Control and Morphology Optimization of Passive Asymmetric Structures for Robotic Swimming

Nana Obayashi †, Graduate Student Member, IEEE, Andrea Vicari †, Kai Junge, Graduate Student Member, IEEE, Kamran Shakir, and Josie Hughes ‡, Member, IEEE

Abstract—Aquatic creatures exhibit remarkable adaptations of their body to efficiently interact with the surrounding fluid. The tight coupling between their morphology, motion, and the environment are highly complex but serves as a valuable example when creating biomimetic structures in soft robotic swimmers. We focus on the use of asymmetry in structures to aid thrust generation and maneuverability. Designs of structures with asymmetric profiles are explored so that we can use morphology to ‘shape’ the thrust generation. We propose combining simple simulation with automatic data-driven methods to explore their interactions with the fluid. The asymmetric structure with its co-optimized morphology and controller is able to produce 2.5 times the useful thrust compared to a baseline symmetric structure. Furthermore, these asymmetric arms are validated on a robotic system capable of forward swimming motion while the same robot fitted with a plain feather is unable to move forward.

Index Terms—Soft robot materials and design, modeling, control, and learning for soft robots, biologically-inspired robots.

I. INTRODUCTION

ASYMMETRY or directionality is a property widely exploited in robotics; from asymmetric friction profiles to enable locomotion [1], [2], asymmetric weight distribution for passive walking [3], asymmetric structures to enable turning [4], or asymmetric control of robots [5], [6]. Biology shows further examples of where passive or active asymmetry in is exploited for advantageous properties. Aquatic creatures are particularly adept at utilizing their body structure or properties to aid their interactions with fluids, enabling complex behaviors to emerge from simple motion patterns. One such animal that exploits asymmetry in structure to aid thrust generation and maneuverability is a marine cnidoid called the ‘feather star’ [7]. These animals can alter their feather-like limb geometry for asymmetrical thrust generation depending on its desired movement. Inspired by this use of geometry to ‘shape’ the thrust generation, soft robotic swimmers that use passive structures that break or change their symmetry could similarly utilize structure change to aid their motion.

Previous work has shown that asymmetric actuators that utilize folding and bending can be used to obtain net positive displacement [8]. Another work has qualitatively investigated an efficient stroke pattern to produce unidirectional thrust with similar passive structures [9]. However, the optimization between the structure and the control input was not explored. In order to exploit passive asymmetry in thrust generating structures that results from passive structures in fluids, we must understand the tight coupling between the dynamic motion and the passive morphology of the asymmetric profile, and the resultant thrust. This requires high fidelity and accurate modeling of both the fluid-soft structure [10] and also the large deformations caused by passive properties of the asymmetric structure. Fluid-solid interaction methods such as the immersed-boundary method are popular for modeling biological systems with large active or passive deformations [11], but are still subject to large reality gaps and requires high computational power [12]. Data-driven approaches are showing potential as a way to explore behaviors of soft structure and fluid interactions by combining simulation [13] and evolutionary algorithms [14] with physical experimentation. Asymmetric flapping causes variations in the vortices forming in the structure’s wake, and quantities like Cauchy number can describe the extent to which the fluid forces dominate and the structure to deform [15], making this an interesting problem also from a fluid dynamics perspective. Utilizing passive asymmetric structures coupled with a suitable input controller should be further explored for designing soft robots, and we also must be able to reliably quantify the benefits gained.

By finding an optimal controller and morphology of the feather that exploits passive asymmetry, we predict that the soft structure can be used to generate useful directionality in thrust compared to a plain feather without any asymmetric profile. Three key contributions summarize this work. First, the rapid and simple fabrication strategy for asymmetric foldable ‘flaps’ allows for a large design space in artificial ‘feathers’ including chordwise and spanwise flaps (Fig. 1), which when actuated in the correct conditions in water, can leverage thrust generation. From this, we make our second contribution of a benchmarking and evaluation platform that leverages a low-cost simulation and a fully autonomous and guided optimization to enable a wide exploration of feather geometry and controller space. This
allows for an efficient quantification of soft body-fluid interactions that are challenging to predict with existing methods that are computationally expensive. The findings from our approach are the final contributions to this work. Introducing passive asymmetry in our feathers can increase useful thrust by a factor of 2.5 compared to a plain feather without flaps. Furthermore, the feather with chordwise flaps that mimic the biological feather star may be more robust to control signal changes with higher thrust performance.

By using the platform to identify target morphologies, followed by automatically exploring the design space of a feather actuation, we demonstrate that asymmetric thrust can be leveraged on robotic hardware (Fig. 1). In the remainder of the letter, we first present the feather designed, methods used to explore this design and co-optimize the controller, followed by experimental results. We will discuss the results and conclude with suggestions for future work.

II. METHODS

To achieve motion through asymmetric thrust, we wish to maximize the difference in thrust between the up- and downstrokes produced by the feather. The thrust is generated through the feather-fluid interactions, which are dependent on the morphology of the feather actuated in a periodic motion at the root. The feather design parameters are first defined, followed by preliminary investigation of feather morphology using a low-cost simulation. Taking a subset of feather geometries, the best controller for each is found through a custom experimental setup and automatic optimization.

A. Feather Design for Asymmetric Thrust

Feathers with two types of asymmetric flaps are designed, as shown in Figs. 1 and 2. When the flaps on the feather are unfolded, the feather has a rectangular shape where it is defined by length, \( l \) and width, \( w \). The feathers with chordwise flaps have joints on either side of the spine with width, \( w_{\text{spine}} \) which is constant at 1 cm. The feathers with spanwise flaps have a joint at a distance, \( l_{\text{root}} \) from the root where the support is.

A parameterized controller is described by the rise time, \( t_{\text{up}} \), fall time, \( t_{\text{down}} \), hold time after rise, \( t_{\text{hold,up}} \), hold time after fall, \( t_{\text{hold,down}} \), and a fixed amplitude, \( A \) as shown in Fig. 2. This controller is chosen so the coupling between the asymmetric design and the motion can be exploited, specifically the speed of the strokes and the recovery time for the flaps. In the downstroke, the feather flaps lay flat against the resistance of the water due to the limited rotation by the feather spine. In the upstroke, the feather flaps are compliant to the flow as there is no rotational limitation provided by the spine. This passive mechanism allows for an asymmetric profile in the down- and upstrokes similar to the feather contractions of the biological feather star.

B. Feather Morphology Selection

As initial exploration of the design space of the feather, a simplified hydrodynamics simulation\(^1\) developed in [16] is used to characterize general trends. The asymmetric feather changes its projected area as the flaps fold and unfold. The simulation calculates the average thrust for a periodic actuation of a feather without flaps. By comparing simulation results of feathers with varying areas, it can inform us of an approximate guess of the width and length ratios of feathers to fabricate. A feather is modeled as a collection of discrete flexible units using Simscape Multibody\(^{\text{TM}}\). The lumped-parameter method [17] allows each

---

\(^{1}\)Key files are available here: https://gitlab.epfl.ch/obayashi/asymmetric-feather
unit modeled as a spring-mass-damper system to experience deformation similar to that of a soft structure, where the stiffness and damping coefficients are tuned to visually match the real system. For each flexible unit, the total lumped external force, $F_{\text{ext}}$, consists of gravitational, $F_g$, buoyancy, $F_b$, hydrodynamic, $F_{\text{hyd}}$, and added mass, $F_a$ forces: $F_{\text{ext}} = F_g + F_b + F_{\text{hyd}} + F_a$. The external force is decomposed into normal and longitudinal components to the direction of flow, with hydrodynamic coefficients obtained from steady-state CFD simulations using the ANSYS software for Reynolds numbers ranging from $10$ to $10^4$.

The actuation at the base of the feather drives the kinematics and deformation dynamics. The simulation captures the non-linear features of the fluid-structure interactions as a dynamic feedback resulting from the motion of the individual elements. Each simulation was run for a specified number of cycles of the periodic motion, and the average thrust, $T$ over one period at the base of the feather is recorded:

$$T = \int_{0}^{T_{\text{period}}} T(t) \, dt \approx \frac{1}{n} \sum_{i=1}^{n} T_i$$ (1)

The trends captured by simulation is used to identify a reduced set of morphologies to experimentally investigate the asymmetric thrust. For identifying a width ratio, $WR = w / w_{\text{spine}}$ for the feather with chordwise flaps, we fix the length, $l = 120$ mm and explore widths, $w = 15-120$ mm in 5 mm increments. Similarly, to identify a length ratio, $LR = l / l_{\text{root}}$ for the feather with spanwise flaps, the width is fixed at $w = 120$ mm and explore lengths, $l = 60-180$ mm in 10 mm increments. The geometries are chosen to be small enough compared to the water tank in the experimental setup to minimize edge effects. With those geometries, we explore all combinations of the motion parameters: $t_{\text{up}} = 0.1, 0.5$, $t_{\text{down}} = 0.5, 1$, $t_{\text{hold}} = 0, 0.5, 1$ seconds.

The simulation results for the maximum normalized thrust ratio across all controllers for width ratio and length ratio are shown in Fig. 3. Aided by observed trends, the morphologies which are most likely to provide highest asymmetric thrust are identified to be centered around $WR = 7$ and $LR = 2$. We choose to explore further experimentally $WR = 5.5, 7.5, 9.5$ and $LR = 1.5, 2, 2.5$ considering fabrication ease and physical sizing in relation to the tank, but also to be able to compare exaggerated morphology differences.

C. Single Feather Experimental Setup

To gather experimental data of the generated thrust, an experimental setup (Fig. 4) is created. A DYNAMIXEL XL430-W250-T servo powers the mechanism to actuate the base of the feather, and a 0.3 kg load cell is used to measure the upwards thrust, $T$. The setup ensures there are no moments applied at the load cell such that it truly measures the upwards thrust. The tank size has been chosen to be significantly larger than the feather to minimize edge effects. A representative time series obtained from the load cell is shown in Fig. 6.
D. Online Optimization of Feather Controller

For a given geometry of the feather, automated optimization of the controller can be performed using the custom experimental setup. As input, we have three control parameter ratios: \( \frac{t_{\text{up}}}{t_{\text{down}}} \), \( \frac{t_{\text{hold}_{\text{up}}}}{t_{\text{hold}_{\text{down}}}} \), and \( \frac{t_{\text{move}}}{t_{\text{down}}} \), where \( t_{\text{hold}} = t_{\text{hold}_{\text{up}}} + t_{\text{hold}_{\text{down}}} \) and \( t_{\text{move}} = t_{\text{up}} + t_{\text{down}} \). Evaluating control parameters as ratios rather than absolute times allowed for meaningful comparison between the various segments of the feather movement. Furthermore, the logarithms of these ratios are used as optimizable variables for a better sampling distribution. The limits for the control parameters are chosen based on mechanical limits of the servo motor. For each iteration of an experiment, the period of the signal is fixed. The single feather in the tank is actuated according to the chosen control parameters for a specified amount of periodic cycles and the thrust data is obtained from the load cell.

Bayesian optimization is known to be one of the most efficient sampling algorithms for black-box functions, especially when there are only a few optimizable parameters [18, 19]. Deterministic Bayesian optimization is deemed suitable to sequentially explore the control parameter design space for reliably quantifying the uncertainty in the system. An exploration ratio of 0.6 is chosen from heuristic trial and error for the given design problem. The optimization objective is to find the control parameter ratios that maximize the integral of the upwards to downwards thrust, or thrust ratio, \( TR \):

\[
TR = \frac{\int_0^T T^+(t) \, dt}{\int_0^T |T^-(t)| \, dt} \tag{2}
\]

where \( T^+(t) \) are the thrust datapoints larger than zero and \( T^-(t) \) are the thrust datapoints smaller than zero. The thrust ratio quantifies the asymmetricity in thrust during the feather’s up- and downstrokes, hence the swimming speed in the upwards direction in the setup (Fig. 4).

E. Robotic Hardware

To explore how the optimized feather can be used on a robotic system, two feathers are connected to an AMX DC5821LV waterproof servo using a four-bar linkage mechanism and actuated simultaneously in the same control sequence to create a robotic swimmer. The robot swims along an extruded aluminium rail (Fig. 5) by flapping its two feathers. The robot has a tether to provide power and control signal.

III. RESULTS

A. Validation of Asymmetric Feather

Prior to optimizing the controller, we explore different feather morphologies to validate the impact of the asymmetric designs. The different feathers are evaluated using a symmetric controller where \( t_{\text{down}} \), \( t_{\text{up}} = 0.25 \, s \) and \( t_{\text{hold}_{\text{up}}}, t_{\text{hold}_{\text{down}}} = 0.5 \, s \). Three different types of feather are investigated: a plain feather with no flaps which provides a baseline for comparison, a feather with chordwise flaps, and a feather with spanwise flaps. Between the three feathers, the unfolded area is identical: \( w = 7.5 \, cm \) and \( l = 11.5 \, cm \). The raw thrust data for each feather is shown in Fig. 6 along with the feather position. In general, during the downstroke, all feathers produce positive thrust and during the upstroke, they produce negative thrust. The integrated thrust is also shown for each feather for better visualizing the asymmetric thrust. 10 sets of thrust data are collected for each feather as they go through five cycles of periodic flapping. Using a symmetric controller, the plain feather produces approximately symmetric thrust (\( TR \approx 1 \)) while for the feathers with chordwise and spanwise flaps, the positive thrust is almost double that of negative thrust (\( TR \approx 2 \)). The asymmetric thrust we obtain solely from the morphology demonstrates a potential for even larger increase in thrust ratio with an improved controller.

B. Controller Optimization for a Single Feather

Examples of the Bayesian optimization progression and parameters searched with an objective to maximize the thrust ratio are shown as Fig. 7 for the feather with chordwise flaps with \( WR = 7.5 \) and one with spanwise flaps with \( LR = 2.0 \) and controller period of 1.5 s. Each experiment is allowed a maximum of 30 iterations, by when the estimated objective value would have converged for this system. By iteration 20, the estimated thrust ratio reaches a stable value of \( TR \approx 4 \) for the controller optimization of the feather with chordwise flaps and all parameters converge. In the optimization of the feather with spanwise flaps, the optimizer is still exploring the parameters at iteration 30. At iteration 19 to 20, the optimizer accounts for the system’s stochasticity and self-corrects its estimated maximum objective trace to \( TR \approx 2.5 \) after a possibly coincidental reading of a high thrust ratio.

The optimized controller for all tested width and length ratios for the feathers with chordwise and spanwise flaps is shown in Fig. 8. The results can be explained in terms of the drag equation commonly seen in literature, \( D = \frac{1}{2} \rho v^2 C_D S \), where \( \rho \) is fluid density, \( v \) is velocity, \( C_D \) is drag coefficient, and \( S \) is area. The goal is for the feather to produce the greatest asymmetric
thrust between its up- and downstrokes. During the upstroke, the feather produces negative thrust, which is minimized with minimum speed and minimum area from folding. However, since speed aids the folding action of the joints, there is a tradeoff in upstroke speed. For the downstroke, the feather produces positive thrust, which should also be maximized exploiting maximum area and maximum speed. However, depending on the morphology, high speed may result in spanwise bending, which reduces the useful area in producing thrust. The hold time after the upstroke helps unfold the feather to its flat, unfolded profile.

In Fig. 8, two periods of raw thrust data is overlaid with the feather positions for the best and baseline controllers. The prominent characteristics of the thrust profile produced by the best controller labeled in the figure caption. In addition to demonstrating the repeatability of the thrust data with the customized experimental setup, we are able to observe varying characteristics in the thrust signals between the best and the baseline controllers. For the feather with chordwise flaps ($WR = 7.5$), the optimized controller compared to baseline helps the feather create higher peaks for both negative and positive thrust, which when integrated produce a higher thrust ratio. This is also true for the feather with spanwise flaps ($LR = 2.0$) with the optimized controller producing larger net positive thrust compared to baseline. The optimization is useful in finding the best balance between the control parameters that are otherwise difficult to generalize.

C. Validation of Optimization for Single Feather

In order to validate the controller optimization for various single feather morphologies, thrust data are collected in the same way as in Section III-A (10 sets of data for five periodic cycles per experiment) for the best, baseline, and worst controllers. The best and worst controllers are found for all feather types through experimental optimization with objectives of maximizing and minimizing the thrust ratio, respectively. The baseline controller is identical to that in Section III-A. The validation results for a plain feather and two different feathers with flaps ($WR = 7.5$ and $LR = 2.0$) are shown in Fig. 9. The plain feather fails to produce any useful asymmetric thrust and even has a tendency to produce more negative thrust ($TR < 1$). The results for feathers with asymmetric joints demonstrates the benefits of utilizing passive but variable morphology to produce a net positive thrust. The best controller optimized for maximum thrust ratio provides more than double net positive thrust than negative thrust ($TR > 2$) and outperforms the baseline symmetric controller for both feather morphologies with flaps. Furthermore, even when optimizing for minimum thrust ratio, the asymmetric profile is capable of producing more positive thrust ($TR > 1$). As a rough comparison of the absolute thrust production between the feather morphologies, the average thrust calculated as (1) is also shown. The plain feather producing very little positive thrust even with...
the best controller demonstrates the difficulty in obtaining useful thrust without asymmetric morphology. The average thrust for the feather with spanwise flaps is lower for all controller types, most likely due to the spanwise bending which decreases the total surface area during thrust production.

D. Full Robot Swimming Demonstration

To validate how the thrust profile transfers to a robotic system, swimming experiments are performed with the full robot (Fig. 5) using the best and worst controllers for the plain feather and feathers with chordwise flaps (WR = 7.5) and with spanwise flaps (LR = 2.0). Fig. 10 shows the average velocity results for the different feather morphologies where the robot swam 30 cm across the aluminum rail for three runs. It should be noted that the servo motors used in the single feather experiments and the full robot experiments are different and there may be variations in the signal. In all cases, the robot using the best controller outperforms the worst controller. The full robot demonstration and the displacement profile for the feather with chordwise flaps is shown (Fig. 10) as a clarification. The variable morphology in the feather helps the robot achieve a maximum speed of approximately 2.5 cm/s, while the robot with plain flaps fails to move forward.

IV. DISCUSSION & CONCLUSION

In this work, we explore an intricate relationship between the feather morphology, movement, and the fluid where the automated online experimental optimization helps identify a controller to produce the most useful thrust for a given structure. The sensitivity of these asymmetric flapping structures to different controllers and environments highlights the need for close co-design of the flapping feather and the controller to enable the flaps to recover. The introduction of passive asymmetry in soft structures can increase the thrust ratio by a factor of 2.5 when compared to a structure of the same area. This benefit requires very little additional ‘cost’ in fabrication or implementation, only exploiting the physicality of the structure. Feathers with chordwise flaps also show higher net thrust for a constant area, reflecting its robustness in changing control signals like the movements by our biological counterparts [7]. Some hypotheses are presented in this work to explain the thrust profiles, but further work is required to better understand the physical complexity of the fluid-structure interactions that lead to these profiles. Whilst this work motivates the inclusion and design of asymmetric structures in soft swimming robots, further work to incorporate such structures and to develop more robust closed-loop controllers is required to generate free-swimming robotic systems which could leverage this morphological exploitation of fluid-structure interactions.

REFERENCES

[1] L. Xu et al., “Locomotion of an untethered, worm-inspired soft robot driven by a shape-memory alloy skeleton,” Sci. Rep., vol. 12, no. 1, 2022, Art. no. 12392.
[2] L. Zhu, Y. Cao, Y. Liu, Z. Yang, and X. Chen, “Architectures of soft robotic locomotion enabled by simple mechanical principles,” Soft Matter, vol. 13, pp. 4441–4456, 2017.
[3] H. Zou and J. P. Schmiedeler, “The effect of asymmetrical body-mass distribution on the stability and dynamics of quadruped bounding,” IEEE Trans. Robot., vol. 22, no. 4, pp. 711–723, Aug. 2006.
[4] R. F. Shepherd et al., “Multigait soft robot,” Proc. Nat. Acad. Sci., vol. 108, no. 51, pp. 20400–20403, 2011.
[5] X. Jia, Z. Chen, A. Riedel, T. S. W. Hamel, and M. Zhang, “Energy-efficient surface propulsion inspired by whirligig beetles,” IEEE Trans. Robot., vol. 31, no. 6, pp. 1432–1443, Dec. 2015.
[6] R. Thandiacakal et al., “Emergence of robust self-organized undulatory swimming based on local hydrodynamic force sensing,” Sci. Robot., vol. 6, no. 57, 2021, Art. no. eabb6354.
[7] N. G. WILD, “Feather stars and their animal invaders,” 2018. [Online]. Available: https://www.youtube.com/watch?v=OyketlthVWg&t=2s
[8] S. Wu et al., “Symmetry-breaking-actuation mechanism for soft robotics and active metamaterials,” ACS Appl. Mater. Interfaces, vol. 11, no. 44, pp. 41649–41658, 2019.
[9] Y. Chen, N. Doshi, B. Goldberg, H. Wang, and R. J. Wood, “Controllable water surface to underwater transition through electrowetting in a hybrid terrestrial-aquatic microrobot,” Nature Commun., vol. 9, 2018, Art. no. 2495.
[10] W. Huang, Z. Patterson, C. Majidi, and M. K. Jawed, “Modeling soft swimming robots using discrete elastic rod method,” in Bioinspired Sensing, Actuation, and Control in Underwater Soft Robotic Systems New York, NY, USA: Springer, Nov. 2020, pp. 247–259.
[11] L. Wang and F.-B. Tian, “Numerical study of flexible flapping wings with an immersed boundary method: Fluid–structure–acoustics interaction,” J. Fluids Struct., vol. 90, pp. 396–409, 2019.
[12] B.-F. Tian, H. Dai, H. Luo, J. F. Doyle, and B. Rousseau, “Fluid–structure interaction involving large deformations: 3D simulations and applications to biological systems,” J. Comput. Phys., vol. 258, pp. 451–469, 2014.
[13] N. Obayashi, C. Bosio, and J. Hughes, “Soft passive swimmer optimization: From simulation to reality using data-driven transformation,” in Proc. IEEE 5th Int. Conf. Soft Robot., 2022, pp. 328–333.
[14] A. Gehrke and K. Mulleners, “Phenomenology and scaling of optimal flapping wing kinematics,” Bioinspiration Biomimetics, vol. 16, 2021, Art. no. 026016.
[15] F. Gosselin, E. de Langre, and B. A. Machado-Almeida, “Drag reduction of flexible plates by reconfiguration,” J. Fluid Mechanics, vol. 650, pp. 319–341, 2010.
[16] F. Stella, K. Junge, N. Obayashi, C. D. Santana, and J. Hughes, “Controlling maneuverability of a bio-inspired swimming robot through morphological transformation: Morphology driven control of a swimming robot,” IEEE RA Mag., vol. 29, no. 4, pp. 78–91, Dec. 2022.
[17] S. Miller, T. Soares, Y. V. Weddigen, and J. Wendlandt, “Modeling Flexible Bodies with Simscapes Multibody Software,” MathWorks, Tech. Rep., 2017.
[18] K. A. Saar, F. Giardina, and F. Iida, “Model-free design optimization of a hopping robot and its comparison with a human designer,” IEEE Robot. Automat. Lett., vol. 3, no. 2, pp. 1245–1251, Apr. 2018.
[19] N. Obayashi, K. Junge, S. Ilic, and J. Hughes, “Robotic automation and unsupervised cluster assisted modeling for solving the forward and reverse design problem of paper airplanes,” submitted, Nov. 2022.