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Using a Shape Memory Alloy Spring Actuator to Increase the Performance of Solar Tracking System

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Abstract— **The exclusive properties (e.g. one way and two way shape memory effect, superelasticity, etc.) exhibited by shape memory alloys (SMAs) offer the possibility of producing smart sun tracking mechanisms for photovoltaic panels (PV panels). This article presents an experimental model, conceived by authors, of an active solar panel tracking system, actuated by two SMA springs working against each other. The shape memory effect enables any SMA spring to work as linear actuator by contracting with great strength and speed when heated. This translating motion is converted into a rotation motion of the photovoltaic panel so that it will be appropriately tilted to directly face the sun during the day time. On one hand, the authors make a brief description of the tracking mechanism, and, on the other hand, they comprehensively explain how the automatic orientation of the photovoltaic panel is controlled. The authors also explain how a SMA spring actually works emphasizing the advantages such a device really exhibits in using it as actuator. The active shape-change control of SMA spring the miniaturization possibilities, easy integration into the system structure, automatic orientation of PV panel (using a programmable logic controller) are underlying an effective increase in the efficiency of such smart sun tracking mechanisms.**

I. INTRODUCTION

The efficient use of renewable energy trend is increasing both globally and at European and national level, which confirms the timeliness and high interest in this field [1] - [18].

Electricity we consume each day comes all at a rate of 80% from fossil fuels and only the remaining 14% comes from renewable sources [2].

The sun is the cleanest and safest source of energy we have and it overflows each year, on our planet, an amount of energy that is about 15000 times higher than the world needs and is expected to continue to do so for at least another 1.5 billion years [1], [2]. Therefore, solar energy will be an increasingly important source of power generation in the new millennium [5], [6].

As Vijay Talekar, Vikram Shindeb et all [3] are stating "Solar energy is becoming one of the important energy in the future as a great renewable energy source". Today the professionals' efforts are focused on finding solutions to capture bigger quantities of energy we receive from the Sun.

We know that solar radiation intensity is higher near the equator and in the desert and that it decreases as we move away from equatorial areas. However, the solar map of Europe shows that on the Romanian territory the solar radiation reaches quite significant levels. Therefore, is understandable the high interest Romania has in promoting the development of photovoltaic energy production and in finding new technological solutions to enable the exploitation of many other beneficial effects of solar radiation.

It is known that photovoltaic panels (PV panels) provide low efficiency. Increasing efficiency in electricity production of the solar PV cells can be achieved either by changing the PV material [7], the concentration of solar radiation or by using solar tracking systems [3]-[18].

Maximizing output power of a solar system is a goal for specialists, in order to increase system efficiency, and in order to reach this goal, it turns necessary to keep panels aligned with the sun. Therefore sun tracking means are required. A solution like this is far more profitable than to buy additional solar panels. The literature shows that the use of sun tracking systems may lead to an increase in their efficiency by 30 to 60 percent [2], [3], [8].

A future PV cells orientation technology is one that uses sun tracking mechanism based on Shape Memory Alloy (SMA) spring or wire actuators [9], [11]-[14].

This paper presents a model the authors have developed that consists in a Smart Sun Tracking Mechanism (SSTM) which uses two Shape Memory Alloy springs as actuators.

According to the control system, sun-trackers are usually divided into two types: the so called "active" one and the "passive" one [1], [7], [9], and [15]-[18].

Passive solar tracking systems work by directly using the solar energy. The passive controlled sun-trackers can be based on memory shape alloys or, more often, in the use of two cylinders and a liquefied gas with a low ebullition point [16]. Usually there are used a pair of actuators working against each other. Both actuators stay balanced as long as they are equally lighted/heated. Due to different lightening/heating of each actuator, the resulting imbalance of forces is used to guide the panel in a sense in which there will be obtained equal lightening/heating of the actuators, the balance of forces being, so, restored.

Solar trackers of passive kind have not too much complex structure (and this might be seen as an advantage) but, in contrast, they have disadvantages like: low efficiency and accidental self-turning off at low temperatures.

As shown in [16], the *active controlled sun-trackers* use motors and mechanical systems in order to send them the appropriate movements to track the sun. These movements are commanded by a controller which is usually based on photosensitive cells (able to detect the direction of the maximum lightening flow) or time-measuring systems [8], [18]. These systems are quite accurate. But, as sort of disadvantage, they have a rather complex structure and requires dedicated maintenance. As motors are energy consumers, accidental continuous movements are usually avoided. Using step movements to save energy is highly desirable. The active controlled sun-trackers involve high costs which are mainly related to accuracy issues.

The solar panel used in our model tracks the sun (during day time) using an active tracking system based on two shape memory alloy.

Using SMA spring-based actuators leads to an increase in the performance of sun tracking systems by offering possibilities of miniaturization, easy integration into the system structure, smooth and precise control – and all that while still assuring outstanding functional performance conditions [12]-[14].

II. SMA Spring Actuator

"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" as N.J. Ganesh, S. Maniprakash et all are stating in [12]. Furthermore, there are standard procedures to design SMA spring-based actuators and these procedures can be easily applied to design springs of a SSTM structure (see for example, [19], [20], [21]). That is why we have chosen two SMA Electric Pistons as actuators in our experimental model.

The SMA Electric Piston, the most important part of our experimental model, was purchased from Mondotronics, Inc. The basic element of this actuator is the SMA spring exhibiting the memory effect which consists in recovering of a predetermined geometrical shape, after a plastic deformation, triggered and completed by a heating process. This effect is based on the solid-to-solid phase transition that can be exploited to achieve a variety of interesting responses. The phase transition (also called martensitic phase transformation) at the root of SMA behavior occurs between the high temperature parent phase, austenite (A), and the low temperature phase, martensite (M). When martensite is heated, it begins to change into austenite and the temperatures at which this phenomenon starts and finishes are called austenite start temperature (As) and respectively austenite finish temperature (Af). When austenite is cooled, it begins to change onto martensite and the temperatures at which this phenomenon starts and finishes are called martensite start temperature (Ms) and respectively martensite finish temperature (Mf).

Martensite is the relatively soft and easily deformed phase of shape memory alloys, which exists at lower temperatures. The molecular structure in this phase is twinned. Upon deformation this phase takes on the second form with detwinned molecular structure.

Austenite, the stronger phase of shape memory alloys, occurs at higher temperatures. The shape of the Austenite structure is ordered, in general cubic. The un-deformed Martensite phase has the same size and shape as the cubic Austenite phase on a macroscopic scale, so that no change in size or shape is visible in shape memory alloys until the Martensite is deformed.

In the literature there is a lot of information describing this phenomenon and how can it be used in the design and implementation of smart actuators reacting to a thermal stimulus [19]-[24].

A. SMA Electric piston operating mode

The SMA Electric Piston (Fig. 1) is a linear actuator mechanism that shortens in length with great strength and speed. An inside placed SMA spring makes all these possible. The SMA spring presents two really different forms (shapes) or "phases" corresponding to two distinct temperatures Mf and Af. At the "low" temperature (Mf), the SMA spring is extended, Fig. 1(a), and can be stretched easily or deformed by a small force. But when heated the spring can reach the "high" temperature Af (by carrying an electric direct current), the SMA spring changes to a much harder form. In this phase, Fig. 1(b), it shortens in length, and exerts the force required to rotate the panel by the desired angle. The SMA Electric Piston used in our model is able to act up to 450g against gravity, yet the SMA Electric Piston itself weighs only 10g. This value of force exerted by SMA spring is enough related to dimensions of our experimental model which is kind of small. For bigger dimensions of panel, SMA springs able to exert bigger forces will be chosen.

If the SMA Electric Piston is overloaded the overforce spring gets into action, Fig. 1(c). The maximum overload force is 6.8N.

Because the Electric Piston is activated by electric heating, the contraction time is highly dependent on the applied current; the higher the current, the faster the heating (up to temperature Af), and the faster the contraction.

In the specific case of our model, the electric current for powering the SMA Electric Piston comes from an external power source which ensures a variable direct current.

Given the above, it follows that the determination of the transformation temperatures is necessary to precisely control the orientation PV panel.

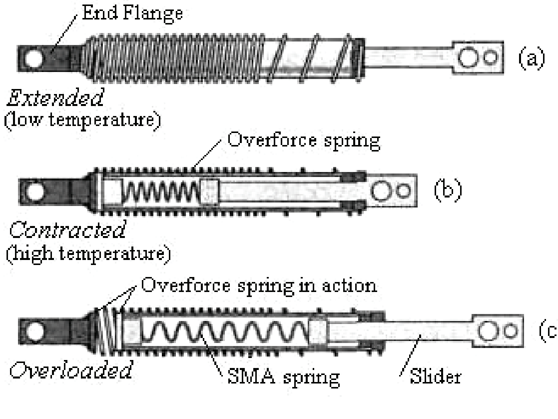

Fig. 1. SMA Electric Piston. © Mondo – tronics, Inc.

B. *Experimental transformation temperaturs*

It is well known that the SMAs exhibit a large temperature dependence on the material's shear modulus, which increases from low to high temperature. Therefore, as the temperature is increased the force exerted by a shape memory element increases dramatically [20, 25]. Consequently, the determination of the transformation temperatures is necessary to describe the dynamical response of our structure.

To characterize the transformations of the SMA spring during the heating regime and cooling regime, corresponding to the actuation of the sun tracking mechanism, it is necessary to establish all the four transformation temperatures: Ms, Mf, As, and Af) [26], [27]. These temperatures are determined using thermal analysis experiments, during heating–cooling regime, under zero stress, and heat transfer of each process. Differential scanning calorimetry (DSC) method was used to determine the required parameters [27]–[33]. The measurements were carried out on a horizontal diamond differential/thermo-gravimetric analyzer from PerkinElmer Instruments in dynamic air atmosphere, using aluminum crucible.

DSC test is a standard tool in the study of phase transformation. By measuring the relationship between power input/output and temperature change, it determines the phase transformation/temperature relation for a small specimen of the material [26].

The temperature range for the DSC measurement was from 15 to 100 ^{o}C under the controlled heating/cooling rate of 10 K/ min, in a continuum dynamic air flow at 150 cm^3/ min. The SMA spring mass has constant value.

The temperatures As and Af, or Ms and Mf have been selected, where the DSC curve deviates from linearity. How to obtain these four temperatures is shown in detail in [27].

Table 1 shows the experimentally obtained results from detailing the heating and cooling DSC curves in the above specified conditions [27].

TABLE I.
DSC PARAMETERS FOR SHAPE MEMORY ALLOY SPRING MATERIAL

Phase transition	Thermal effect endo/exo	Transformation temperatures/^{o}C
Martensite to austenite (at heating)	Endothermic	As = 47.60 Af = 66.80
Austenite to martensite (at cooling)	Exothermic	Ms = 49.66 Mf = 27.10

III. EXPERIMENTAL SUN TRACKING SYSTEM DESCRIPTION

The structure of the solar tracker built by using shape memory alloy actuators (Fig. 2) enables PV panel orientation after one single axis so that the system is able to track the sun from east to west (azimuth) during the day. The system has not a second axis to seasonally correct any change that may occur in the vertical zenith angle. This is because a value situated between the boundary values of the zenith angle can be chosen as a fixed tracking angle, maintaining a small error margin throughout the year.

In other words, tracking the sun from east to west significantly increase energy production (by about 28%), while tracking the zenith would make only a small improvement in energy production (about 4%), but the cost would be double [13]. However, the same design principles might be applied to the second axis, if desired.

The structure of the intelligent sun tracking system of photovoltaic panel (Fig. 2) includes four basic components:

1 – sun tracking mechanism based on SMA springs;
2 – photovoltaic panel;
3 – programmable logic controller (PLC);
4 – DC power supply for PLC;
5 – structure supporting platform.

A. *SMA springs-actuated sun tracking mechanism*

This mechanism (Fig. 3) has two springs built of SMA (Ni-Ti alloy) as basic elements. One spring ensures the continuous motion from east to west, during the day, and the second spring ensures the solar receiver return to its initial position.

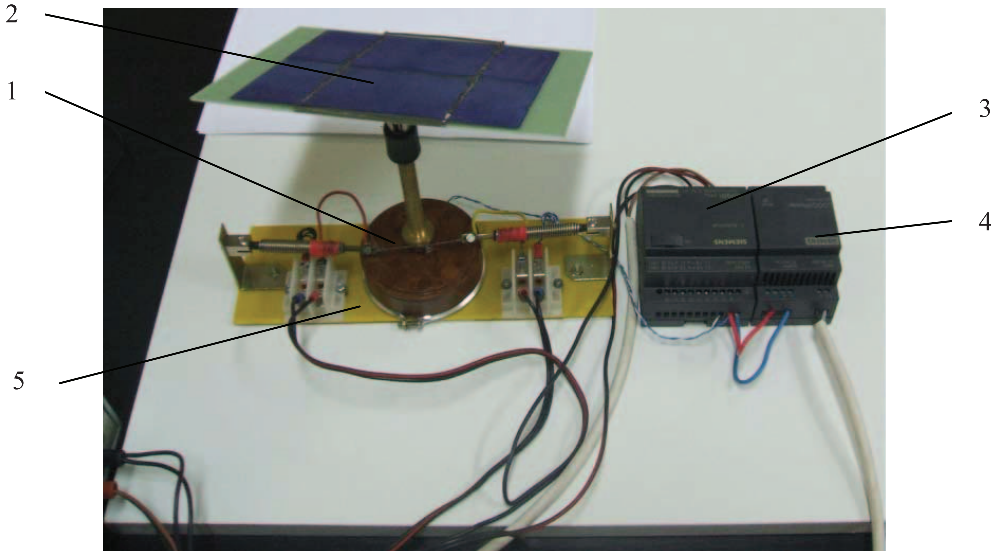

Fig. 2. The experimental SMA-based sun tracking system.

The smart sun tracking mechanism described in this paper is designed and built to enable the solar receptor (PV panel) to track the sun for 120° hour angle (roughly from 9am to 5pm) and to maintain the solar receptor rotation axis just perpendicular to the equatorial planar surface.

As the day starts, the solar receptor is in such a position that at 9am the sunlight is perpendicular or at least close to perpendicular to receiver. Angular positioning the solar panel during the day will be every hour, moving at a pace of 15° clockwise.

At 9am the PLC will control DC power to the first SMA spring (item 1 of Fig. 3) so that the spring is compressed providing so a 2mm linear movement of the piston. This compression gives rise to a certain number of actuating elements that provide rotational movement of the panel through an angle of 15° clockwise. These sequences are repeated every hour, the last orientation occurring at 5pm. Early next morning, the second SMA spring (item 2 in Fig. 3) will receive DC power so that, through a linear displacement of 16 mm of its piston, it will send the panel back to its initial position.

B. *Programmable Logic Controller (PLC)*

To control the automatic orientation of the photovoltaic panel a SIEMENS LOGO! 24Co 6ED1 052 –2CC01–0BA6 was chosen, due to the following advantages:

- small dimensions;
- logic functions AND, NAND, OR, NOR, etc. and switching functions can be implemented with just a push of a button;
- quick and easy programming by using graphic elements;
- the possibility to view and modify the program directly to the device;
- multiple functions of switching states sequentiality, time-dependent command and control, counting and comparing analogical values.

The PLC programming is done using dedicated sof ware LOGO! SOFT COMFORT.

Figure 4 shows an electric scheme corresponding to controlling power supply for actuators (SMA springs) ensuring the solar panel orientation.

Referring to this scheme, the symbols appearing in the figure have the following meaning:

a) *concerning the input – output blocks*:

AI – input of the rotating displacement transducer U = 0 ÷ 10V / 0 ÷ 360;

F1 – clockwise positioning controlling concerning the E to W movement;

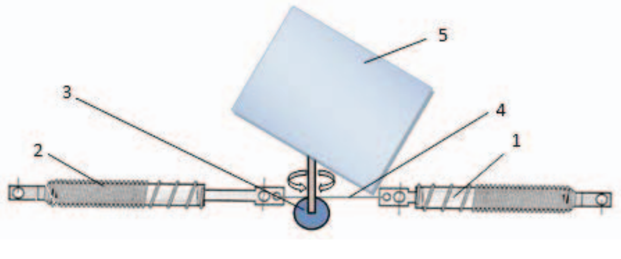

Fig. 3. SMA springs-actuated sun tracking mechanism: 1- SMA Electric Piston ensuring the E-W panel motion; 2- SMA Electric Piston ensuring the W-E panel motion; 3- racing transducer; 4-traction cable; 5- PV panel.

F2 - initial state positioning controlling concerning the W to E movement;

Q1-Output 1 - output to hourly power supply controlling of the first SMA spring (item 1 in Figure 3). This SMA spring ensures the E to W movement;

Q2-Output 2 - output power supply controlling of the second SMA spring (item 2 in Figure 3) that ensures the return to the initial state.

b) *for the first hourly cell components*:

B010 - Special functions timer – Retentive On – Delay;
B011 - Special functions timer – On / Off- Delay;
B004 - Analog threshold trigger;
B019 - NOT – Basic functions;
B005 - AND – Basic functions;
B003 - OR – Basic functions.

Timing blocks "Retentive On - Delay" are programmed for timings in the 1 hour to 8 hours range.

The "Analog threshold trigger" blocks receive at their inputs the signal from the race transducer. This signal is compared with the prescribed voltage corresponding to the scheduled angular displacement (Table 2) cutting, this way, the power supply to the first SMA spring (item 1 in Figure 3). So, the exact position of the panel is ensured.

Each and every cell zone includes blocks similar to those mentioned in the case of the first cell and orders, at output Q1, the connection to power supply of the first SMA spring. Its piston makes a 2 mm movement. This movement corresponds to a 15° rotation of the orientation mechanism. This movement is felt by the "Analog threshold trigger" comparator that orders the power supply cutting, according to the prescribed position.

After 8 hours of use, the last cell positioning the panel at 120° from the initial position, orders the next cell, whose timing is set to 16 hours, i.e. at 9am.

This cell orders, through Q2 output, the connection to power supply of the second SMA spring that ensures the panel return to its initial position 0^{o}.

TABLE II.
VOLTAGE VALUES AT THE TRANSDUCER OUTPUT IN CORRELATION WITH HOURLY DISPLACEMENT VALUES

Hour	Racing transducer	
	Angular displacement [^{O}]	Voltage [V]
9am	0	0
10am	15	0.417
11am	30	0.833
12am	45	1.25
1pm	60	1.67
2pm	75	2.08
3pm	90	2.5
4pm	105	2.92
5pm	120	3.33

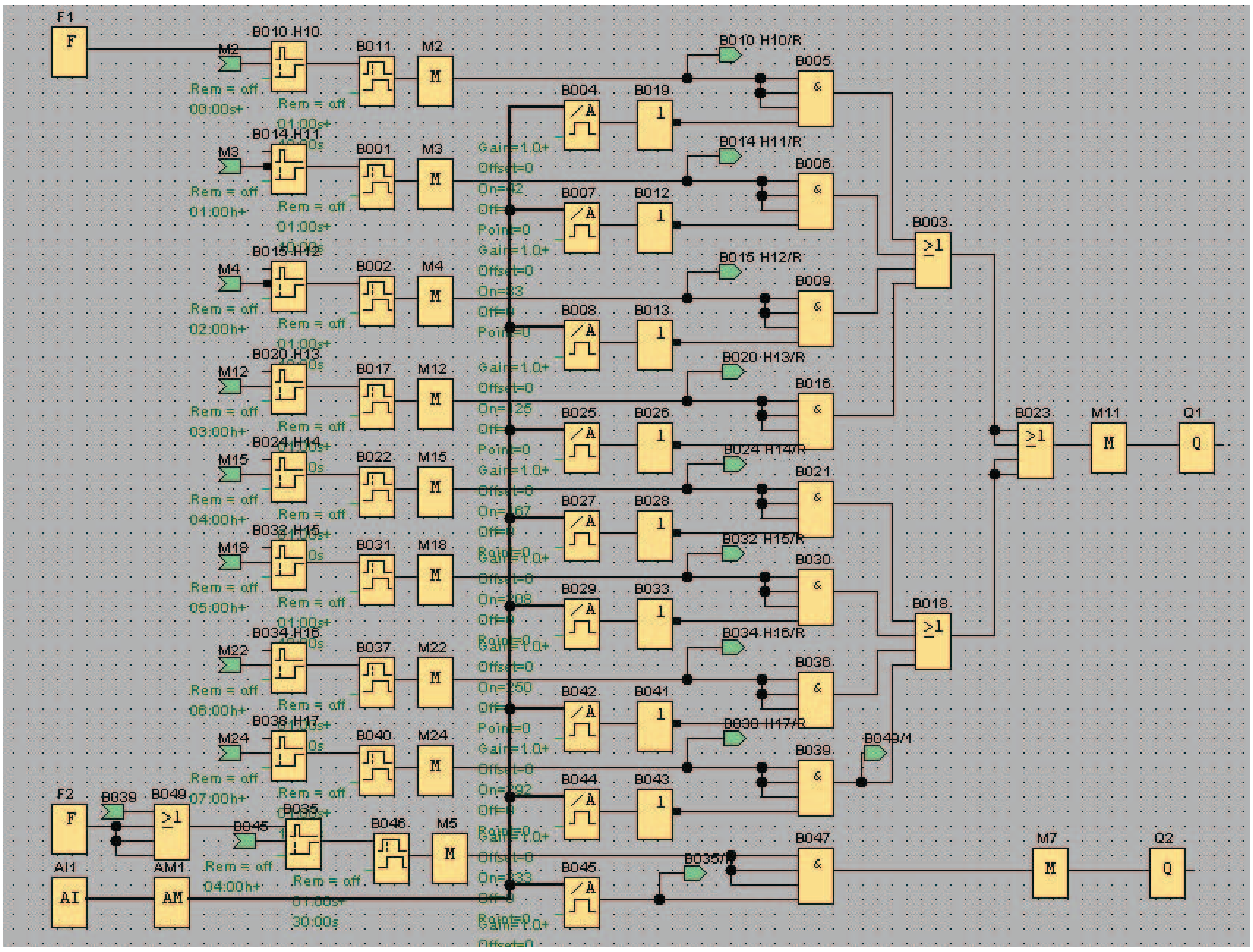

Fig. 4. PV orientation electric scheme.

IV. CONCLUSIONS

The proposed sun tracking mechanism can successfully replace any traditional mechanism (based on electric motor actuation) with an intelligent mechanism which actuation is made with shape memory elements.

Using SMA-based actuators reduce the size and cost of a sun tracking mechanism, while providing more precise guidance of photovoltaic panels. The intelligent mechanism the authors have developed is designed and constructed to allow solar receiver to track the sun for an 120° angle clockwise (roughly from 9am to 5pm).

The SMA spring actuators incorporated in our SSTM do perform: very simple design, low weight and volume, big number of functioning cycles, higher overall functional performances, directly applied linear action, low noise, pollution-free operating and good positioning resolution. Depending on the geometric characteristics of the SMA elements, their number, the type of SMA material and associated mechanical structure, different values of output parameters (stroke, force, and torque) can be obtained.

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