Appel A Projets II : formulaire de candidature

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Nom du projet : **3D-printed long fiber architectured materials applied to elongated-body soft swimming biomimicry-robots.**

Résumé du projet (5 lignes en anglais) :

Our goal is to use the 3D-printed long fiber composites AM to develop a demonstrator prototype as tool to understand the mechanical functional consequences of the fibers and other aspects of elongate body morphology in soft swimming robots, and to help develop robotic devices.

Volet complémentaire pédagogie demandé : ✓ Oui ☐ Non

Contenu scientifique (3 pages maxi) Contexte scientifique

Biomimicry, by learning from nature's concepts and design principles, is driving a paradigm shift in modern materials and mechanics science. More or less deliberately, from its beginning, robotics also took inspiration from nature to design its robots. Robots resembling to human arm were designed using discrete mechanisms devoted to the manipulation tasks of industrial manufacturing processes. These discrete mechanisms consist of serial chains of rigid bodies connected by lumped degrees of freedom (multibody systems). With the passage of time, taking inspiration from the wide diversity of the animal kingdom, the researchers in this field started developing mechanisms with more and more internal degrees of freedom, hence introducing a new generation of robots called as hyper-redundant systems since they may be considered as having an infinite degree of redundancy with respect to the six dimensional task consisting of moving a rigid body in space. Even, nowadays, the robotics have entered into the era of soft robotics where the robots have no rigid bodies in their structure. In this case, the source of bio-inspiration is provided by soft animals. From the mechanical point of view these systems can be considered as continuous systems having an infinite number of degrees of freedom. More particularly, swimming capacity of fishes is far superior in many ways to what has been developed by nautical science and technology. They use their streamlined bodies to exploit fluid mechanical principles. The fish and surrounding vortices together constitute a unified and remarkably efficient swimming machine. In this context, the nonlinear Cosserat beam model has attracted attention soft robotics community for modelling arms made of soft materials. It has been used for modelling locomotion of continuum elongated animals as snakes, worms and fish with the aim of understanding the secrets of their performance and to reproduce them on bio-inspired devices (Boyer et al., 2017, 2006) and understanding fluid interactions occurring between a swimming elongated fish and an ambient flow (Candelier et al., 2013, 2011).

In the Cosserat approach, the idea consists in considering the robot body as a hyperelastic beam subject to finite displacements and small strains defined by a continuous assembly of rigid cross sections. Such body is controlled through distributed laws of internal strains or torque. As shown in Figure 1, the medium is modeled by a continuous set of rigid cross sections (here elliptic) stacked along a material line (called backbone) parameterized by a coordinate $X \in [0;1]$ which plays the role of a continuous label for the cross sections. To each X -cross section, a mobile cross-sectional frame $F(X) = (\boldsymbol{O};\boldsymbol{t}_1;\boldsymbol{t}_2;\boldsymbol{t}_3)(X)$ is attached, where $O(X)$ and $\boldsymbol{t}_1(X)$ coincide with the center of the cross section and its unit normal vector, respectively. Thus, in this approach, the strain state of the body is also totally specified by two vector fields, also depending only on X and time T, which correspond to the tangent field of the material axis of the body $\partial\mathbf{r}/\partial X$, and to the torsion and curvature vector field of the sections $\boldsymbol{k} = K_X\boldsymbol{t}_1 + K_Y\boldsymbol{t}_2 + K_Z\boldsymbol{t}_3$. Finally for the purpose of three-dimensional manipulation or locomotion, the minimal kinematics consists in imposing $K_X = 0$, in this case the robot cannot twist around its backbone, nevertheless it can roll around it, by combining the two bending curvatures K_Y and K_Z. In this case, the platform is of "universal joint type". If we go further, by imposing $K_Z = 0$ the robot is a planar one as those designed for planar swimming. Finally, note that the constraints imposed by robot architecture design can be interpreted as specific time evolutions, and that from a dynamics point of view, these constraints will induce internal reaction forces and torque fields. In the same manner, time evolution of the internal d.o.f. will be imposed by the corresponding internal control torques and forces. Since at this point, the internal deformations are **directly imposed** through a time strain law. This approach was largely used in ANR Program *Robot Anguille Autonome pour Milieux Opaques – RAAMO* and in the ERC Project *Anguilliform robot with electric sense ANGELS.*

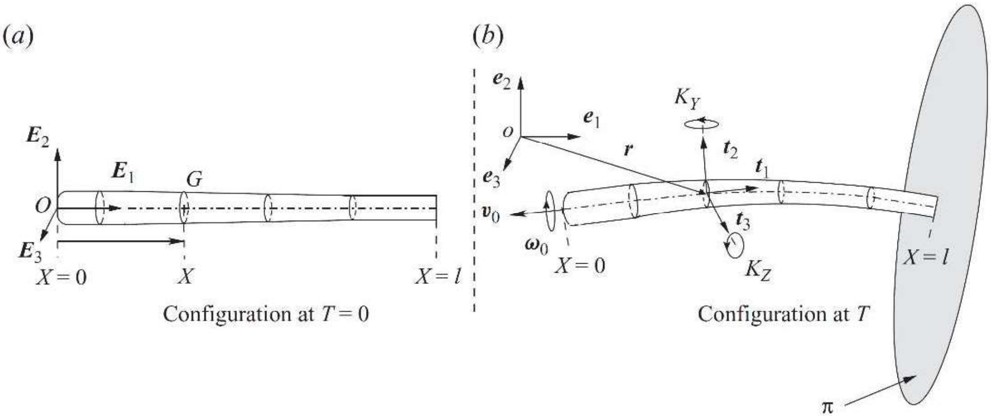

Figure 1: Frames and parametrization of a hyper-redundant robot (Candelier et al., 2013)

Though being originally motivated by the study of passive beams in finite deformations, the above approach can be adapted to model several systems relevant to bio-inspired and continuum robotics. Recently Boyer et al., 2019 explores new powerful approach based on the **strain parametrization.** This new dynamic model of Cosserat beams consider the **strain of muscles inside an elongated animal**. This formulation allows even more realistic description of the robot locomotion. In the strain parameterization approach the field of stress components is governed by an active constitutive law decomposed into two parts: the first one for the autonomous time-dependent internal forces and/or torques produced by the actuation (i.e. the exogenous rhythmic stress field governed by a central pattern generator) and a second one used for modelling a certain damping and stiffness of the muscles that are here mounted in parallel with the actuation. This new approach will be explored in the ANR Project *Théorie Cosserat pour les robots élancés contrôlés en déformation – COSSEROOTS*.

Many elongate fishes (here called elongated-body soft swimmers), such as eels, have evolved to be extremely flexible. They achieve this flexibility because they have eighty or more individual vertebrae in their vertebral columns. This means that each individual vertebral joint bends relatively little, even when the fish twists and bends at extreme angles to maneuver through crevices and under rocks. The result is a body which behaves more like a continuous flexible elastomer than a stiff jointed animal. Since the backbone in these fishes is very flexible, they rely on other parts of their anatomy for structural support (Mehta et al., 2010). One major structure is the skin. Many researchers have studied the skin of fishes, quantifying its basic structure in several species, including eels, tuna, trout, hagfish, and sharks. In all fishes, the skin has a crossed array of helical **fibers** that wind around the fish's body, creating an **anisotropic composite material** (Danos et al., 2008). The angle of the cross-woven collagen fibers play an important role in function and, in some species, may help to transmit muscular forces toward the tail (Hebrank and Hebrank, 1986; Wainwright et al., 1978). Elongate fishes could be characterized as fiber-wound tubes. Several studies have discussed these structures and proposed optimal fiber angles to support different types of movements. For example, to prevent kinking and resist longitudinal expansion of the tube during locomotion, the optimal fiber angle is about 55-60°, but to resist torsion, the optimal angle is 45°. The fiber angle was measured by Donatelli et al., 2018 at several points along the length of the body. In all six species studied by authors, the fiber angle was between 45° and 55° disposed in crossed-helical array (Figure 2). Gemballa and Bartsch, 2002 the orientation of fiber further contributes to functional variation within the skin (Figure 3). The front

60° orientation is optimal for extreme curvatures (noted above as K_Y) while back region 45° orientation is optimal for restricting torsion in steady-state swimming (Hebrank, 1980). There have been numerous fish-inspired robotic designs. Though many fish are flexible animals, most of these robots are made from stiff materials which do not mimic the system well. An silicone rubber skin was prosed in (Machado, 2011) as part of ANR–RAAMO and an experimental rig was developed to characterize (Machado et al., 2012) and modeling (Machado et al., 2014) but limitations of a single material (without fibers) were pointed out.

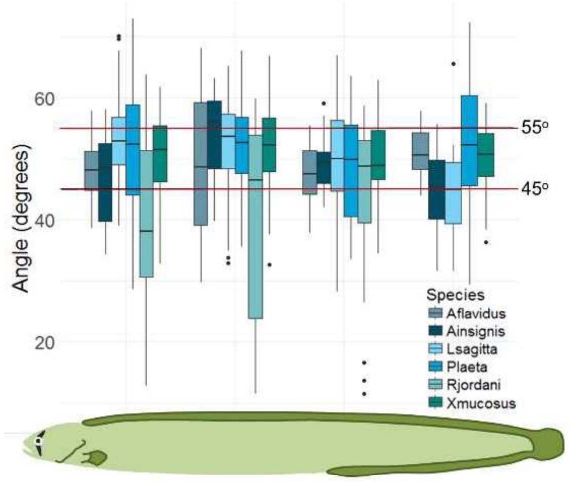

Figure 2 - Fiber Angle of Six Species of Elongate fishes: The x axis is position along the body, with the head on the left and tail on the right. The y axis is fiber angle. Red lines indicate that most fish have fiber angles that fall between 45° and 55°. (Donatelli et al., 2018)

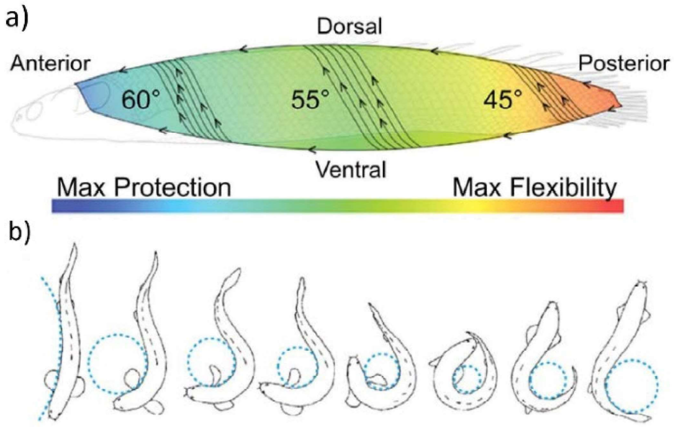

Figure 3 - The global organization diagram: (a) spatial functional differentiation color map of unit shape ranging from maximum protection (blue) to maximum flexibility (red). (b) Functional differentiation is adapted to the varying bending curvature K_Y (blue dashed line) during the swimming motion of the fish. (Duro-Royo et al., 2015; Gemballa and Bartsch, 2002)

To design soft robots that mimic the flexibility of elongate fishes, we need materials/structures that mimic the material properties of their anisotropic bodies. However, the complicated structural architectures in nature far exceed the capability of traditional design and fabrication/process technologies, which hinders the progress of biomimetic study and its usage in engineering systems. Additive manufacturing (AM), or simply called 3D printing, has created new opportunities for manipulating and mimicking the intrinsically multiscale, multimaterial, and multifunctional structures in nature. Nevertheless, the addition of fibers to various AM technologies is of increasing interest in academic and industrial communities.

Our goal is to use the **3D-printed long fiber composites** AM to develop a prototype as tool to understand the mechanical functional consequences of the fibers and other aspects of elongate body morphology in **soft swimming robots**, and to help develop robotic devices. More precisely, the printed prototype will give new reliable information in terms of strains of the structure into strain parametrization Cosserat framework.

Programme

L'étude d'une structure imprimée avec des composites fibres longues adresse plusieurs questions concernant la modélisation et la prédiction du comportement de ces composites émergents, par exemple l'influence des paramètres de fabrication sur la nature du matériau et l'adhésion entre les différentes couches imprimées (Quan et al., 2015). Pour cela, l'équipe se proposent de faire l'acquisition d'une machine d'impression 3D fibres continus utilisant dans un premier temps essentiellement 4 matériaux : fibres de carbone continues et fibres de verre continues toutes enrobées dans une matrice de thermoplastique et aussi du filament thermoplastique (ou thermoplastique « élastomère » - TEPs) renforcés de différents types et longueurs de fibres courtes. Ensuite nous nous proposons de mener nos investigations sur les quatre points suivants :

- Caractériser le comportement mécanique des matériaux mis en œuvre sur des éprouvettes de composites réalisées avec différentes stratégies de fabrication uniquement en statique sur des éprouvettes homogènes et sur des plaques trouées avec différentes concentration de contraintes en s'appuyant sur des moyens d'essais performants (MTS hydraulique traction-torsion, et dispositif de corrélation d'images 3D) afin d'étudier la résistance de ces matériaux et les critères de défaillance associés.

- Ensuite nous pourrons valider nos premiers résultats sur le développement et la caractérisation de la tenue mécanique d'un « tronçon caractéristique » d'un robot subissant un chargement statique complexe dans un banc d'essai structure. Cette étape permettra d'enrichir ou d'identifier les paramètres matériaux (constitutifs) de la loi de comportement du modèle général permettant de décrire la déformation du corps de l'anguille lors de la nage.

- Tous ces travaux s'appuieront sur les compétences reconnues du LMA sur la modélisation des matériaux composites du point de vue macroscopique ou micro mécanique. Une méthode d'homogénéisation en champs complets permettant de prendre en compte la microstructure du matériau ainsi que le comportement de chacun de ses constituants pourra être utilisé pour prédire le comportement mécanique de la peau (structure) fabriquée par FA. Ces résultats seront complétés par des mesures d'observations pré et post essais sous micro-tomographe au laboratoire LMA.

- En parallèle des travaux cités ci-dessus, le laboratoire IUSTI (déjà partenaire du projet ANR - COSSEROOTS) travaille sur le développement de la modélisation de la nage passive et active, portant sur le modèle dynamique de nage (connu sous le nom de *Large Amplitude Elongated Body Theory*). Ces travaux font partie des compétences reconnues dans l'IUSTI sur la modélisation des interactions fluide structure survenant lors de la nage anguilliforme dans un écoulement uniforme et non-uniforme.

Retombées attendues

Cette étude permettra de déterminer les paramètres constitutifs des matériaux composites obtenu par FA. Une première « architecture » du matériau du corps d'un robot anguille continue devra être proposé. Elle permettra d'enrichir la compression des lois de locomotion et les lois d'interaction fluide structure.

Le projet présenté fait partie des thématiques transversales traitées à l'IMI. Par ailleurs, la thématique liée aux robots souples (*soft-robotics*) est actuellement en plein essor dans la communauté scientifique internationale. La réussite de ce projet pourra permettre à terme de développer de manière pluridisciplinaire des solutions innovantes de robot nageur et de son pilotage par loi de comportement fluide/structure directe.

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