Proposal Form
PhD Thesis / Research residency stay
China Scholarship Council (CSC)/ENS Rennes
Call for projects 2022

FIELD: MECHATRONICS / MECHANICAL ENGINEERING / ELECTRICAL ENGINEERING / FLUID DYNAMICS

THESIS / RESEARCH SUBJECT TITLE

Smart Underwater Morphing Structures:
A Universal Building Block for Bio-Inspired Underwater Flexible Robotics

Type of PhD: please tick the appropriate box:

- Joint PhD/cotutelle (leading to a double diploma) : YES ❑ or NO ☑
- Regular PhD (leading to a single French diploma) : YES ❑ or NO ☑
- Research residency visit (for students enrolled at a Chinese institution who will be invited to a French institution to carry out a mobility period) : YES ☑ or NO ❑

Name of French doctoral school (if applicable): N/A

Name of host laboratory and research team: CNRS SATIE laboratory, Electric Energy Systems team
Website: http://satie.ens-paris-saclay.fr/

Name of French Supervisor: Dr. Gurvan JODIN

Name of PhD director-s in Chinese university (if applicable):

- Name: Dr. Dixia FAN
- Position: Assistant professor at West Lake University
- E-mail: fandixia@westlake.edu.cn

If previous collaborations with the Chinese co-director/university, please elaborate:

Dr. FAN and Dr. JODIN met during the 2016 APS conference. Their formal collaboration was initiated in 2018 during graduate and postdoctoral studies at MIT (Boston, MA, USA). This collaboration on advanced experimental hydrodynamics led to a prestigious publication in Science Robotics 2019 [1].

This collaboration continues on the bio-inspired robotics modeling and design. In specific, three IEEE OCEAN2021 conference papers were presented. In addition, a further collaboration has been established on the funding proposal to Human Frontier Science Program (2nd selection step in progress), together with the Department of Zoology of Cambridge University (UK).

Another aspect of the collaboration is related to STEM education with an underwater robot. For instance, several summer camps in Shanghai in 2019 led to the EDUCON2020 conference paper [2].

Currently, Dr. Fan and Dr. Jodin have been cosupervising several undergraduates. This application focuses on the first Ph.D. candidate to be co-supervised by Dr. Fan and Dr. Jodin.

[1] **D. Fan**, **G. Jodin**, T.R. Consi, L. Bonfiglio, Y. Ma, L.R. Keyes, G. E.Karniadakis, M.S. Triantafyllou, 2019. A robotic Intelligent Towing Tank for learning complex fluid-structure dynamics,
Science Robotics, 4(36), https://doi.org/10.1126/scirobotics.aay5063
[2] A. Li, **G. Jodin**, **D. Fan**, H. Xie, Y. Yu, C. Sun, L. Gu, J. Xu, J. Zhu, 2020. STEM 3.0 for Chinese Students with Sea Perch Underwater Robots: An Experimental Summer Camp for Hands-on Thinkers in Shanghai,
EDUCON2020 IEEE Global Engineering Education Conference

Research proposal abstract (1500 words max.):

The following abstract describes the global project of the funded Ph.D. This proposal consists in funding a 1 year research residency visit of the Ph.D student in France. This visit might start in October 2022.

Over the past century, considerable energy has been expended in exploring and exploiting the ocean environment, and however, until today, more than 80% of the ocean territory is still unmapped, unobserved, and unexplored. This lack of effort is mainly due to the substantial technological challenges that ocean vehicles and structures face when operating in the physically, chemically and biologically harsh aquatic environment. These challenges include intense pressure in the deep water, large unsteady forces within the water medium due to waves, current, and turbulence, corrosion and biofouling.

To address the aforementioned issues, one solution is to take inspiration from natural organisms. Compared to the traditional rigid-body vehicles that are powered by propellers and waterjets, nature provides alternative solutions, which for certain applications can prove to be more agile and effective solutions to overcome the aquatic environmental constraints. A major difference and defining property in natural underwater propulsion is flexibility. Though the flexibility varies widely across fish and marine mammals, different studies have commonly shown that the passive and active control of the flexible body and/or appendages can result in an enhanced propulsive efficiency and an improved force profile manipulation.

Having identified the benefit of a flexible body in improving hydrodynamic performance, especially in transient conditions and within turbulent flow, several researchers have integrated such a concept in designing new aquatic transportation prototypes with soft robotics. Researchers have proposed less costly techniques to build aquatic robotic systems, such as casting silicone with intricate geometries. These new fabrication methodologies have been applied to build novel soft manipulators for underwater delicate sampling, robotic fish showing better swimming efficiency and capable of agile maneuvering for the field environmental surveillance.

Problem and scientific locks

Bio-inspired designs and aquatic soft and rigid robotics have proven the worthiness as underwater vehicles. However, all the current soft robot applications in the aquatic environment share the same significant design, fabrication, and control challenges for better vortical flow control and sensing, compared to their bio-compartment. One reason to be noted is that treating soft vs. hard structures as two extreme opposites is a false dichotomy, as flexible robots can take advantage of both soft and hard components in their operations.

That being said, a pandora box containing all sizing and design parameters is opened. Indeed, not only parameters related to underwater robot design must be chosen, but characteristics of rigid and soft materials, their geometries and interface, the required sensors and actuators, the control laws must be designed for such an underwater flexible robot.

A system approach is required, and the following scientific locks are identified:

- Tunable specifications of Universal Building Block system,

- Rigid-soft matter material selection and interface for underwater flexible robot,
- Rigid-soft robot prototype making,
- Underactuated fluid-flexible structure interaction modeling,
- Flexible body posture feedback,
- Actuator for rigid-soft underactuated structures,
- Control and sensing of soft underwater robotic system,
- Experimental validation.

All these locks are part of a global topic and are addressed with projects cosupervised by the research teams.

Tasks for the research proposal

The science problem is limited to the following tasks to match a four-year doctoral degree plan for a Ph.D. candidate at Westlake Univ. and the one-year exchange study plan at ENS Rennes:

Phase 1: Bibliography and specification

- 6 months, West Lake University, China
- Content:

From the state-of-the-art rigid/soft robotic actuator/sensor/system for marine applications, the work frontier is finely defined, with the specifications of a universal modular bio-inspired flexible robot. Notably, the following subsystems are defined: Modular flexible actuation system (bone and muscles), Smart skin (skin and sensory organs), Control and sensing (nerve and brain), Design and test cases.

The first flexible actuation system is designed as a proof of concept to serve as a test bench for the following phases.

Phase 2: Sensors (Proprioception and smart skin)

- 12 months, SATIE laboratory, ENS Rennes, France
- Content:

The underactuated flexible concept defined in Phase 1 requires information feedback to be controlled.

The purpose of the visiting year in France is to design an innovative "smart skin" tailored for the robotic building block providing the necessary feedback. The bio-inspired smart skin consists of 1) distributed proprioception devices that inform the shape of the flexible structure and 2) distributed flow sensing devices that inform the surrounding flow dynamics and loads on the system. Such devices will benefit the French laboratory's expertise in electromechanical transducers. The university's MakerSpace is a useful prototyping resource for quickly setting up experiments.

Therefore, after studying the available process from the laboratory and state of the art, parametric sensor models are created. At the same time, the feedback requirements are modeled, allowing a model composition that will provide parametric sizing models for design. Prototypes of the underactuated flexible structure featuring the smart skin will be made for validation purposes. This proof of concept would confirm sizing laws to be later included in global system design.

Experimental validation will be performed in a new experimental platform the student will help set up. This experimental facility consists of a water tank specifically designed to study bio-inspired complex underwater transducers, funded by the Rennes metropolis.

This modeling and experimental work is expected to be published.

Phase 3: Control and sensing of soft underwater robotic system (nerve & brain)

- 12 months, West Lake University, China
- Content:

A more careful investigation into the fluid dynamics of the modular rigid-soft system with smart skin will be conducted in the towing tank and water tunnel facility at Westlake University. In addition, corresponding numerical simulation will be conducted to further understand the complex fluid-structure coupling process.

Based on the system characters, several control strategies will be proposed and implemented to better manipulate the designed smart morphing structure in the water.

Phase 4: Robotic design and test (system approach)

- 18 months, West Lake University, China
- Content:

Based on the aforementioned studies (biological inspiration, structural design, smart skin prototyping, fluid dynamics analysis and control algorithm development), a systematic investigation into the design and construction of a bio-inspired morphing underwater robot will be conducted.

Publications of the laboratory in the field (max 5):

G. Jodin, Y. Bmegaptche Tekap, J. M. Saucray, J. F. Rouchon, M. S. Triantafyllou, M. Braza 2018.
Optimized design of real-scale A320 morphing high-lift flap with shape memory alloys and innovative skin, Smart Materials and Structures, 27(11), 115005, http://stacks.iop.org/0964-1726/27/i=11/a=115005

S Calisch, N Gershenfeld, **D Fan, G Jodin**, M Triantafyllou 2019.
Fabrication and characterization of folded foils supporting streamwise traveling waves,
Journal of Fluids and Structures,
https://doi.org/10.1016/j.jfluidstructs.2019.01.004

Zhangyang Qi, Jiashun Guan, Ang Li, **Gurvan Jodin, Dixia Fan**, Filippos Tourlomousis 2021. AI-Powered Self-Propelled Flapping Foil Experimentation: Construction and Control of a Deep Reinforcement Learning Driven Intelligent Testing Platform.
Global OCEANS conference 2021, San Diego – Porto, September 20–23, 2021.

G. Jodin, V. Motta, J. Scheller, E. Duhayon, C. Döll, J.F. Rouchon, M. Braza 2017
Dynamics of a hybrid morphing wing with active open loop vibrating trailing edge by Time-Resolved PIV and force measures,
Journal of Fluid and Structures, https://doi.org/10.1016/j.jfluidstructs.2017.06.015

D. Fan, G. Jodin, T.R. Consi, L. Bonfiglio, Y. Ma, L.R. Keyes, G. E.Karniadakis, M.S. Triantafyllou, 2019.
A robotic Intelligent Towing Tank for learning complex fluid-structure dynamics,
Science Robotics, 4(36), https://doi.org/10.1126/scirobotics.aay5063

Date: 29/11/2021

G. Jodin

Signature of the French Supervisor: