Cephalopod-inspired soft robots: design criteria and modelling frameworks

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Abstract

Cephalopods (i.e. octopuses and squids) are taken as a source of inspiration for the development of a new kind of underwater soft robot. These cephalopod-inspired, soft-bodied vehicles entail a hollow, elastic shell capable of performing a routine of recursive ingestion and expulsion of discrete slugs of fluids via the actual inflation and deflation of the elastic chamber. This routine allows the vehicle to propel itself in water in a very similar fashion to that of cephalopods. This mode of pulsed jetting enabled by the actual body shape variations can ideally benefit from the positive feedback provided by impulse-rich discontinuous jet formation and added mass recovery. This work is complemented by extensive modelling efforts which are meant to aid in the process of mechanical design optimization as well as providing an advanced tool for biomechanical studies of living cephalopods.

I. Introduction

Bioinspired underwater propulsion has earned remarkable recognition in the scientific community thanks to its undeniable technological and scientific potential. In underwater applications, where robot-aided operations are plentiful and where even the simplest task often becomes a daunting challenge, the recourse to agile and efficient vehicles is progressively becoming mandatory. Among the various modes of bioinspired locomotion, fish-like caudal and finned propulsion have gathered the most interest, spurring the development of a plethora fish-mimicking robots [1].

As opposed to fish-like swimming, the locomotion of cephalopods has gained only limited credit, possibly due to its supposedly poor efficiency. Lacking a proper skeletal structure, cephalopods have evolved a propulsion strategy based on consecutive phases of ingestion and expulsion of finite slugs of water executed by the expansion and collapse of an elastic chamber [2], the mantle. In recent times, however, evidence has started to emerge which highlights the occurrence of at least two important dynamics phenomena involved in the pulsed-jetting of these soft-bodied organisms which could overturn the notion according to which cephalopods belong to the low-efficiency end of the spectrum of sea dwellers. First, experimental evidence exists which associates the discontinuous expulsion of fluid with the formation of impulse-rich jets, which, in turn, are responsible for an augmented thrust compared to the case of a comparable continuous jet [3]. In the second place, theoretical arguments suggest that the shrinkage of the mantle volume during axial acceleration of the specimen guarantees a positive feedback on thrust production via the recovery of the kinetic energy associated to the variation of added mass [4].

The swimming skills of cephalopods are thus related either with the nature of the jet expelled or with the phenomena dependent on the variation of shape which the body undergoes while swimming. These aspects are both linked to the unique capability of cephalopods to alter their body volume thanks to the absence of a skeletal structure. Being capable of designing a fully deformable soft-vehicle which performs a swimming routine analogous to that of cephalopods not only provides an advantage in terms of locomotion performances, but it also guarantees resilience to impacts and the flexibility to move through cramped spaces or narrow apertures.

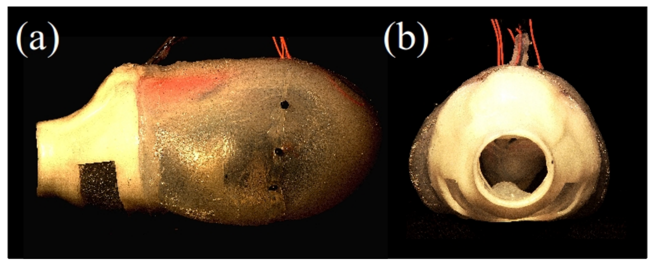

Fig. 1. Side (a) and frontal (b) view of our cephalopod-inspired soft robot: the circular opening is the outflow nozzle, while the crescent shaped aperture on the ventral side of the vehicle is an ingestion valve for easing the refill stage of the propulsion.

It is, thus, the authors' opinion that, by taking inspiration from cephalopods, it will be possible to design aquatic soft bodied robots with superior maneuvering ability and endowed with highly advantageous structural characteristics. This will provide an invaluable tool in the context of underwater operations as well as a useful experimental framework to study the biomechanics of cephalopods.

II. State of the Art in Cephalopod-inspired propulsion

The acknowledgement that the geometrical parameters of the jet can be modulated with the scope of optimizing the amount of thrust produced per pulsation ([5], [6], [7], [3]) has promoted the efforts to design pulsed-jet thrusters capable of exploiting this asset in the frame of aquatic propulsion ([8], [9], [10]). With the exception of the work of [11], all research devoted to mimicking the cephalopod-inspired locomotion has focused exclusively on the pulsed nature of the flow at the

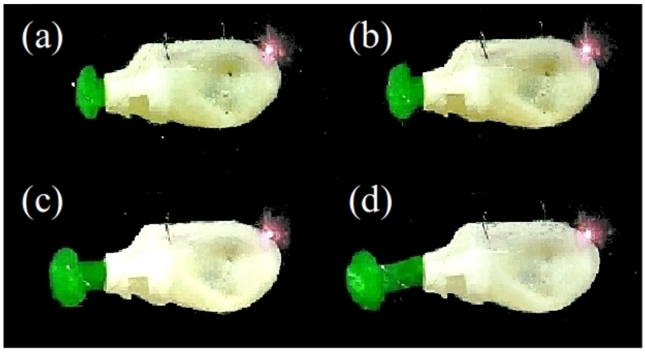

Fig. 2. Four successive frames of the collpase stage of our cephalopod-inspired soft robot during one propulsive cyle. The fluid initially stored in the elastic chamber, dyed with fluoresceine, rolls into a vortex ring as it is expelled.

nozzle-exit plane during propulsion. The state of the art of cephalopod-inspired pulsed-jet propulsion devices essentially consists of piston-like actuators implemented in standard torpedo-shaped vehicles. These devices benefit exclusively from the production of the vortex ring at the nozzle-exit plane, clearly receiving no contribution from the added-mass-related effects.

III. Soft-bodied cephalopod-inspired vehicles

In order to take advantage of the entire range of assets of cephalopod propulsion, it is necessary to replicate the pulsed-jetting routine of cephalopods by accounting for the actual body-shape changes. In the process of developing a robotic artifact capable of performing a propulsion routine trustworthy resemblant that of swimming cephalopods, the compliant nature of the structure was taken as one of the key factors among the design principles.

We have developed and tested a series of soft-bodied, pulsed-jetting, aquatic vehicles ([12], [13], [14]), see Fig. 1, which propel themselves in water by performing a routine very much resemblant that observed in living specimen. These vehicles are composed of an elastic, hollow shell acted upon by cables distributed over the internal walls of the shell and pulled radially inward by the cyclic rotation of a crank mechanism actuated by a standard electric motor. Under the pointwise cable loading, the shell undergoes periodic phases of collapse, see Fig. 2 and inflation. During these stages the robot expels and successively ingest ambient fluid. Cable-driven actuation deals with the collapsing phase of the propulsion, while the inflation of the elastic cavity is guaranteed by the passive behaviour of the elastomeric material which the shell is composed of.

Our work has so far entailed essentially two major lines of research: vehicle design and actuator modelling. Recursive testing performed in controlled environments with different prototypes demonstrated that a crucial role in determining the average axial translational speed of these kind of vehicles was played by the elastic response of the shell to the inflation and deflation phases of the actuation.

A first simplified model which predicts the performances of the vehicle based on the temporal variation of the cross section of the shell acted upon by cables [13] suggests that, for given design specifications (crank length, size, geometry and material properties of the elastic shell, number and arrangement of the cables employed), an optimal swimming speed exists in coincidence with the synchronous action of the actuator which operates the shell collapse and the development of elastic energy which determines the speed of inflation of the shell. These results, on one hand provide us with useful indications as to the design criteria which will require consideration in the optimization of the design and actuation routine of this kind of soft-bodied pulsed-jet vehicles. On the other hand they underline the importance of the passive phase of the actuation (i.e. the refill stage) which is controlled by the geometrical/material properties of the shell.

In order to infer optimal design characteristics of this new kind of robots, a more in depth analysis of the elastic response of the shell to both actuation and hydrodynamic loadings is needed. To do so, the development of an *ad-hoc* hydroelastic model has been undertaken. This model is meant to capture the dynamics of the robots elastic shell by accounting for a Reissner axisymmetric shell [15], [16] coupled with a potential flow model for the continuous pressure distribution exerted by the internal and external fluid throughout the actuation cycle [17]. This model has so far been tested against the experiments performed with the available prototypes of the cephalopod-inspired vehicles and a qualitative representation of the comparison is shown in Fig. 3.

IV. Conclusions

Upon developing and testing a series of robots which are capable of replicating the actual swimming routine of cephalopods and having formulated the suitable modelling

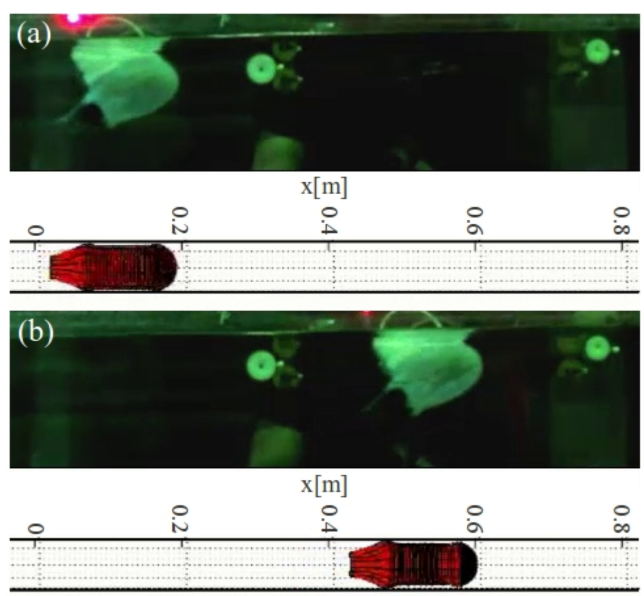

Fig. 3. Two frames taken from the soft robot testing experiments and the respective numerical modeling counterparts.

tools to test the hydroelastic response of such vehicles, we can finally extend our work to the study of the fine scale dynamics involved with their unconventional mode of aquatic propulsion. This entails, for instance, verifying to what extent vortex-ring-enhanced thrust production and added mass recovery can co-participate to the overall performances of a cephalopod-inspired robotic artifact as well as derive accurate estimate of energy expenditure during pulsed-jetting via proper body-shape variation. This may eventually provide new insights in the estimation of swimming efficiency not only of the robotics artefact presented herein, but of living cephalopods, as well. This we consider to be of interest to a diversified audience of biologists, roboticists and fluid dynamicists who may have had only marginal exposure to this niche of research.

V. Acknowledgments

This work was partly supported by the RoboSoft Coordination Action and the Foundation Grant PoseiDRONE.

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