29th Congress of the International Council
of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

AN UAV LANDING GEAR SYSTEM ACTUATED THROUGH SMA ACTIVE ELEMENTS

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Keywords: *Unmanned Aerial Vehicle, Shape Memory Alloy, Landing Gear*

Abstract

In the paper at hand, the conceptual design of a UAV deployable landing gear, based on Shape Memory Alloy (SMA) technology, is presented.

The system, made of four legs, whose rotary motion is commanded by SMA torque springs acting around pivots, is supposed to favor the landing task, absorbing impact loads.

A dedicated numerical tool was realized and implemented, to describe the working of a SMA torque spring.

On the basis of specifications in terms of admittable weight, available space, necessary power supply, the conceptual design of the deployment system was dealt with.

1 Introduction

The UAV herein considered is a Small Unmanned Aerial System (SUAS) equipped with a parafoil wing for patrolling, intelligence, surveillance reconnaissance and telecom network, with advanced characteristics of transportability, lightness**,** and quick configurability. It is characterized by a relative simple architecture with a fuselage, a parafoil connected to the main body by wires, and a landing gear (Fig. 1). The fuselage hosts the flight control unit, the power supply, the engine, the payload and the landing gear (Fig. 3). All the components are designed to allow a compact packaging and a rapid deployment on the ground, to keep the system mass, complexity and cost low. In Tab. 1 the main features are reported in terms of sail dimensions, total weigh and energy available on board.

Fig. 1. SUAS

Sail span [m]	1.6
Sail area [m^2]	2.4
Weight [kg]	5.0
Energy [Wh]	38.5

Tab. 1. SUAS main features

The system is conceived to perform missions at low altitude (300 m above the sea level) and short endurance (1h); a typical mission is illustrated in Fig. 2

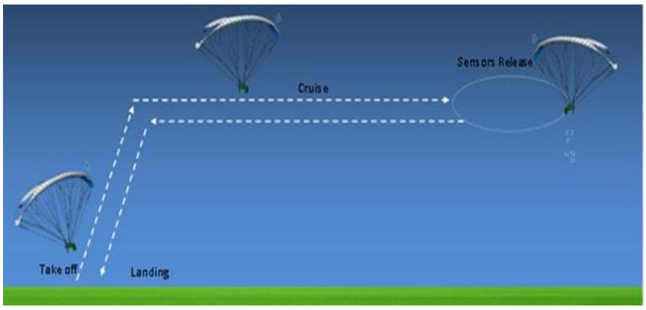

Fig. 2. SUAS typical mission

The object of this work is the design of the deployment system of the landing gear.

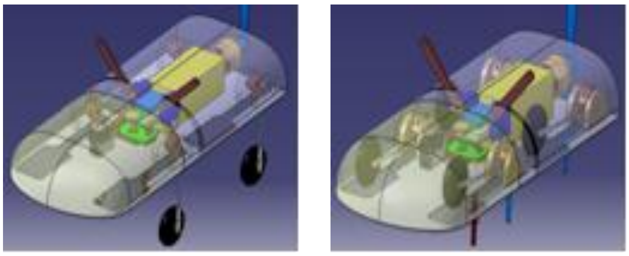

Fig. 3. Landing gear system integrated within the fuselage: retracted (right), deployed (left)

Due to the large transmittable forces and displacements, to their compactness and good integrability level, the shape memory alloy (SMA) materials were considered to this purpose. The idea is to substitute conventional servo-actuators, (made of several components and, thus, more prone to damage), with monolithic, compact SMA springs, able to absorb the external loads and, at the same time, actuate the deployment. Two torque springs were installed per each pin, operating in antagonistic way: one assuring the elastic recovery and the other producing rotation when heated.

A dedicated numerical model was implemented, taking into account the bending working of the spring wire. The angle - torque curves for no activated and fully activated configurations were computed and used to impose the equilibrium between the antagonistic springs.

Then a prototype of a leg of the landing gear, integrated with the SMA springs was realized. A preliminary experimental campaign aimed at monitoring the main working parameters during the activation (i.e. leg angular position and temperature of the SMA spring) showed a good agreement with the numerical prediction and highlighted the feasibility of the concept.

The work concludes with a performance comparison between the proposed concept and the conventional servo-actuator installed onto the landing gear.

2 Specifications

In order to design and develop the SMA based system[1-5], some high level requirements, or specifications, are reported. First of all, in order to guarantee that the system is allowable inside the fuselage, the dimensions have to be compatible with it and the landing gear weight has to be compatible with the MTOW (Maximum Take off weight) defined for the SUAS system and mission.

The main requirements and constrains that have driven the landing gear design and development, with a brief description, are listed below:

- **Deployment rotation and response time:** the SMA system must guarantee a rotation equal to or larger than 90deg within 10s. Due to SUAS mission requirements, and in particular altitude and speed, a 10-second time is sufficient to guarantee the right landing procedure. More in detail, the reference UAS has a 350m operative altitude and a 1m/s descent rate; the idea is to open the landing gear at 100m altitude, and after 10 seconds, to continue the descent for about 90 seconds with a fully deployed landing gear.
- **Arm retraction:** the arm must be completely stowed within the fuselage within 150s from take-off. It has to be closed before reaching the operative altitude.
- **Weight:** the total weight of the landing gear actuator system, including the hub and the clutches, must be less than 30g. In order to be compatible with the MTOW and to allow a system weight saving to use for onboarding different payloads
- **Power-energy supply:** power absorption shall be lower than 4 W. Assuming a 10s deployment time, this value corresponds to 0.01 Wh, available from the SUAS batteries.
- **Volume available**: the available volume is 7 x 10 x 5 cm.

3 SMA based deployment system

The landing gear system consists of 4 arms intrinsically able to absorb the impact loads without any additional damping mechanism.

Each leg of the landing gear is hinged to the supporting structure of the UAV, inside the bottom part of the fuselage. The deployment of the system occurs when the legs rotate around their pivots by an angle of about 90 deg, passing from a retracted configuration (legs parallel to the fuselage water line and included in it) to a fully deployed configuration. Front and aft legs rotation lies onto the same planes, inclined with respect to the fuselage symmetry plane, to assure the lateral stability; in Fig. 4 sketches reproducing the legs longitudinal and lateral inclinations are illustrated.

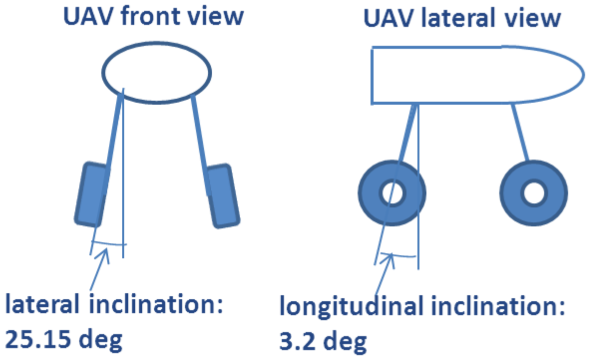

Fig. 4. Longitudinal and lateral inclinations of the legs

A detail of the hinged connection of the legs to the fuselage supporting structure is given in Fig. 5.

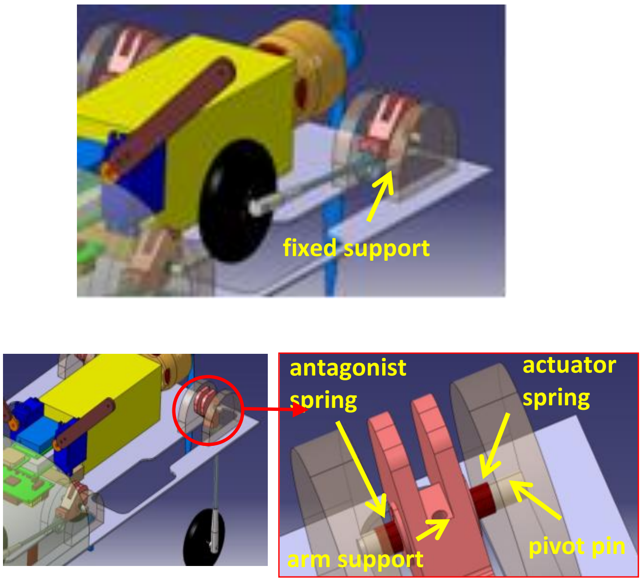

Fig. 5. Hinge connection of the leg to the fuselage supporting structure

On the fuselage base *fixed supports* contain the *pivot pin* to allow the rotation and assures the anchorage of the legs to the fuselage. *Pivot pin* pass through *arm support* and two antagonistic torsion springs were installed on it. Each spring is fixed on one side to the *fixed support* and the other side to the *arm support*.

The springs mounted were pre-stressed to maintain the leg in horizontal attitude (i.e. retracted); the heating of one of them, namely "*actuator spring*", produces a variation of the angular equilibrium point, with the consequent rotation and deployment.

4 Simulation strategy

The springs considered in this work are made of a SMA wire wrapped around the axis of rotation of the legs. The wire of these springs is practically bent as rotation occurs around the pivot; the result is a torque moment acting on the leg [6-11],[15-18] [21].

The fact that the spring wire is only bent allows an easy modeling approach. Referring to the scheme of Fig. 6 (c), the cross section strips undergo different stress, depending on their distance from the center of the section. In the case of a linear elastic material (stress - strain linear dependence) and for circular cross section, the stress linearly increases moving from the middle to the periphery of the section. In the case of a non linear stress-strain law, even assuming a linear strain distribution along the section, the resulting bending moment will include the contribution of non linear stress.

Considering the case of a SMA spring initially in austenite phase and subjected to a torque action, the resulting bending moment will have different effects on the strips of the cross section. Strips very close to the center will undergo a small deformation and the austenite phase will be preserved; on the contrary, as the strip distance from the middle arises, the austenite to martensite transformation will be enforced, due to the larger strain.

The idea adopted for modeling the springs is described in the flowchart of Fig. 6.

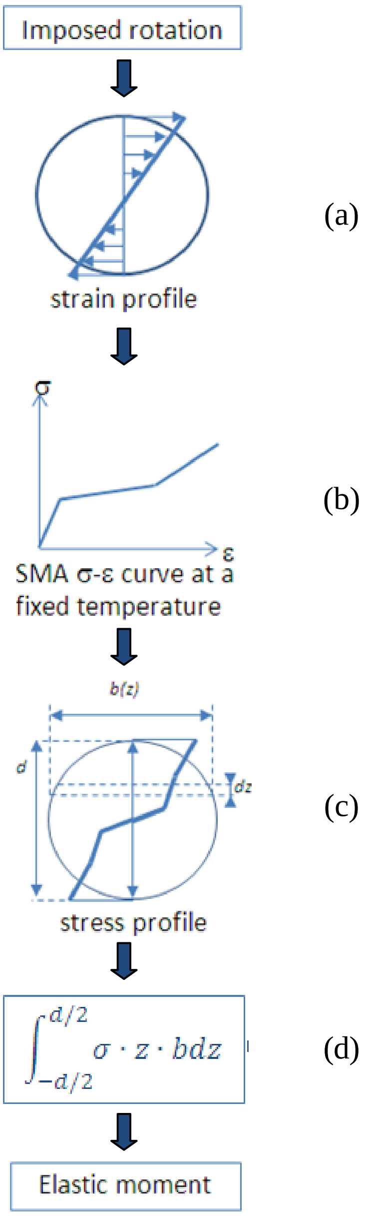

Fig. 6. Modeling flow-chart

In practice:

1. an angular rotation, ϑ, of the spring is assigned
2. the corresponding cross section rotation, $\widehat{\vartheta}$, is obtained dividing ϑ by the wire length, *L*
3. the displacement of the outer strip is then computed as product of $\widehat{\vartheta}$ by the radius, *R*
4. the strain ε along the thickness is then estimated assuming it linear along the thickness
5. the stress distribution is then computed through the stress-strain law of the SMA material
6. the bending moment, *M*, is finally computed integrating all the stress values on the cross section
7. Repeating these steps for all the rotations within the working range, the torque – rotation curve and, thus, the rigidity of the spring is computed, at a certain temperature.

Two specific curves can be computed: one referring to the spring at high temperature (that is the temperature at which the deployment occurs); the other one referring to the spring at environmental temperature and thus in retracted no-activated configuration. The behavior of two SMA antagonistic springs (one active and the other giving the elastic reaction) can be represented onto a momentum-rotation plane as shown in Fig. 7.

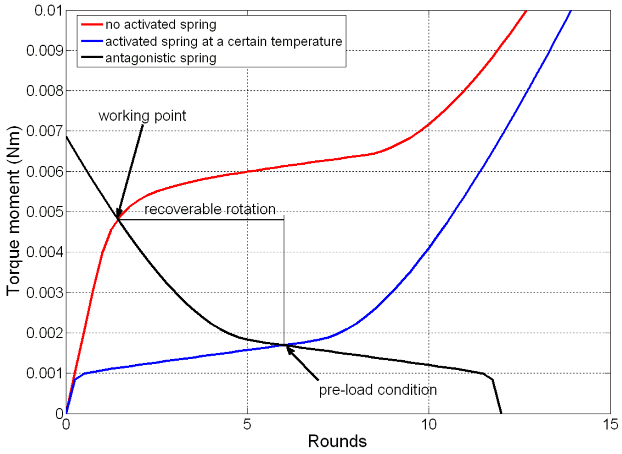

Fig. 7. Torque-rotation plane: actuator spring before activation (blue), active spring activated (red), antagonistic spring (black)

The blue and red curves represent respectively the active spring behavior before heating (environmental temperature) and after heating at a certain temperature. The black line (mirror image of the blue one) describes the behavior of the antagonistic spring. Black and blue lines cross at a point namely “pre-load condition”, corresponding to the equilibrium between the springs before activation. This point is characterized by a certain torque value and, thus, by a certain stress level, that will restore the system during the deactivation (cooling) phase. This value has to be adequately high, assuring the retraction of the legs when not electrically supplied. Black and red lines cross at the so called “working point”, representing the new equilibrium between the antagonistic spring, at a temperature higher than the environmental one. The horizontal distance between the pre-load and working points is the rotation recoverable at a certain working temperature.

5 Design

The approach described in the previous section was adopted to define the main features of the deployable system.

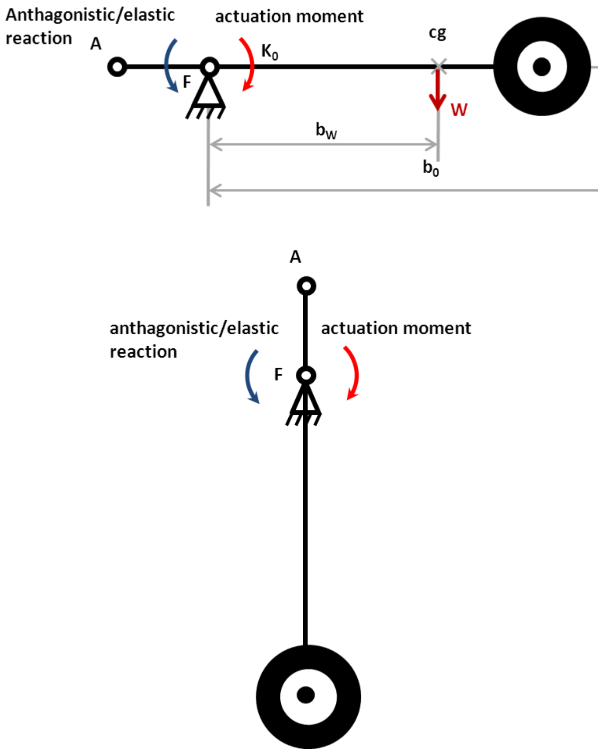

Fig. 8. Retracted scheme (top) deployed scheme (bottom)

With reference to the scheme of Fig. 8, reproducing a leg of the landing gear hinged and integrated with the two springs, the following parameters were considered for the sizing of the SMA actuator: the weight, W, of the leg and of the tire; the distance, b_w, from the pivot, F, of the center of gravity; the total length of the leg and of the tire, b_0.

The SMA springs had to meet the requirements below:

1. full deployment: leg rotation of at least 90 deg
2. horizontal (retracted) attitude even in presence of the weight action, inducing a downward rotation
3. the spring dimensions (external diameter, wire diameter, number of coils) has to be compatible with the available space (see Fig. 5)
4. the stress level within the springs has to be held as much as possible, even for the most severe condition (full activation)
5. the aerodynamic loads must not interfere with the deployment

The main features of the SMA material chosen for the springs, NiTinol, are reported in Tab. 2.

Austenite Young mod. (GPa)	38.1
Martensite Young mod. (GPa)	28.3
Max recoverable strain (%)	8.0
Density (kg/m^3)	6450
Specific heat (cal/g °C)	0.20
Austenite start temperature (°C)	27.5
Austenite finish temperature (°C)	40.8
Martensite start temperature (°C)	34.0
Martensite finish temperature (°C)	19.4

Tab. 2. SMA main features

In Tab. 3 the design parameters of the landing gear chosen in this work are summarized.

Leg and tire weight (g), W	10.0
Center of gravity (cm), b_W	12.5
Leg length (cm)	17.0
Spring mean diameter (mm), D	5.0
Wire diameter (mm), d	0.5
Spring coils	6
Max shear stress (MPa) (*)	450.0
Spring stiffness (Nmm/round) (**)	2.04e-2
Rotation due to the weight (deg)	3.0
Recovered rotation (deg) (***)	122.4
Energy for heating (Wh) (****)	2.65e-3
(*) material allowable stress: 500 MPa (**) martensite condition (***) maximum temperature: 120 °C (****) environmental temperature: 25 °C	

Tab. 3. Landing gear design parameters

A maximum recoverable rotation of 122.4 deg was predicted (thus meeting requirement 1). This result was obtained through the torque-rotation plane graph of Fig. 9, similar to the one illustrated in the previous section (Fig. 7). In this case the pre-load condition was obtained for a fraction (0.6) of turn. This choice represents a good compromise between the necessity of obtaining a total rotation greater than 90 deg and keeping the stress within the spring lower than the allowable one.

The weight induced rotation was of 3 deg; to meet requirement 2, the leg pivot has to be upward spliced.

The considered dimensions of the springs are compatible with the geometric limitations and with the requirements on the stress level (max stress of 450 MPa against the allowable one of 500 MPa); finally, observing the architecture sketched in Fig. 5, the aerodynamic action will not hinder the landing gear deployment, but on the contrary will favor it (requirement 6).

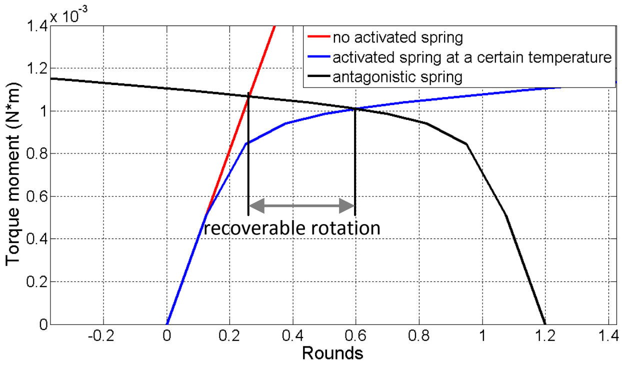

Fig. 9. Torque-rotation plane for the selected spring.

6 Experimental tests

An experimental campaign was organized to verify the ability of the SMA actuator to produce the desired deployment.

A dedicated prototype was realized, made of the following main components: a supporting plate integrated with the leg axis; the leg itself splined on the middle of the axis and having locking clips to fix the edges of the springs; the springs mounted in antagonistic way around the axis, at the two sides. [13-14].A dedicated set-up was assembled to run the test. The set-up block scheme is reported in Fig. 10.

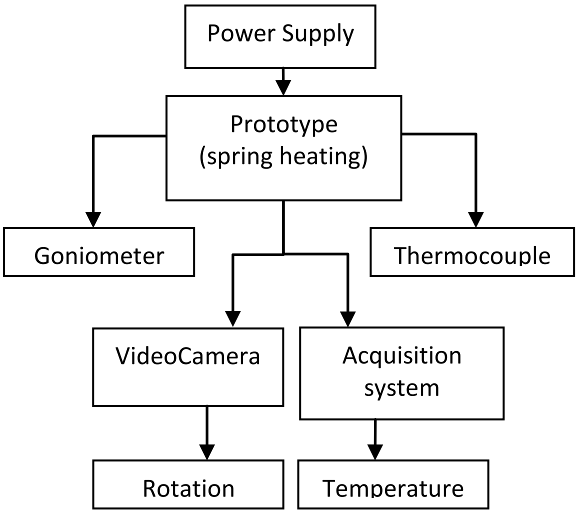

Fig. 10. Set-up scheme

The main components are: the prototype, a power supplier for heating the spring; a thermocouple sensor to measure the current temperature; an acquisition system. A detail of the instrumentation is given in Tab. 4. The setup was also integrated with a goniometric label to have an immediate idea of the achieved rotation. Finally a video camera was also used to capture the leg rotation.

A picture of the prototype and a detail of the axis integrated with the spring are shown in Fig. 11 and Fig. 12.

Acquisition system	IMC Cronos PL/8, Sampling rate 20kHz
Power supply	DELTA Elektronika ES 030-10: 0-30V, 0-10V
Temperature sensor	K thermocouple; measurement range: -200-1260°C, sensitivity: 41 µV/°C

Tab. 4. Set-up instrumentation

The landing gear system has to guarantee just the deployment of the leg, that is its vertical rotation of 90 deg with respect the horizontal line. In this operation the active spring is favored by the gravity force that gives an opening moment around the pivot. To be more conservative, the experimental tests were performed by rotating the legs against the action of the gravity force, which is enforcing the leg rotation in the closing retracting verse.

The tests were performed respecting the following procedure:

1. the leg was set in vertical position (fully deployed configuration); in practice, the springs were fixed at the axis clips achieving the initial equilibrium in vertical position
2. the power supplier was switched on, this way starting the electrical supply at a fixed preset current
3. the leg rotation was shot by the videocamera, synchronized with the acquisition system, monitoring and storing the temperature data measured by the thermocouple
4. after achieving a maximum temperature of 120 °C, the supplier was switched off, waiting for the cooling and the leg coming back to the initial vertical position.

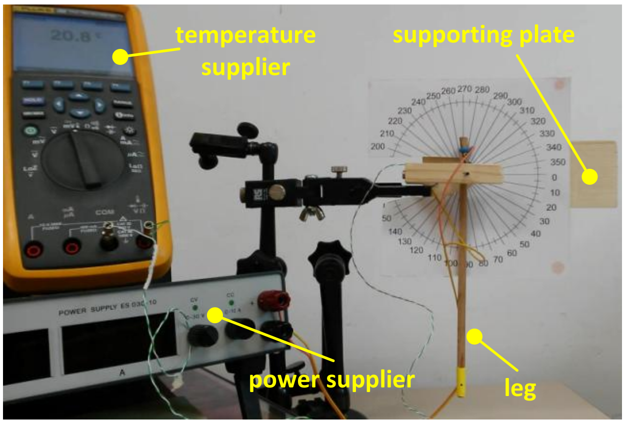

Fig. 11. Prototype

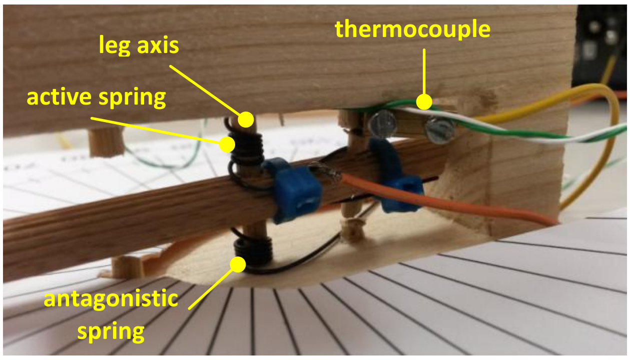

Fig. 12. Prototype detail

The tests allowed relating the temperature of the active spring to the angular rotation.

In Fig. 13 and Fig. 14 the leg deployment status versus the spring current temperature and the trajectory of the tire pivot are reported. A power of 1.22 W, corresponding to a current of 1.75 A, was necessary to achieve the maximum temperature of 120 °C in 10 s and corresponding to a complete rotation of 110 deg (larger than the required one of 90 deg).

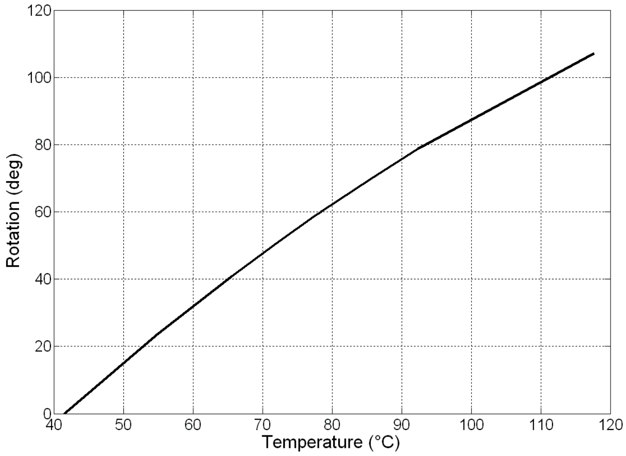

Fig. 13. Rotation vs. temperature, heating phase

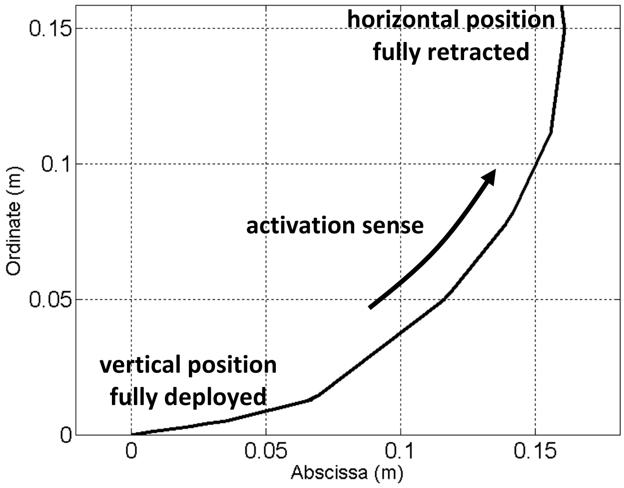

Fig. 14. Trajectory of the tire axis

7 Performance vs specifications

The design and development of a landing gear encompasses several engineering disciplines such as structures, mechanical systems, aerodynamics, material science, and so on.

The conventional landing gear design and development for aerospace vehicles is based on the availability of several critical components/systems such as forgings, machined parts, mechanisms, sheet metal parts, electrical systems, and a wide variety of materials such as aluminum alloys, steel, titanium, beryllium, and polymer composites. Current small unmanned aerial systems and aero models, typically, use servomechanisms linked to retractable landing gear to provide the leg activation/retraction.

A servomechanism consists of a large number of moving parts such as gears, bearings, shafts, motor coils, etc. The complexity of a servo requires a considerable percentage of the volume, power and weight of the entire UAV. Moreover the reliability of the system strongly depends on the number of components moving each other's. One of the purposes of the design presented in this work was the global simplification of the actuation part, constituted just of one active spring and of an antagonistic one.

	Conventional Servo-Actuator	SMA actuator	Requirement
Weight (gr.)	54	38	25
Volume (cm^3) (*)	90.5	15.8	
Activation time (s)	2	8	10
Energy (Wh)	0.0037	0.0026	0.01
Power (W)	6.66	1.125	3.6
* arm and wheel component not included			

Tab. 5. Performance comparison

A comparison was performed between a conventional servo actuator, used for this kind of application, and the SMA based one.

When designing for a particular application, several key parameters are specified, including output force, displacement, and frequency. Size and power constraints may also be specified. Based on these few parameters alone, it is desired to be able to look at the vast array of existing actuators and see which candidates match. It is important to realize the entire spread of possibilities and alternatives to meet the requirements of a given application. The weight, the housing volume, the required power were taken into account and compared in the next table [19-20]:

Note that, comparisons based directly on design parameters will be more useful in the design process.

8 Conclusions and further steps

In the paper at hand, the design of a deployable landing gear, based on the shape memory alloy technology, was presented.

The system, made of four legs, whose rotary motion is commanded by SMA torque springs acting around pivots, is supposed to favor the landing task, absorbing impact loads.

After a critical overview of the requirements, issued in terms of deployment angle, activation/deactivation time, system installation, weight and dynamic behavior, the system working principle was introduced, describing the main design parameters and their effect on the performance, and a dedicated numerical tool was realized and implemented, to describe the working of a SMA torque spring.

The work presented highlighted the possibility of realizing a deployable landing gear based on SMA technology and oriented to UAVs. Further steps will be carried out and further efforts will be spent on this topic. The conceptual design above illustrated will be further developed an optimized up to arrive at an executive drawing of the system. The resulting device will be installed onto the UAV. Tests lab., both static and dynamic, will be addressed with the scope of characterizing the behavior of the landing gear integrated within the UAV and to highlight and solve eventual problems due to the interaction with the other onboard systems. Then the flight tests will be performed, monitoring with dedicated sensors the behavior of the landing gear components during a typical mission.

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