continued use. This means that the transformation temperatures of the SMA spring material should be such that the wire would be in its fully martensitic state at the ambient temperature, and upon being exposed to sunlight concentrated on it by lenses provided in the mechanism, it should go into the fully austenitic state in a reasonable interval of time actuating the movement of the sun tracker.

The SMA actuator cooling times (for natural cooling) are logarithmic, and in still air ambient conditions, the resetting time (cooling) can pose a problem for the springs made of wires larger in diameter [18]. It was also verified that the forces needed to be developed by the SMA spring for tilting the receptor were within the maximum allowable force that the spring made of 0.5 diameter wire could support according to the standard design procedure recommended for SMA springs. Therefore, it was decided to fabricate a spring actuator using 0.5mm diameter NiTi SMA wires appropriately heat treated and shape set to achieve the desired actuation and stiffness properties. The procedure followed for doing this is described in Annexure I.

There are standard SMA spring design procedures available in literature [17-18] for specific actuation force and stroke requirements. For example, the design procedure described for lifting a constant load to a given height in a complete thermal cycle could have been adopted for the current design. However, our previous experience in designing tension springs according to the recommended standard procedures had brought to light the limitations of such procedures arising from an assumption that treats the behavior of the SMA in cold condition to be independent of manner in which loading was carried out. It was therefore deemed necessary to devise some of our own tests to assess the efficacy of the recommended design procedure and introduce some modifications. In the following section, an overview of the standard design procedure and the logic adopted in arriving at the same [17-18] are described and critically assessed in the light of the results obtained by experiments carried out on the spring. Tables I and II provide all the data for the current SSTM mechanism and spring actuator.

2.4.1 Standard design – An overview of the existing procedure:

The design procedure adopted for the SMA spring is a clear departure from the conventional approaches to spring design adopted for steels in which the intrinsic material properties such as Young's modulus stay constant in the temperatures ranges in which they function [17-18]. In the case of Ni-Ti SMA however, a large change in the rigidity modulus occurs over a relatively narrow range of temperature increasing from low to high temperature as shown in Fig.4., resulting in a concomitant increase in the spring stiffness as one takes it from a low to a high temperature. The change in modulus with temperature is, in fact, the result of a reversible martensite to austenite solid state phase transformation. This aspect of the material property is taken into account in the design of SMA (Ni-Ti) spring, to arrive at a standard formula for wire diameter, spring diameter and number of coils for achieving a specified stroke and force in a thermal cycle. Force vs. displacement behavior of the SMA spring is assumed to be linear in the low and high temperature states. In addition, two design conditions are imposed: one on the maximum shear stress allowable in the austenitic state and the other on the maximum shear strain allowable in the low temperature state. These conditions allow one to choose the appropriate dimensions of the spring to generate a given force and displacement combination.

The details of the recommended standard design procedure referred from [17-18] are given below for completeness sake so that the relevance of the characteristic experiments that have been conducted in this work could be put in perspective.

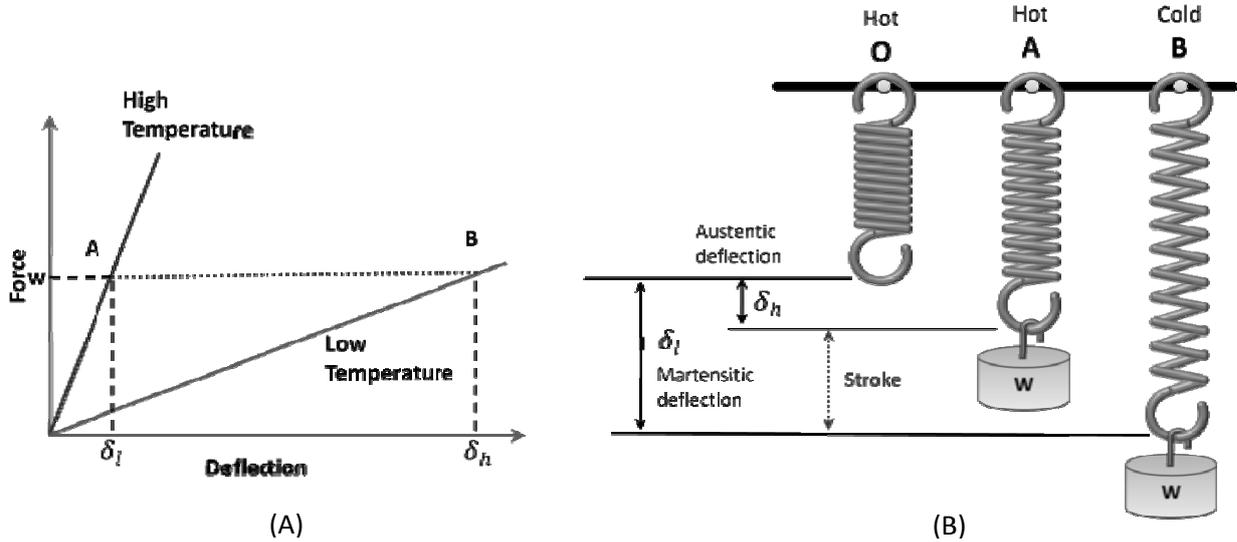


Fig.4 (A) Idealized SMA spring force vs. deflection behavior for standard SMA spring design, (B) configurations of the SMA spring under hot, hot with load and cold with load condition shapes [17]

In the standard design procedure, the aim is to arrive at the wire diameter 'd', the spring diameter 'D', and the number of turns 'n' for a spring that will deliver a force 'P' and a stroke 'S' in a full actuation cycle. The appropriate values of shear moduli ' G_h ' in the hot and ' G_l ' in the cold states, the maximum allowable shear stress ' τ_c ' in the austenitic state, and the limit on shear strain ' γ ' in the cold state are input parameters in this design procedure. The procedure is described below.

The maximum shear stress allowable in the austenite state ' τ_c ', from the fatigue considerations puts a constraint on maximum allowable force on the spring ' P_{max} '. The shear stress in the wire and the force on the spring can be related using,

$$\tau_c = \frac{W8CP_{max}}{\pi d^2} \quad (1)$$

Where,

C = Spring index (D/d), value between 6 to 10

W = Wahl correction factor, where $W = \frac{4C-1}{4C-4} + \frac{0.615}{C}$

From equation (1), it is possible to find out the maximum allowable design load. Equation (2) is an expression that allows one to decide on the number of coils using, d , D , S and the allowable shear strain difference, $\Delta\gamma = (\gamma_l - \gamma_h)$ where γ_l is the maximum low temperature martensite shear strain allowable and γ_h is the high temperature shear strain. The limit on the low temperature martensitic shear strain is to ensure adequate cycle life without functional degradation.

The number of coils (n) can be calculated by,

$$n = \frac{Sd}{\pi\Delta\gamma D^2} \quad (2)$$

The deflection of the spring (δ) in hot or cold state, assuming the material to be elastic is given by,

$$\delta = \frac{8PD^3n}{Gd^4} \quad (3)$$

where,

P = the force exerted by the spring

G= the rigidity modulus in the appropriate state.

Thus, the stiffness (K) can be calculated as

$$K = \frac{Gd^4}{8D^3n} \quad (4)$$

Where G pertains to the appropriate shear modulus – cold, G_l or hot, G_h .

Therefore, the total load to stroke relationship can be obtained for the spring in the cold and the hot state as shown in Fig.4, K_l and K_h for low and high temperature stiffness.

The maximum possible stroke (S_{max}) can now be expressed as,

$$S_{max} = P \left[\frac{1}{K_l} - \frac{1}{K_h} \right] = \frac{8PD^3n}{d^4} \left[\frac{1}{G_l} - \frac{1}{G_h} \right] \quad (5)$$

2.4.2 Application of the standard design to the SSTM SMA spring actuator

In this section, the design procedure that has been adopted for the SSTM SMA spring actuator is described. In the current design of SSTM, the total force that needs to be generated by the spring during actuation is made up of 1) the SSTM driving force (F_{sm}) that is needed to tilt the SSTM assembly in the hot condition and 2) the force that is needed to restore the spring to its low temperature configuration once the tilting action has been completed and the spring had cooled down to ambient temperature. Experiments were carried out to determine the maximum SSTM driving force (F_{sm}) that was needed to tilt the SSTM. The load on the spring during heating denoted by F_h is the sum of the SSTM driving force and the restoring force. During cooling the load on the spring F_l , is only the restoring force. Thus, we have,

$$F_h = \text{the restoring force} + \text{SSTM driving force} (F_{sm}) \quad (6)$$

F_l = the restoring force

$$F_{sm} = F_l - F_h$$

For different loading conditions in the hot and cold states the maximum possible stroke (S_{max}) of the spring is equal to difference between deflection of spring in cold state (δ_l) by the restoring force (F_l) and the deflection of the spring in the hot state (δ_h) by the sum of the SSTM driving force and the restoring force (F_h).

$$S_{max} = \delta_l - \delta_h \quad (7)$$

By applying Equation (5) in equation (7), we have

$$S_{max} = \left(\frac{8D^3n}{d^4} \right) \left(\frac{F_l}{G_l} - \frac{F_h}{G_h} \right) \quad (8)$$

From equation (6) &(8), we can find the bias load, F_l to be

$$F_l = \frac{\left(\frac{d^4 S_{max}}{8D^3} G_l \right) (1/n) + F_{sm} \left(G_l / G_h \right)}{(G_h - G_l)} \quad (9)$$

Thus, from the above equation (equation (9)), we find that the restoring force, F_l , and the number of coils, n , are inversely related to each other. In this SSTM design, the restoring force is chosen first and the force on the spring (F_h) in the hot state is calculated using equation (6), then the minimum number coils is computed appropriately using the strain criteria (equation(2)).

The pertinent data relating to the current SSTM spring actuator used for calculations in the standard design procedure are provided in Tables 1 and 2. The material properties for NiTi are taken directly from literature [17-18]. It has been mentioned in the section on standard design (Section 2.4.1) that a limit has to be put on the allowable shear strain in the low temperature state to ensure sufficient number of actuation cycles. It can be seen from the design procedure that the number of coils to realize a certain value of stroke is also dependent on the value of this shear strain as in equation (2). Assigning the value of 1.5% for the shear strain recommended in [18] (more discussion on this value can be found in ref. [19]) and using the Equation 2, the number of coils required for achieving the specified stroke is found to be 8. However, it is interesting to note that if one were to impose a more stringent condition on the maximum allowable shear strain there is a significant increase in the number of coils required. For example, for a limiting shear strain of around 1%, the number of coils required raises to around 50. To accommodate for lesser shear strain, a spring with 52 coils has been fabricated. It is found that the calculation related to the determination of number of coils required is very sensitive to the design load and limiting shear strain specification. Further studies have to be carried out in order to assess and develop a procedure in order address this sensitivity.

Table 1. Properties of the spring actuator used in design calculation

Values used in the standard design calculations:	
Wire diameter (d)	0.5mm
Spring index (C)	10
The maximum shear stress allowable in the austenite state (τ_c)	100 – 200 MPa
the maximum allowable shear strain (γ_l)	1.03 %
Stress-free austenite transformation temperatures (start to finish temperatures)	56.4°C to 63.8°C
Stress-free martensite transformation temperatures (start to finish temperatures)	42.9°C to 36.4°C
High temperature modulus (G_h)	20700Mpa

Low temperature modulus (G_l)	2750Mpa
Bias force (F_l)	0.49 N
Value arrived at using the standard design procedure:	
Average spring diameter (D)	5mm
maximum allowable force (P_{max})	0.85 to 1.72 N
the number of coils (n)	50

Table 2. SSTM Design Parameters and Fabricated spring specifications

SSTM Requirement:	
The required Stroke (S)	7 mm
SSTM driving force (F_{sm})	1.18 N
Fabricated spring specifications	
Wire diameter (d)	0.5mm
Average spring diameter (D)	5mm
the number of coils (n)	52
SSTM specifications	
Hot test temperature	$\geq 65^\circ \text{C}$
Cold test temperature	$\leq 35^\circ \text{C}$
No of actuation /day	24
The hour angle tilting rang	-60° to 60°
The tilting hour angle /actuation	5°
The actuation duration	20 min

2.4.3 Characterization of the SMA spring actuator

The functional performance of the SMA spring actuator is determined by the load-deflection characteristics. Experiments have been conducted on the fabricated SMA spring to assess its performance. In the standard design procedure described in the previous sections, one is required to obtain the force-deflection characteristics in the high and low temperature conditions of the spring actuator, for calculating the stroke at any given load.

Two different conditions of loading are assessed for validating the results obtained from design calculations.

Case 1: The load-deflection plots for the hot condition (temperature needed to obtain fully austenite state. In the test it was taken to be above 85°C) and the cold condition (temperature needed to obtain fully martensite state – below 25°C) are arrived at independently. This is achieved by first taking the temperature of the stress free spring corresponding to the fully martensitic state and then applying various loads and measuring the deflection for those loads in order to arrive at the load-deflection in this cold state. And similarly, taking the temperature of the spring corresponding to the fully austenitic state (hot state), the deflection was measured for different loads at the hot state to arrive at the load-deflection plot in the hot state. Using the plots thus obtained, the stroke is calculated as the difference in the elongations between the cold and the hot state curves for the corresponding load.

Case 2: The spring is first taken to the hot state (fully austenitic state). Load is applied at this state and the deflection measured. Then, the temperature is lowered to bring it to the fully martensitic state with the load on and the deflection is measured at the low temperature state. This procedure is repeated for every load for which deflection is measured. The stroke is simply the change in deflection measured for every load thus applied.

Fig.5 (a) & (b) show the results of the two cases of tests performed on the SMA spring that has been fitted to the SSTM. Of the three experimental curves shown in Fig.5 (a), the high temperature load-deflection curve marked red is the same for both the types of tests (Case 1 and Case 2). The force-deflection curve marked dark-blue pertains to the measurements in the cold state mentioned in Case 1. The curve marked sky-blue pertains to the measurements in the cold state deflection mentioned in Case 2 test. As can be seen, the cold state load-deflection for Case 1 indicates a very high stiffness of the spring compared to that observed for the curve related to Case 2. The strokes calculated using Case 1 and 2 are presented in Fig.5 (b). It is to be noted that the magnitude of stroke computed for a particular load using Case 2 is much greater than that computed using Case 1. The shear modulus for the martensite state assumed in the case of standard theoretical design calculation plays a crucial role in its closeness to the actual condition (see Tables 1 and 2). From the results, it is clear that the shear modulus used in the standard design [17-18] for the cold state should pertain to that of the load-deflection obtained for Case 2. The shear modulus taken in theoretical calculations in this design seems to match with the measured.

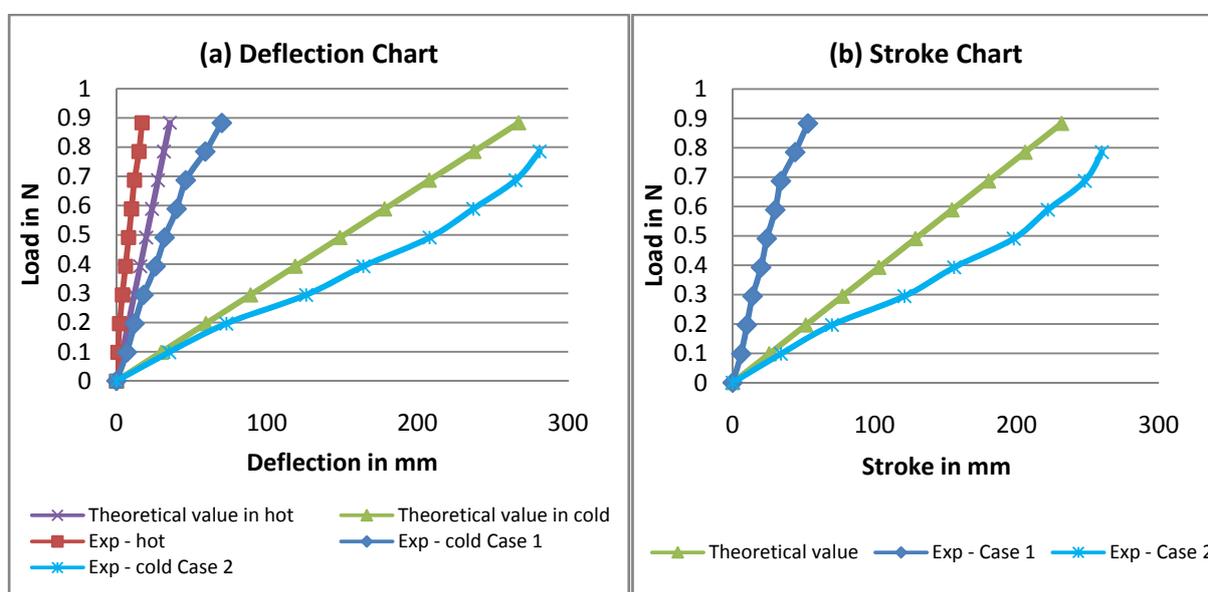


Fig.5 (a) Load Vs deflection chart of SMA spring obtained from experiments (Case 1 and 2) and theoretical design calculation, (b) Load Vs stroke chart of SMA spring- experiments (Case 1 and 2) and theoretical design calculation.

2.4.4 Discussion

A first glance at the standard design procedure leads one to the following expectations.

- 1) For a given wire diameter it should be possible to arrive at the maximum load that the spring can support in its actuating cycle. (See Equation 1)
- 2) The number of coils ‘n’ for realizing the required stroke can be independently arrived at by using Equation 2, once the limit on the low temperature shear strain (γ_l) is fixed.

However, a closer look at the design equations reveals that once the value of P and S are chosen, the required number of coils (n) gets automatically fixed without requiring an externally imposed limit on the shear strain recommended in the standard design Equation 2. Because of the significant difference in the stiffness values of the SMA in its austenitic (hot) and its martensitic states (cold) the strain values registered by the SMA spring at a constant load would be widely different in the hot and cold states. The consequence of this difference would be that, when the

spring is under the maximum load allowed by Equation 1 the cold state shear strain experienced by the spring, would exceed the maximum shear strain of 1.5% recommended in the standard design procedure. For example, under the load $P = 1.18 \text{ N}$, the cold state shear strain (γ_1) in the spring would be 4.46%, far greater than 1.5%.

Correspondingly, the stroke values used for obtaining the number of coils using the limiting cold state strain in the Equation 2 is less than that obtained using the maximum load given in Equation 5 which is more appropriate and closer to the characteristics predicted in experiments as mentioned in section 2.5.3. The stroke values used in Equation 2 and to limiting the cold state strain within the recommended value for the real situation is achieved by providing external stopper in the restoring operation (cooling).

In the SSTM, both hot and cold stopper are used to achieve the required function. In order to provide consistent actuation strokes, a hot stopper is also provided. Fig.3 shows the two hard stops provided in SSTM. The authors also believe that the cold stopper would improve the performance in relation to both the structural fatigue and against the degradation of the actuation function. Further investigations need to be carried out to optimize the performance with the inclusion of hard stops. The functionality of the fabricated model is tested with sunlight and achieved the functionally. A video of the functional model in its working action is available in [20].

3 Conclusions:

From the study presented here that primarily deals with the design and fabrication of the smart sun tracking mechanism using SMA, the following important conclusions are drawn:

1. It is possible to design and develop a sun tracking mechanism using SMA that directly uses sunlight without the need for any additional external power source.
2. The SSTM can be designed as a compact system since the current design uses SMA both as a sensing and an actuating element with direct heating from sunlight.
3. The tilting of the receptor is triggered at regular intervals of time depending on the angular movement of the sun. It should be noted that time intervals of trigger can be changed by tuning the system appropriately.
4. The characterization experiments and the related design calculations indicate that changes have to be made in the standard procedures presented in current literature in order properly design the SMA spring actuator, given the loading conditions.
5. Conservative decisions on the design have been made in this exercise providing hard stops both during the heating and the cooling stages of the actuator.
6. In order to make sure the structural fatigue and functional fatigue life of the actuator are enhanced, in the current design of the SMA actuator in the SSTM, it was decided to provide a larger number of coil spring actuator than needed by design calculations.

The proposed SSTM model designed and fabricated in this project as a proof of concept sun tracking mechanism. However, the following need to be addressed in order to make it possible to realize such a design in the real life solar equipment.

1. The temporary gaps because of passing clouds are yet to be addressed in the current closed loop control system.
2. A more general approach to designing an SSTM is needed to take into account the variations in design parameters such as load on the SMA actuator, time interval for tilt triggering, etc.
3. Further studies have to be conducted to address the sensitivity of the device to ambient temperature in realizing the actual reliable working model.

4 Annexure I

4.1 Heat treatment and shape setting of the SMA spring actuator:

Heat treatment and shape setting of the SMA spring are combined in single process and it persuades the phase transformation temperatures and shape of the SMA spring. The actuation temperature is one of the important parameters in SMA spring actuator and it depends on the phase transformation temperatures of the SMA

A close coiled spring with 5mm mean diameter of 52 coils, using 0.5 mm diameter NiTi wire, was wound around the shape setting jig that was specifically made for producing the SMA spring that was to be fitted into the sun tracking mechanism. This was given a heat treatment and shape setting process at 700°C on 30 minutes. The choice of 52 coils was made, anticipating the possibility of changes in stroke requirements that could come to light during the field trails. It is known that one could always find means of restricting the stroke to desired levels by appropriate choice of active number of coils in the sun tracking device.

After shape setting the phase transformation (actuation) temperatures of the spring has been found out from the DSC result. The martensite to austenite phase transformation temperature (A_s & A_f) is (56.4°C to 63.8°C) peak 59.6°C and the austenite to martensite phase transformation temperature (M_s & M_f) is (42.9°C to 36.4°C) peak 40.3°C. From this we ensured required actuation temperatures have been achieved.

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