ON THE INTEREST OF RELIABILITY METHODS IN ROBOTS DESIGN INTEGRATING SMART MATERIALS

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In this article we aim to show the interest of integrating reliability criteria into new design methodologies of robots embedding smart materials. Indeed, the notions of reliability, safety, sustainability have not yet spread in the robotic field. Yet the materials used as well as their architectural layout are key performance parameters with respect to a given task and environment. This lack is particularly visible in the new generation of robotic systems embedding soft and active materials, and so-called "soft robots". We present here some applications in neurosurgical robotics and grasping tasks currently developed by our team with a methodology based on the concept of "smart layer". We analyze then the interest of integrating reliability methods by discerning two aspects: one related to the context of the tasks to be performed, illustrated by the variation of the safety factor of a shape memory alloy for a loading operation, and another related to the manufacturing process of the active/containing material assembly. The proposed analysis provides an incentive for the development of innovative design and manufacture methodologies of robotic systems with soft and active materials, taking into account operating criteria in safety for degraded modes, beneficial to their potential commercial utility.

Introduction. Today's advanced machines must be able to perform predefined tasks automatically so that they can be called "robots". For this, they have become multiphysical systems with several functional levels [1]. The definition of the tasks to be performed arises from the stakeholders' requirements from the different applicative or economic sectors. Advances in robot development methods are made necessary as these requirements evolve to be more complex for greater versatility, structural miniaturization and more advantageous cost. A search for solutions in important development is based on the modification of their mechanical and electronic architectures by the integration of smart materials active to external stimuli or whose flexibility allows to perform functions such as actuating, sensing or stiffness variation [2]–[4]; this is the field of "soft robotics" [5], [6]. Models and simulations in this field are mainly used for the optimization of flexibilities or internal architecture of the device with respect to desired motions and forces [7], [8], control [9] and energy transduction [10]. Reliability and damage studies have not penetrated the field, despite a definite interest in placing these devices on the market [11]. We have already developed some studies studies on active materials and structures in the past [12], and think that it is interesting to generalize them to this new kind of robots. In the following, we present our current developments based on the concept of smart layer within robotic devices, then analyze the potential contribution of reliability methods.

Current work on robots with smart layer. The work currently conducting requires a fine integration of active components into flexible devices. The main frameworks are biomedical and industrial engineering, with the following developments:

- A neurosurgical device for the progression in the brain in complex trajectories.
  Figure 1 shows a first characterization of progression to internal regions following a non-rectilinear path, with keypoints given by the neurosurgeon.

- A gripper with handling capabilities enhanced by an architectural reconfigurability.

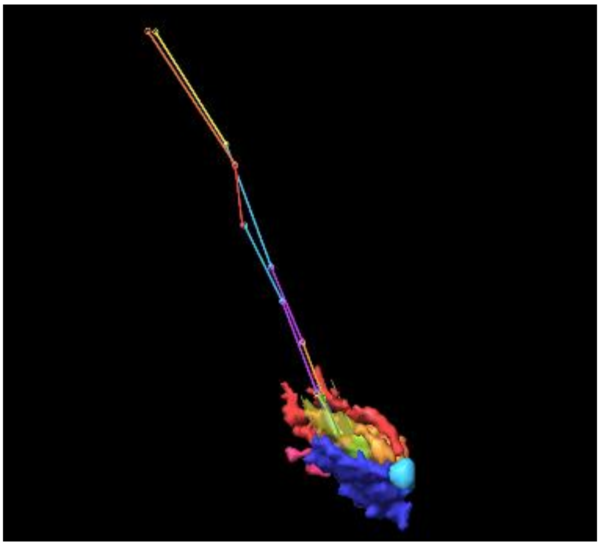

Figure 1 Robot for progressing along complex trajectories towards inner areas of the brain (with iPlan

The active components must be integrated in an area as thin as possible to leave space available to other functions, for example circulation of matter. This area, which can be called “smart layer”, must then embody one or more components into a coating material like silicon. It is destined to assume the actuation by deflection, sensing and transmission of information. The design methodological approach is then:

- mechanical characterization of the tasks and the environment,
- optimal positioning of the active components inside the device,
- design of the manufacturing machine for the components and the surrounding material, use of additive manufacturing and materials chemistry,
- modeling and control in real time of the actuating.

To this set of tasks we aim to add a milestone on reliability.

Analysis of the reliability methods interest. Reliability is a term that can encompass several aspects. For our devices, the most important ones are the constraints of not crossing the limit of elasticity nor buckling, and the control over time of the chemical stability influencing the hysteresis of the active properties. Indeed, these phenomena induce a bias on the movements and exerted efforts. Damage emergence and crack propagation models to predict the functioning in degraded mode can furthermore be very important in the case of heavily security constrained applications such as intracorporeal medical interventions. The specificity of the work to be carried out is that it is not only a simple post-conception characterization, but should also intervene in the phase of conception of the devices. We propose some guidelines hereafter.

In the context related to the tasks to be performed, the main aspects to take care of are the efforts resulting from the tasks, supplemented by the contacts with the environment. These efforts can be mastered for planned tasks in an arranged environment, or they may be partly random in an uncertain context. For a progression inside the brain, these efforts can be of the order of 5 N (experiments in agar-agar gel, whose characteristics are near of the brain [13], details not presented here). For grasping tasks, they depend on the type of object to be manipulated. The current grippers have mainly anthropomorphic functionalities. In a context of collaborative robotics, the efforts at stake can be of several tens of Newton. It is advantageous during the preliminary design to have an idea of their impact on the material safety. This can be illustrated by an example involving a shape memory alloy (SMA). SMA can function, among other properties, with a memorized shape that can be recovered by Joule effect after deformation (austenitic phase). If this shape is constrained and sufficiently heated to remain austenitic, it is possible that the yield point is reached, causing the irreversible loss of part of the memorized shape. A simulation with Ansys (with ideal elasticity hypothesis, figure 2) shows that for a sheet with characteristics given in table 1, the safety limit (ratio of the yield stress by equivalent stress) is reached for a load of **35 N** at the base: the same order of magnitude as the gripper's context.

Table 1. Useful SMA parameters

Parameter	Value
E_A, Young's modulus in austenitic phase (with memorized shape)	63 GPa
ν, Poisson's ratio	0.33
σ_y, yield point (in austenite)	650 MPa
L x H x T (dimensions)	30 mm x 10 mm x 1 mm
Non-linearities	Large deflection

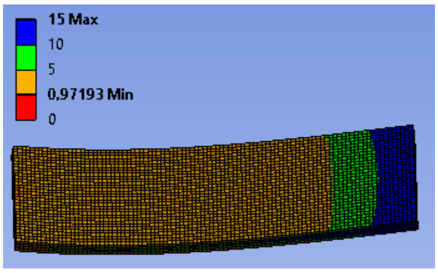

Figure 2. Safety factor of the SMA sheet for

In the context of the embedding material and manufacturing process, we note that the containing material and their fabrication have an influence on the possibilities of functioning and the dimensioning of the overall structure. Indeed, it is predictable that the properties of the components taken separately are not the same as those post-integration. The choice of the manufacturing process is a process involving both the product parameters (geometry of the robotic device, materials) and those of the selected processes (type of machine, settings). The approach is necessarily different from the one needed for the tasks' context which consists in unitary simulations, and it should be here rather carried out incrementally:

- Discretization of the problem into blocks of elementary geometry, each block consisting of a combination of active material/containing material, capable of displacing or generating a force.
- Experimental qualification of each block according to the obtaining process (operating limits, evolution of active properties after manufacturing, modes of failure). A model of reliability behavior must then be drawn from these characterizations.
- Definition of the assembly process of the elementary blocks in a complete device to get closer to the device designed and optimized with respect to the specifications. It is then necessary to use the behavioral model of the previous step.

Conclusion

This article aims to sensitize on the importance of combining works on reliability and robotics embedding smart materials, and the current weak presence of such combination in design methodologies and manufacturing processes. This is particularly true for soft robots that integrate deformable materials and materials active in response to multiphysics stimuli. A new path has been opened by building on the concept of smart layer in robotic devices and analyzing a potential approach taking into account various aspects related to the reliability of internal and external components. Current incentives for eco-design also lead to other further interest in degradability and self-repair phenomena.

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