

Towards Amphibious Robots: Asymmetric Flapping Foil Motion Underwater Produces Large Thrust Efficiently

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Abstract—The development of amphibious robots requires actuation that enables them to crawl as well as swim; sea turtles are excellent examples of amphibious functionality, that can serve as the biomimetic model for the development of amphibious robots.

In this paper we have implemented the observed swimming kinematics of *Myrtle*, a green sea turtle *Chelonia Mydas* residing in the Giant Ocean Tank of the New England Aquarium, on the 1.5-meter long biomimetic vehicle *Finnegan the RoboTurtle*. It is shown that these kinematics result in outstanding performance in (a) rapid pitching, and (b) rapid level turning. The turning radius for the rigid hull vehicle is 0.8 body lengths, a remarkable improvement in turning ability for a rigid hull vehicle.

Still *Finnegan's* performance lags the live turtle's performance by about 20%. Careful observations have shown that turtles employ a fin motion in-line with the direction of locomotion; this degree of freedom was not available to the *Finnegan* fins, as presently designed. Experimental tests on a flapping fin equipped with this third degree of freedom have shown that the in-line motion enhances the fin's performance.

This hydrodynamic result is doubly beneficial to an amphibious robot, because it allows for further enhancements in the hydrodynamic function of fins, while the in-line motion allows the same fins to be used for crawling on land.

I. INTRODUCTION

The growing interest in robots operating in the surf zone has inspired underwater vehicle designers to develop amphibious robots capable of operating on land as well as in the ocean. This problem is challenging because different gaits are required for walking/crawling on land and for swimming in the ocean. Sea turtles are excellent biomimetic examples for amphibious robot development, because of their ability to swim and maneuver effectively, yet they can crawl on the shore using their flippers as well.

While flexible bodies and conformable propulsive structures are nearly ubiquitous in marine animal locomotion, body flexibility dramatically reduces underwater vehicle payload space, and the advent of compact actuation for conformable fins awaits dramatic improvement in artificial muscle technology. Sea turtles demonstrate that body flexibility is not essential to achieve high maneuverability and good motion control when using flapping high aspect ratio foils, and may serve as a powerful inspiration for the design of underwater vehicles.

Over the last five years we have developed, constructed and tested a biomimetic, rigid hull vehicle, roughly in the shape of a sea turtle, named *Finnegan the RoboTurtle*. The vehicle is 1.5 m long, and 0.55 m wide, and is propelled exclusively by four independently controlled high aspect ratio fins ([?], [?]). Each fin allows two-degree of freedom angular motion; each degree of freedom is actuated by a separate motor, allowing a high-power rolling motion (angular motion about the x -axis), and a lower-power pitching motion (angular motion about the y -axis); see [?].

Extensive tests have demonstrated that the vehicle can propel itself efficiently at speeds up to 2 m/s, while it has superior maneuverability [?], far exceeding the maneuverability of rigid hull, torpedo-shaped autonomous underwater vehicles (AUV). For example, two of the most commonly used AUVs, the *Remus* and the *Bluefin Odyssey*, have turning radii between 2 and 3 body lengths, while *Finnegan* has a turning radius of about 0.8 body lengths. Flexible body animals have even better maneuverability; the sealion, for example, has a turning radius of 0.3 body lengths at a speed of 2.5 body lengths per second.

Data on turning turtles are not available in the literature. A number of studies exist, detailing the kinematics of steady swimming in juvenile and hatching sea turtles, and researchers have extensively studied the limb beat frequencies of sea turtle swimming during diving and foraging tasks, but no published studies of limb kinematics during transient maneuvers exist. To determine how sea turtles use their limbs to control attitude and direction in confined spaces, the limb kinematics and associated body motions of *Myrtle*, a green sea turtle *Chelonia Mydas*, residing in the Giant Ocean Tank of the New England Aquarium were recorded and analyzed. Through the use of multiple cameras, her behavior while she was encouraged to maneuver in pursuit of food was captured.

This paper presents the efforts to emulate the limb kinematics of *Myrtle* using *Finnegan*, which have been highly successful, while new insight on the mechanisms employed by rigid hull animals to enhance maneuverability are identified.

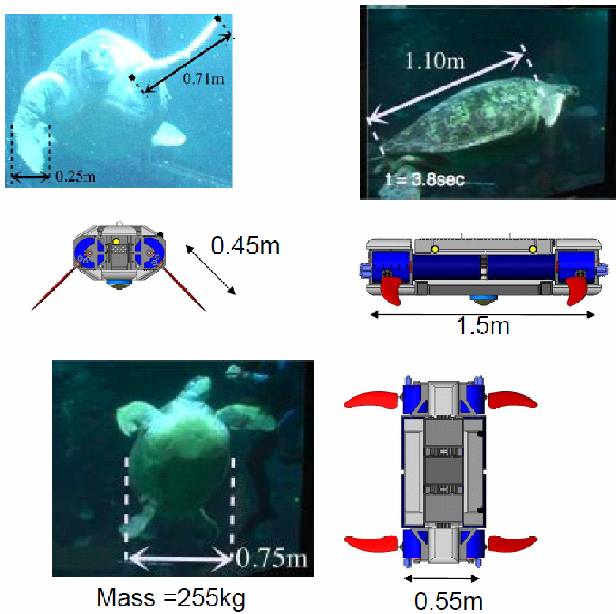


Fig. 1. Geometric features of the New England Aquarium sea turtle *Myrtle* and the biomimetic robot *Finnegan*.

II. METHODOLOGY

Figure 1 shows side by side the features of the New England Aquarium sea turtle *Myrtle* and the biomimetic robot *Finnegan*. The turtle has carapace length 1.1 m and width 0.75 m, mass 255 kg, and is driven by two forelimbs with a span of 0.71 m and chord 0.25 m; and hindlimbs with span 0.6 m and chord 0.40 m. The robotic vehicle has comparable dimensions, but with a more elongated shape: Length 1.5 m, width 0.55 m, while it is driven by four identical foils spanning 0.45 m each.

A. Turtle Kinematics

The hard shelled Green turtle, *Chelonia Mydas*, swims and maneuvers with a pair of high aspect ratio forelimbs in combination with a pair of lower aspect ratio hind limbs. The hard shell and limited conformability of the limbs makes the Green turtle an excellent candidate to inspire vehicle design and control. Although turtles exhibit several other modes of motion, the focus of this study is on the power stroke where the turtle uses the fore limbs to produce thrust, while the hind limbs are used as rudders. These strokes employ a lift-based mechanism of generating thrust, as confirmed by the angle of attack measurements done by Davenport et al [?].

To determine how sea turtles use their limbs to control attitude and direction in confined spaces, the limb kinematics and associated body motions of *Myrtle*, a green sea turtle *Chelonia Mydas* residing in the Giant Ocean Tank of the New England Aquarium, were recorded and analyzed. Through the use of multiple cameras, her behavior while she was encouraged to maneuver in pursuit of food was captured. A number of studies exist detailing the kinematics of steady swimming in juvenile and hatching sea turtles, and researchers

have extensively studied the limb beat frequencies of sea turtle swimming during diving and foraging tasks, but no published studies of limb kinematics during transient maneuvers exist.

A number of useful general observations are possible before proceeding to analysis of selected maneuvering behaviors. *Myrtle* appeared to be negatively buoyant at all times within the 10 m deep Aquarium tank. *Myrtle* controlled her position in the tank almost exclusively through actuation of yaw and pitch, whether during active maneuvering or steady swimming; *Myrtle* did not translate directly in sway or in heave, and rolled no more than 15 to 20 degrees from level during the experiments.

Body pitch ranged from -10 to +90 degrees during experiments. *Myrtle* preferentially swam with body pitch ranging from approximately 10 to 60 degrees when positioning herself for feeding or swimming steadily against the prevalent current within the cylindrical tank. She appeared to be stable in pitch and roll, but not so stable that her attitude was unaffected by the large roll and pitch moments generated during routine swimming or maneuvering.

When presented with food above her head, *Myrtle* pitched up as far as 90 degrees, using large amplitude forelimb motion; however, when presented with food below her head, *Myrtle* spiraled down with level body (i.e. zero body pitch) if unable to reach the food by extending her head downwards. When attempting to retrieve food or search for food behind her, *Myrtle* changed her heading through yawing turns, rather than large angle maneuvering in roll or pitch. In this paper we will focus on the motions that involved lift based strokes, which are the rapid pitching and level turning.

B. Rapidly Pitching Turtle

Myrtle was observed rapidly pitching upwards and ascending, both prompted and unprompted by the diver offering food. When prompted by food presented above her head, *Myrtle* typically pitched upwards rapidly and then allowed both her forward and her upward motion to stall while craning her neck to reach the food. During unprompted ascents to breathe at the surface *Myrtle* typically continued to use both forelimbs to swim up and out of the camera viewing area.

Pitch was initiated with a large-amplitude synchronous forelimb downstroke, with a moderate anterior component, and a high induced angle of attack during the fastest portion of the stroke. The initial downstroke was followed by a highly feathered upstroke with approximately the same duration as the downstroke. The hind limbs were stretched out to the side and held nearly horizontal (i.e. parallel to the ground) throughout the motion, presumably either acting as passive control surfaces, or simply reducing the opposing pitch moment created by drag; i.e., both, reducing drag directly by presenting a lower angle of attack, and by bringing them closer to the center of gravity.

Through this combination of limb action, *Myrtle* was able to achieve pitch angles of up to 80 degrees within a single cycle of forelimb motion. In Figure 2, *Myrtle* is pitching up with the intention of swimming to the surface, and continues to execute

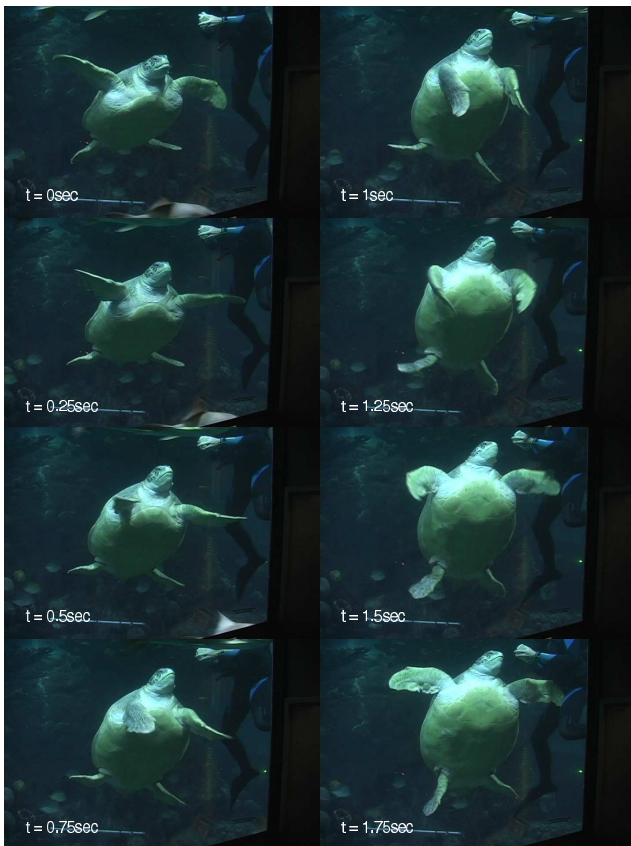


Fig. 2. Front view of rapid pitching maneuver to retrieve food. Myrtle achieved a high pitch angle through a single rapid down- and forward- stroke of her pectoral fins with a high angle of attack to the flow.

swimming strokes after she exits the last frame. As a result, she is motivated to maintain surge speed even as she pitches up to a significant angle. In this case, the very beginning of the synchronous downstroke which initiates the pitching maneuver, from $t = 0$ to $t = 0.25$ s, is accompanied with some forward motion. This foil motion appears to be intended to set up the rest of the downstroke, during which the forelimbs are swept backwards with respect to the pitching and surging body, most importantly during the highest velocity portion of the downstroke from $t = 0.5$ to $t = 1.0$ s. The portion of the upstroke which is visible before Myrtle swims out of frame (from $t = 1.75$ s on) is a highly feathered recovery stroke, which brings the forelimbs back forward level in preparation for the next downstroke. The period of the total stroke here is greater than 2.75 s.

C. Swimming Turtle

Myrtle was observed during multiple instances of swimming as she circled around the tank against the slight prevailing current. During all the instances recorded in detail below, she swam within a body length of the tank window, which forced her to continuously adjust her heading slightly. Her depth and body pitch angle vary within a few meters and approximately 30 degrees within each recorded instance of steady swimming.

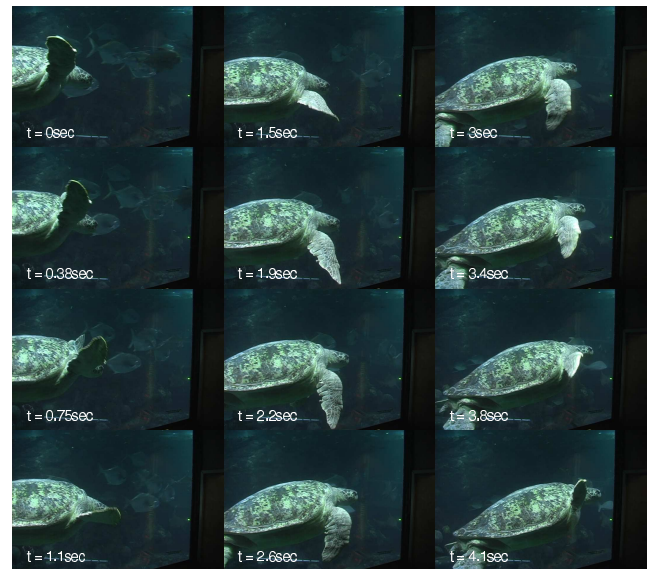


Fig. 3. Side view of representative steady swimming stroke.

Myrtle was also observed accelerating straight and level from a nearly stationary state.

The following observations were noted:

- The forelimbs remained in phase during steady swimming.
- A limited anterior/posterior component to the forelimb motion was observed during steady swimming.
- Speed was controlled using variable forelimb frequency - to accelerate from a standing start, forelimb frequency was double that of the steady swimming case.
- The duration of the forelimb down stroke during throughout observed level forward swimming ranged from 1.0 seconds (recorded during acceleration) to 1.7 seconds.
- The duration of forelimb up stroke ranged from 1.5 seconds (recorded during acceleration) to 2.7 seconds.
- The ratio of down stroke to following upstroke period ranged from 0.6-0.7.

Figure 3 shows a side view of Myrtle swimming past a single camera, which is set back from and at angle to the aquarium window. This view illustrates typical variation in body pitch angle on the time scale of a single stroke, as well as the lower twist angle of the downstroke as compared to that of upstroke, which results in a higher angle of attack, greater thrust force, and higher torque requirements.

III. BIOMIMETIC MANEUVERS USING FINNEGAN

In Figure 4 we show the biomimetic maneuver achieved using Finnegan and implementing the kinematics observed in Myrtle for the rapid pitch maneuver, achieving 60 deg pitch in less than 1.5 s, as shown in Figure 2 above. As shown, the resulting motion is very close to the live animal's; Finnegan's performance in rapid pitching is close, but about 15% lower than Myrtle's

A different biomimetic maneuver was attempted next to achieve a rapid turn by 180 deg. Figure 6 shows a side view

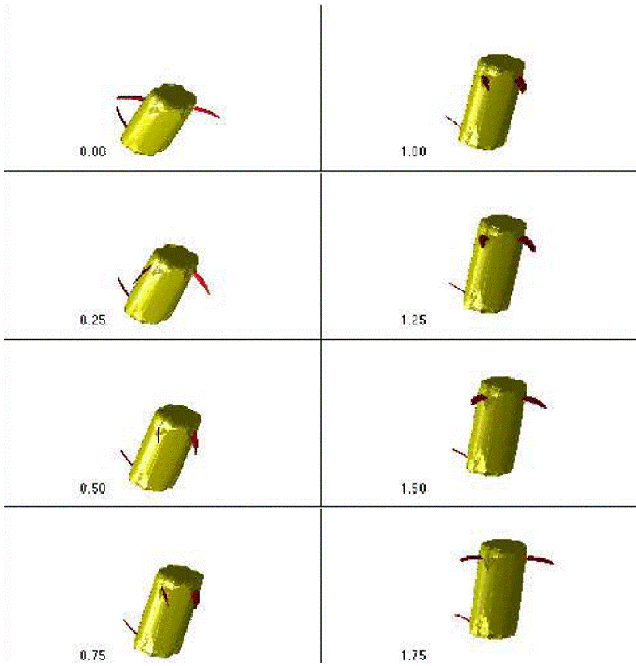


Fig. 4. Biomimetic maneuver by *Finnegan* emulating the sea turtle kinematics observed in *Myrtle* (Figure 2).

of representative level turn with active participation of both forelimbs. This view highlights the extension of the outside forelimb as it is thrown forward just as the downstroke is initiated.

In Figure 6, both forelimbs are near the maximum possible downward excursion in the first frame at $t = 0$ s. From $t = 0$ to between $t = 1$ s, both limbs are in the recovery stroke. While the recovery stroke of the outside limb continues until between $t = 1.7$ and $t = 2$ s, the upward stroke of the inside limb ends around $t = 1.3$ sec, after which it starts a downward sweep with the blade perpendicular to the resulting flow. The downward stroke of the inside limb continues through to $t = 2.7$ s, during which time the outside limb has completed significant anterior motion, with the blade feathered, and begun the lift-based power down-stroke, which continued to the last frame at $t = 3.7$ s. From this view it is apparent that while the motion of the outside limb contains a significant posterior component with respect to the body, it is brought down nearly vertical with respect to the laboratory frame as a result of the turning motion of the body. It is clear that the inside forelimb downstroke ends with the limb well past vertical underneath the body. The effect of the forward motion of the outside forelimb is illustrated - contrast the forelimb position in frames at $t = 1.3$ and 1.7 s to the forelimb extension from the frames from $t = 2.3$ to $t = 3.7$ s. *Myrtle* achieves a heading change of between 80 deg and 90 deg during the period pictured here, for an average heading rate of between 21 *deg/s* and 24 *deg/s*.

In Figure 5 we show the biomimetic maneuver achieved using *Finnegan* and the same kinematics observed in *Myrtle* and shown in Figure 6. *Finnegan*'s performance was an

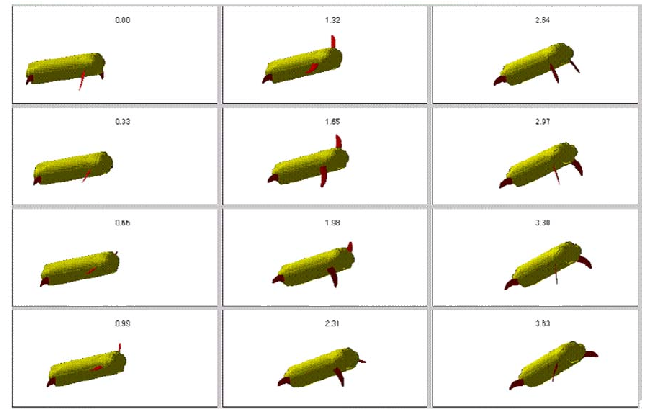


Fig. 5. Biomimetic maneuver by *Finnegan* emulating the sea turtle kinematics observed in *Myrtle* (Figure 6).



Fig. 6. Biomimetic maneuver by *Myrtle*.

average of 16 *deg* per second, about 25 to 30% lower than *Myrtle*'s. The turning radius was less than one body length, clearly a superior turning performance for a rigid hull vehicle.

IV. DISCUSSION

By implementing the kinematics of the live turtle on the biomimetic vehicle *Finnegan*, we were able to emulate the animal's function to a significant degree. However, *Finnegan*'s rigid fins are constrained to move in two degree of freedom motion (two angular motions), one degree of freedom inducing motion perpendicular to the direction of the robot's motion, and a second degree of freedom consisting of a twisting angle; whereas *Myrtle*'s fins are flexible and, in addition, they can move in a third degree of freedom, in-line with the direction of motion.

Careful observation of the kinematics of *Myrtle* show that the in-line motion appears to play a significant effect on its hydrodynamic performance. As already observed by Davenport [?] and Wyneken [?], the fore-limb kinematics

of sea turtles, even in steady forward swimming, are highly asymmetric, because they involve a significant in-line motion: The upstroke can take up to twice as long as the downstroke to complete, and there is also significant limb motion in-line with the swimming direction, as the fore limbs are pulled back along the body during the downstroke, and pushed forward against the flow during the upstroke.

This is to be expected, because the sea turtle morphology is such that the forelimbs can produce much more torque in the downstroke than the upstroke. Especially juvenile turtles are barely capable of raising their limbs out horizontally from the shoulder when held in air [?]. Large torque during downstroke, but only small upstroke torque, is required for crawling along the beach, where the fins are moved also in the in-line direction, to drag the body along the ground. Steady swimming in turtles typically consists of a powered, high angle of attack downstroke, generating forward thrust and maneuvering forces, followed by a feathered upstroke, as noted by Wyneken [?]. Direct observation of Myrtle, also showed that there can be a significant anterior-posterior motion of high aspect ratio oscillating foils during transient maneuvering behaviors.

In-line motion is very useful to amphibious robots for crawling, hence it is interesting to establish whether their use also during swimming and maneuvering is detrimental, indifferent, or beneficial to efficiency of locomotion. We have investigated the effect of in-line motion on an isolated high-aspect ratio foil, allowed to move in three degrees of freedom. The rectangular foil was towed at constant velocity U and forced to move (a) in linear oscillatory motion transversely to the flow (heave), (b) in linear oscillatory motion in-line with the flow (surge), and (c) in angular oscillatory motion (pitch) about an axis parallel to its span and located at the one-third point from the leading edge. The oscillatory motion consisted of a power downstroke with large maximum angle of attack, α_{max} around 40 deg; and a feathering upstroke with a nearly zero angle of attack. For a stationary observer we define the *advance angle*, defined as the angle of the foil trajectory with respect to the direction of motion, evaluated at the middle of the power downstroke. This parameter measures the effect of in-line motion, since it can reach large values as the amplitude of in-line motion increases.

Figure 7 shows the propulsive efficiency of the foil as function of the advance angle and with parametrically varying Strouhal number St . The advance angle was changed for a given Strouhal number by changing the in-line motion (surge). The Strouhal number is defined as $St = 2 A f/U$, where A is the amplitude of cross-flow motion (heave), f the frequency of oscillatory motion and U the forward speed of tow. The experiments were conducted at Reynolds number 13,000 and for Strouhal numbers in the range of 0.2 to 0.6; the optimal advance angle, which corresponds to peak efficiency, was found to be around 100° .

It is clear that a properly selected in-line motion, combined with a power downstroke, enhances efficiency. This is an important result because it signifies that amphibious vehicles

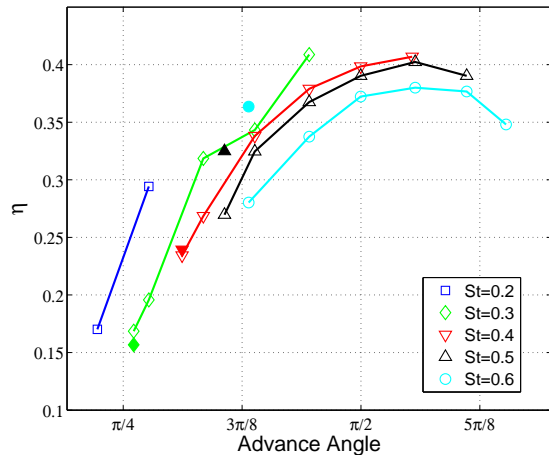


Fig. 7. Efficiency, η , of thrust production versus the advance angle for foils with downstroke $\alpha_{max} = 40^\circ$, upstroke $\alpha_{max} = 0^\circ$, for parametrically varying Strouhal number St . Filled symbols indicate η for symmetric foil motions, with downstroke $\alpha_{max} = 40^\circ$, upstroke $\alpha_{max} = 40^\circ$, and no in-line motion, for each value of St .

can be designed, which are capable of crawling on land and can use the same kinematic for efficient swimming and maneuvering.

Future tests will show whether the in-line motion will allow Finnegan to fully achieve the performance of the live turtle.

V. CONCLUSION

We have implemented the observed kinematics of Myrtle, a live turtle of the New England Aquarium, to the biomimetic robot Finnegan. We show results for two rapid maneuvers, a rapid pitching maneuver, and a rapid level-turning maneuver. In both cases Finnegan provided outstanding maneuvering performance, coming close to the live animal's performance by nearly 75% to 80%. The radius of turning was less than one body length, a superior performance for a rigid-hull vehicle.

The fins of Finnegan were rigid and capable of moving in a two degree of freedom motion. Subsequent observations have shown that turtles employ a third degree of motion, in-line with the direction of motion. An investigation of the effect of this motion on the efficiency of propulsion has shown that it can have a substantial and beneficial hydrodynamic effect.

The ability to move the fins in the in-line direction is also an essential feature for crawling on the ground, hence leading to efficient designs of amphibian vehicles.

ACKNOWLEDGMENT

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REFERENCES

- [1] M. Wolfe, S. Licht, F. Hover, and M. Triantafyllou, "Open loop performance of "finnegan the roboturtle"," in *Proceedings of the International Society of Polar and Offshore Engineering*, San Francisco, California, June 2006.
- [2] S. Licht, V. Polidoro, M. Flores, F. S. Hover, and M. S. Triantafyllou, "Design and projected performance of a flapping foil AUV," *IEEE Journal of Oceanic Engineering*, vol. 29, no. 3, pp. 786–794, July 2004.
- [3] S. Licht, "Biomimetic oscillating foil propulsion to enhance underwater vehicle agility and maneuverability," PhD Thesis in Oceanographic and Mechanical Engineering, Massachusetts Institute of Technology, MA, June 2008.
- [4] P. O. J. Davenport, Sarah A. Munks, "A comparison of the swimming of marine and freshwater turtles," *Proceedings of the Royal Society of London, Series B, Biological Sciences*, vol. 220, no. 1221, pp. 447–475, Feb. 1984.
- [5] J. Wyneken, "Comparative and functional considerations of locomotion in turtles," PhD Dissertation, University of Illinois at Urbana-Champaign, Department of Ecology, Ethology and Evolution, 1988.