APPLICATION OF SHAPE MEMORY ALLOY ACTUATOR: ROVER PROPULSION

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ABSTRACT

The vehicle which is used to explore the terrains of planets and its moons is called Rover. Rover used to explore the Moon is called a Lunar Rover. Usually these rovers use electrical motors for their propulsion. The power required for electric motors is produced by solar panels. Solar panels increase the weight and volume of the mission. This is undesirable for any space mission. Here the choice of using shape memory alloys as actuator for propulsion of the lunar rover is explored.

Shape memory alloys are metals, which exhibit two very unique properties, shape memory effect and the pseudoelasticity. All that shape memory alloys need, to provide actuation force is high temperature to heat them and low temperature to cool. The solar radiation available on moon can be directly used to heat shape memory alloys. Since there is no atmosphere and also no heat source other than the Sun the temperature under the shade on the moon is low. Exploiting this, a prototype has been constructed and tested in earth environment.

1. INTRODUCTION

1.1 Rovers for Exploration

Rover is a crewed or uncrewed vehicle, used especially in exploring the terrain of a planet and its satellites. Weight, power are always big concerns during design of the rover. Now the researchers are exploring the potential of shape memory alloys as the new alternate for the rover locomotion. The advantage being light in weight, no external power source required other than solar radiation energy.

Different types of power sources are used for actuation of rovers in various space missions. Radioisotope thermoelectric generator (RTG) is used to produce power for locomotion of the rover. But RTGs need sturdy containers to store radio isotopes used in mission [1].The disadvantage of using solar panels for electric power generation is high volume and weight to power ratio, and also high cost.

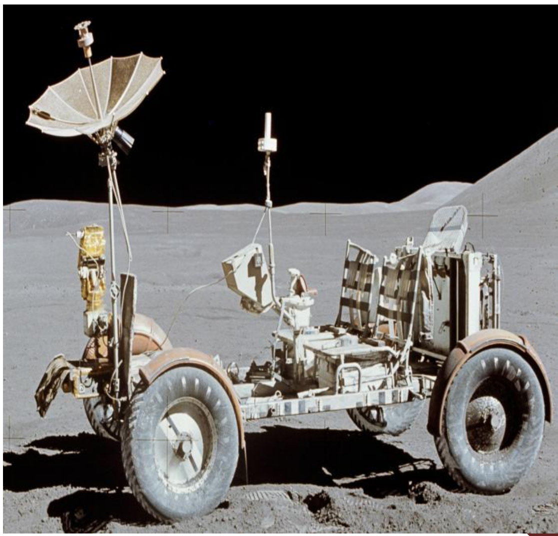


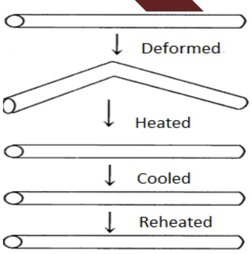
Fig:1.1 Apollo 15 rover [5]

1.1 Shape Memory Alloys

Shape memory alloys (SMAs) are metals, which exhibit two very unique properties, shape memory effect and the pseudo elasticity. Shape memory alloys have two stable phases high-temperature phase called austenite (BCC crystal structure) and the low temperature phase called martensite (FCC crystal structure).

1.2 Shape Memory Effect

Certain materials (SMA) can remember and regain their original shape even after large deformation just by heating. This property is known as shape memory effect. Shape memory effect is again of two types: one way shape memory effect, two way shape memory effect.



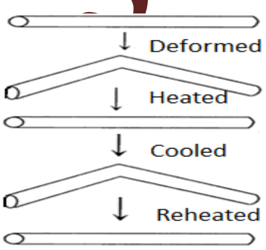


Fig:1.2 One way shape memory effect

Fig:1.3 Two way shape memory effect

Mechanism of shape memory effect

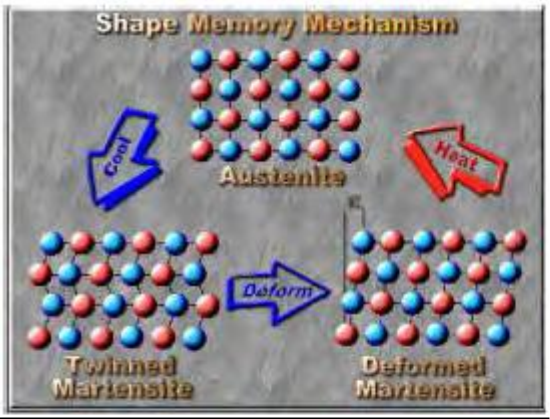


Fig:1.4 Mechanism of SME

1.3 Pseudo Elasticity

The capability of some SMAs to fully regain the original shape when the mechanical load that causes the deformation is with drawn is termed as Pseudoelasticity

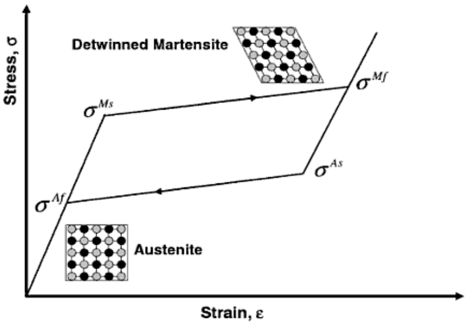


Fig:1.5 Superelasticity of SMA

2. IDEATION:

Mechanism with locking gear

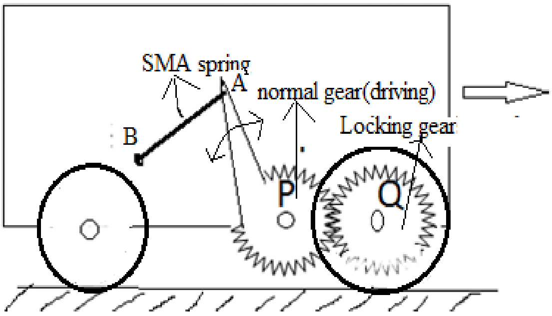


Fig:2.1 configuration of idea

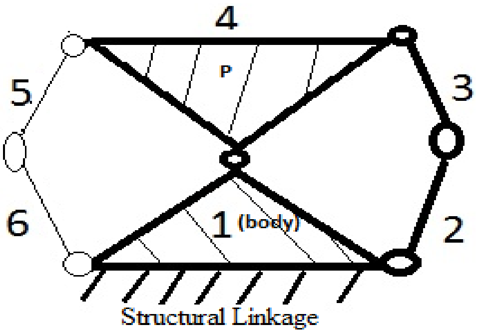


Fig:2.2 Structural linkage

In fig Link 1 represents the body of the rover. Dyad (5&6) is equivalent of SMA spring. The four bar linkage of 1234 is equivalent of locking gears P&Q. The locking gear P can freely rotate about its centre but the locking gear Q can freely rotate in the Counter-clockwise direction only and requires torque in the opposite case. When the shape memory wire contracts because of solar radiation falling ,it will pull the extended portion of arm at point a shown in the fig,causing the gear P to rotate in counter clock wise direction which in turn will rotate the gear Q in clockwise direction. Gear Q is mounted to another co-axial wheel (touch the ground).Then this wheel causes the vehicle to move forward because of traction between terrain and the wheel.

2.1 Description and working of prototype

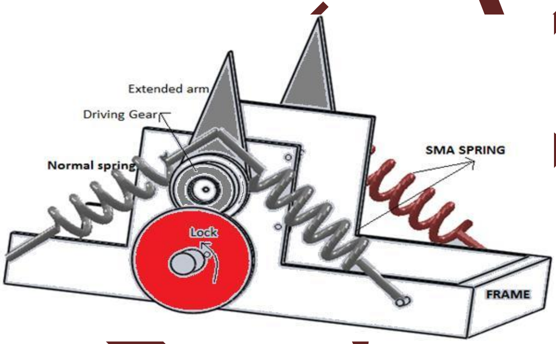


Fig:2.3 Solid works Model of Prototype
Rear and Front wheels are not shown)

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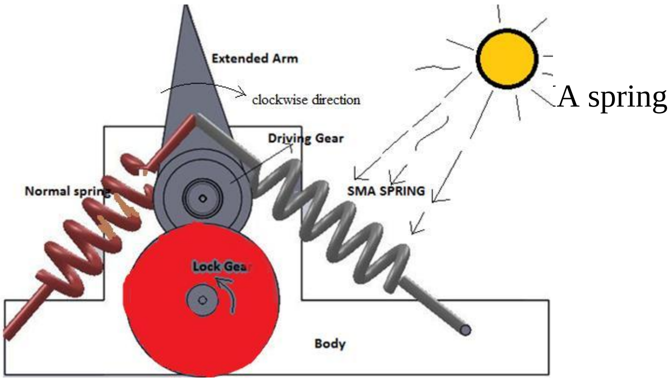
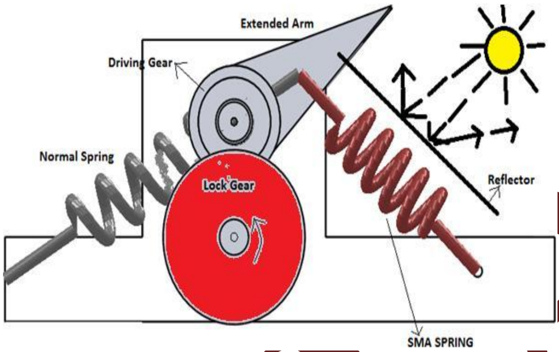


Position 1: Solar radiation is falling on SMA spring (Heating)



Position 2: Solar radiation is NOT falling on SMA spring (cooling)

3. ANALYSIS OF ROVER

The previous chapter gives the qualitative idea of the working of mechanisms and functioning of various parts of the rover. This chapter looks at the quantitative aspects involved like the mechanics of the rover, thermo mechanical modeling of the SMA, and thermal modeling of the SMA.

3.1 Mechanics of Rover

Here basic analysis of wheeled rover is discussed. The analysis is done for two cases when rover is placed above flat ground, above an inclined plane road. Symbols used in the description are mentioned below.

W-Weight of the rover,
W_h -weight of each wheel,

L-wheel base,
a, b are the distances of the wheels A and B from Centre of gravity,
H-Height of C.g. from the ground,
g-Acceleration due to gravity,
f-Acceleration of the vechicle.
R_A, R_B – Reactions on wheel from ground,
r- Radius of the wheel,
K-Radius of Gyration of the wheel
.

Case 1: Rover on a flat base ϴ=0°

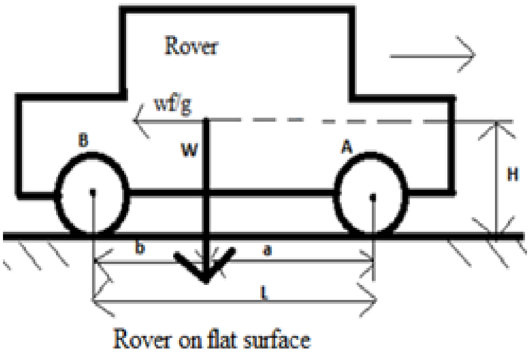


Fig:3.1 Rover on flat surface

Table:1 Equations for the case when the rover is on flat surface

S.No	Conditon	Remarks and Results
1	Four wheeled rover at rest on flat base	Reactions on wheel, $R_A = \frac{W \times b}{2 \times L}$ $R_B = \frac{W \times a}{2 \times L}$
2	Four wheeled rover moving towards left with an acceleration f	Reaction on wheel $R_A = \frac{W \times b}{2 \times L} - \frac{W \times f \times H}{2 \times L \times g}$ $R_B = \frac{W \times a}{2 \times L} + \frac{W \times f \times H}{2 \times L \times g}$ Torque required to accelerate the vehicle $T = \frac{f \times r}{g}\left[\frac{W}{2} + 2W_h \frac{k^2}{r^2}\right]$
3	Four wheeled rover moving towards left with an deceleration f	Reaction on wheel $R_A = \frac{W \times b}{2 \times L} + \frac{W \times f \times H}{2 \times L \times g}$ $R_B = \frac{W \times a}{2 \times L} - \frac{W \times f \times H}{2 \times L \times g}$ Torque required to decelerate $T = -\frac{f \times r}{g}\left[\frac{W}{2} + 2W_h \frac{k^2}{r^2}\right]$

Case2:Rover On inclined Surface ϴ=45°

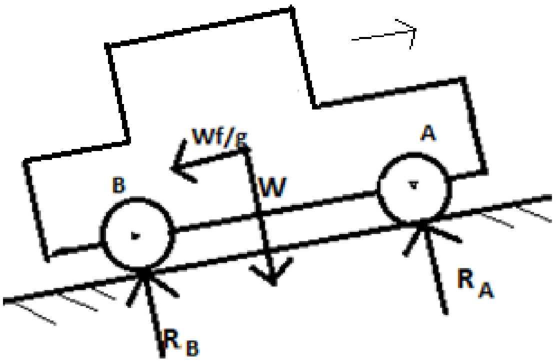
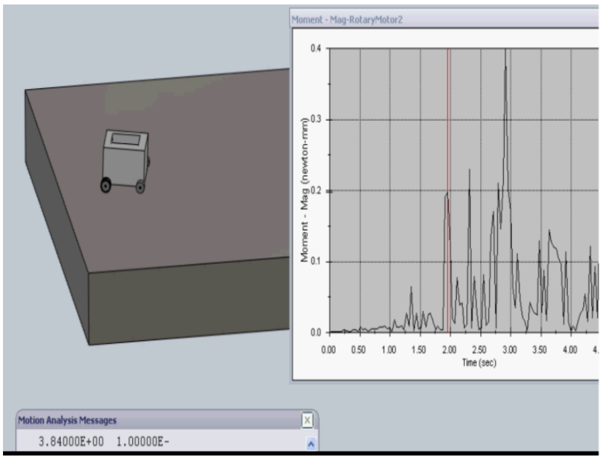


Fig:3.2 Rover on 45^0 Inclined Plane

Table:2 Equations for the case when the rover is on 45^0 inclined plane

S.No	Conditon	Remarks and Results
1	Four wheeled rover at rest on flat base	Reactions on wheel, $R_A = \frac{W\times b}{2\times\sqrt{2}\times L}$ $R_B = \frac{W\times a}{2\times\sqrt{2}\times L}$
2	Four wheeled rover moving towards left with an acceleration f	Reaction on wheel $R_A = \frac{W\times b}{2\times\sqrt{2}\times L} + \frac{W\times f\times H}{2\times L\times g}$ $R_B = \frac{W\times a}{2\times\sqrt{2}\times L} - \frac{W\times f\times H}{2\times L\times g}$ Torque required to accelerate the vehicle $T = r\times\left(\frac{f}{g}\left[\frac{W}{2} + 2W_h(\frac{k^2}{r^2} + \frac{g}{\sqrt{2}})\right] + \frac{W}{2\sqrt{2}}\right)$
3	Four wheeled rover moving towards left with an deceleration f	Reaction on wheel $R_A = -\frac{W\times b}{2\times\sqrt{2}\times L} + \frac{W\times f\times H}{2\times L\times g}$ $R_B = -\frac{W\times a}{2\times L} - \frac{W\times f\times H}{2\times L\times g}$ Torque required to decelerate $T = r\times\left(-\frac{f}{g}\left[\frac{W}{2} + 2W_h(\frac{k^2}{r^2} + \frac{g}{\sqrt{2}})\right] + \frac{W}{2\sqrt{2}}\right)$



Graph:1_ shows Torque required to drive the vehicle at constant speed of 30 RPM with respect to time (g=1.6 m/s^2) (Torque analysis In Solidworks)

4. THERMAL MODELLING:

Heating and cooling time for SMA is given in this section. Modelling is done for the two cases one assuming the rover is on ground and the other assuming the rover is on moon. Assuming the only heat source for heating the Shape memory element (spring) is solar radiation coming from parabolic reflective concentrator , the energy balance of the SMA spring at any temperature T is given by the following differential equation.

Nomenclature:

X_{AM} - enthalpy of transformation from martensite to austenite

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A_F - austenite finish temperature

A_S - austenite start temperature

C_{AM} - austenite to martensite specific heat of the SMA

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M_S - Martensite Start temperature

M_F -Martensite finish temperature

C_S - Spring index of the SMA springs

d_S -Wire diameter of SMA springs

S - surface of the spring

h - total convective heat transfer coefficient

4.1 Modelling for the case when rover is on the earth

On earth the heat loss is by convection and the heat loss through radiation is less compared to the heat loss due to convection.

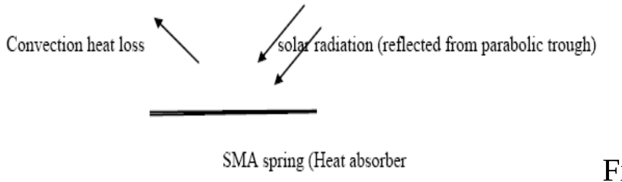

Fig:4.1 Diagram showing heat interaction on Earth.

Convective heat exchange

$$mc\frac{\partial T}{\partial t} + hS(T - T_a) = Q$$

Where c is the (equivalent) specific heat at temperature T, m is the mass, S is the total surface of the SMA spring, h is the total convective heat transfer coefficient and Q is the fraction of solar radiation that is absorbed by the Shape memory alloy spring

The specific heat for the forward (C_{AM}) and reverse(C_{MA}) transformation can be written below

$$Q = \rho_c \alpha S_{eff} G_b$$

$$C_{AM} = \frac{C_A + C_M}{2} + \frac{X_{AM}}{M_S - M_F}$$

$$C_{MA} = \frac{C_A + C_M}{2} + \frac{X_{MA}}{A_F - A_S}$$

Cooling time of spring

$$t_{cool} = \frac{mC_{AM}}{hS}\left\{\ln\left(\frac{M_S - T_a}{M_F - T_a}\right)\right\}$$

Heating time of spring

$$t_R = \frac{mC_{MA}}{hS}\ln\left\{\frac{Q}{hS(A_S - T_a) - Q}\right\} + \frac{mC_{MA}}{hS}\ln\left\{\frac{hS(A_S - T_a) - Q}{hS(A_F - T_a) - Q}\right\}$$

In all the above equations, the surface S, the mass m and the convective coefficient h are supplied by the following expressions[10] (m = mass density of the SMA)

$$S = \pi^2 C_S N_S d_S^2$$

$$m = \rho\frac{\pi^2 C_S N_S d_S^2}{4}$$

$$h = (6.13 - 17.5d_S - 2.7C_S - .33N_S + .93d_SC_S + .08d_SN_S)\ Wm^{-2}$$

4.2 Modeling for the case when the rover is on the Moon

In this case the major difference is that on the moon there is no atmosphere and hence no convection heat transfer. Here the prominent mode of heat exchange is though radiation and conduction only.

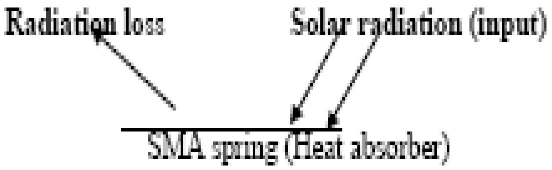

Fig:4.2 Diagram showing heat interaction on Moon.

$$mc\frac{\partial T}{\partial t}+\sigma_b S(T^4-T_a^4)=Q$$

Cooling time is given by

$$t_{cool}=\frac{\log(T-T_a)}{4a^3}-\frac{\log(T+T_a)}{4a^3}-\frac{\tan^{-1}(T/T_a)}{2a^3}$$

Heating time is given by

$$t_H=\int_{T_a}^{A_s}\frac{mc_M}{\sigma_b(T^4-T_a^4)}dt+\int_{A_s}^{A_f}\frac{mc_{MA}}{\sigma_b(T^4-T_a^4)}dt$$

σ_b is Stefan–Boltzmann constant=5.670 X 10^{-8} $wm^{-2}K^{-4}$

4.3 Thermomechanical modeling of the Shape Memory Alloy

Stress induced in the Shape Memory alloy

For forward transformation (A□ M),

$$\xi_1=\exp\left(\frac{\sigma-0.0083T+0.0672}{0.0019T-.0191}\right)$$

$$\xi_2=\exp\left(\frac{-3.0457+\sqrt{3.0457^2-4\times4.0349\times(0.6584-\sigma)}}{2\times4.0349}\right)$$

$$\xi=\min(\xi_1,\xi_2)$$

For reverse transformation (M□ A),

Critical temperature is given by T=130.3 x σ + 38.1.

Below critical temperature $\xi_3=\exp\left(\ln\xi_0+\frac{T_0-T}{200}\right)$

Above critical temperature $\xi_4=\exp\left(\frac{T+32-189.9\times\sigma}{10.7\times\sigma-48.3}\right)$

Using the above equations stress in the Shape Memory alloy can be found for the given (σ, T).

SUMMARY AND FUTURE SCOPE

Designing and building prototype of a Shape memory alloy actuated rover using solar radiation is taken as task

Actuation force, response time can also be improved on material front. With improvement in these areas the shape memory alloys can become the potential candidates for propulsion of the rover.

Nitinol springs[8]

Prototype:

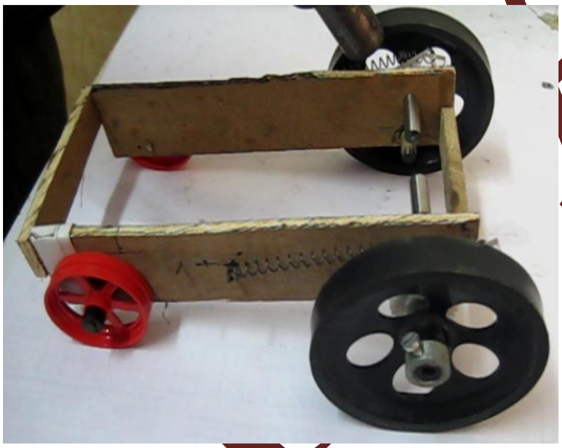

Fig : Shows the Prototype

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