

Satellite Pointing System based on EAP actuators

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Abstract

This paper presents a new concept design for satellite attitude control. This new concept is based on the use of electroactive polymer beams which control the rotations of a satellite taking advantage of the angular momentum conservation of the whole system. By employing electroactive polymers, a compact and lightweight pointing system is obtained which allows to reduce the need of noisy spinning devices usually requested for satellite attitude control. In this framework, experimental ground testbeds and issues related to the performance of electroactive polymers in space environments are investigated and discussed. Multibody simulation results are also presented in order to show the feasibility of the proposed new concept. A neural network architecture is considered to identify the pointing system and a predictive control is employed to guide satellite rotations. Simulation results obtained using the proposed control strategies are shown and the performance of the proposed pointing system are discussed.

1 Introduction

This study investigates innovative technological solutions for aerospace use. Although aerospace community is considered very conservative about the use of new technologies (reliability, in fact, is a very demanding requirement in the aerospace field), electroactive polymers (EAP) attract engineers because of their inherent advantages. In fact, they are light, compact and perform large deflections with a relative small amount of energy. However, their properties must be carefully considered in a space environment. For this reason, the European Space Agency (ESA) is currently assessing the performance of EAPs with the purpose of employing them in future space missions.

This paper focuses on the use of EAPs to actuate pointing systems. Applications concern the control of satellite

attitude as well as the actuation of cameras and gimbals for space use. One of the advantages of using EAPs is to take advantage of their double actuator/sensor behavior. In fact, they could be employed as actuators during pointing operations and then switched as passive dampers to reduce mechanical vibrations of the structure in which they are fixed. Successful studies have been already carried out using piezoceramics (C.Kaiser *et al.*, 2003) and new studies are now in progress considering the use of EAPs.

This paper proposes a new concept design in which an extended EAP actuator is able to smoothly change the attitude of a satellite through its controlled large deflections. The contents of this paper are organized as follows. Section 2 describes the dynamic modeling of the preliminary test-rug that the authors are proposing, and also suggests to control the system with a neural network controller which uses a simplified dynamics of the system. Section 3 briefly introduces the compelling features of EAPs for space use. Section 4 discusses possible test-beds which could be designed to perform experiments of the satellite pointing system. Section 5 presents multi-body simulations assessing the feasibility of the study. Section 6 shows how a Neural Generalized Predictive Control have been used to control the system. Section 7 presents the results of the control strategies discussed in section 6. Last section draws conclusions suggesting directions for future research on this topic.

2 EAP for space use

Space exploration requires medium and long term development of suitable systems capable of providing the necessary levels of functionality for survival in demanding environments. There is a constant drive to reduce the mass and power consumptions of space travel vehicles and the devices placed in space serve to perform increasingly complex tasks. Consequently, novel designs for surface and space travel based upon unique technologies, such as new types of actuators and other motion systems, are required.

Several kinds of EAPs have been fabricated with very different characteristics (Y. Bar-Cohen, 2001). However, space presents a challenging environment with many extremes of temperature, pressure, radiation and energetic particles. From studies sponsored by the European Space Agency (Contract No 18151/04/NL/MV, 2004) (D. De Rossi *et al.*, 2004), dielectric elastomers seem to be the most suitable kind of EAP for space use. In fact, they can work within a high temperature range (e.g. silicon based elastomers exhibit glass transition around -130°C) and the polymer could be chosen to be space qualified both for out-gassing and for high-energy radiation.

For the purpose of this study, however, the authors performed analyses and simulations considering commercial available EAPs as the first experiments will be in on-ground test facilities. The Ionic Polymer Metal Composites (IPMC) were therefore selected. These EAPs exhibit long cycle life in terrestrial environment and high performance in deformation. In addition, they present the same non-linear behaviour and low repeatability of the dielectric EAP elastomers and therefore experiments performed using IPMC will be highly significant for future on space tests.

3 Modelling

3.1 Preliminary test-rig dynamic modelling

The basic configuration that has been chosen for the test-rig (sketched in Fig. 1) and that is currently being assembled is that of a one degree of freedom platform with two electroactive polymers attached to it. The EAPs will be provided by Environmental Robots Inc., which supplies commercial available Ionic Polymer Metal Composites suitable for being used in air. The dynamic of such a flexible system is highly non linear and its modelling is complicated by the complex structural behaviour of the artificial muscles. The multi-body analyses performed for similar configurations (Izzo *et al.* 2004) and valid upon the assumed modes hypothesis, is not here valid any more as the displacement of the generic point of the structure is there modelled as the sum of a rigid displacement and a flexible one:

$$\vec{r}_p = \vec{r}_p^r + \vec{r}_p^d$$

the deformation is then written in terms of the assumed modes. When the flexible part is made of electroactive polymer components, this modelling becomes quite troublesome as very large deformations become possible and the benefits of linear elasticity may not be exploited any longer.

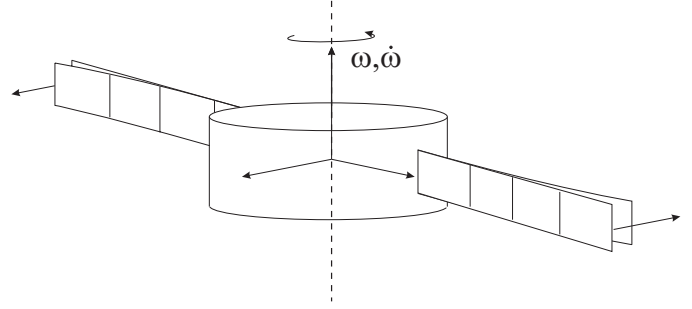


Fig. 1 The test-rig under definition is a one degree of freedom body with one/two artificial muscles attached.

A possible solution is to consider the deformation as linear and the reference configuration as dependant from the voltage applied. To illustrate this we here consider a finite degrees of freedom system whose behaviour approximates that of the test-rig configuration. Such a system is shown in Fig. 2 where each torsion spring is exerting a momentum equal to:

$$\tau_i = k_i (\mathcal{G}_i - \bar{\mathcal{G}}_i(V))$$

The angles $\bar{\mathcal{G}}_i(V)$ describe the reference configuration that is dependant upon the voltage applied to the electroactive polymer.

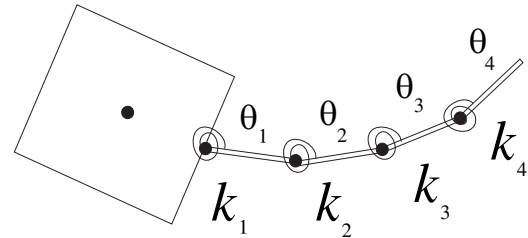


Fig. 2 A finite degrees of freedom system approximating the test-rig dynamic

In this way we may write the equations of motion for the system, after having identified the correct values for the elastic parameters. Though quite elementary, this modelling allow us to have a first understanding of our complex problem. In particular, it allows to correctly relate our control parameter, i.e. the voltage applied, to the controlled dynamic, i.e. the orientation of the main platform. It is clear that the relation between the undeformed shape of the EAP and the voltage V has to be studied in order to identify correctly the relations $\bar{\mathcal{G}}_i(V)$.

Due to the hysteresis cycles that currently existing EAPs undergo (Y. Bar-Cohen, 2001), these relations are actually dependant on the whole history of the applied voltage.

The design of a controller for such a system is obviously quite difficult. The non functional relationship between the control variable and the system output prevents

classical techniques to be applied, or at least lessen their efficacy. A Neural Network (NN) should be able to learn the dynamics due to the hysteresis cycle and a NN based controller could achieve, at least in this case, better performance than a standard one. The investigation of this possibility is certainly intriguing and was therefore here pursued. Not having yet assembled the test-rig, the performance of such a controller was preliminarily simulated upon a much simpler dynamics.

3.2 Simplified dynamics for the NN controller

A very simple system was chosen at this stage to test the NN design and capabilities. The system, shown in Fig. 3, is made by a central platform able to rotate freely and by a rigid arm connected to it via a frictionless joint. The control variable considered is a torque τ applied between the arm and the platform.

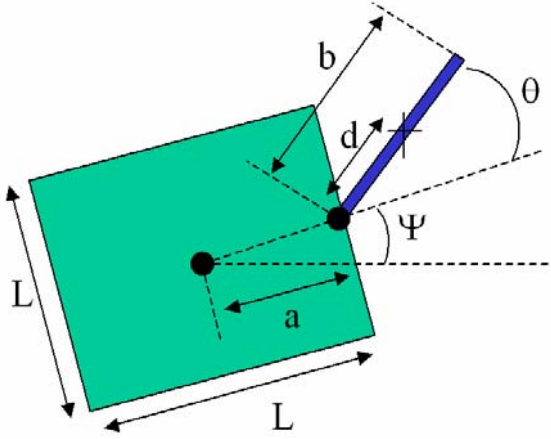


Fig. 3 System considered for the preliminary NN test

The equation of motion for such a system may be written straight forwardly by using Lagrange formalism. Considering $q = (\vartheta, \psi)$ as Lagrangian variables, we may write:

$$\begin{cases} \frac{d}{dt} \left(\frac{\partial T}{\partial \dot{\psi}} \right) - \frac{\partial T}{\partial \psi} = Q_{\psi} \\ \frac{d}{dt} \left(\frac{\partial T}{\partial \dot{\vartheta}} \right) - \frac{\partial T}{\partial \vartheta} = Q_{\vartheta} \end{cases}$$

where T is the kinetic energy of the system and Q_x are the Lagrangian components of the active forces. After some manipulations of kinematic relations, it is possible to show that the following expression holds for the kinetic energy of the whole system:

$$T = \frac{1}{2} (I_a + md^2) (\dot{\psi} + \dot{\vartheta})^2 + \frac{1}{2} (I_p + ma^2) \dot{\psi}^2 + \frac{1}{2} [2mad \cos \vartheta (\dot{\psi} + \dot{\vartheta}) \dot{\psi}]$$

where we have introduced I_p , the moment of inertia of the platform with respect to its centre of mass, and I_a , that of the arm with respect to its centre of mass. We also have introduced the mass of the arm m . We note that the kinetic energy does not depend upon ψ and that the relative Lagrange equation of motion expresses therefore the conservation of the total angular momentum of the system with respect to the fixed point of the platform. Such a motion invariant assures us the controllability of the spacecraft platform using the torque τ .

Performing the necessary derivatives and taking into account that the Lagrangian components of the active forces are:

$$\begin{cases} Q_{\psi} = 0 \\ Q_{\vartheta} = \tau \end{cases}$$

we may finally write the resulting equations as:

$$H(q)\ddot{q} + h(\dot{q}, q) = Q$$

where H is a 2×2 matrix defined by the following components:

$$\begin{aligned} H_{11} &= I_s + I_a + m(d^2 + a^2) + 2mad \cos \vartheta \\ H_{12} &= H_{21} = I_a + md^2 + mad \cos \vartheta \\ H_{22} &= I_a + md^2 \end{aligned}$$

and:

$$h = \begin{bmatrix} -mad \sin \vartheta (\dot{\vartheta} + 2\dot{\psi}) \dot{\vartheta} \\ mad \sin \vartheta \dot{\psi}^2 \end{bmatrix}$$

These equations hardly describe the dynamic of our test-rig, but they may be used to gain insight into the design of the Neural Network controller highlighting the difficulties and the potentiality of its application to the real case.

4 Test-beds

Testing systems which are designed to operate in space is a compelling issue. Several efforts have been done by the international space agencies in order to design and build testbeds able to simulate the absence of gravity. The techniques which are mostly used require a large amount of investments as in the case of parabolic flights, free-falling towers, sub-orbit flights and underwater experiments (C.Menon *et al.*, 2004).

To conduct the first experiments of the proposed pointing system, three simplified testbeds have been carefully evaluated. The first testbed consists of an air-bearing platform which well simulates the absence of gravity for two dimensional experiments. This testbed has been extensively used in several facilities of the space agencies

and in many universities (J.L.Schwartz *et al.*, 2003). The main problem of this testbed concerns the dimension and the weight of the air-bearing platform. The platform, in fact, should keep pressurized tanks on board to enable the air to flow through electro-mechanic valves. As commercial available EAP actuators have a very small size, the effect of their movements results negligible on the attitude of the air-bearing platform if this is too large. The air-bearing testbed was therefore considered a good solution only for customized EAP actuators where their dimensions can be opportunely selected.

The second testbed which was taken into account is the torsion pendulum. This testbed is nowadays considered one of the most accurate experimental setup to measure rotations along one axis. This testbed is used, for example, for testing the test masses of LISA space mission where the accuracy of the inertial sensor is $1 \cdot 10^{-9} \text{ m/Hz}^{0.5}$ (LISA Final Technical Report, 2004). Despite of its high performance, the torsion pendulum is highly sensible to external perturbations and therefore requires a long time for its stabilization. Experiments were performed by the authors using a dyneema cable with a diameter of 0.1 mm and 1m long. Using a sealed chamber mounted on a damped granite table, the torsion pendulum took 60 hours to reduce its torsional oscillations to few arc-seconds of amplitude. This peculiarity makes it difficult to identify the proposed pointing system. The preliminary control tuning, in fact, asks for a robust and stable system which allows several tests in a reasonable time.

The testbed which has been selected for the future first experiments is made of a low friction revolute joint in which the satellite test mass will be fixed. A rotary variable differential transformer (RVDT) will be integrated on the revolute joint in order to measure the rotations of the satellite test mass without interfering with the system dynamics. The main drawback of this setup is that the satellite test mass is constrained to rotate around a fixed axis which will not always coincide to the center of mass (CM) of the whole system (satellite test mass and EAP actuator). However, the mass of the EAP actuator is negligible respect to the satellite test mass and therefore the center of mass of the whole system can be consider, with a certain amount of approximation, coincident with the mass of the satellite test mass.

5 Multi-body simulations

Multi-body simulations were performed in order to assess the feasibility of experiments on a ground testbed. The system was modelled as a satellite test mass having a diameter of 10cm. The EAP actuator had dimensions of commercial available EAP samples (1cm*4cm*0.3mm). The EAP actuator was modelled as a rigid body linked to the satellite test mass by means of a revolute joint. The satellite test mass was constrained to rotate around a revolute joint positioned on its centre of mass. Simulations were performed controlling the rotation between the satellite test mass and the EAP actuator.

These analyses made it possible to chose the right specifications of the platform and to select adequate sensors.

Fig. 4 and Fig. 5 show respectively the input provided by the EAP actuator and the response of the satellite test mass. Friction forces were considered in order to simulate the real dynamic behaviour of the system.

With reference to Fig. 3, the specifications of the model are summarized in Table 1. The effect of the friction forces is shown in Fig. 5. The friction coefficients used for the simulations are $\mu_{\text{static}} = 1$ and $\mu_{\text{dynamic}} = 0.3$. The diameter of the pin joint which constrains the displacements of the satellite test mass is 1 cm.

The analyses which were performed show that a realistic experimental setup can be designed to prove the feasibility of the pointing system proposed in this paper. Next step will concern the simulation of a flexible EAP actuator which will more accurately predict the behavior of the satellite test mass.

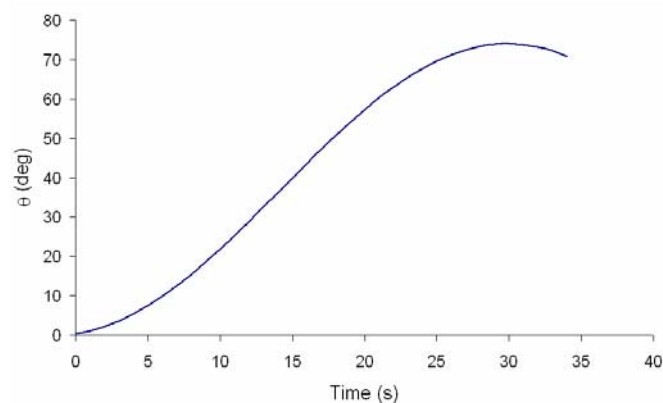


Fig. 4 Rotation input for the multi-body simulations

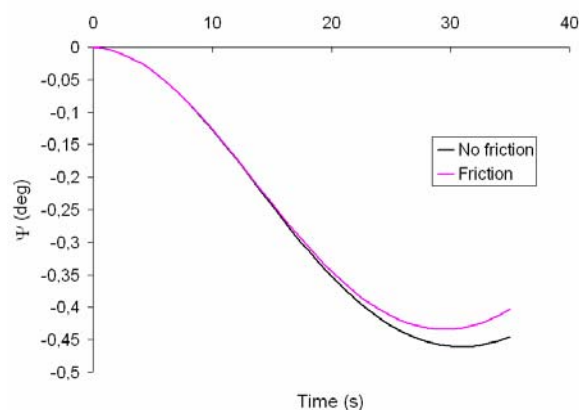


Fig. 5 Satellite test-mass rotation controlled by an EAP actuation

L (m)	A (m)	D (m)	B (m)
0.1	0.05	0.02	0.04
Mass Satellite (Kg)	Mass Actuator (Kg)	Inertia Satellite (Kg m ²)	Inertia Actuator (Kg m ²)

0.1	$3.37 \cdot 10^{-4}$	$1.67 \cdot 10^{-4}$	$1.8 \cdot 10^{-7}$
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Table 1 Specifications of the simulated system which correspond to the specifications chosen for the real experimental test-bed.

6 Control system

In order to control a future real system made of a six degrees of freedom (DOF) satellite and a large deflectable actuator, a neural network predictive controller could successfully be developed. A control based on a neural network architecture (NNA) was therefore analyzed especially because the plant is highly non-linear. A NNA is also suitable to identify the EAPs which show low repeatable dynamic behavior, considerable hysteresis and which perform large deflections. For this feasibility study, a simplified two-dimensional system was analyzed. The yaw of the satellite was considered the angle to be controlled using the motion of the flexible EAP actuator. Another simplification was made for the actuator which was modeled as a rigid body linked to the satellite by means of a revolute joint.

The Neural Generalized Predictive Control (NGPC), which was used to guide the system, was developed at NASA Langley Research Center (D.Soloway and P.J. Haley, 1996). This controller uses a neural network architecture to predict plant responses. An optimization algorithm computes the control signals that optimize future plant performance. The NGPC architecture is sketched in Fig. 6.

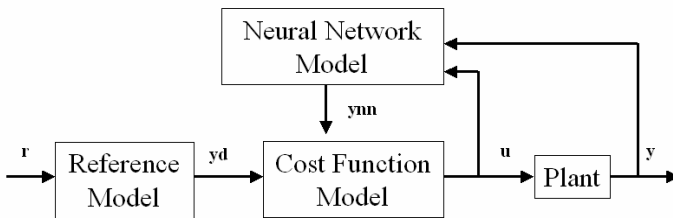


Fig. 6 NGPC architecture

The input \mathbf{r} is presented to the Reference Model which gives the desired output \mathbf{y}_d . Taking advantage of the output of the Neural Network Model, the Cost Function Model (CFM) finds the optimal value \mathbf{u} which is presented to the plant. The NGPC includes two switches which exclude the plant during the CFM optimization.

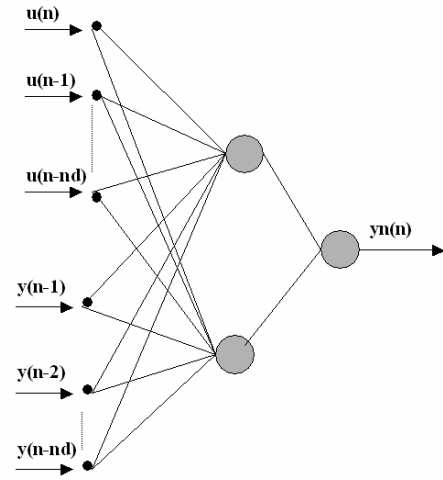


Fig. 7 Neural Network Architecture

The CFM optimizes the plant performance over a future time horizon specified by the user. The neural network architecture uses inputs and plant outputs to predict future values of the plant output. The structure of the neural network model is shown in Fig. 7. The neural network is trained offline in batch mode, using data collected from the operation of the plant. The Back-error propagation paradigm was used for the NGPC (D.B.Parker, 1987).

The NGPC controller was chosen as it is suitable to control a wide range of non-linear systems. This control architecture is therefore expected to be efficient also for the three-dimensional large deflectable system model which will be considered in future analyses.

7 Results

Matlab environment was considered to assess the quality of the control algorithm. In particular, the authors used the "Control - Systems - Neural - Network - Toolbox" of Simulink. The neural network which was employed had six hidden layers, two delayed plant inputs and two delayed plant outputs. The Levenberg-Marquardt back-propagation (M.T.Hagan *et al.*, 1996) was chosen as network paradigm. The CFM was based on the backtracking minimization (Dennis and Schnabel, 1983).

The model of the physical system, which was used for the simulations, was based on the real experimental testbed whose specifications are shown in Table 1.

The performance of the control system was assessed presenting a step input of the angle Ψ to the controller. The step occurs after ten seconds from the beginning of the simulation and has an amplitude of 0.1 degree. As the only actuator of the system was the EAP actuator, the controller was constrained to control only the angle θ .

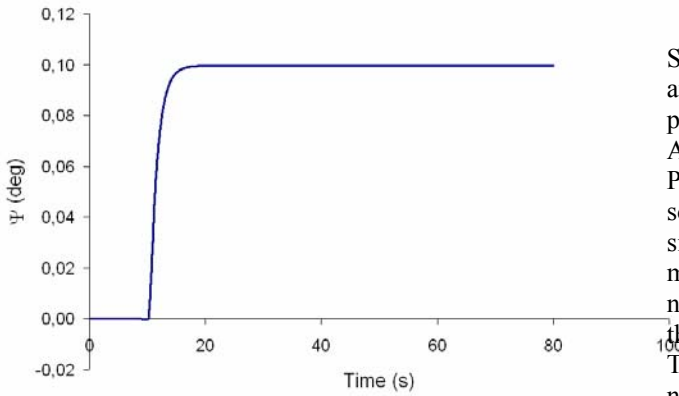


Fig. 8 Satellite test mass rotation output

Fig. 8 shows the output of the satellite test mass induced by the step input. The output is smooth and without overshoots. The amount of time for this operation is about 5 seconds which is a very interesting result as the torque requested by the EAP actuator is less than $0.35 \mu\text{Nm}$ as shown in Fig. 9. In order to limit the torque exerted by the EAP, the neural network was trained using small torque inputs ($\pm 1 \mu\text{Nm}$).

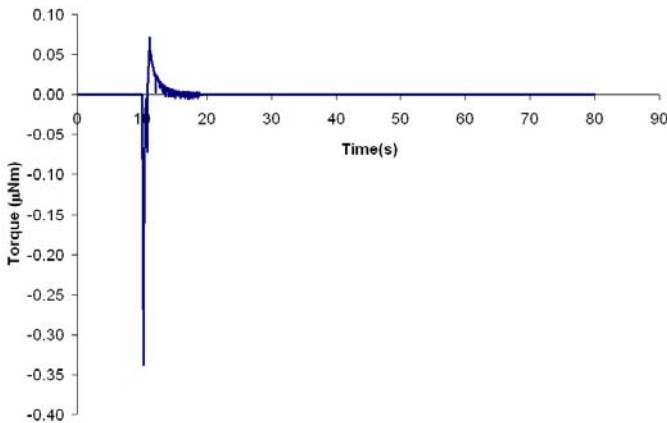


Fig. 9 Torque requested by the EAP actuator

Fig. 10 shows the displacement of the angle θ . As the mass and inertia of the EAP actuator were small compared to those of the satellite, the maximum rotation of the actuator was about 26.2 degree. The transient phase of θ is smooth and without overshoots.

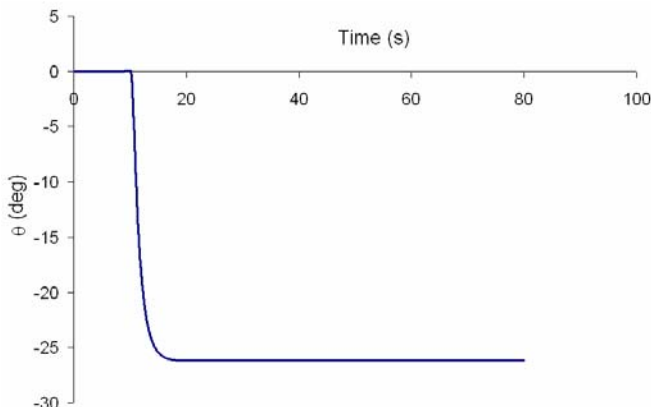


Fig. 10 Rotation of the EAP actuator

Simulations were performed for different step amplitudes and the results had similar good performance as those previously shown.

Although, on the whole, the Neural Generalized Predictive Control produced good results, it presented some drawbacks. The controller, in fact, required a significant amount of on-line computations. This was mainly due to the predictive optimization algorithm which needed considerable computational resources to control the system. The “Control – Systems – Neural – Network – Toolbox” had also the limitation to train completely the neural network off-line. Although in one hand this is convenient for the real-time speed of the control algorithm, on the other hand this does not take into account the changes that may occur in the system. The EAPs which are today available, in fact, change their performance during the time. They rapidly deteriorate requiring different voltage for the same displacements. As in space the duration of the operations is usually not an issue, the future development will concern the partially on-line training of the neural network architecture. The robustness of the NGPC will be also assessed using a real experimental setup.

8 Conclusions and Future work

Space applications ask for better technologies and new materials even if reliability and repeatability are always demanding requirements. In this framework, the authors propose a new satellite pointing system architecture which uses EAP materials as actuators. The system is first simulated using multi-body software to assess the feasibility of the proposed concept. Then, the use of a neural network architecture is proposed to identify the system which is non-linear and exhibits large deformations. The Neural Generalized Predictive Control, which is employed to control a simplified two dimensional model of the system, performs well. Future work concerns a more sophisticated model of the plant which includes a multi-link system that simulates the large deflectable EAP actuator. Experimental tests are also foreseen. The three testbeds which have been analyzed in this paper will be built and fully used to assess the feasibility of the proposed pointing system.

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