Mechanical design of a large scale amphibious walking and swimming robot

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1 Introduction

This paper describes the conceptual design and operating principles of an oscillating foil propulsion system for an unmanned underwater vehicle which has the acronym TURTLE ("Tele-operated Unmanned Robot for Telemetry and Legged Exploration"). This will be designed to be a 6-legged swimming and walking amphibious robot, fitted with foils (or flat fins) which can be manipulated with several degrees of freedom to produce highly efficient underwater propulsion forces. The legs will each have four degrees of freedom, of which the fourth is rotation of a foil that is fitted to the 'shin' to provide propulsion for swimming.

By manipulating the movements and rotations of this foil, propulsion forces can be generated to implement a variety of swimming modes, each with its own advantages and disadvantages. The foils attached to the fins allow the Turtle to be controlled in all six degrees of freedom. It will also be an amphibious robot that will be able to transition between swimming mode and walking mode, for walking on an underwater surface or over dry land if power considerations permit. It must then be powerful and strong enough to support itself and light payloads while walking over the rough or undulating surfaces commonly found on a beach.

The mechanical design will allow the absolute position and orientation of the body to be accurately controlled relative to the ground surface, whether above or below water, for the purpose of precision control of onboard tools and sensors. The space frame construction method allows large scale, strong, rigid structures and manipulator limbs and links to be built while keeping material cost, weight and actuator energy usage to very low levels. Such lightweight and energy efficient robots will be useful in many practical applications, especially in areas such as oil and gas exploration, drilling, mining, construction, automated agriculture, military equipment and space exploration.

2 Objectives

The Turtle robot should be able to demonstrate the following objectives:

1. The robot must require no cable or umbilical wires and be fully remote controllable while on dry land or floating on top of water. While submerged underwater (up to 50 m deep) it must be autonomous if no data link can be established.
2. The robot must be able to perform reliable, stable walking over rough terrain such as is found on a beach: sand, soft muddy ground and rocks. It should be able to walk sideways along slopes without tipping over.
3. While submerged, the robot must be able to transition between swimming and walking modes without losing balance or becoming unstable.
4. The robot should have buoyancy control such that it can be neutrally buoyant, can float on the surface or can have negative buoyancy to walk on the bottom.
5. The robot should be able to swim in still water at a speed of at least 1 metre per second and walk on land with a moderate top speed
6. The robot should be self-balancing at all times, correcting its posture when subjected to external disturbances or unexpected slippery surfaces.
7. The robot must automatically select suitable leg movements or foot positions to achieve accurate body positioning and orientation. It must be possible to position onboard tools such as cameras, sensors and surveying equipment precisely relative to the terrain.
8. The robot should have several digital cameras and include all sensors necessary for its accurate control. It must be able to retain data logged while out of contact, for transmission to a ground station when it surfaces. It should also be able to transmit any data directly, if requested.
9. The robot should have energy for a sustained mission. While submerged and moving gently this might even be extended to days, while more strenuous movement on land should allow for at least 3 hours of non-stop operation. A silent source such as battery or compressed air is preferable to power involving combustion.

Six legs were chosen for the design to ensure good overall stability for walking. In nature, most insects have a rigid central body and six or more legs to keep them stable. Creatures with four or fewer legs have a flexible spine to move the centre of gravity to a stable position. The Turtle has a rigid central body, so six legs are needed to keep its centre of gravity well within the boundaries of the polygon defined by the feet that touch the ground (also known as the ‘stability polygon’).

Walking gaits currently proposed for the Turtle include:

- crab walking (sideways left/right)
- insect walking (forwards/backwards)
- turning (left/right)

- rotation on the spot (clockwise/anti-clockwise)
- walking at different ride heights (adjusting the height of the main body above the ground)
- transitioning from standing to swimming mode, by lifting off the sea floor, perhaps by gentle upwards flapping.

Swimming modes of the current Turtle designs include:

- flapping propulsion (forwards/backwards swimming by tilting the foil on each shin and flapping each leg up and down with the hip tilting actuator)
- ascending (rising or getting closer to the sea surface by flapping foils on all legs)
- descending (diving, using the foils on all legs)
- turning (left/right using differential thrust)
- rotation on the spot (clockwise/anti-clockwise)
- rowing (with knees bent at 90 degrees and the yaw actuators rotating all foils while controlling all foil angles to maintain each foil surface orthogonal to the desired direction of travel during the power stroke)
- feathering (with knees bent and the knee bending actuators fanning the lower shin foils in a tail swishing manner)
- transitioning from swimming mode to standing mode, in preparation for walking either when sinking to the bottom or emerging from the water.

3 The advantages of oscillating foil propulsion over rotary propellers

Most man-made underwater vehicles and powered marine vessels that have been built over the past century have relied on rotary propellers as the primary means of propulsion. Several experiments by engineering researchers (Triantafyllou et al 1995) have shown that propellers cannot achieve energy transmission efficiencies greater than approximately 40% because much energy is wasted in generating radial and angled flows (typically helical type flows) where exiting water does not always move opposite to the desired direction of travel. Figure 1 shows an illustration of helical jet-streams (high velocity fluid flows) created by the rotating blades of a propeller.

For example, in the case of a typical fixed-pitch propeller for an outboard engine of a boat, the blades of such a propeller waste significant amounts of energy because much of the fluid flow leaving the blades does not travel in a direction that is opposite to the desired direction of travel. Only the force components of such high velocity fluid flows which are parallel and opposite to the desired direction of travel (or the propeller shaft) are useful for generating reaction thrust forces on the blades in the direction of travel.

An alternative effective method of propulsion for underwater vehicles is to use oscillating foils, often mimicking flipper and fin designs used by dolphins and fish. Several robotics researchers (Hirata et al 2000, Kato 1998 and Suzuki et al 2007) have designed and built articulated flippers and fins to propel fish-like underwater vehicles using conventional electric motors and rotary actuators.

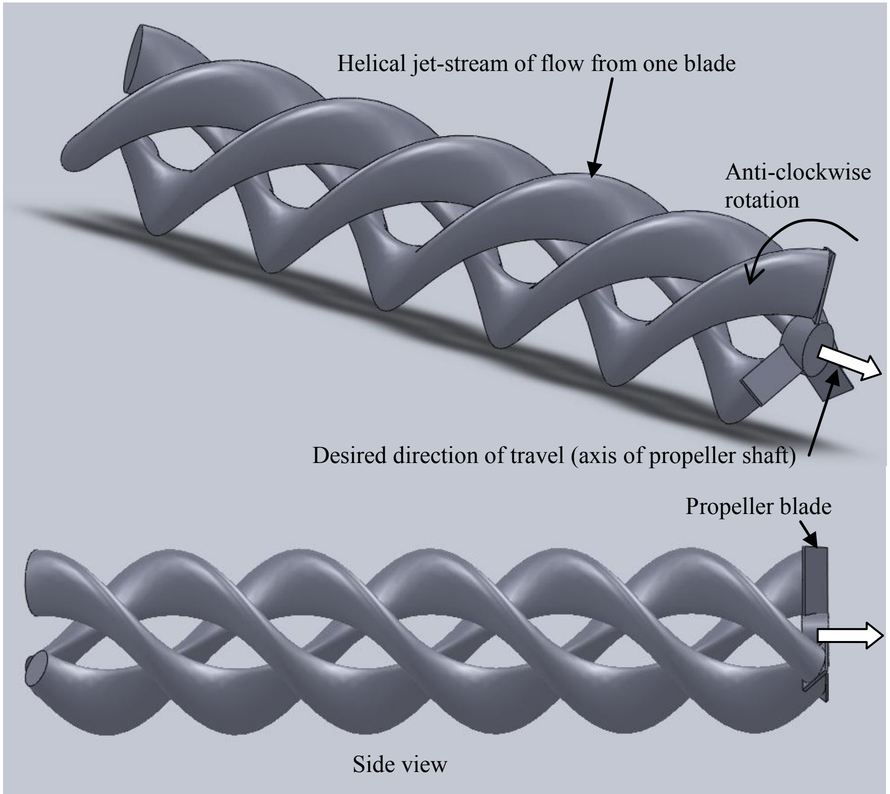

Fig 1. Hydrodynamic 3D volumes of the jet-streams behind a 3-bladed rotary propeller

For example, Triantafyllou et al (1995) measured energy efficiencies as high as 80% for oscillating foils that imitated the behaviour of the tail fin of a fish (including sharks and dolphins), under controlled experimental conditions. Mechanical robotic dolphins have been built and described by Yu et al 2006 and Nakashima et al 2006.

For fish, sharks, dolphins and seals, most of the propulsion force for forward movement is generated by the repetitive swishing action of the tail (foil). Direction changes and low-speed translational and rotary moves are controlled by their pectoral fins which perform actions such as flapping, feathering and rowing motions, as shown in Figure 3. Typically, the power stroke of the fin (or foil) creates much more water drag (or thrust force) than the return stroke.

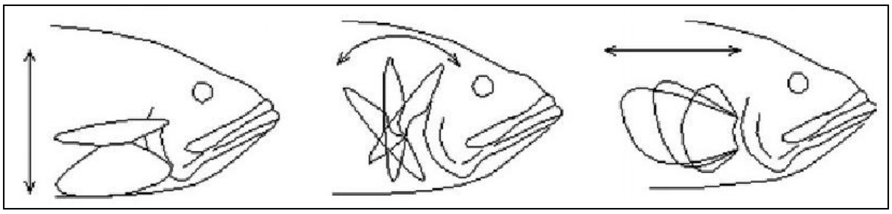

Fig. 3. Repetitive motions performed by the pectoral fins of fish to control fine motion

4 Underwater vehicles that use articulated fins for propulsion

Oscillating foils appear to provide superior energy efficiency compared to propellers and they have the potential to allow farther travel and operating distances given a limited supply of onboard energy (e.g. electric battery charge, fuel, etc.) compared to vessels powered by energy-wasting rotary propellers. Because large foils (or fins) also move much slower than rotary propellers, in general, they are less susceptible to serious damage in the event of a collision with an obstacle, and they would not be as dangerous or life-threatening to swimmers, divers or surfers who happen to come into contact with their slow moving parts.

Turtles are unique among marine creatures because they use their articulated pectoral fins as the primary means for locomotion, hence, their front pectoral fins are typically longer and larger in proportion to their overall body size, compared to the pectoral fins of marine animals with large tails (fish, sharks, whales, seals and dolphins). The fins of a turtle operate like birds wings in many ways. They can generate high levels of hydrodynamic thrust based on the orientation angle of the fin and the speed of flapping or rowing. Twisting sets the tilt or pitch angle of the fin, but repetitive feathering action is not used by turtles as a primary means of locomotion. Figure 4 shows the swimming action of a common 'Green Sea Turtle'.

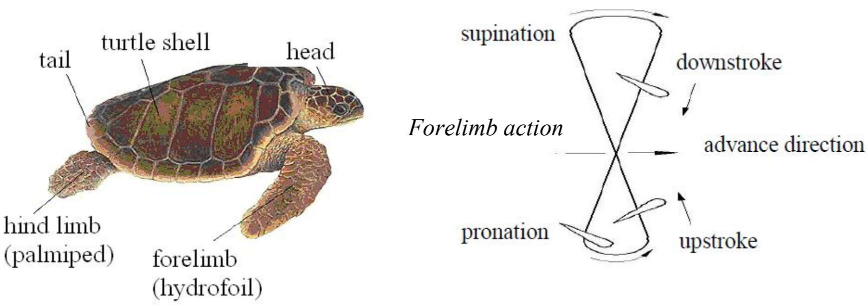

Fig. 4. Swimming action (right) of a 'Green Sea Turtle' (from Zhang et al 2008)

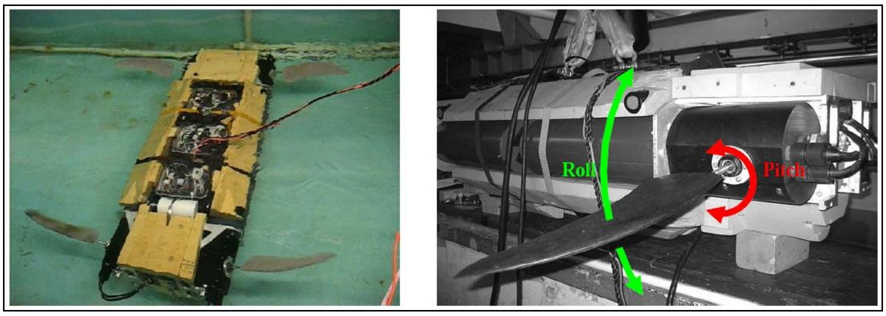

Fig. 5. Finnegan articulated fin underwater vehicle (left); Two d.o.f. per leg (right)

One turtle-like robot that mimics the swimming style of the common turtle is the Finnegan (RoboTurtle) built at MIT (Wolf et al 2006). An early prototype of the Finnegan in Figure 5 shows the pitch and roll degrees of freedom for each fin.

The Finnegan robot is capable of forward and reverse swimming at controllable speeds. It is capable of a top straight-line swimming speed of 1.38 m/s in the forward direction. Finnegan's maximum rising speed (heave velocity) is 0.4 m/s, its maximum sideways sway speed is 0.46 m/s, and its highest turning rate (or yaw rate) is 80.2° /s. Each fin has two degrees of freedom, namely, one for flapping the fin up and down (pitch) and the other is for twisting (or tilting) the fin to a desired angle of orientation (roll). The fin operates just like a 'moving vane' that creates a jet-stream of exiting high-speed fluid at an angle parallel to the tilt angle of the fin. Due to the rotational nature of the flapping motion (for pitch), there is some radial component of this exiting jet-stream which occurs at right angles to the desired direction of travel (aiming towards the end of the fin). Flapping a tilted fin up and down achieves forward thrust (using the "pitch" degree of freedom). Each time a fin makes a power stroke, part of that energy goes into accelerating the main body in the opposite direction to the fin's overall movement. This energy-wasting bobbing effect is explained by Newton's Law: "For every action, there is an equal and opposite reaction" (or 'principle of conservation of energy').

One interesting design for an amphibious vehicle that can swim and walk (albeit clumsily) is the AQUA robot shown in Fig. 6 (Georgiades 2005 and Dudek et al 2005). The AQUA robot is based on the earlier designs of the Shelley-RHex and Rugged-RHex aquatic robots developed by the University of Michigan USA and McGill University, Montreal, Canada. It features six rotating 'legs' which operate like variable speed controlled wheels or swimming paddles.

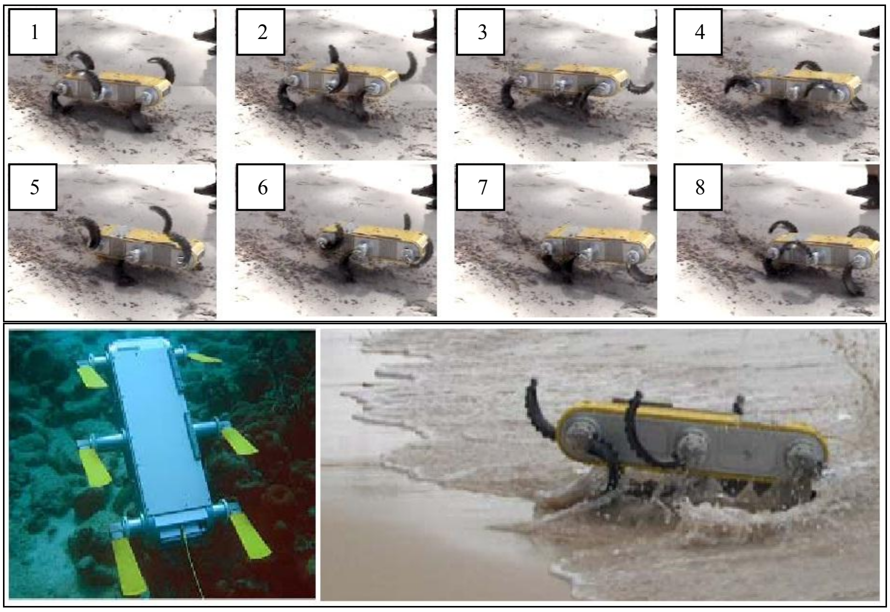

Fig. 6. AQUA: With flippers for swimming (left) and 2-spoke legs for walking (right)

Although Georgiades 2005 and Dudek et al 2005 claim that AQUA is a walking robot, AQUA does not use leg-like stepping or retractable movements for its legs or feet, because the feet move like wheels, each having a fixed leg length. The legs behave like the spokes of a wheel or like paddles when the foot is off the ground, however, their rotational speed is dropped when the foot is in contact with the ground in order to maintain a stable 'tripod' walking gait (i.e. three feet are always supporting the robot at any time). This leg design is superior to a wheel, especially when travelling over uneven ground or tall obstacles because the leg or foot can make initial contact with the top surfaces of high objects like steps or tall obstacles, making it ideal for climbing over small objects. The feet (or the ends of the spoke-like legs), however, have serious limitations. A foot cannot be controlled or placed at an out-of-plane ground position relative to the robot body since the ends of each leg (or paddle) can only traverse the locus of a circle, lying within one plane only (i.e. the single plane of rotation for the leg).

Walking performance over rough ground and body control for the AQUA robot is typically clumsy, wobbly and appears anserine due to the fixed length of each leg. Underwater swimming performance for the 2-spoke design is also poor due to the symmetry of its design. Unfortunately, the 2-spoke leg/flipper design is not effective for submerged applications. Because the control surfaces of the 2-spoke paddles produce symmetric thrust forces about the drive shaft, there can be no net thrust force produced in one desired direction, therefore, it is not possible to generate net forces for straight-line underwater swimming. The AQUA vehicle can swim underwater well if it is fitted with a single-spoke oscillating flipper that is not symmetrical about the drive shaft. A feathering-type action is used for propulsion.

The Shelley-RHex, Rugged-RHex, and AQUA robots are capable of moving over dry land and overcoming small obstacles but the 2-spoke leg design is clearly unsuitable for unmanned underwater vehicle (UUV) applications. Even the single-spoke design, despite being adequate for UUV applications, produces bumpy or jerky walking performance. This is because the robot has no ability to place its feet at the best possible foot locations to avoid deep potholes or high obstacles by choice. Hence, it is not possible to accurately control the position and orientation of the AQUA robot's body (i.e. height above the ground, and roll, pitch and yaw orientations) while travelling or standing over rough terrain or very uneven ground. These limitations make it difficult or impossible for the AQUA robot to set precise positions and orientations of sensors and tools attached to its central body, relative to the supporting surface.

The company iRobot™ are currently manufacturing and selling a foil-actuated UUV marine robot called the 'Transphibian', designed mainly for surveillance and reconnaissance missions. Like the legs of the AQUA, the fins of this robot can rotate, allowing it to perform low-speed crawling movement on the sea floor. The 'Transphibian' swims submerged to its destination, guided by periodic GPS updates. Built-in ballast tanks also help it to ascend (rise) and descend (dive).

Fig. 7. iRobot™ 'Transphibian' foil-actuated swimming robot (from www.irobot.com)

The MIT 'Finnegan', the 'AQUA' and the iRobot 'Transphibian' foil-propelled robots appear to be the best performing state-of-the-art foil-propelled swimming robots that have been built. AQUA appears to show promise as a general purpose amphibious walking and swimming vehicle, however, its single-degree-of-freedom leg design imposes many functional limitations and restricts the versatility of this type of robot for high-precision tool positioning applications.

5. Design outline of the Turtle

Three varieties of hexapod Turtle designs are currently being investigated and analyzed, appearing to be able to satisfy all the main objectives of this project. They will be referred to by the following names:

- **Hexa-short**: 3 legs on each side of a short 3.5 m long rectangular body. *Advantages*: Strongest thrust forces for straight-line swimming using 3 actuators performing the rowing or flapping on each side; symmetric foot positions permits fast walking in forward and sideways directions. *Disadvantage*: If the leg workspaces overlap, legs can easily collide or damage each other if there is a controller or position sensor error. If the leg workspaces are designed so that they do not overlap, then 3 legs on each side of the robot would make the body far too long and bulky.
- **Hexa-long**: 2 legs on each side of a long rectangular body with 1 leg at each end. *Advantages*: Very large stability polygon (perhaps the most stable of all hexapod designs); good thrust forces for straight-line swimming using 2 actuators on each side. *Disadvantages*: very long body (almost 7 metres long) will make it difficult to maneuver or turn in small or tight spaces; the rotating foils on the legs at the small end of the body may be used as rudders for underwater steering but both cannot contribute propulsion forces for the rowing and flapping styles of swimming.
- **Hexa-round**: 1 leg on each side of a hexagon-shaped body. *Advantages*: Symmetric circular array of the legs can prevent legs hitting or damaging each other because no workspaces are overlapping; the circular arrangement of the legs allows for fast turning or rotation on the spot in both walking and swimming modes. *Disadvantages*: Generally slower than the other types of hexapods for straight-line walking or swimming due to the shorter or more limited range of movement for the leading and trailing legs, especially for rowing and flapping type swimming modes.

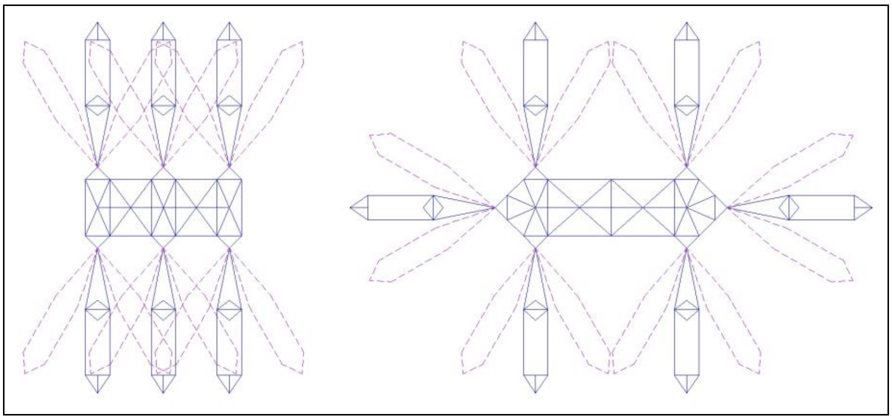

Fig. 8. Top views of the structural layout of the Hexa-short (left) and Hexa-long (right)

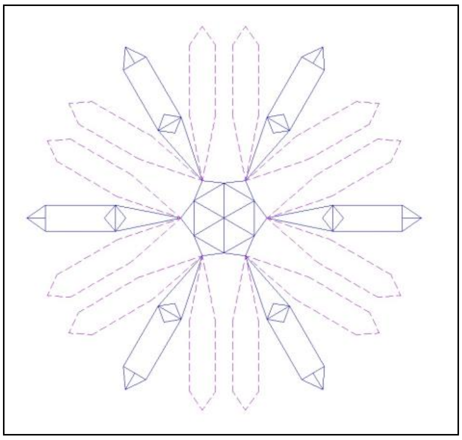

Fig. 9. Top view of the structural layout of the Hexa-round (dotted lines show extreme leg positions; legs are shown fully extended in a flat position). Standing length: 3.2 m.

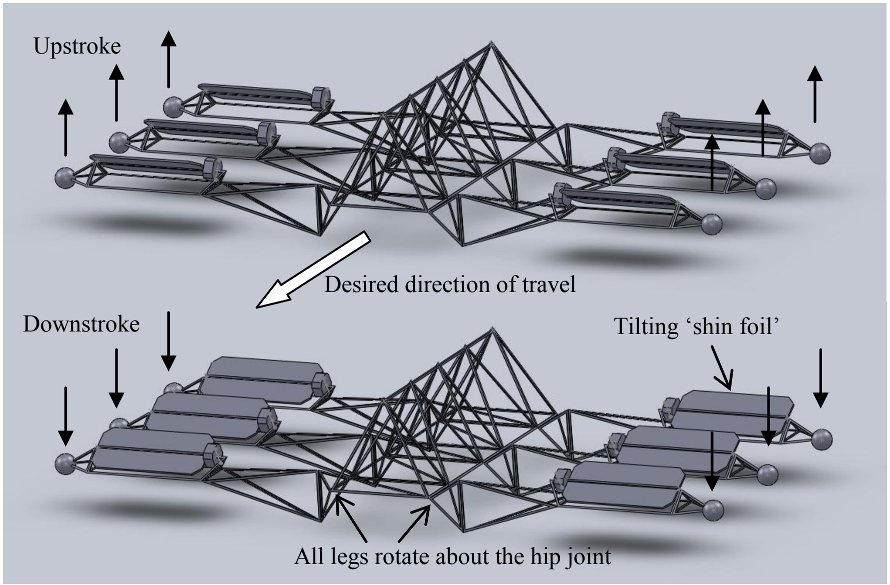

Fig. 10. Foil positions for the flapping mode of swimming (actuators removed for clarity)

Figure 10 shows the 'tilting foil' positions for the flapping mode of swimming. This style of propulsion is very similar to the one used by the 'Finnegan' robot and actual marine turtles. Some upwards and downwards 'bobbing' action for the body of the robot is expected during motion, but bobbing could be cancelled out if two legs go one way, opposite to the middle leg, on each side of the robot. This style of swimming, especially for the Hexa-short design, could produce very high swimming speeds due to the low drag imposed by the foils. The 'flat rowing' swimming style is shown in Figure 11, where foils behave like oars of a row boat.

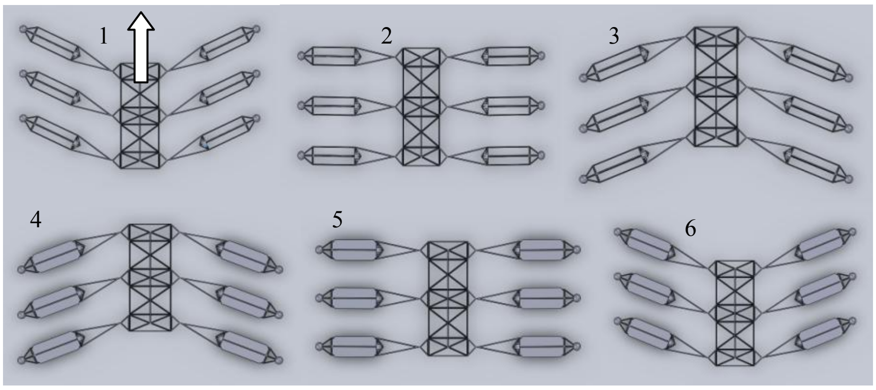

Fig. 11. Top view of foils for the ‘flat rowing’ mode of swimming (actuators removed)

In Figure 11, positions 1, 2 and 3 represent the ‘Power stroke’, where the foil is vertical and produces much drag as each leg is rotated backwards. At the end of the power stroke, the foils rotate and become horizontal, as shown in position 4. This helps to reduce water drag significantly during the return stroke, illustrated by positions 4, 5 and 6. This cycle repeats so that the robot can swim in the desired direction shown by the big white arrow. Steering of the robot can be achieved by reducing the speeds or stroke lengths of the legs on the side of the robot you wish to turn towards. For example, to turn right, the robot would reduce the speed or stroke lengths of the right side legs relative to the left. Another form of propulsion is the ‘bent rowing’ mode of swimming. In this mode, the knees are bent and the legs can still rotate just like in Figure 11 for the ‘flat rowing’ mode.

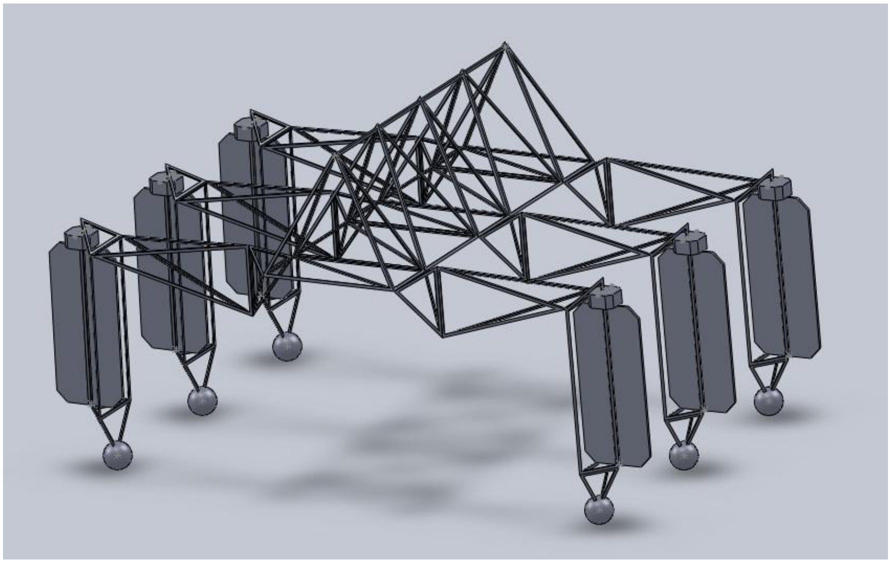

Fig. 12. Foil positions for the ‘bent rowing’ mode power stroke (linear actuators removed)

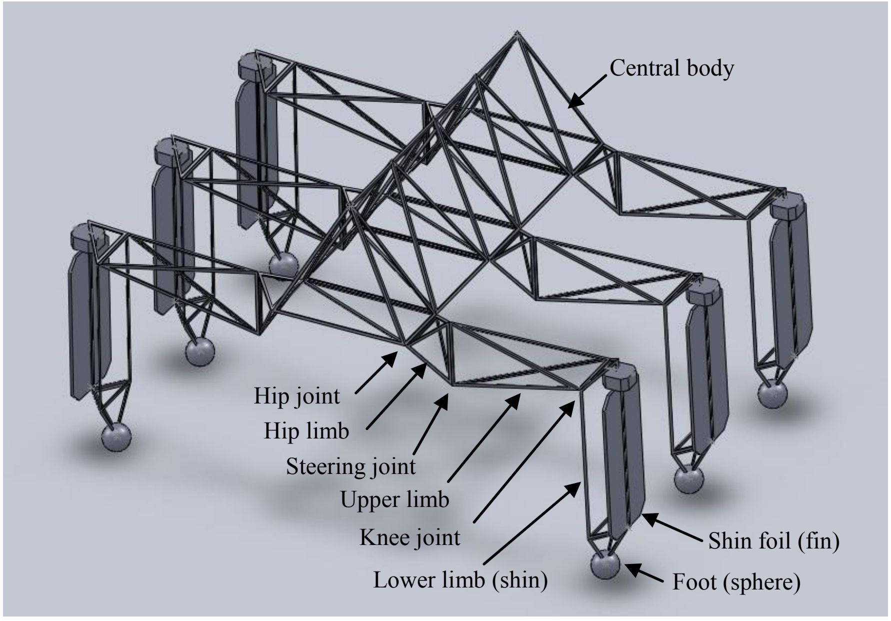

Fig. 13. Foil positions for the 'bent rowing' mode return stroke (linear actuators removed)

Note that in Figure 12, it is possible to position control the angles of the shin foils so that their surfaces remain orthogonal to the desired direction of travel at all times during the power stroke, resulting in maximum forward thrust force, minimum energy wastage and perhaps the most energy efficient propulsion possible.

The 'feathering' mode of swimming can be implemented by repeatedly rotating all shin foils about the knee joints while keeping the same foil twist orientation shown in Figure 13. This is achieved by simply using the knee bending actuator to wiggle the lower limb of the leg back and forth like the tail of a fish to produce upward thrust forces. This 'feathering mode' of swimming can only produce upward thrust for the Turtle robot, however, such forces can be pointed to certain vector directions by raising or lowering the position of the knee or by turning it. (i.e. rotating the hip limb and/or the upper limb of each leg to different angles will provide different orientations and positions of the knee joint, or knee shaft).

Linear actuators are able to provide a range of motion of about 90 degrees for the hip joint (for rotation of the hip limb), about 60 degrees of rotation for the steering joint (for rotating the upper limb) and about 110 degrees of rotation for the knee joint (for rotating the lower limb). For swimming, it is important for the linear actuators to be completely waterproofed so that salt water and contaminants do not enter the motors or ball-screw components. Research is currently being undertaken to develop water-proof sealing for high-speed, high precision ball-screw linear actuators.

An alternative is to use a conventional rotating actuator, a motor with special gearbox, carrying an output lever that connects with a fixed rod in place of the ball-screw. Sealing might be easier, but all methods will be considered.

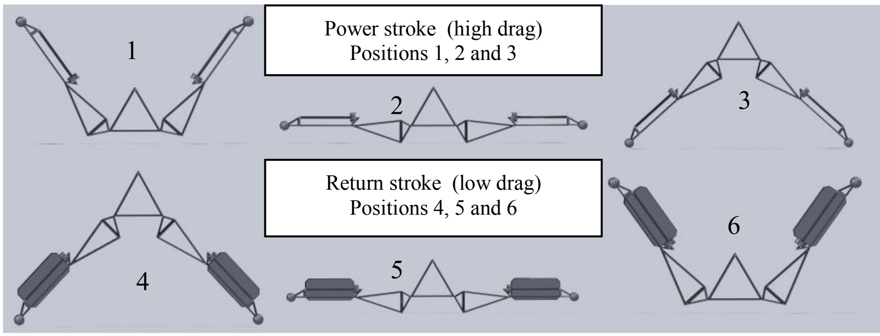

Fig. 14. Side view of shin foils in 'flapping mode' ascending or rising (actuators removed)

Figure 14 shows the 'flapping mode' style of propulsion for ascending or rising upwards. Sequence 1, 2, 3, 4, 5, 6 is useful as a rising movement, especially for a walking to swimming transition. If the positions shown in Figure 14 are played in the order 3, 2, 1, 6, 5, 4, the Turtle would achieve a descending, diving or sinking movement or a swimming to walking transition. Positions 3, 2, 1 would create the power stroke and positions 6, 5, 4 form the return stroke. When making a transition, it is important to keep 3 feet on the ground (3 knees bent), while the other 3 legs perform the rising or diving work with 'flapping' movements.

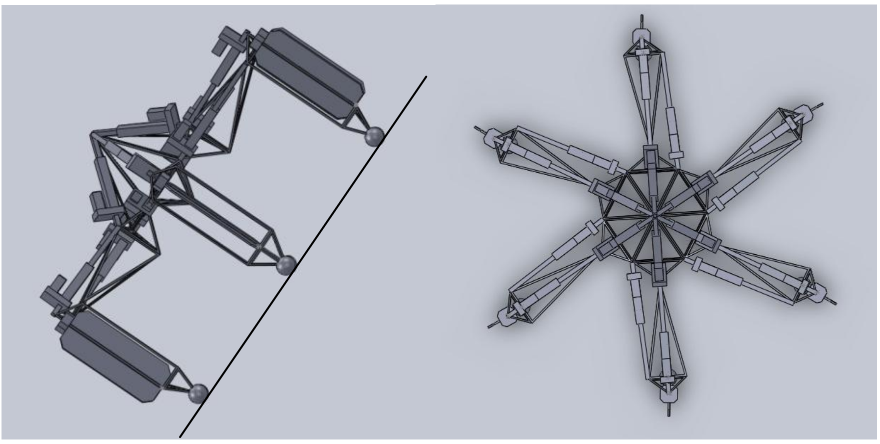

Fig. 15. Side view (left) and Top view (right) of the Hexa-round design (actuators shown)

There are many types of forward walking gaits for hexapod robots described in mobile robotics literature. The most import and fastest of the stable walking gaits is the alternating tripod gait, whereby three feet are always on the ground at any time, while three feet advance quickly above the ground to prepare for the next tripod foot positions. The most stable albeit slowest gait would be to advance just one foot at a time while keeping five feet on the ground. Another gait would be to lift two feet at a time and keep four feet on the ground and this is a good compromise between the need for speed and high stability. The subjects of robot leg kinematics, dynamics, motion simulation and gait control is beyond the scope of this paper, but these topics are expected to be analyzed in future papers describing the development of these types of walking and swimming robots. Figure 17 shows the ranges of motion for the hip joint and the knee joint of a leg. The A-matrices and inverse kinematics solution for this leg will be described in a future paper describing foot control, gait control and foil control for the Turtle.

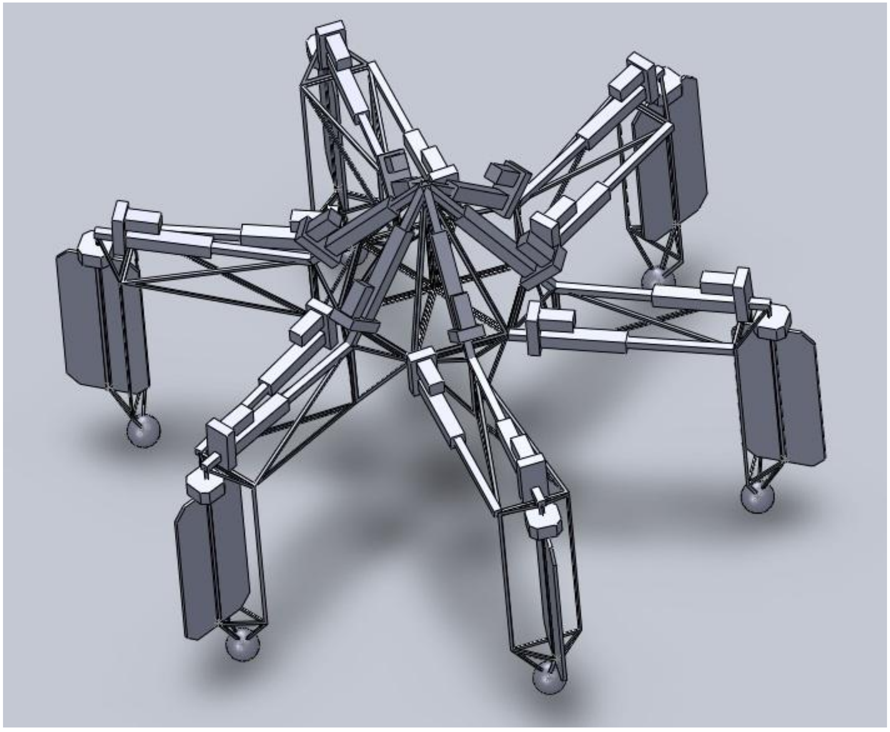

Fig. 16. Pictorial view of the Hexa-round conceptual design (actuators shown)

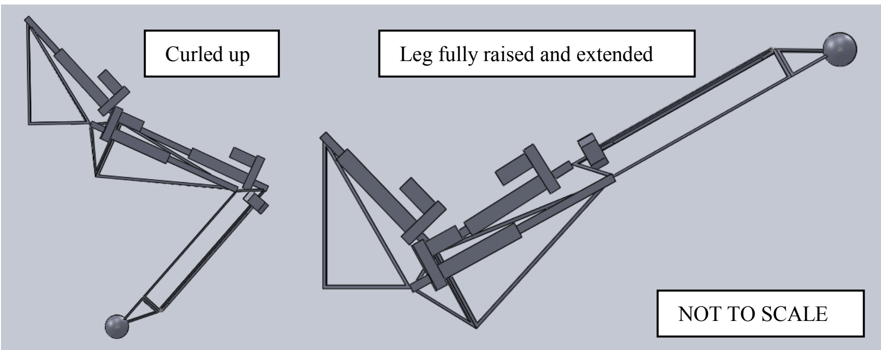

Fig. 17. Side views of TURTLE leg: Curled up (left) and fully raised and extended (right)

5 Conclusions

This paper presented the main goals and objectives of the Turtle amphibious project and briefly described the design and operation of three technically feasible hexapod designs capable of executing several different kinds of swimming modes. It is expected that waterproofing of the electric actuators, power supplies and electronics will be a major challenge. Achieving reliable long-distance wireless and underwater communications and finding suitable foothold positions are also major challenges. Despite this, the authors are confident that this project is feasible.

It is hoped that Turtle type robots will become ubiquitous in the near future and will be used in a wide variety of industries and applications.

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