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Design concepts for a hybrid swimming and walking vehicle

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Abstract

This paper describes the design and proposed control methods for a 6-legged swimming and walking robot that can be used in a variety of different transportation and equipment control applications above ground, under water and above water. Known as the TURTLE (Tele-operated Unmanned Robot for Telemetry and Legged Exploration), a prototype of this mobile robot is currently being designed and developed for experimental testing in the near future. It will be powered by rechargeable electric batteries (to be recharged by solar panels) and all of its actuators will be electric motors, each controlled and monitored by onboard microcontrollers supervised by an onboard master computer. The TURTLE will be fitted with several high-resolution digital cameras, 3D laser and sonar scanners, an IMU (Inertial Management Unit), electronic compass, GPS (satellite navigation) module, underwater sonar transceiver hardware and two or more types of long-distance wireless communications hardware. The first prototype of the TURTLE will focus on basic tasks such as remote video surveillance, 3D terrain surface scanning (above ground and underwater), basic swimming styles, basic walking styles, climbing over large rocks and walking over very rough ground and steep terrain. This paper describes the main objectives, basic performance specifications, functions and mechanical design solutions that have been developed so far for this project. It covers details of the various different swimming modes and feasible solutions for achieving the main design objectives.

Keywords: amphibious, hybrid, swimming, walking, robot

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1. Introduction

Most UUVs (Unmanned Underwater Vehicles) employ several rotary propellers, each able to be pointed to a known direction to provide vectored propulsion thrust forces and position and orientation control for a rigid central body. Experimental research by Triantafyllou et al [1] proves that rotary (blade) propellers waste significant amounts of energy and are usually only less than 40% energy efficient while producing forward thrust for a vehicle. On the other hand, research shows that propulsion based on oscillating foil mechanisms, like the tail fin of a shark, fish or a dolphin, can typically deliver energy efficiencies as high as 80% while producing forward thrust. Research into oscillating foil propulsion has resulted in the development of a variety of different marine robots based on the designs of fish, dolphins, turtles and other marine creatures. The TURTLE (Tele-operated Unmanned Robot for Telemetry and Legged Exploration) is designed to be a very energy efficient long-distance ocean traveler that will rely on flapping or oscillating motions of its foils to produce controlled thrust, while underwater or while floating. An onboard ballast tank will also assist with rapid rising and diving motions, like the kinds performed by a typical submarine. It is intended to be remote controlled using long-distance radio and/or satellite communications and should operate autonomously for long periods of time if such remote control is unavailable. This robot will also be able to change from swimming to walking mode, and vice versa. It is expected that the legs will be powerful enough to carry and move the entire body and its payload over undulating,

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unstructured surfaces and even over steep terrain, such as over large boulders and rocks on a beach, over soft sand dunes and across fairly steep hill slopes. Multi-degree-of-freedom articulated legs also allows accurate positioning of the TURTLE body to a known height and orientation (tilt angle) relative to a solid supporting surface, for the purpose of accurately controlling the position and orientation of onboard tools or measuring instruments.

The main aims of the first TURTLE prototype robot are to develop a reliable and energy efficient UUV (Unmanned Underwater Vehicle) that can swim underwater around large oil rigs, surge tanks, pipelines and other similar hardware, and return real-time video and/or photo images to a remote operator. Its ability to swim and walk over solid surfaces (including over steel tanks and pipelines) will allow it to be useful as a general-purpose work platform on which a variety of remote controlled tools and instruments can be mounted. The following two subsections describe the background for this research.

1.1. Producing hydrodynamic propulsion forces using oscillating foils

Hirata et al [2], Kato [3] and Suzuki et al [4] had designed and built articulated foils (or fins) to propel fish-like underwater vehicles using electric motors and rotary actuators. Mechanical robot dolphins have been built and described by Yu et al [5] and Nakashima et al [6]. Fish, sharks, dolphins and seals achieve forward movement from the repetitive swishing action of their rear tail (or foil). Directional 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 Fig. 1. The power stroke of the fin (foil) produces much more water drag (thrust force for forward propulsion) than its return stroke.

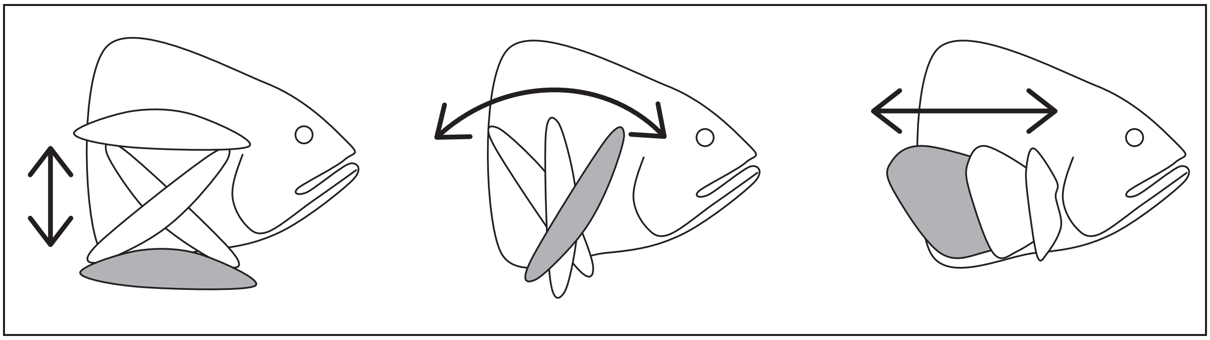

Fig. 1. (a) Flapping motion (up and down) (b) Feathering motion (rotation or tilting about one end) (c) Rowing motion (sideways)

Oscillating foils are capable of providing up to double the energy efficiency of rotary propellers, therefore, 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 conventional rotary propellers. Because foils (or fins) also generally move slower than rotary propellers, they are less susceptible to serious damage in the event of a collision with an obstacle and they would present lower risks of injury to swimmers, divers or surfers who happen to come into contact with their slow moving parts. Figure 2 shows the swimming action of a Green Sea turtle's forelimb, based on Zang et al [7].

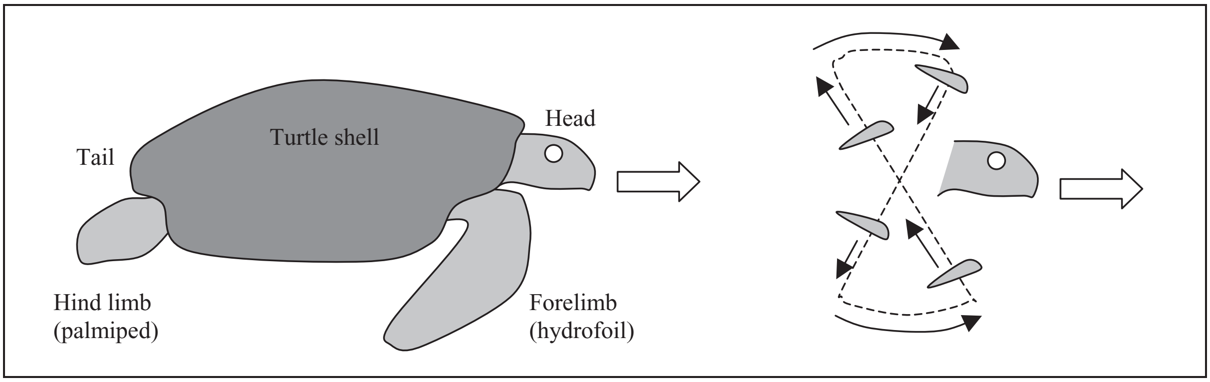

Fig. 2. (a) Green Sea Turtle (b) Side view of Forelimb movement for forward propulsion

1.2. State of the art in oscillating foil propulsion technology used for UUVs

One turtle-like vehicle that imitates the swimming style of the common Green Sea turtle is the Finnegan (also known as ‘RoboTurtle’) built at MIT, and described by Wolf et al [8]. The Finnegan robot can perform forward and reverse swimming at variable speeds. It can reach a top straight-line swimming speed of 1.38 metre/s in the forward direction. Finnegan’s maximum rising speed is 0.4 m/s, its maximum sideways sway speed is 0.46 m/s and its highest turning rate (yaw rate) is 80.2° /s. Each foil has two degrees of freedom, namely, one for flapping the fin up and down (roll) and the other is for twisting (or tilting) the fin to a desired angle of orientation (pitch). The foil works 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. Because of the rotational nature of the flapping motion (for roll), 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), and this represents wasted energy. Flapping a tilted fin up and down achieves forward thrust. 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 the ‘principle of conservation of energy’). Flapping tilted fins is not the most energy efficient form of oscillating foil propulsion.

One interesting design for an amphibious vehicle that can swim and walk (albeit clumsily) is the AQUA robot shown described by Georgiades [9] and Dudek et al [10]. The AQUA amphibious vehicle 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.

Although Georgiades and Dudek et al claim that AQUA is a walking robot, AQUA does not use leg-like stepping or retractable movements for its legs or feet, because its feet move like wheels, each being of a fixed leg length. The legs move like the spokes of a wheel or like paddles when the foot is off the ground. 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 slightly better than a simple 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 ends of the spoke-like legs, however, have serious limitations. An AQUA foot cannot be controlled or placed at a precise 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 locomotion over rough ground and body control for the AQUA and RHex type robots appears clumsy, wobbly and anserine due to the fixed length of each leg. Underwater propulsion is possible if each foot is a single-spoke oscillating flipper that is unsymmetrical about the drive shaft. A repeating feathering-type action is used to generate propulsion by oscillating each paddle in a manner similar to the swishing of a fish tail.

Shelley-RHex, Rugged-RHex, and AQUA-type robots are capable of moving over dry land and overcoming small obstacles but the 2-spoke symmetrical leg design is unsuitable for UUV applications. Even the flat foil 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.

A US-based robot manufacturing company, iRobot^{TM} (www.irobot.com), is currently marketing a foil-actuated UUV marine robot called the ‘Transphibian’, designed for surveillance and reconnaissance missions. Like the legs of the AQUA, the fins of this UUV can rotate, allowing it to perform low-speed crawling movement on a fairly flat sea floor. It is designed to swim submerged to its destination, guided by periodic GPS updates. Built-in ballast tanks also help it to ascend (rise) and descend (dive). Unfortunately, this robot was not intended for walking over very rough terrain and over steep surfaces. At present, it seems there are no highly energy efficient walking and swimming (amphibious) robots that can perform transportation tasks on land as well as underwater and while floating above water. Also, there are very few UUV robots that have been built which employ oscillating foils as the primary means of propulsion. Hence, further research and development in the area of oscillating foil propulsion is justifiable and could lead to more innovations in marine robotics.

2. Design goals and objectives for the TURTLE project

The main objectives for the development of the TURTLE (Tele-operated Unmanned Robot for Telemetry and Legged Exploration) are listed in Table 1. Mechatronic engineering design principles are used to blend essential mechanical, electrical, control and software technologies into a single unified system, where all components of the system must work harmoniously and cooperatively, or in a synergistic manner, to achieve all the stated objectives. A ‘top-down’ design approach was used to ensure that all the main design objectives are realized by practical means and solutions (i.e. working designs) that perform specific essential functions which help satisfy all objectives, design requirements and constraints.

Table 1. Objectives of the TURTLE prototype robot

1	Robot must be able to perform stable walking over rough terrain and geometrically irregular or unstructured surfaces such as is found on a beach, including bumpy ground, soft sand, muddy ground and large boulders.
2	Robot must be self-correcting and self-balancing at all times, able to correct its posture and remain stable and upright even when subjected to external disturbances or unexpected slippery surfaces or collisions with other objects.
3	Robot must be able to automatically select suitable foot positions and leg movements to achieve the desired body position and orientation relative to a supporting surface, to achieve precise positioning of onboard tools such as cameras, sensors and surveying equipment, relative to the terrain.
4	Robot must be able to swim in still water at variable controlled speeds of up to 1 m/s at top speed, and walk on land with variable controlled speeds of up to 1 m/s (3.6 km/hour).
5	Robot must be able to transition between swimming and standing / walking modes (while submerged) without becoming unbalanced or unstable.
6	Robot must feature buoyancy control so that it can be neutrally buoyant, it can float on the surface of the water with positive buoyancy, or it can have negative buoyancy to allow walking on an underwater surface (like the sea bed). (This may be achieved using an onboard ballast tank)
7	Robot must require no tether cable or umbilical wires and should be fully remote controllable while on dry land or while floating on the water surface. While submerged underwater, it should be able to operate reliably to a depth of 50 m and it must be fully autonomous if no data link can be established. It should also be able to automatically save itself from being forever lost at sea, due to an unexpected system or controller failure.
8	Robot must be equipped with necessary digital cameras and essential sensors required for accurate body and leg control. It must also 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	Robot must have sufficient energy and ability to be recharged for long sustained missions. While submerged and moving gently, this might even be extended to several days, while more strenuous movement on land should allow for at least 3 hours of non-stop operation at 50% maximum power output. (A silent power source, such as a rechargeable battery, fuel cell or compressed air is preferable to power involving combustion. For long sea missions, the robot may be fitted with onboard solar panels which can be used to recharge onboard electric batteries, or it may work cooperatively with a floating autonomous boat or marine vessel fitted with large solar panels and a battery bank, which can quickly recharge the robot's onboard batteries when it is docked beside the vessel. Such a floating support vessel could communicate with the submerged UUV using sonar communications and be able to send data to a remote operator using satellite communications (modem) or a long-range wireless link).

Six legs was chosen for the TURTLE design to ensure good overall stability for walking. Most insects have a rigid central body and six or more legs to remain stable. Mammals, birds and reptiles 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 (COG) well within the 'top view' boundaries of the polygon defined by the feet that touch the ground (also known as the 'stability polygon'). If the COG vector points outside of this stability polygon, the body becomes statically indeterminate, or unstable, because a positive moment exists to rotate the body about the feet forming the edge of the stability polygon closest to the COG vector. In this case, there are no available feet to resist the COG or weight vector for the entire body, and this weight vector cannot be cancelled out by reaction forces (of feet) on the supporting ground.

Proposed walking modes currently planned for the TURTLE include:

- crab walking gait (sideways left/right movement. A gait is a repeating or cyclic pattern of foot movements.)
- insect walking gait (forwards/backwards movement)
- turning (left/right turning is achieved by controlling the stride length or stroke movement for each supporting foot)
- rotation on the spot (clockwise/anti-clockwise)
- walking at different ride heights (adjusting the height of the main body above the ground, or relative to a surface)
- transitioning from standing to swimming mode (lifting off the sea floor by flapping of foils or purging ballast tank)

Proposed swimming modes of operation for the TURTLE 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 legs straight so all foils act like oars; or with knees bent at 90 degrees so yaw actuators rotate all legs while each foil surface is kept 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 onto land (can be achieved by leg flapping motions and / or flooding the ballast tank.)

3. Swimming modes for the TURTLE robot

Several different kinds of swimming and walking motions can be performed by the TURTLE robot. Controlling the foot movements and walking gaits of hexapod (or 6-legged) walking robots is thoroughly documented in the literature, since 6-legged walking robots are by far the most common type of walking vehicle. Therefore, this paper will focus on the basic operating principles of the TURTLE hybrid vehicle under different swimming and underwater modes of operation. The proposed TURTLE design employs all the different methods of propulsion shown in Fig. 1, namely:

- Straight-leg flapping (all foils moving in same direction, up and down, but tilt angle changes on the return stroke)
- Straight-leg balanced flapping (3 foils move one way and 3 foils move in the opposite direction to avoid bobbing)
- Straight-leg flat rowing (similar to the action of several parallel rowing oars on an ancient 'Viking ship')
- Bent-leg rowing (foil is oriented for maximum drag for the power stroke, and minimum drag for the return stroke)
- Bent-leg feathering (similar to fish-tail propulsion requiring repetitive bending or rotation of the 'knee joint')

In order to achieve all the desired performance goals in Table 1 and perform the proposed walking and swimming modes of operation mentioned previously, the leg must be very strong, very stiff (resistant to deflection), very lightweight (to minimize wasted energy and permit high acceleration rates), produce little water drag, be corrosion-proof, economical to manufacture and highly flexible, able to freely position its foot within a very large workspace or working volume for excellent adaptability to rough or unstructured terrain. After considering four different feasible robot leg designs for this project, the final design shown in Fig. 3 appears to best solution for satisfying all of the project's objectives successfully. A large rotating (position controlled) foil is located on the 'shin' portion of the lower-limb. This foil (fin) and this leg design can perform all of the different methods of propulsion listed above, as will be described in the following sections.

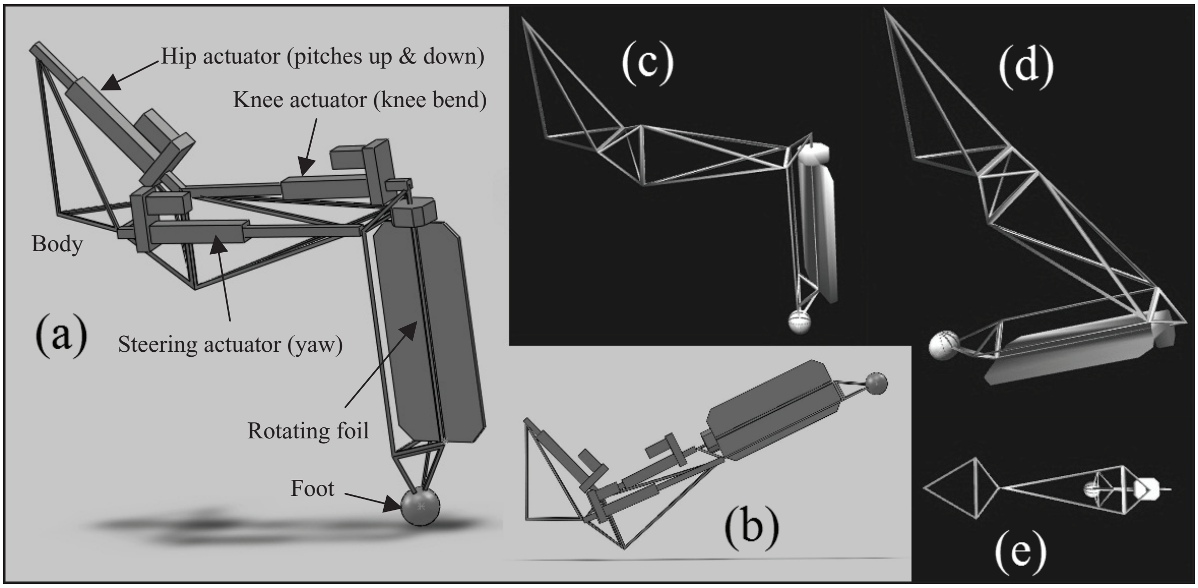

Fig. 3. (a) Bent leg; (b) Straight leg – raised to highest foot position; (c) Foil rotated; (d) Leg curled; (e) Top view (Linear actuators hidden for c, d & e)

All of the limbs or rotary links of the TURTLE leg (and their linear actuators), except for the lower 'shin link', are each made of a 'tetrahedral pyramid' unit, the simplest and most robust 'building block' for a space frame structure. Tetrahedral space frames are extremely rigid, lightweight and incredibly strong for their weight. Tetrahedral pyramid space frames can transmit forces while producing much lower material stresses than regular long beams with a constant cross-sectional area. Regular links made from beams or long hollow tubes tend to produce potentially high bending stresses due to transverse or side loads (perpendicular to the beam axis). Tetrahedral pyramid space frames, on the other hand, focus almost all bending moments on the ‘node’ connections and joints (or corners of the pyramid), which are the only structural components that need to be very thick and very strong. The long connection members that join such nodes together transmit only axial tension or compression forces. Space frame connection rods produce effective (or Von Mises) material stresses that are generally much lower than those developed in beam-type links of similar length made from hollow tubes, which must handle all the bending stresses at their ends. In most robot manipulator applications, side loads can create very high bending stresses that can potentially damage a structure, however, normal axial stresses (either tension or compression loads) are usually much lower than bending stresses. The most likely method of failure for space frame links is buckling failure due to excessive compressive loading on one connection rod (which is highly unlikely if external or reaction loads are applied only at the ‘node’ points, because several rods share the transmitted load or combined load as axial tension or compression only).

3.1. Straight-leg flapping

For this kind of propulsion, each leg is kept straight and the entire leg flaps up and down like the wings of a bird. The foil is oriented at approximately 45° to the direction of movement for the body and changes direction (rotating about 90°) for the return stroke. The side of the ‘leading edge’ of the moving foil determines the general ‘direction of movement’ of the entire vehicle. In this mode of swimming, the foil acts like a ‘movine vane’, similar to the blades of a typical electric fan. One serious problem with this mode of swimming, is the net reaction force of these movements will cause the central body to move in the direction opposite to the movement of the feet (i.e. During the downstroke, the body will move up slightly, and during the upstroke, the body will move down.)

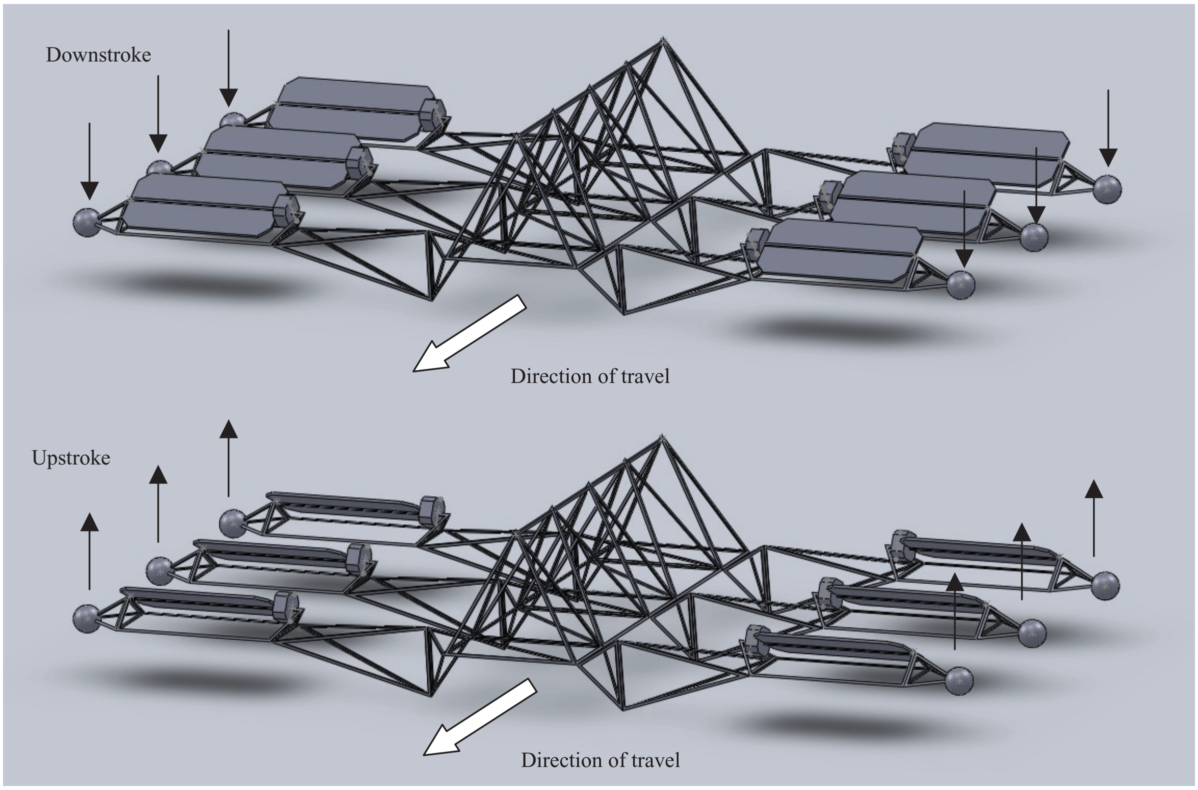

Fig. 4. Straight-leg flapping mode of swimming (linear actuators removed for better visibility of space frame links)

3.2. Straight-leg balanced flapping

The ‘bobbing effect’ resulting from the ‘Straight-leg flapping’ style of swimming cannot be avoided. This style of propulsion is quite similar to the one used by the ‘Finnegan’ robot and actual marine turtles. Some up-and-down ‘bobbing’ action for the body of the robot is expected during motion, and this kind of unsteady body movement may be undesirable especially if accurate 3D surface scanning must be performed by onboard sonar scanners. Bobbing can be cancelled out or reduced significantly if two legs move one way, opposite to the middle leg, on each side of the robot, so that all reaction forces are cancelled out for both sides of the robot. This style of swimming could possibly produce very high swimming speeds due to the low drag imposed by the foils. 'Straight-leg balanced flapping' is illustrated in Fig. 5.

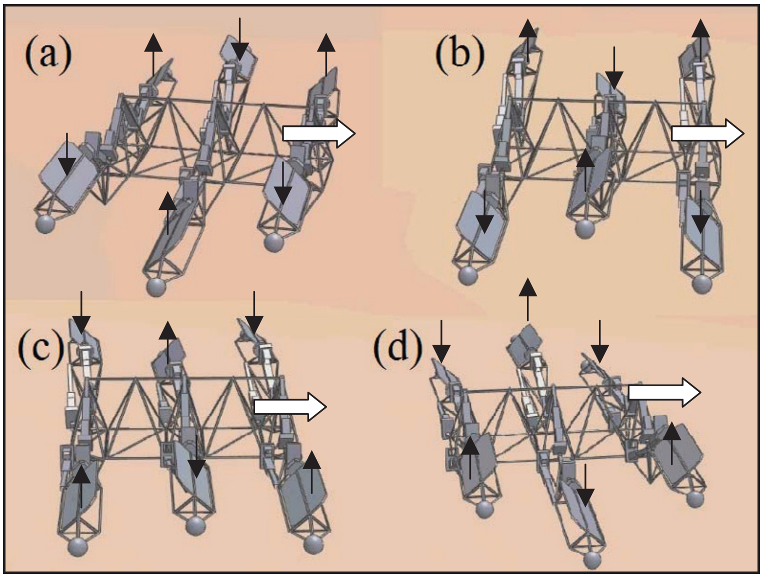

Fig. 5. Straight-leg balanced flapping (Foil positions: a, b, c, d, a, b, c, d repeat)

3.3. Straight-leg flat rowing

This mode of swimming is requires the foils to move in a similar way to paddles or oars on a rowboat. During the 'power stroke', the foil must be rotated to be vertical to produce high drag as each leg is rotated (yawed) backwards (Positions 1, 2 and 3 in Fig. 6). At the end of the 'power stroke', the foils rotate to become flat and horizontal to reduce water drag significantly during the return stroke (Positions 4, 5 and 6 in Fig. 6). Differential steering control can be achieved by reducing the speeds or stroke lengths of the legs on the side of the robot that it needs to turn towards.

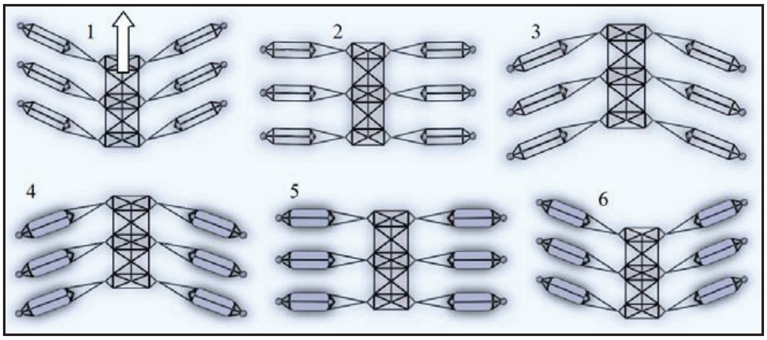

Fig. 6. Straight-leg flat rowing showing 'Top views' of foils (Foil positions: 1, 2, 3, 4, 5, 6 repeat)

3.4. Bent-leg rowing

In 'Bent-leg rowing', the knees are bent at approximately 90°, the legs still rotate just like in Fig. 6 (as seen in the 'Top View'), however, the orientation of the foils must be controlled so that their surfaces remain perpendicular to the desired direction of travel (during the 'power stroke') to produce high drag. Also, the foil surfaces should become parallel to the direction of travel (during the 'return stroke') to produce minimum drag. Figure 7 shows these foil positions for the 'bent-leg rowing' mode of swimming. In this mode of swimming, care must be taken to ensure the feet or legs will not collide with any solid objects, including other legs. The direction of travel for the body will be opposite to the movement of the foils during the 'power stroke'. This mode of swimming could possibly be the most energy efficient form of propulsion for this TURTLE UUV design, because all hydrodyamic forces generated by the foils are opposite to the desired direction of travel, resulting in maximum possible energy transfer to the surrounding water in a direction parallel to the desired direction of travel. Perhaps the only disadvantage to this form of propulsion is the lack of attitude control for the body, because the body may roll, pitch or yaw (rotate or tilt) during travel, however, two or more legs (perhaps the two middle legs) could be used to provide thrust forces to correct the orientation or attitude of the body during travel (by using 'Bent-leg feathering' or even 'flapping' or 'foil tilting'). Any of the foils can be rotated to act like the ailerons on the wings of an aircraft. Many hybrid control schemes and different combinations of leg control are possible for this method of propulsion.

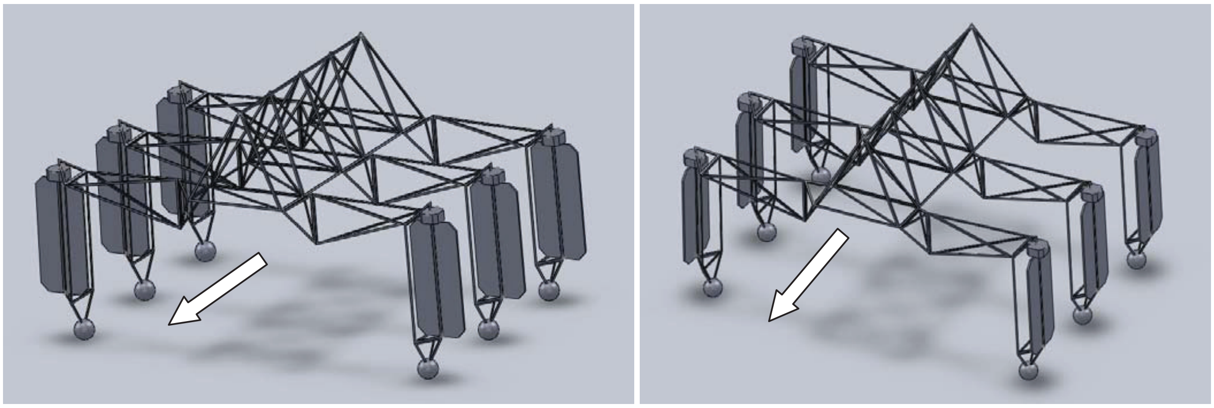

Fig. 7. Bent-leg rowing: (a) Power stroke foil positions (b) Return stroke foil positions

3.5. Bent-leg feathering

The 'feathering' mode of swimming can be performed by repeatedly rotating all shin foils about the knee joints while keeping the same foil orientation shown in Fig. 7(b). The knee bending actuator shown in Fig. 3(a) can wiggle or rotate the lower limb of the leg back and forth like the tail of a fish to produce downward thrust forces to help propel the body upwards. This feathering type action can only produce upward thrust for the body of the robot, however, such forces can be pointed to desired vector directions by raising or lowering the position of the knee or by turning it. (i.e. simply 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). Reaction forces that could possibly move the body can be cancelled out if the foils on one side of the TURTLE body mirror the action of the foils on the other side. For example, all foils can maintain the foil position shown in Fig. 7(b) and all knees can bend at the same time by curling or folding all legs at the same rate. For the return stroke, all legs can extend at the same rate, at the same time. This action would produce an effect similar to fish tail oscillations, or 'swim fins' worn on the feet of divers. The energy efficiency and effectiveness of this type of propulsion has yet to be simulated and tested.

3.6. Ascending and descending movements

The TURTLE robot will have an onboard ballast tank to help regulate its net buoyancy or effective weight force in a similar way to how a submarine floods and purges its ballast tank (with compressed air) to perform diving and rising movements (respectively). This feature could even save the entire robot in the event of a serious system failure, whereby the ballast tanks can be instantly emptied (purged, or filled with air) to force the TURTLE to rise to the surface and float. Figure 8 shows how the shin foils can be used to assist with ascending (rising) and descending (diving) moves so that the ballast tanks do not have to be used very often and compressed air can be preserved. For ascending, the foil is tilted to produce the highest possible drag and the feet are pulled downwards (Positions 1, 2 and 3 represent the 'power stroke' for ascension). At the bottom of the 'power stroke' (Position 4), the foils must rotate to produce low drag as the leg returns to the top position (Position 6) to complete the 'return stroke'. Therefore, when ascending, the TURTLE must follow the sequence of positions 1, 2, 3, 4, 5 and 6 as shown in Fig. 8, and this cycle is repeated. For descending, the 'power stroke' sequence would be Positions 3, 2 and 1 (in that order), and the 'return stroke' would be Positions 6, 5 and 4 (in that same order), so the entire sequence is 3, 2, 1, 6, 5, and 4. The foils may also be kept level while flapping, like in Fig. 9(c) or 9(d).

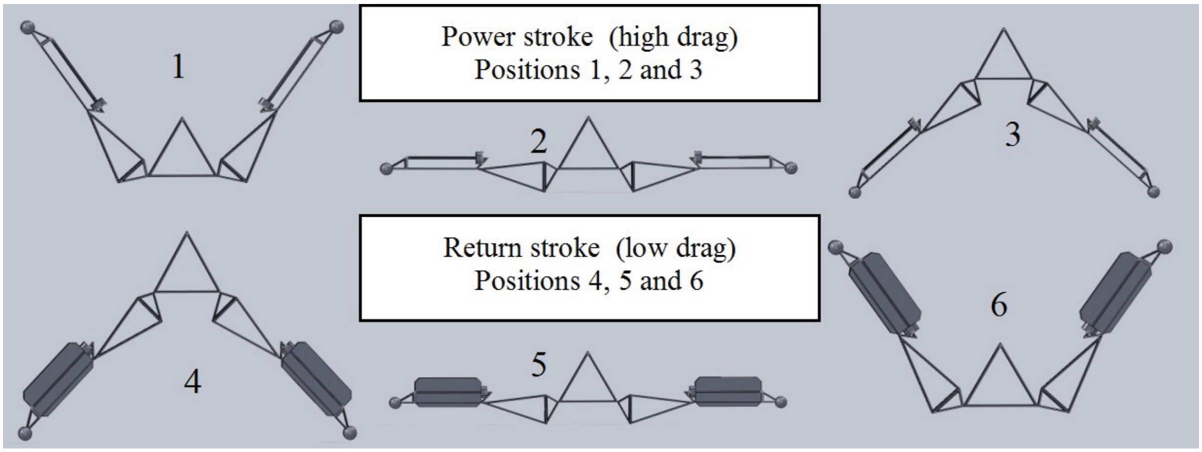

Fig. 8. Leg and foil positions for ascending while submerged (assuming neutral buoyancy for the entire body)

3.7. Transition movements

'Transition movements' occur between the modes of swimming and standing, or between standing and swimming. They help to prepare the feet or legs for the next mode of operation. Transition movements for legs may also occur between different 'gaits' or styles of walking, to prepare feet for their initial foot positions. When making a transition between standing and swimming, or vice versa, 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. During the transition from standing to swimming, 3 legs support the body on the ground while 3 flapping legs provide vertical thrust to generate lift so the body can gradually ascend. For faster lift off, the supporting feet could push the body upwards rapidly and the ballast tanks could be purged.

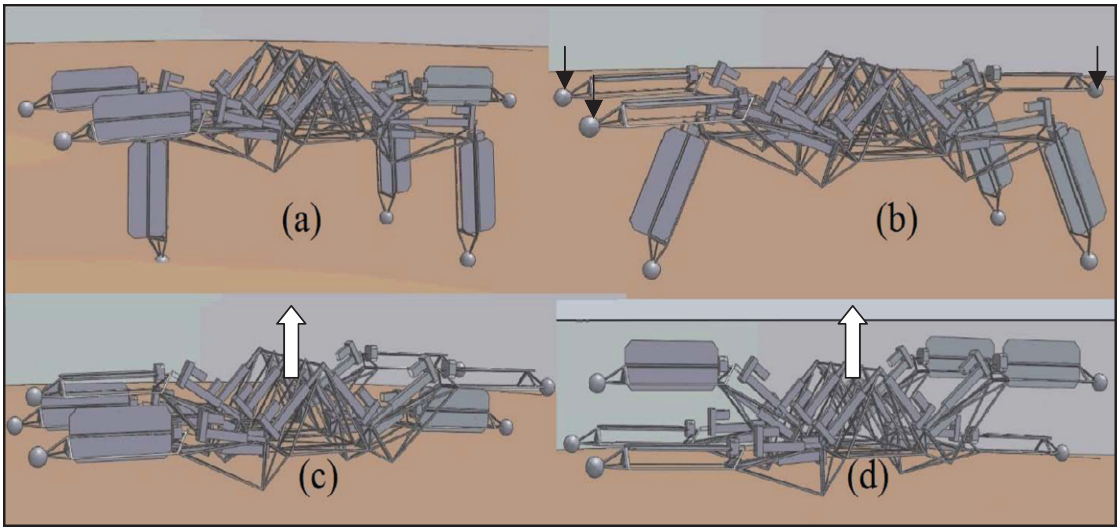

Fig. 9. Standing to swimming transition: (a) 3 legs lift; (b) 3 feet perform flapping to lift body; (c) supporting feet lift off ground; (d) balanced flapping

4. Future work

Electric ballscrew linear actuators will be used to rotate the limbs on each leg of the TURTLE robot because they are typically energy efficient (typically about 90% energy efficient) and produce high forces at very high speeds. For example, a 1 kW DC motor can produce about 92 kg.f or about 900 N of thrust force at a very high speed of 1 m/s, which is ideal for satisfying the performance objectives of this project. The first prototype will be built with position-controlled DC brushless motors (for driving ballscrew linear actuators) and DC stepper motors (to rotate the foils),. All of the robot's electric motors, linear actuators, electronic devices and controllers, including all linear actuators and precision bearings, need to be completely shielded or protected from salt water and other dirt and contaminants typically found in sea water. Custom moulded or 3D printed flexible rubber bellows (similar to extendable and retractable accordion-type air bellows) appear to be viable solutions for keeping actuators completely dry. After meticulous and assiduous searching through the products of about 15 different manufacturers of linear actuators (located from all around the world) over a period of 6 months, the author has not found even one high-speed commercially-available waterproof electric linear actuator that is suitable for driving this robot underwater in a high pressure, corrosive, potentially dirty marine environment. Therefore, an ideal, high-speed waterproof electric linear actuator needs to be custom designed and built to meet the specific needs of this project.

Motion control will be achieved via a central program running on an onboard PC, which will communicate with and command several different 'slave' microcontroller chips, each of which is responsible for low-level control tasks like positioning the ballscrew linear actuators and the shin foil for one leg. One or more embedded microcontroller chips will be used for driving all the actuators on each leg. Work has started on developing 3D simulation and control software for the entire robot using 3D game development tools for Microsoft^{TM} Windows^{TM} (XP / Vista / 7). Figures 3(c), (d) and (e) are actual 'screen shots' of a real-time 3D simulation and control program written for testing the kinematics and control of a TURTLE leg. All the solid models shown in this paper were created using SolidWorks^{TM} CAD software. These dimensionally accurate models were imported into 3D Studio Max^{TM} and exported as .3DS (file) objects. Such objects are used by the 3D simulation and control software which will allow all robot motions and even complete missions to be planned and simulated 'offline', prior to hardware testing. The 3D model of the TURTLE robot will be updated in real-time as new sensor data is received by the remote operator's PC (which can communicate with and command the onboard PC).

5. Conclusion

In conclusion, the hybrid robot design presented in this paper appears to be able to achieve all of the project objectives described in Table 1. This project presents many new and complex control challenges, especially for an oscillating-foil powered vehicle. Keeping the electric motors and all onboard electronic components waterproof will be a major design and manufacturing challenge. It is hoped that robots based on this TURTLE design will become ubiquitous 'general-purpose' field robots that will be used in many different industrial and service applications in the not-too-distant future. The author wishes to acknowledge Professor John Billingsley (USQ, Australia) for first suggesting the idea of adding paddles to the legs of a walking robot to turn it into an amphibious vehicle, and for his ongoing contributions and support for this project.

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