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Design and Modelling of TorsioSquid: A squid-inspired underwater bot

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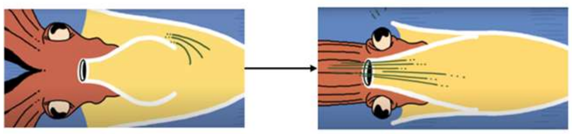
Abstract

Underwater soft robotics is an emerging field due to the increased need for underwater exploration and surveillance, which requires blending with natural habitats. Although previous work has been done mimicking fishes and octopuses, only a few have tried to imitate the mantle movement of squid. Mimicking the mantle's propulsion mechanism could lead to a compact design, which we have presented through the TorsioSquid, a bio-inspired robotic system. Its unique propulsion is achieved through a synergy of torsional buckling [1] and Bowden cables arranged in a helical pattern around a semi-ellipsoidal Ecoflex shell. At its heart, a linear actuator drives the system by pulling on the cables, inducing controlled buckling and mimicking the squid's mantle movement to generate thrust. In previous similar works, rigid components like motors and gears have been used to mimic squids [2]. These components often fail under cyclic loads. Our design of TorsioSquid prioritizes using softer components like bowden cables and torsional buckling to mimic squids. We have simulation results specifically and have estimated the mass of TorsioSquid to be 800 g and length of 540 mm through its CAD model. Using Ansys, we concluded that TorsioSquid achieves a notable mass ejection rate of 0.4 kg/sec, contributing to significant thrust force.

Working of Squid Mantle



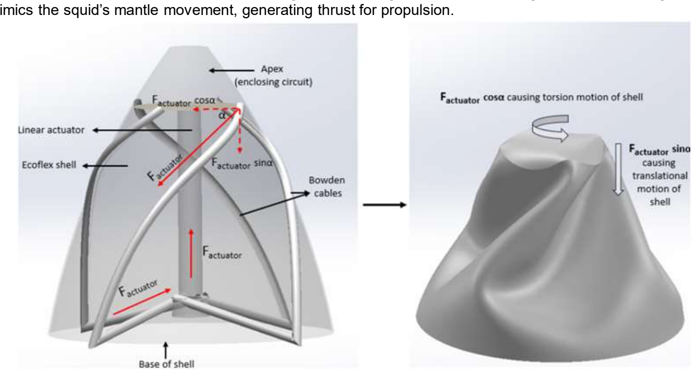
Intake stroke of Mantle | Exhaust stroke of Mantle

Why mimicking Squids ?

- **Compact Design** – Enhanced maneuverability and deployment in confined spaces
- **Rapid Propulsion** – Squids use a combination of jet propulsion and fin movements for their navigation.
- **Control and Stability** – By modulating the expulsion of water, adjustment to external disturbances are handled.
- **Energy Efficiency** – Efficient muscle contractions and water expulsion, results in relatively low energy consumption

Design of TorsioSquid

Key to TorsioSquid's actuation is a unique combination of torsional buckling and Bowden cables. Bowden cables arranged helically around the shell have one end connected to the linear actuator and the other fixed to the apex. As the actuator retracts, it pulls on the cables, inducing axial and tangential forces, causing controlled buckling of the shell. This mimics the squid's mantle movement, generating thrust for propulsion.



FBD and working of the TorsioSquid during backstroke of linear actuator

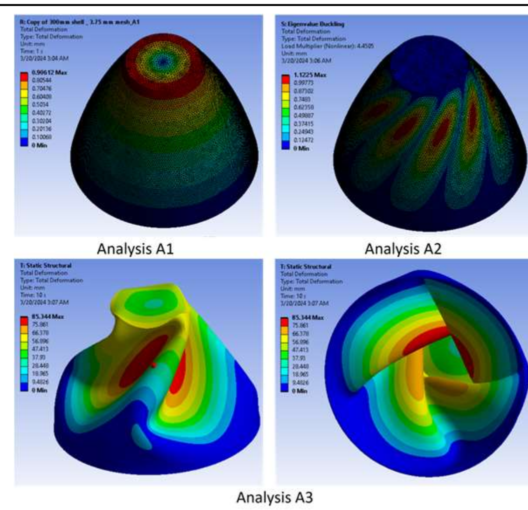
Equations and Boundary conditions

- Thrust force = Exit velocity * Mass ejection rate
- Mass ejection rate = Density of water * $\triangle V$
- Translation load [1] = (A+w)*(sinαf - sinα0) = 37 mm
- Rotational load [1] = (Helix parameter)*(αf - α0) = 45 degrees

Where $\triangle V$ = Volumetric deformation
A = Major axis = 298 mm
w = Shell thickness = 2 mm
αf = Final helix angle = 56.25 degree
α0 = Initial helix angle = 45 degree
Helix parameter = 4*n = 4
n = no. of turns of the helix around the semielliptical surface

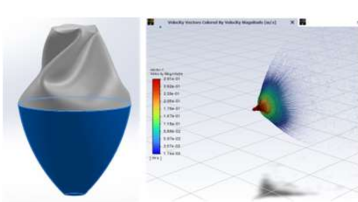
Simulation and Analysis

- **Analysis A1:** A 1-degree rotation has been applied to give Pre-stress to the shell.
- **Analysis A2:** Eigen buckling analysis to create geometrical imperfections in the shell.
- **Analysis A3:** Translational and rotational load are applied in steps of t = 10 secs on the geometrically imperfect shell to generate folds in the semi-ellipsoidal shape, replicating the volumetric deformed state.
- **Obtaining volumetric reduction** - Importing the volumetric deformed state in Analysis A3 of the shell in Solidworks and comparing it with the initial one gives us the volumetric deformation $\triangle V$.



Nonlinear buckling and eigenvalue buckling to find $\triangle V$

Usage of the nozzle to increase the exit velocity



A semi-ellipsoidal-shaped nozzle with an exit diameter of 50 mm can increase the exit velocity, thus increasing the thrust force

Performance metrics

ΔV (cm^3)	Mass ejection rate (kg/s)	Exit Velocity (cm/s)	Thrust Force (N)	Acceleration (m/s^2)
4077.032	0.4077	20.76	0.0846	0.105

We calculate the mesh convergence error to verify our simulation results. We get a **0.7 % mesh convergence error**, which gives our simulation results reasonable accuracy.

References

1.) Lorenzon, Lucrezia & Lucantonio, Alessandro & Costi, Leone & Zrinscak, Debora & Arleo, Luca & Cianchetti, Matteo. (2024). Harnessing Mechanical Instabilities in the Development of an Efficient Soft Pump for an Artificial Heart Ventricle Simulator. IEEE/ASME Transactions on Mechatronics. PP. 1-11.

2.) Caleb Christianson et al 2020 Bioinspir. Biomim. 16 016014

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