Spider-inspired embedded actuator for space applications

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Abstract

A novel mechanism inspired by spider legs is presented and discussed in this paper. The mechanism has the potential to be used in future space applications, although the harsh space conditions, and in particular outgassing, should be carefully addressed in the design of a space-qualified model, The mechanism, called "Smart Stick", has one degree of freedom and is actuated by a pressurised fluidic system. The prototype, which has been designed, built and tested, is of compact size and presents a repeatable behaviour. The relation between pressure and rotation is approximately linear when the pressure is less than 1.2 MPa. The mechanism is suitable for a modular configuration in which several Smart Stick modules are joined together. This modular configuration allows large rotations and does not increase the complexity of the actuation.

1 Introduction

This work proposes a novel, integrated joint-actuator for space use. The mechanism takes inspiration from spider limb joints, and can be efficiently integrated in lightweight structures.

1.1 Inspiration from nature

Most animals have opposing muscles to articulate their joints: 1) flexors, which are used to bend the limbs, and 2) extensors, which straighten the joints. In spider legs, however, some joints do not have extensors. Muscles inside the prosoma (see Fig. 1) can increase the fluid pressure inside the spider, acting as a pump. The pressurised fluid inside the limbs can therefore extend some joints of the spider's legs.

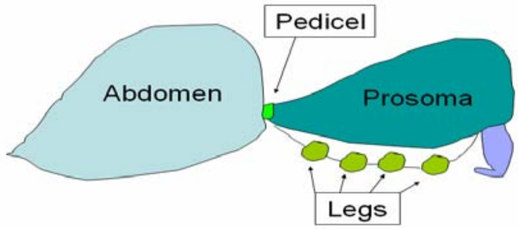

Fig. 1 Sketch of spider parts

1.2 Inflatable systems

Space applications require structures, mechanisms and systems that are able to fulfil challenging tasks, while keeping their volumes and masses to a minimum. Gossamer structures are already a reality in the space field and research is giving new results thanks to the use of innovative materials and technologies. The Echo Balloon, the Inflatable Torus Solar Array Technology (ITSAT), the Inflatable Antenna Experiment (IAE) and the inflated-spherical-wheel rover are just few examples of space inflatable structures which have been tested in the past years (Jenkins, 2001; Yoseph Bar-Cohen, 2000).

The use of inflatable mechanisms has some limitations due to the harsh space environment. Charged and high-energy particles, gas loss, solar ultraviolet and space radiation play an important role in the selection and development of inflatable materials.

In terrestrial use, pneumatic systems are often used for actuation. Pneumatic actuators are generally very fast but difficult to control. Often a 'bang-bang' control is used. Double-acting cylinders are advisable for differential pressure control. In this case, however, the complexity, cost and weight are increased. Muscle bio-inspired pneumatic actuators, firstly conceived for use in artificial limbs in the 1950-60's (Knight and Nehmzow,2002) are now used and commercialised for anthroform bio-robotic arm development. This simple device consists of a braided sleeve, usually made of nylon wires, which contains a deformable bladder. Compressed air is used to inflate the bladder, and, since the strand is less extensible, an axial contraction of the actuator occurs. They are characterised by a high strength to weight ratio but the need for storage of compressed air in autonomous systems limits their use.

1.3 Hydraulic mechanisms

Literature on space inflatable systems that use liquid fluids as the inflating means is not as common as that for gas inflatable systems. Hydraulic mechanisms are generally not chosen for on-orbit/planets applications (Benaroya, Bernold, M.Asce and Koon Meng Chua, F.Asce, 2002), for several reasons, e.g.:

1. Liquid fluids outgas
2. Liquids are temperature sensitive
3. Liquids are heavier than gases
4. Hydraulic pumps induce vibrations and cavitations can occur

The use of liquid fluids can, however, lead to new solutions and applications if the space hazards are carefully considered. The use of closed systems (no exchange with the environment) and low outgassing fluids characterized by low sensitivity to temperature changes can lead to the design of hydraulic space-qualified systems. Inflatable systems could also be designed by controlling the elasticity of the liquid tank. Miniaturized hydraulic mechanisms can be of particular interest. In fact, space applications do not generally require high force actuators, while mass must always be minimized. Taking advantage of their high strength-to-weight ratio, miniaturized hydraulic mechanisms could represent a compelling new approach.

1.4 The challenging space environment

A fundamental challenge for the use of inflatable space mechanisms is the space environment. Temperature range, pressure and atmospheric (if any) composition must be considered when a space mechanism is designed. Table 1 summarises salient characteristics of some planets of the Solar Systems (Barik, 2001).

Outgassing and fluid leakage are important issues which must be considered during the design phase of space mechanisms. Considering, for instance, a probe on the Mars surface, the pressure is in the range of 0.7-0.9 kPa, whereas on Venus there is a pressure of 9320 kPa. Mars has an average temperature of 63°C whereas Venus is at about 464°C, which could be prohibitive for conventional inflatable space architectures. The design of inflatable systems must therefore carefully take into account the surrounding operational environment.

In the framework of this study, which is at an early stage, the Earth environment was considered, because prototyping was considered a necessary step for the mechanism synthesis. Modifications must therefore be introduced when a different environment is considered.

Table 1 Planet characteristics

	T (°C)		Pressure	Composition
	Range	Average	(kPa)	
Mercury	[-173,427]	179	None	K (31.7%)
Venus	[-44,500]	464	9320	CO_2 (>96.4%)
Earth	[-69,58]	7	101	N_2 (>78%)
Mars	[-140,20]	-63	0.699-0.912	CO_2(>95.3%)
Jupiter	[-163,/]	-121	>10100	H_2(>81%)
Saturn	[-191,/]	-130	>10100	H_2 (>93%)
Uranus	[-214,/]	-205	>10100	H_2 (>82%)
Neptune	[-223,/]	-220	>10100	H_2 (>84%)
Pluto	[-240,-218]	-229	None	CH_3

2 Leg extension system in spiders

The legs of several arthropods (arachnids, diplopods, chilopods, pauropods) have joints that can be classified as hinge joints (Manton, 1958a, 1958b). The anatomical form of the joint often does not permit the presence of antagonistic extensors, which are often substituted by hydraulic systems. The empty spaces in between muscles and skeleton are usually filled with hemolymph. This pressurised liquid is used as a means to pressurise the spider's joints. Thin channels supply hemolymph to peripheral segments through the leg.

Parry and Brown, in 1959, carefully investigated spider legs and their pressurised mechanism. They showed experimentally that the active extension, which occurs at the hinge joints of the Tegenaria legs, is based on a hydraulic mechanism. They measured the internal pressure in the leg of an intact spider, established an empirical relation between the internal pressure and joint torque, and performed measurements of the actual torque developed when a spider accelerates a mass attached to its leg.

Many methods used to measure the leg inner pressure take advantage of the thin flexible articular membranes at the joints. Parry and Brown, for instance, used a sleeve sealed over the leg. The pressure in the sleeve was slowly raised until the membrane collapsed (Parry and Brown, 1959). Blickhan and Barth, in 1985, used a transducer with a tip smaller than the leg blood channels. The measurement system was mounted on freely moving spiders and also connected to several points of the hunting spider *Cupiennius salei* by means of tethers with negligible weight.

The mechanism for leg extension is now well documented in various spiders and whipscorpions (Sensenig and Shultz, 2003 and 2004). *Aphonopelma* have an inner pressure of about 5.3-8 kPa (Stewart and Martin, 1974) and in walking *Mastigoproctus* the fluid arrives at a pressure up to 9 kPa (Shultz,1991). Blickhan and Barth, in 1985, measured up to 70kPa on *Cupiennius salei* legs (130kPa during autonomy). Several hypotheses have been supported by experiments to explain how the prosoma natural pump works (Parry and Brown, 1959; Shultz, 1991; Stewart and Martin, 1974; Wilson and Bullock, 1973; Anderson and Prestwich, 1975).

Biologists were also able to measure the torque exerted by pressurised limb joints. It was shown that the torque increases approximately linearly with pressure (Sensenig and Shultz, 2003). The tibia–basitarsus joints of the tarantula *Aphonopelma* exert 20–74 mN mm when a pressure over the range 2.5–9.8 kPa is provided. Recent research reported high-resolution images, using transmission electron microscopy (TEM), which show cross-sections of spider legs. By studying the legs of *Leiobunum Nigripes*, Guffey (Guffey, Townsend and Felgenhauer, 2000), e.g., observed the presence of a single tendon, within a hemocoelic space, connecting the tarsal claw to the claw-flexing musculature of the tibia. The spider mechanism is also able to provide explosive force. High pressure can extend the rear legs, allowing spiders to jump (Parry and Brown, 1959).

There have not been many attempts to design engineering models of spider joints. One of the most remarkable works was done by Schworer, Kohl and Menz (1998). Their mechanism was actuated by nitrogen and was able to lift a weight of 8.2mN. The mechanism was built using extremely expensive equipment and processes (e.g. LIGA) suitable only for micro-systems.

3 Problem definition

Fig. 2 shows a flow diagram of the mechanism to be designed. A command is given to an actuator, which compresses the working fluid. The induced reversible deformation of an inflatable structure produces a rotation of a flexible joint. The joint rotation is fed back by a sensor in order to correct the command.

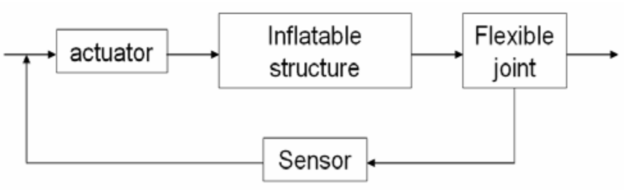

Fig. 2 Flow diagram

The system should have a closed fluid system in order to reduce leaking problems and outgassing phenomena, which are compelling challenges for space mechanisms. There are no limitations on the working fluid, which could be a gas or a liquid.

The synthesis of the novel bio-inspired mechanism described in this paper focuses on the inflatable structure embedded in a flexible joint. The sensor unit and the mechanism used to compress the working fluid are not analyzed at this stage. The mechanism is intended for operation in the space environment. However, the breadboard described in this paper was designed for terrestrial experiments.

Besides space and robotic applications, the proposed fluidic actuator could also be used in wearable equipment, e.g. smart bra (see patent document Lira, Angrilli and Debei, 2003).

4 Smart Stick

The novel conceived mechanism, called “Smart Stick”, is based on the use of a miniaturised tube (outside diameter 1 mm). The tube can be embedded into flexible structures to obtain integrated systems. Fig. 3 shows the shape and dimensions of the miniaturized pipe obtained by plastic deformation. The part of the micro-tube having elliptical shape constitutes the “fluidic actuator” of the system. Fig. 4 shows the tube embedded in the “Smart Stick” structure. The actuator acts upon hydraulic principles and the effects of the pressurisation are stiffness variation and bending force generation in the structure.

The actuator manufacturing process can be repeated along the whole tube. The repeated process allows easy fabrication of a series of miniaturised fluidic actuators. By folding and deforming the micro-tube, mechanical connectors are avoided making the system simple, reliable and light.

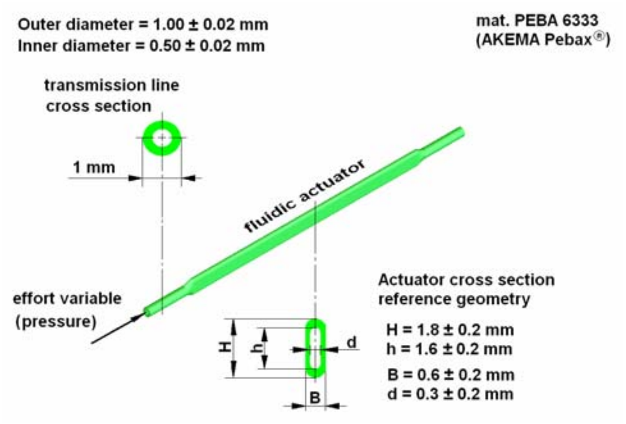

Fig. 3 Fluidic actuator

The design was conceived taking into account the manufacturing process and the robustness of the actuator. The case of a bi-phase fluid was also considered. The system is suitable for a closed loop control, which regulates the pressure *p* (effort variable) in the actuator.

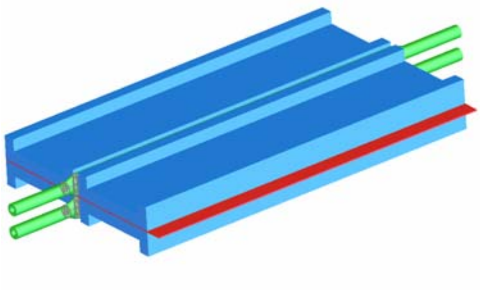

Fig. 4 Elastic joint with two Joint-actuators

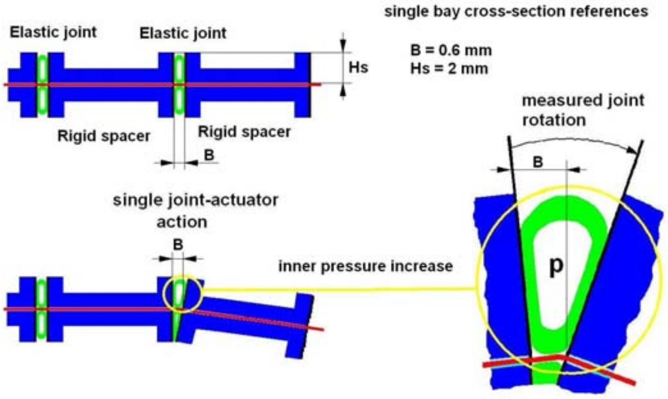

Fig. 5 Smart stick module, rigid spacer (blue), metal foil (red), fluidic actuator (green)

5 Prototype design

The length of the actuators which were designed was 30 mm. The elliptical section of the micro-tube (see Fig. 3) was repeated along the tube every 15 mm. The tube was bent between each two elliptical sections in order to convey the working fluid to different joints. Fig. 5 shows the rotation of a mechanism module induced by the deformation of the pressurised tube.

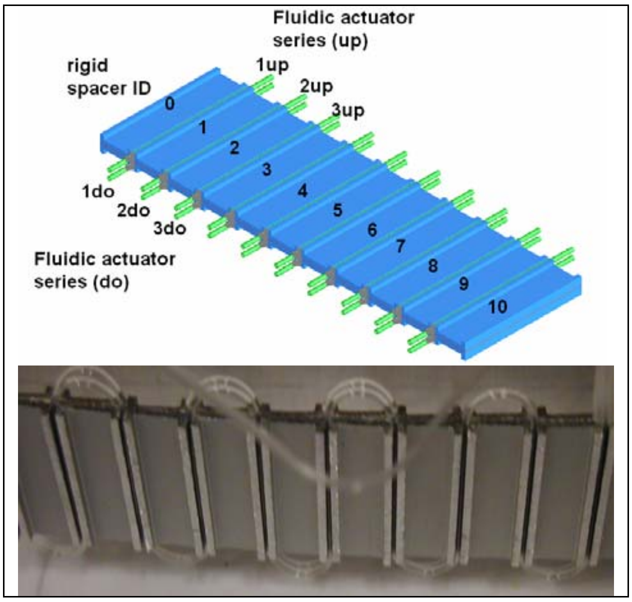

Fig. 6 Prototype with two series of fluidic actuators and 10 elastic joints.

The pressurised tube expands, bending the inner metal foil along the bay. Eleven rigid spacers are glued to each side of the metal foil to ensure that each joint-actuator works properly. In order to guarantee a controllable bending variation of the joint in both directions, the smart-stick module is symmetrical with respect to its longitudinal axis.

Multiple modules of the smart stick can be embedded into one structure. Fig. 6 shows both the design and the prototype which was built. This prototype has 10 elastic joints and 20 fluidic actuators.

The action of actuators on the same side of the mechanism make it bend with a constant curvature when no external loads are applied. By changing the position of simultaneously-actuated joint actuators, different shapes of the smart stick can be obtained.

6 Fabrication

The prototype was built using the components described in Table 2.

The procedure to fabricate the prototype is as follows:

1. The spacers, which had a “C” shape, were accurately glued to a flexible metallic joint (steel foil).
2. The elliptical shape of the fluidic actuators was obtained by compressing the micro-tubes between two parallel surfaces.
3. The fluidic actuators were positioned between two consecutive spacers. Friction and

compressive forces were sufficient to keep the actuators in their positions.

Table 2 Characteristics of the components of the smart stick system

Component	*Material*	*Dimensions*
Flexible joint (foil)	Steel	Length 94 mm Width 30 mm Thickness 0.1 mm
Spacers	Aluminium alloy Al-Mg series 6000	"C" shape: 8mm x 2 mm Thickness 1 mm
Micro-tubes (fluidic actuators)	AKEMA Poly Block Ammide (Pebax® 6333)	Outer diameter: 1 mm Inner diameter: 0.5 mm (see Fig. 3)

7 Experimental characterization

A smart-stick module was tested in order to obtain the relation between fluid pressure and joint rotation (water was used as the working fluid). An empirical model is useful to predict the behaviour of the smart stick in the control algorithm. Fig. 7 shows the elastic joint in vertical configuration obtained by fixing the rigid spacer (n-1). A vertical configuration was used to reduce the influence of the gravitational force.

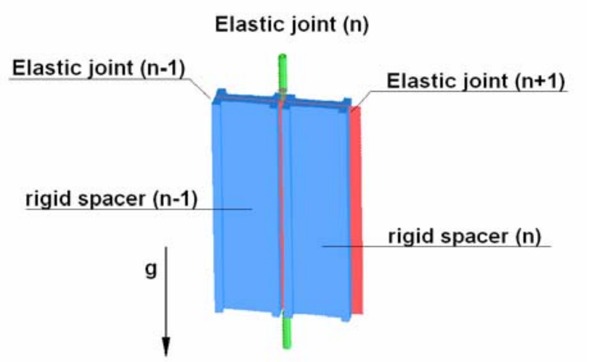

Fig. 7 Elastic joint in vertical position with only one fluidic actuator in the bay

Gravitational forces do not cause appreciable deformations as the inner metal foil has high flexural stiffness around an axis perpendicular to the axis of joint rotation.

During the experiment no external loads were applied to the elastic joint (except gravity). The free evolution of the system was analysed considering the action of only one fluidic actuator (Fig. 5). Eight complete cycles, obtained by increasing and decreasing the pressure in the fluidic actuator (range 0-1.2 MPa), were carried out. A linear model can be used when the relative pressure is between 0.1 MPa and 1.2 MPa.

8 Optical test bench

The first pair of rigid spacers (Fig. 7) is fixed and referred to the incoming ray trace. Fig. 8 shows the circular mirror fixed on the second pair of rigid spacers. In the nominal horizontal position, the mirror is perpendicular to the rays coming from a laser source fixed to a screen frame. Depending on the mirror angle, the reflected ray trace moves on the screen, by a measured distance M.

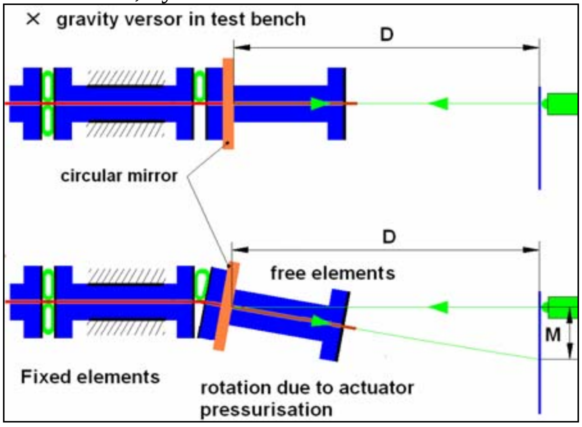

Fig. 8 Sketch of the test bench

8.1 Test bench overall dimensions

The distance (D) between the mirror and the laser source (see Fig. 8) is 2 m. The uncertainty associated with D, with a level of confidence of 68.3 %, is $\delta_D = 1.5$ mm. The uncertainty in the direct measurement of deflection distance (M), with a level of confidence of 68.3%, is $\delta_M = 0.5$ mm.

The rotation of the smart stick module was computed by the following equation:

$$\theta = \frac{1}{2} arctg\left(\frac{M}{D}\right) \quad (1)$$

For small angles the previous equation can be simplified:

$$\theta \approx \frac{1}{2}\left(\frac{M}{D}\right) \quad (2)$$

The uncertainty associated with the angle θ (δ_θ) can be computed as follows:

$$\delta_\theta = f(\theta, M) = \sqrt{\left[\left(\frac{\partial\theta}{\partial M}\right)\cdot\delta_M\right]^2 + \left[\left(\frac{\partial\theta}{\partial D}\right)\cdot\delta_D\right]^2} \quad (3)$$

By substituting equation (2) in equation (3):

$$\delta_\theta = \sqrt{\left[\left(\frac{1}{2}\frac{1}{D}\right)\cdot\delta_M\right]^2 + \left[\left(-\frac{1}{2}\frac{M}{D^2}\right)\cdot\delta_D\right]^2} \quad (4)$$

the uncertainty of $\delta_\theta \approx 0.08°$ results (68.3% level of confidence).

Considering the assumption of the model and additional variables that were neglected, the

uncertainty i_θ of the angle θ can be assumed to be equal to 0.3° (99.7% level of confidence).
Fig. 9 shows the experimental setup (two fluidic actuators are represented).

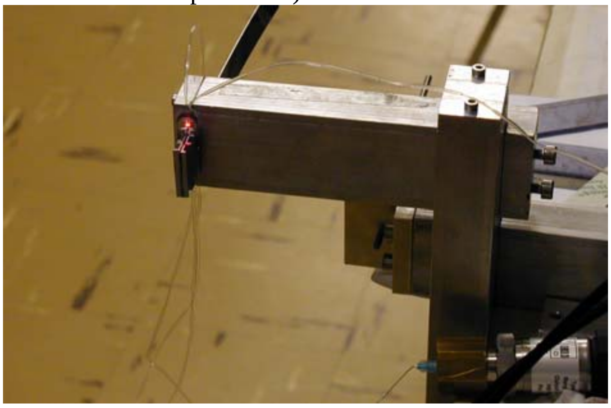

Fig. 9 Elastic joint in test bench

The uncertainty in the effort variable p (pressure of the working fluid) was i_p=0.013 MPa (99.7 % level of confidence) as declared in the calibration certificate of the pressure gauge which was used.

9 Test results

Several tests were performed in order to characterize the behaviour of one module of the smart-stick. Fig. 10 shows that the rotation of the joint can be approximated with a linear function (blue line). Fig. 10 concerns the use of one module of the smart stick having embedded only one fluidic actuator.
Fig. 11 shows experimental results for eight cycles using the same joint module. A fitting of the experimental data was performed in order to obtain an empirical equation that could be used for control purposes:

$$\theta = \theta(p) = 3.57\,p + 0.13 \qquad (5)$$

where the angle is in degrees and the pressure in MPa. The uncertainty (99.7 % level of confidence) associated with the slope of the function is ±0.13 and that associated with the intercept is ±0.24°.
A more accurate measurement procedure is required to appreciate the non-linear behaviour of the Smart Stick which is mainly caused by the fluidic actuators made of plastic (Pebax® 6333). Improvements are foreseen by using material with better elastic performance for the miniaturized tubes.

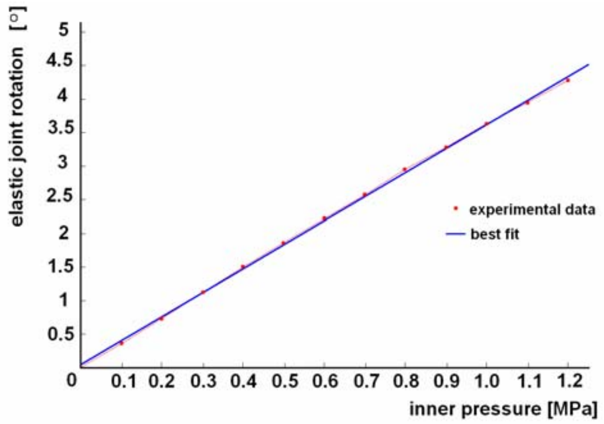

Fig. 10 Experimental results of one smart stick module with only one fluidic actuator. Red line: experimental results. Blue line: linear fitting curve.

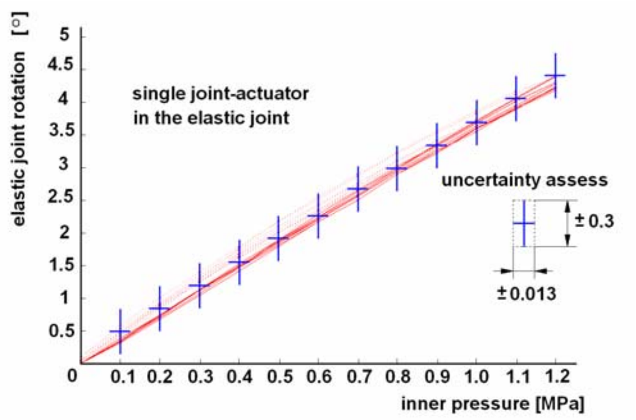

Fig. 11 Multiple cycles of one smart stick module (only one fluidic actuator)

10 Future improvements and designs

In order to increase the performance of the smart stick, a careful selection of the material employed is needed. The use of aerogel and lighter and more flexible materials for the joints is being considered. Improvement in the design will focus on multiple parallel mini-tubes which can bring more flexibility to the system.
The fundamental next step necessary to obtain a complete mechatronic breadboard for space applications will be the realization of the multi-module smart stick incorporating a closed fluid loop. Fig. 12 shows a sketch which presents the concept idea of a closed fluid loop.

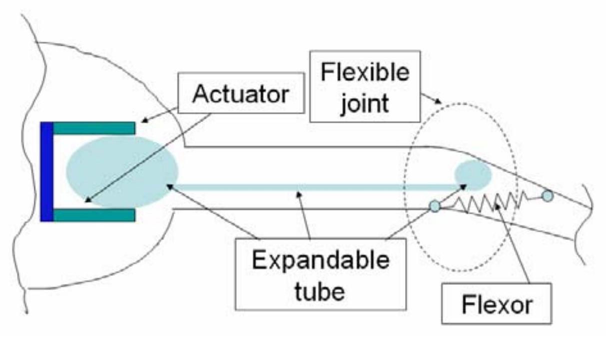

Fig. 12 Sketch of the closed fluid loop

The working fluid is confined inside a closed tube with expandable parts. The actuation is performed by squeezing one end of the tube. The actuation mechanism could include smart materials such as piezoelectric materials, shape memory alloys and electro-active polymers (Rossi, Carpi, Jeronimidis, Gaudenzi, Tralli, Zolesi, and Ayre, 2004). The use of a closed fluid loop, which allows us to overcome outgassing issues, is considered to be a critical point for a successful hydraulic space mechanism. Magnetorestrictive fluids could also be used in future work to improve torque performance.

The realization of a compact mechatronic system made of an electronic unit and a closed loop smart stick, integrated with the actuation unit, will also be promising for commercial applications including the toy market.

11 Conclusions

A novel flexible joint with an embedded actuator is presented in this paper. The novel mechanism is inspired by spider joints and hydraulic closed system. The proposed mechanism can be fabricated using traditional and inexpensive processes and methodologies. The modularity of the mechanism can be used to design joints for large displacements. The miniaturized prototype which was built and tested using an optical test bench showed the feasibility of the design and suggested improvements for a future design.

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