PREFACE

> *"Natural and human technologies differ extensively and pervasively. We build dry and stiff structures; nature mostly makes hers wet and flexible. We build of metals; nature never does. Our hinges mainly slide; hers mostly bend. We do wonders with wheels and rotary motion; nature makes fully competent boats, aircraft and terrestrial vehicles that lack them entirely."*
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> — Steven Vogel, *Cat's Paws and Catapults*

As has been eloquently highlighted by Vogel, the mechanical and structural designs conceived by human engineering and those that result from natural evolution possess, more often than not, fundamentally differing properties. Throughout millions of years of evolution, nature has selected exceptionally efficient tools for an equally extraordinary diversity of requirements; a natural equivalent can be found for almost every human necessity. The aim of this thesis is to explore the use of principles that stem from natural evolution to enhance the performance of engineered mechanisms, focusing on systems whose role is to interact with a fluid environment. The contrast between bio-inspired and bio-mimetic approaches should be emphasized; the purpose of this work is not to merely replicate nature's mechanisms, nor are they considered as an optimized unimprovable solution. Rather, its intent is to combine principles from nature's operation with an engineering foundation to ideate an overall improved design.

Among the differences between natural and human designs, perhaps the most remarkable lies in the disparate use of materials. Engineers commonly employ metals and other stiff constituents, which are difficult to deform and simpler to design. Nature, on the other hand, tends to fashion more flexible materials, using the added complexity to its advantage. Flexibility plays an important role in practically every natural design and is the primary driving principle in countless of its mechanisms. The effect of compliance on a structure is particularly notable when it is subjected to fluid forces from its environment. The aero- and hydrodynamic forces that act on a body submerged in a fluid are dependent both on the body's shape and its motion. In the case of a flexible structure both of these properties are a function of its deformation, which is, in turn, dependent on the fluid forces that are exerted on the structure. This interdependence results in coupled physics between solid deformation and fluid mechanics, which can no longer be considered separately. The field concerned with the study of this coupled behavior is aptly called the field of solid-fluid interactions, and will be the subject of Part I of this thesis. The interactions between solid and fluid add a level of complexity that may be detrimental to the mechanical system, increasing the number of possible failure modes of the structure. They also provide, however, additional degrees of freedom to tinker with that may be exploited to our advantage with careful design. Inspired by the flutter of leaves in the wind, Part I of this thesis is dedicated to the analysis of an inverted flag, a flexible cantilevered plate clamped at its trailing edge that is unactuated but subjected to a uniform flow. The resonance between solid motion and fluid forcing generates large amplitude unsteady deformations that may be used for energy harvesting purposes.

Part II of this thesis draws inspiration from a different natural design. Due to the suitability of metallic components and electromagnetic motors, engineered propellers for aquatic locomotion generally make use of continuous rotational motions. Nature, however, generates propulsive forces through flapping, paddling and jetting. Flapping propulsion is achieved through periodic motions of a plate-type propeller and commonly entails the coupling of lift and thrust forces. This coupling results in complex physics, but eliminates the need of multiple force-generating surfaces. Based on the caudal fin of fish, Part II of this thesis aims to combine both flapping propulsion and the large, although not continuous, rotations of human propellers. A fin capable of generating rotations in three degrees of freedom is proposed as a combined propulsive and maneuvering system for use in autonomous underwater vehicles. The analysis delves into the optimization of the three-dimensional motion to be followed by the fin in order to generate desired maneuvering forces.

In accordance with these two distinct topics, this thesis is divided into two independent parts, with this preface serving as a reminder of the underlying encompassing topic and the origin of the principles at hand.