Design and Experimental Verification of a Biologically Inspired Multi-Modal Wing for Aerial-Aquatic Robotic Vehicles

Richard J. Lock, Ravi Vaidyanathan and Stuart C. Burgess

Abstract—This paper describes the modeling, design, experimental testing and optimization of a flapping foil for use as an aquatic propulsive device on a robot capable of aerial and aquatic modes of locomotion. Motivation for the research stems from numerous avian species which use the same flapping mechanism as a means of propulsion in both mediums. The main aim of this research is to establish the optimal kinematic parameters during aquatic operations that maximise non-dimensionalised performance measures, such as propulsive efficiency. Optimization of said parameters enables the direct comparison between outstretched and retracted wing morphologies and permits scaling for future robotic vehicles. Static foils representing the wing in both an extended and retracted orientation have been manufactured and tested over a range of kinematics. The gathered results enable validation of previously developed numerical models as well as quantifying achievable performance measures. This research focuses on the mechanical propulsive efficiencies and thrust coefficients as key performance measures whilst simultaneously considering the required mechanical input torques and the associated thrust produced.

I. INTRODUCTION

Through the continuing miniaturization of sensors, electronics and power storage, small robotic vehicles that would have once been unfeasible to manufacture are emerging in the robotics community. Vehicles capable of aerial, terrestrial, and even aquatic locomotion are now showing increasing maturity in design. At this time, however, the challenges of robotic design for vehicles capable of locomotion through multiple media have received less attention in robotic literature; while a few examples exist (e.g. [1], [2], [3], [4]), mechanics and control paradigms related to multiple modes of locomotion are not well-established in robotic design. In particular, the design tradeoffs involved between transitioning from aerial to aquatic locomotion modalities have yet to be addressed by the research community. Many questions are yet to be answered by the academic community, such as:

- How do mechanisms and power distribution alter when considering robots with multiple modes of mobility?
- What are the benefits/costs in implementing dual use locomotion mechanisms versus disparate means?
- Are there natural systems that may inspire solutions to the issues involved in multiple modes of locomotion?

We introduce and explore the premise that studying avian species that competently demonstrate both aerial and aquatic mobility solutions will elucidate insights into these questions.

Industrial applications of a robot capable of aerial and aquatic locomotion include the offshore oil industry, where the vehicle could fly from remote oil rigs, subsequently diving underwater to inspect pipe work, environmental monitoring and exploration and maritime counter-terrorism operations where a boarding crew could launch a small robot to conduct both aerial and aquatic inspection/surveillance. The development of aerial/aquatic multi-modal vehicles would represent a generational leap in robotic utility.

The aim of this research is to investigate the potential for using a morphing wing akin to the certain avian species which are observed to retract their wings into the body during aquatic operations but that use the larger wing plan area during aerial operations. The presented work details the testing procedure used to determine the projected performance of a robot that utilises a retracted flapping wing during aquatic locomotion. We have developed and refined a model capturing key features of the extended and retracted wing. Static foils representing a wing in these orientations have been fabricated and subjected to testing over a range of kinematic parameters. The gathered results offer preliminary validation of a previously completed numerical model as well as showing achievable performances of a flapping foil, specifically the implications of the feasibility of using a retracted wing akin to that of the avian species in water.

II. AVIAN INSPIRATION

Within the domain of small robotic vehicles, natural systems still surpass man-made robotic systems in virtually every measure of performance. A case in point is the common guillemot, Uria aalge, a seabird capable of flying distances as far as 30km out to sea at velocities of approximately 19 m/s, whilst also being able to swim proficiently underwater at speeds of 1.5 m/s [5], [6], [7]. During aquatic operations, typical operating kinematics reduce compared to aerial locomotion with the flapping frequency reducing from approximately 9 Hz to 2.5 Hz when moving from air to water. The capacity to shift morphology and movement between mediums obviously forces a performance compromise in functionality in each individually, which in the case of a natural system will be found through an evolutionary process. In order to establish

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Richard J. Lock (corresponding author) and Stuart C Burgess are with the Department of Mechanical Engineering at the University of Bristol, Bristol, BS8 1TR, UK, (richard.lock;stuart.burgess)@bristol.ac.uk Ravi Vaidyanathan is with the Department of Mechanical Engineering at Imperial College London, London, SW7 2AZ, UK and the US Naval Postgraduate School, Monterey, CA, USA, NV 93943 (r.vaidyanathan@imperial.ac.uk).
and quantify these compromises for subsequent applications within the robotics community, numerical modeling and empirical analysis is required to elucidate these trends. This alteration in wing shape of the guillemot can be seen in Figure 1.

![Figure 1. Guillemot during aerial and aquatic locomotion (adapted from unpublished BBC footage)](image)  

## III. Modeling

The following research oscillates static foils with a harmonic flapping motion similar to that exhibited by biological examples that utilise a lift based propulsion strategy. Several birds utilise a flapping technique underwater that develops lift on both the up and down stroke, which is then resolved into forward thrust, including species that are also capable of aerial operations [8]. This change in modality consistently sees the avian species retracting their wings inwards during aquatic operations and as such provides the main motivation behind attempting to quantify this aquatic mechanism, for the potential future use within a multi-modal system.

The kinematic trajectory of the flapping foil arrangement was chosen to be similar to that of the guillemot, utilising a two degree of freedom flapping motion consisting of roll and pitch operating in a harmonic motion with the same circular frequency $\omega$ (rad/s). The roll motion, relating to the larger wing flapping action is governed by:

$$\phi(t) = \phi_0 \sin(\omega t)$$  \hspace{1cm} (1)

where $\phi_0$ is the maximum roll amplitude in radians. Similarly the pitch motion, relating to the twisting action of the wing is governed by:

$$\theta(t) = \theta_0 \sin(\omega t + \psi)$$  \hspace{1cm} (2)

where $\theta_0$ is the maximum pitch amplitude in radians and $\psi$ is the phase angle between pitch and roll. It has been highlighted in previous work that a phase lag of $90^\circ$ is the most suitable arrangement which shall be adhered to here [9]. This results in equation 2 changing to:

$$\theta(t) = \theta_0 \cos(\omega t)$$  \hspace{1cm} (3)

Provided the maximum roll amplitude and pitching amplitude are known, the kinematics of the flapping foil are fully described. This is graphically shown in Figure 2.

## IV. Performance Measures

Although the majority of underwater robotic vehicles rely on rotary propulsion, flapping wing approaches have been the subject of several investigations in robotic literature (e.g. [11, 12]). Where this research differs from the previous work is that the presented wing arrangement is designed with the long term aim of being used in both mediums, acting as a fixed wing (i.e. not flapping) vehicle in air enabling aerial locomotion, as well as utilising the flapping mechanism for aquatic operations. This therefore introduces additional factors that must be considered when looking at the chosen wing design.

Through initial numerical modeling of the system [13], the use of a retracted wing that enabled a reduction in wing plan-form area indicated that this could improve efficiency when considering typical missions the vehicle would potentially complete [14].

Static foils representing both the extended and retracted wing shapes have been tested over a range of kinematic parameters, whilst recording key variables from within the system. From this gathered data consisting of torque measurements and thrusts generated, the non-dimensionalised mechanical propulsive efficiency and thrust coefficients for each foil shape are determined.

The first foil has the 2 degrees of freedom are arranged perpendicular to one another with a rectangular foil plan-form area, and second with the pitch axis mounted at $45^\circ$ to the roll axis, with the attached foil representing an equivalent wing to that of the initial rectangular plan-form area but which has been subjected to a retraction akin to a parallelogram as seen in Figure 3. Both static models have the same chord length and symmetrical foil profile, described by a NACA 0012 profile and they have been fabricated so that they represent the same leading edge semi-span dimension.
mechanical power into the system compared to the useful mechanical power out of the system, represented by the following equation:

\[ \eta_{prop} = \frac{\bar{P}_{out}}{\bar{P}_{in}} \]  

(4)

where \( \bar{P}_{in} \) represents the mechanical power into the system and \( \bar{P}_{out} \) the useful mechanical power out of the system. The mechanical power into the system is determined by measuring the torques associated with each degree of freedom and then multiplying by the relevant angular velocities:

\[ P_i(t) = \tau_i(t), \omega_i(t) \]  

(5)

where \( P_i(t) \) is the power (W), \( \tau_i(t) \) is the torque (Nm) and \( \omega_i(t) \) the angular velocity (rad/s), all of which are time dependent. The \( i \) represents the degree of freedom in question. \( \bar{P}_{in} \) is then calculated by determining the time averaged value for each degree of freedom and combing to give the overall value.

\( \bar{P}_{out} \), representing the useful mechanical power out of the system is calculated based on the product of the generated thrust in the forward direction and the forward velocity in which the foil is traveling:

\[ P_{out}(t) = F_x(t), U_f(t) \]  

(6)

where \( F_x(t) \) is the generated thrust (N) and \( U_f(t) \) is the forward velocity (m/s). The time averaged value \( \bar{P}_{out} \) is subsequently determined.

The thrust coefficient, \( C_t \), is also calculated to provide an additional performance measure by the following equation:

\[ C_t = \frac{\bar{F}_X}{1/2 \rho U_f^2 A_{foil}} \]  

(7)

where \( \bar{F}_X \) is the time averaged thrust in the forward direction (N), \( \rho \) is the density of the water (kg/m^3) and \( A_{foil} \) is the surface area of the foil (m). The retracted foil shape has a surface area of 63\% of the extended wing. Utilising equation 7 allows comparisons to be made between the different models taking into account this alteration in foil size.

Through a combination of the actual measured values combined with the non-dimensionalised values given by equation 4 and 7, the implications of various kinematic changes can be determined for the different wing shapes, allowing comparisons to be made between the two.

V. EXPERIMENTAL PLATFORM

A. Flapping Foil Arrangement

The main requirement of the experimental arrangement is the ability to flap static foils whilst the 2 degrees of freedom are mounted perpendicular to one another or at 45\° to one another as shown in Figure 4. This is achieved by allowing the connection terminal of the pitch and roll axes to be re-aligned depending on the arrangement under investigation. At this stage this action cannot be actively controlled during testing and is therefore either fixed in one arrangement or the other.
subsequent post-processing.

Strain gauges, Vishay type EA-13-240LZ-120/E, mounted to the support beam below the platform were used to quantify the amount of thrust generated by the flapping motion, again set up in a full bridge arrangement. The load cell is highlighted in Figure 6. In order to achieve the required motions, Maxon EPOS 70/10 motion controller units were utilised for the roll and pitch motion. The motion controllers utilise on-board PID control strategies. Velocity control was selected as the control strategy for the motion. The command signals required by the motion control units were sent via serial (RS232) communication. The overall flapping arrangement, suspended below the testing platform can be seen in Figures 5 and 6.

B. Aquatic Testing Environment and Dynamic Testing Platform

Considering how the mechanical propulsive efficiency is calculated it is apparent that throughout the course of the testing, constant forward velocity of the carriage is required so that the amount of useful mechanical power out of the system can be quantified. To achieve this, a movable carriage suspended above a water tank has been developed. The overall dimensions of the water tank are 15 x 1.5 x 1.6m, of which the actual test runs cover a horizontal distance of 10.5 m. The carriage was constructed from bespoke lengths of aluminium profile sections. The completed platform can be seen in Figure 6.

In order to control the motion of the platform, a continuous drive belt, a Contitech Synchrodrive type 10 5M HTD, was connected to the platform via a free spinning pulley at one end of the tank, and another connected to a pulley directly connected to a DC motor. The DC motor, a Parvalux type PM4C 24V + MB Gearhead, was controlled via an additional motion controller, where by ultimately the velocity of the motor, which was in turn connected to a pulley of known diameter, was controlled via an analogue signal. This analogue signal was generated by the NI DAQ 6211. A closed loop control strategy was then implemented by connecting a HEDS 5540 encoder to the shaft of the motor, with the digital encoder signal being fed back through the same NI DAQ 6211 card. This assured that the desired platform speed was maintained during testing.

C. Overall Experimental Control Interface

During the experimental work, the entire operation was controlled through a user interface within National Instruments LabVIEW 2010. This environment was designed so that all the variables could be set according to the desired kinematics, subsequently controlling both the flapping foil motion and the velocity of the towing platform whilst simultaneously gathering data relating to the torques experienced in the shafts, the thrust generated by the flapping arrangement and then compiling the entire data set relating to the time dependent values of the various foil kinematics and recorded inputs.

At each test run a file was exported and saved for post-processing. The interface was designed so that once the amplitude and frequency of the roll and pitch motions were specified in the front panel, the velocity trajectories required by each motor were determined with these time dependent values subsequently sent as commands to the EPOS motion controllers via serial (RS232) communication.

VI. RESULTS

Due to the high number of kinematic variables, the effects of maximum roll and pitch amplitudes on the outputted performance are the key focal points in this paper, investigating the implications of variations in these whilst initially operating at a discrete flapping frequencies of 0.75 and 1.0 Hz and with the forward velocity set at 0.5 m/s for both the extended and retracted wing shape. The maximum roll amplitude was varied between 20° and 40°, and the pitch between 10° and 30° at increments of 5°. Each parameter set was then tested a minimum of 5 times, outputting a data set as described in section V-C. An example of a typical data set for one run can be seen in Figure 7.

![Complete data set for individual test run](image)

Figure 7. Complete data set for individual test run (Retracted wing, \(\theta_o = 40^\circ, \theta_p = 30^\circ, f = 0.75Hz\) and \(U_f = 0.5m/s\))

Post-processing of the results was carried out in Matlab 2009b (Mathworks Inc.). As the aim was to determine the torques associated with the flapping motion, a technique was required to eliminate the torque associated with oscillating the pitch motor, mounted as shown in Figure 6. In order to eliminate the need to complete additional test runs, the decision was made to numerically calculate the torque and subtract it from the gathered results. To do this, an equation of motion for the pitch motor about the roll axis was determined. Firstly the inertia tensor was determined from the pitch motor assembly, assuming constant density of the motor and gearhead. This allowed each to be modeled as a
solid cylinder. Combining this with the values relating to the polycarbonate case and the top and bottom mounting plates provided the overall tensor to use in the calculations. In addition the effects of gravity also had to be considered. These gravitational forces were calculated for each component and combined with the inertial contribution. The equation of motion was modified depending on whether the pitch motor was mounted vertically or in the retracted orientation.

To determine the average values based on the repeated runs the data sets were partitioned so that the periods of platform acceleration and deceleration were eliminated. An example of this data can be seen in Figure 8. Time averaged values were then calculated as detailed in section IV.

A. Numerical model validation

As discussed in section IV, previous research saw the development of a numerical model to simulate the empirical testing presented within this paper [13]. Utilising the numerical model enabled the development of a large solution space, investigating the implications of alterations in geometry as well as kinematics. This is also possible with the presented experimental setup, but alterations in geometric properties would require many different foils to be manufactured. The aim was that if the model matched the empirical results for the extended and retracted foil shapes presented, the numerical model could be utilised in future work with an elevated degree of confidence in the outputted values and eliminate the need to manufacture many different foil sizes in order to determine an equivalent solution space.

A comparison of the predicted and recorded values for the retracted wing shape can be seen in Figure 9. It can be seen that the results of the numerical model over estimates for all the values. This has lead the authors to reconsider parameters and assumptions made within this model, particularly the manner in which the lift coefficient was modeled over the course of the flapping motion and the way in which the added mass associated with the water was calculated. However, the model can still be utilised as it consistently over estimates the values, which can therefore be accounted for in future modeling, acting as a preliminary factor of safety.

B. Retracted and extended foil performance

The overall results for the extended and retracted wings tested at the same kinematics can be seen in Figures 10 and 11. Starting with the overall mechanical power into the system it can be seen that the retracted wing requires less than the extended wing, as would be expected with the reduction in foil surface area associated with this orientation. It can be seen that in general the mechanical power into the system for the retracted foil is approximately a \( \frac{1}{4} \) of that of the extended wing. However, the thrust generated also reduces, with the thrust produced by the retracted wing being as low as 15% of that generated by the extended wing at equivalent kinematics. Similarly this comes as no surprise considering the reduction in surface area hence the use of the propulsive efficiency and thrust coefficient as much more applicable performance measures, which non-dimensionalises the results considering this reduction in surface area, but before discussing those values consideration will remain with the actual thrust generated.
Ultimately, the generated thrust is required to provide propulsion and overcome the drag associated with the non-force producing appendages. This drag component is referred to as the parasitic drag. As this research is investigating the feasibility of utilizing a retracted wing for aquatic locomotion, it would be of use to know how large a theoretical fuselage this flapping technique could propel. To do this, we work back from equation 8 relating to parasitic drag:

$$D_{par} = \frac{1}{2} \rho U_f^2 S_b C_d$$  \hspace{1cm} (8)$$

where $D_{par}$ is the parasitic drag (N), $S_b$ is the frontal area (m$^2$) and $C_d$ is the drag coefficient. Remaining with the inspiration for the current robot stemming from birds with this capability, a drag coefficient determined for bird bodies can be used in equation 8 [15]. The generated thrust has to counter the parasitic drag, therefore by substituting two times the value of generated thrust in place of the parasitic drag, twice due to two foils, and then re-arranging the equation to make the frontal area the subject, an estimate of fuselage size can be determined. Substituting in the determined values from the empirical testing gives a frontal area of 0.018 m$^2$, i.e. a cylinder with an approximate diameter of 0.15 m. This process is simplistic in its nature but does offer an initial estimate of fuselage size limitations.

Considering the non-dimensionalised performance measures, a reduction is once again observed when looking at the retracted wing compared to the extended. Looking at the propulsive efficiencies, it can be seen that the maximum propulsive efficiency drops when looking at the retracting wing. It is apparent that comparable efficiencies cannot be achieved by this retraction in shape with the fixed kinematic parameters presented. However, it should be noted that the difference in maximum achievable propulsive efficiencies reduces as the flapping frequency increases.

Considering the thrust coefficient, a similar trend exists that sees the maximum value again decrease when considering the retracted wing, but the magnitude of this difference is also seen to decrease when considering the increase in flapping frequency.

Figure 11 provides the results when increasing the flapping frequency to 1 Hz. The performance in this case is observed to be far closer when compared with the extended foil operated at the lower kinematics.

It can be seen that the retracted wing now creates greater than 1 N of thrust for various roll and pitch angle combinations, but what is also important to note is that the mechanical propulsive efficiencies and thrust coefficients are now far more comparable to the extended foil with maximum values above 0.4 and 0.35 compared to the extended foil at 0.55 and 0.4.
However, as would be expected, as the amount of thrust produced by the retracted foil increases so too does the mechanical power into the system. What can be concluded from this is that because of the comparable performance between wing orientations, if an aerial/aquatic robotic vehicle required a specific amount of thrust, the retracted foil orientation would be able to provide this thrust almost as efficiently as the extended foil, but allow the larger extended wing to be used during aerial operations.

The authors stress the fact that the presented results represent a very small portion of actual potential operating kinematics. As shown in [13], the optimal kinematic parameters to use vary for all combinations of mission requirements. Improvements of performance for the retracted wing shape could be achieved by operating at higher flapping frequencies for the given forward velocity. It is therefore the authors aim to continue investigations into the implications of kinematic variations in an attempt to establish if under the right parameter sets, comparable performance measures can be achieved.

Using a retracted foil in this manner does have potential and when considering additional design constraints such as the requirement to minimise overall mass of the vehicle, the implications that the reduced foil requires less power to flap essentially means that a smaller driving mechanism would be required to generate the flapping motion. This would certainly help in minimising the overall vehicle size, and enable the long term goal of using a larger wing during aerial operations and then retract it in this manner for aquatic locomotion.

VII. Conclusions

The conclusions that can be drawn from the presented research relating to the feasibility of using a retracted wing as a means of propulsion during aquatic operations on a multi-modal vehicle are:

- Retracted foil shown to produce sufficient thrust to propel a feasibly sized vehicle fuselage at correctly selected kinematics
- The swept back foil profile reduces the required power to drive the motion to approximately a 1/4 of the equivalent extended foil profile for the same kinematic conditions, but this comes with a reduction in thrust production and overall performance
- At the presented kinematics, the retracted foil does not achieve the same level of propulsive efficiency or thrust coefficients as the extended orientation
- Increasing flapping frequency demonstrated an improvement in retracted foil performance but still does not match the extended orientation
- The use of a retracted foil has potential as a means of propulsion during the aquatic locomotion of an aerial/aquatic multi-modal vehicle

Future work will see the development of a more complete solution space providing a greater insight into the potential optimal kinematics to use when utilising a retracted flapping foil. Flexible foils shall also be investigated to try and establish the role of coupling between neuro-mechanics and control stability in morphing structures adapting to locomotion transfer. Additionally, investigations into the synergy of the findings relating to mechanical propulsive efficiencies and potential compact driving mechanisms and associated electric efficiencies shall be completed in order to develop a clearer foundation for the mechatronic development of a prototype vehicle.

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