2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

Ninja Legs: Amphibious One Degree of Freedom Robotic Legs

Bir Bikram Dey, Sandeep Manjanna and Gregory Dudek
Centre for Intelligent Machines
McGill University
Montreal, Quebec, Canada H3A 0E9
Email: msandeep@cim.mcgill.ca

Abstract— **In this paper we propose a design of a class of robotic legs (known as "Ninja legs") that enable amphibious operation, both walking and swimming, for use on a class of hexapod robots. Amphibious legs equip the robot with a capability to explore diverse locations in the world encompassing both those that are on the ground as well as underwater. In this paper we work with a hexapod robot of the Aqua vehicle family (based on a body plan first developed by Buehler et al. [1]), which is an amphibious robot that employs legs for amphibious locomotion. Many different leg designs have been previously developed for Aqua-class vehicles, including both robust all-terrain legs for walking, and efficient flippers for swimming. But the walking legs have extremely poor thrust for swimming and the flippers are completely unsuitable for terrestrial operations. In this work we propose a single leg design with the advantages of both the walking legs and the swimming flippers. We design a cage-like circular enclosure for the flippers in order to protect the flippers during terrestrial operations. The enclosing structure also plays the role of the walking legs for terrestrial locomotion. The circular shape of the enclosure, as well, has the advantages of an offset wheel. We evaluate the performance of our design for terrestrial mobility by comparing the power efficiency and the physical speed of the robot equipped with the newly designed legs against that with the walking legs which are semi-circular in shape. The swimming performance is examined by measuring the thrust generated by newly designed legs and comparing the same with the thrust generated by the swimming flippers. In the field, we also verified that these legs are suitable for swimming through moderate surf, walking through the breakers on a beach (and thus through slurry), and onto wet and dry sand.**

I. INTRODUCTION

In this paper we examine the design and development of truly amphibious legs for a hexapod walking robot. Legged mobility has often been envisioned as the most versatile locomotion strategy possible for terrestrial robots. Likewise, the use of actuators with flippers can provide an exceptionally large degree of mobility and versatility in the underwater domain. What has proven elusive to date, however, is a simple leg design that exhibits the advantages of terrestrial walking legs as well as the motile efficiency of flippers when underwater. It is this type of hybrid that we develop and evaluate in this paper. We refer to these amphibious legs as Ninja legs as the design resembles a spinning ninja star. Figure 1 shows the class of amphibious robot known as "Aqua" equipped with the ninja legs.

The leg design and associated assembly we propose in this paper have attributes of flippers, legs as well as wheels. Our design is targeted to the Aqua hexapod vehicle that

Fig. 1. a) Aqua robot walking on a beach with the Ninja legs. b) Aqua swimming in the sea water with the Ninja legs.

uses a RHex-based body design [2] to walk on land, but which is also capable of swimming [3]. One of the important characteristics of this class of vehicles is the open-loop walking using simple legs that are free of internal actuators or moving parts. This simplicity is especially important for amphibious applications where salt water, dirt and corrosion would be exceedingly problematic for any complex leg design.

The use of flippers for swimming underwater has been examined in the context of several different robotics projects. Flippers, as opposed to thrusters, allow to versatile motion and flexible dynamics. They are clearly widely used by biological organisms with exceptional dynamics as well as by human scuba divers. It is notable; however, that few animals with flippers have the ability to walk efficiently on dry land. In fact the same properties of flexibility that allow flippers to work well in the water impede their use on land. Legs, particularly those used for the Aqua robot and originally designed for the RHex vehicle, have excellent terrain traversal properties but are poorly suited for swimming. Likewise, while wheels have, of course, proven very efficient for locomotion on land, they have serious limitations as actuators in the water.

In this work we start by introducing the properties of the existing semi-circular walking legs and the swimming flippers used by the Aqua class robots for mobility on land and in water respectively. Then we discuss our design approach to combine the advantages of both walking legs and swimming flippers into the ninja legs. We also introduce the gaits used by the robot for both walking and swimming maneuvers. Later we reason about the mechanical and hydrodynamic properties of the ninja legs. We evaluate the performance of our design and present the results in the experimental section.

978-1-4673-6357-0/13/$31.00 ©2013 IEEE

II. Related work

There has been a body of prior work in the field of amphibious robots and amphibious robotic legs. Amphibious robots find many applications in reef studies, terrain mapping, search and rescue, etc. Amphibious legs equip the robot with a capability to explore diverse locations in the world encompassing both those that are on the ground as well as underwater.

Recently there have been some amphibious robots designed to operate with legs to walk and swim effectively. The design by Boxerbaum et al. [4] has six legs which can be used as wheels on land and propellers under water. An alternative design by Yu et al. [5] is equipped with four circular legs and two flippers for swimming. The circular legs are used as wheels for land locomotion and as propellers for underwater mobility. In these designs, the legs have more than one degree of freedom which is achieved by using multiple actuators per leg. The ninja leg design is simplistic with 1DOF, yet helps in achieving complex maneuvers. The reduced number of actuators in our design makes the robots operations robust. Also the flippers do not introduce any harm to the marine life.

The amphibious six-legged amphihex-robot in the study by Liang et al. [6] uses six adaptable legs which can adapt to both swimming and walking. The Aqua class robots are heavier because of the casing designed to sustain high pressures at depths about 30 meters under water [3]. These amphihex-legs have a limitation on the strength of the legs to support the weight of a heavy robot like Aqua class robots. But the ninja legs are built to take heavy loads.

The choice of walking and swimming gaits also affect the performance of the robotic legs. The gait used for different maneuvers of the robot affects the power efficiency and range of physical speed of the robot. There have been many studies done on the walking gaits of legged robots. The coordination of the robot legs in the phasing of stance and stroke are designed to achieve a similar dynamic effect as that in a cockroach [7]. The cockroach uses an alternating tripod gait in which a set of three legs, the front and hind legs on one side and the middle leg on the opposite side, move as one unit. This stable unit is alternated with the tripod formed by the remaining three legs [8]. Many studies have reported an efficient performance of tripod gait for walking of the legged robots [9] [10] [7] [11]. Several studies have also been done on the swimming gaits for legged robots. A study by Nicolas Plamondon et al. [12] discusses gaits like middle-off, hovering, sinusoid, alternate, etc. for the efficient swimming of an Aqua-class vehicle similar to the one used in this work.

III. Problem Statement

Several different classes of leg design have been previously developed for Aqua-class vehicles, including both robust all-terrain legs for walking, and efficient flippers for swimming. Notably, however, the walking legs have extremely poor efficiency and limited thrust when used for swimming in the water, and the flippers are completely unsuitable for terrestrial locomotion since they are unable to bear the physical load of the robot due to the flexibility they require for efficient swimming.

RHex legs are semi-circular robotic legs made of fiber glass. These legs are widely used in legged robots for terrestrial locomotion [2] [7] [13] [10] and provide a combination of simplicity, load bearing capacity, compliance and robustness. Many studies have been done on these legs, including gaits used to make these legs efficient for climbing stairs [14], walking on rough terrain [15], running [16], etc. The Aqua robot in this work is capable of using semi-circular walking legs, first developed for the RHex vehicle, for walking and running. Several minor variants of these legs have been examined for use in swimming on the surface or underwater with limited success. Simply put, the asymmetric semi-circular shape of the legs and the lack of flexibility make them unsuitable for swimming with any known gait.

The Aqua robot uses simple flexible flippers [17] for swimming underwater. These flippers not only generate thrust, but are also capable of thrust vectoring when an appropriate gait is applied. Thrust vectoring is the ability to maneuver the direction of the thrust generated by the flippers in order to achieve rapid turns and maneuverability of the vehicle. This allows Aqua to roll, pitch, yaw, surge, and heave [18], which enable it to maneuver in complex 3-dimensional trajectories. These flippers are designed only for swimming and they cannot take the weight of the robot to support it for walking.

A long standing problem is to develop robust robotic legs designed to perform both effective terrestrial and efficient underwater maneuvers. With the design presented in this paper, we have attempted to address the problem of adapting to different modes of locomotion of the robot.

IV. Design Approach

A better understanding of the underlying principles of the semi-circular walking legs and the flippers is required in order to incorporate their advantages in the amphibious legs. In this section we survey the important features of both semi-circular walking legs and flippers for swimming. To be able to better appreciate the design aspects of the amphibious legs, we have to look into both mechanical and hydrodynamic properties of both the earlier designs.

The design of semi-circular walking legs provides many advantages in the functioning of the robot. Previous studies have shown that the lower vertical stiffness of these legs reduces the shock on the robot's body by acting as a low-pass filter on the impact forces that are generated from the ground contact [19]; the semi-circular shape is highly efficient for this and can even permit energy-efficient stair climbing, rough terrain mobility and slope climbing capabilities to the robot [14]. These semi-circular legs can also be modelled as a Spring Loaded Inverted Pendulum (SLIP) model [20], thus can be used to study and improve the performance of the robot in walking and climbing maneuvers [21].

Compliance in the flippers reduces the energy required to generate thrust [22]. The flippers used by Aqua are made of stainless steel rods with a cover of nylon fabric

[17]. The stainless steel rods act as flat cantilever springs, thus providing the required compliance for the flippers. The oscillating flippers generate a reverse Karman Vortex Street that propels the robot forward [23] [24]. The shape and the compliance of the flippers play a key role in generating the reverse Karman Vortex. The design we propose considers the importance of reverse Karman Vortex in generating the thrust.

In this work, we propose a design in which a structure encloses the current flipper, in order to protect the flippers during terrestrial operations. The enclosing structure also performs as the walking legs for terrestrial locomotion.

A. Offset Wheel Enclosure

The semi-circular design of standard RHex walking legs has many advantages due to its shape, as discussed above, but the semi-circular shape is only effective in one direction of rotation [2]. If the leg counter-rotates in the opposite direction from its normal walking mode, the point of contact is only at the tip of the semicircle and the leg behaves like a straight rod. Adding a complementary semi-circular leg facing in the opposite direction to that of the original walking leg will form an offset wheel. Thus, the design of an enclosure with a shape like an offset wheel is effective as it provides the advantages of traditional semi-circular walking legs in both the directions. This was the major motivation behind making the enclosure to be circular in shape.

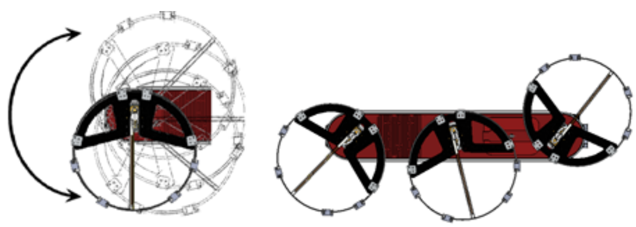

Fig. 2. Ninja leg acting as an offset wheel.

An enclosure of circular shape was designed to contain the flippers used for generating thrust underwater (or on the water surface). This whole structure, consisting of a circular enclosure along with the flippers, will rotate at an offset from the center as seen in Figure 2. This allows us to have the advantages and some disadvantages of an offset wheel. Since the enclosure is a cage-like structure, with an extensive open area for water to flow through, the flippers inside can still generate enough thrust for the robot's swimming.

V. Walking and Swimming Gaits

As discussed earlier, the tripod gait has good performance for walking or running operations of the legged robots. There have been studies which report the efficiency of the tripod gait in the RHex like hexapod robots [9] [10] [7] [11].

In the Aqua robot walking behaviors are based on variations of a rotary gait, while swimming behaviors depend on variations of an oscillating leg motion. Figure 3 shows a sequence of snapshots displaying the mechanism of the tripod gait for Aqua fitted with ninja legs. While one tripod formed by three legs of the robot is in contact with the ground and actuating the robot forward, the other tripod formation is circulated rapidly around to be ready for the next support phase [11]. A complex dynamic interaction between the robot and the ground is created due to this quick alternation of support coupled with the compliant nature of the legs. The speed of the tripod alternation can be controlled by varying the frequency of the leg motor rotations.

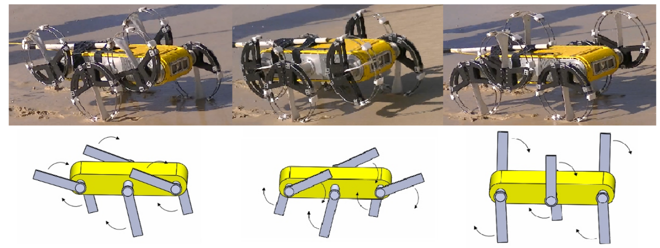

Fig. 3. Tripod walking gait of the Aqua robot when equipped with the Ninja legs. The animation clearly displays the same tripod gait with straight legs.

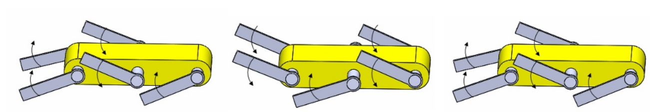

Fig. 4. The animated display of middle-off swimming gait of aqua.

Aqua is capable of achieving complex 5DOF trajectories underwater by oscillating leg motions [18]. Each leg has a single controllable degree of freedom which can be used for a complex gait generation underwater. In general, a swimming gait corresponds to a particular combination of constant phase offsets. Aqua has well-developed kicking gaits for forward locomotion. These gaits are based in simple oscillatory motions of the flippers with various phase and amplitude offsets, similar to the standard kick of a human swimmer [25]. In this work, we use the middle-off gait swimming (Figure 4) for the experiments. In this gait, the phase offset is zero for all four corner legs and the offset is 180^0 for the two middle legs [12]. This gait permits limited amounts of pitch, roll and yaw. The oscillation frequency represents the number of oscillations per unit time and the amplitude of oscillation is the angel swept by the leg during one complete oscillation. We vary the frequency and amplitude of oscillation in our experiments.

VI. Mechanical Properties of the Ninja Legs

The Aqua robot uses the tripod gait for walking therefore three of the legs must be able to support the weight of the robot. The robot weighs roughly from 16 kg to 18 kg with the batteries. For safety and robustness, the ninja legs we fabricated with enough strength so that one leg can take the weight of the whole robot.

As mentioned earlier, compliance is a critical property of a robotic leg, hence we need the ninja legs to be compliant. The enclosure is the part which acts as leg when the robot is in walking mode. Hence, we used bent spring steel rods to make the circular shaped enclosure. The legs with light-weight help the motor drain less power. Also the legs need to be slender so that the drag profile in the direction of the water flow is low. After Finite Element Analysis (FEA) modelling with different designs and shapes, we discovered that the enclosure required supporting material for the bent rods. This support was required to be strong, light-weight and slender. Carbon fiber plates are used to reinforce the structure as they increase the strength of the legs and are light-weight and slender. The plates are semicircular in shape and are fit parallel to the direction of water flow. Figure 5 shows the detailed structure of the ninja legs.

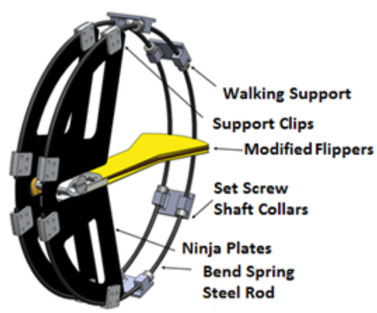

Fig. 5. Illustrated diagram of the Ninja Leg.

The bend rods are coupled to the carbon fiber plates with the stainless steel support clips. The structures made of derlin are added to support the efficient walk of robot on granular terrains like sand. The semi-circular walking legs of Aqua have a diameter of 187 mm, whereas the offset enclosures in ninja legs have a diameter of 263.6 mm. This increase in diameter shortens the effective arm length, as shown by the arrow in Figure 6. We observed that this shortening of arm length reduces the leg motor current required for the robot to go from sit mode to stand mode.

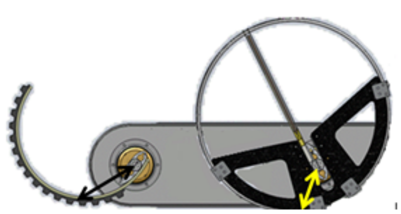

Fig. 6. Comparison of the effective arm length between the semi-circular walking legs and the Ninja legs.

The semi-circular walking legs have compliance for 78.39^0 of the motor rotation (Figure 7b). Whereas, the ninja legs have compliance for about 120.9^0 of the motor rotation (Figure 7a). The remaining 239.1^0 of rotation does not permit compliance because of presence of the carbon fibre plate.

One of the major concerns was the capability of the robot to walk on granular terrains like sand, snow, etc., with the ninja legs. As the rods are thin, there is a chance of digging into the terrain. Hence, we added the walking supports to increase the area of contact between the legs and the terrain. The placement of walking supports on the rods determines the effective arm lengths and the direction of its vortex shading (Figure 7c).

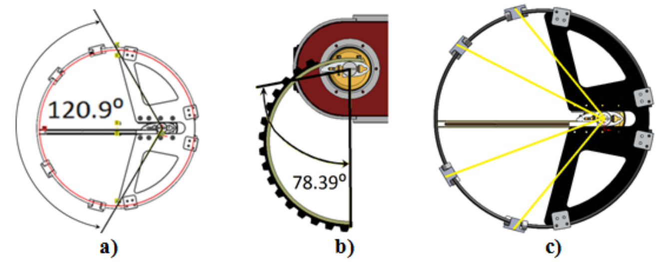

Fig. 7. a) Compliance span for Ninja legs. b) Compliance span for semi-circular walking legs. c) Effective arm lengths of the Ninja legs on granular terrain.

VII. Hydrodynamics of the Ninja legs

We also had to re-design the flippers to accommodate them inside the circular enclosure of the ninja legs. The reduction in the length of the flippers reduces the generated thrust. So we produced a new design with different shape and reduced length and weight. The compliance of the new flippers is same as the old ones as it is important for efficiency.

The previous studies [26] and our experiments on the test bed show that the efficiency in thrust increases with high aspect ratio. We increased the aspect ratio of the flippers by reducing the total area, while keeping the same span. Figure 8 shows the comparison between the old and the new flippers.

$$AspectRatio = \frac{Span^2}{Area}$$

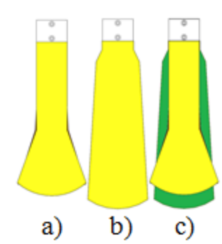

Fig. 8. a) The modified flippers for Ninja legs. b) The swimming flipppers of Aqua. c) Span comparison of new and old flippers.

We should note that in practice, the performance of the flippers can depend on complex interactions (eg. vortex shedding) that a single flipper analysis or test cannot capture.

VIII. Experimental Setup

A. Description of the Aqua Robot and its legs

As mentioned earlier, the robot used for the experiments [3] is a hexapod amphibious robot which is capable of walking on rough terrain, swimming on the water surface and deep underwater swimming. There are many types of legs designed to aid the robot with varied kinds of locomotion: a semi-circular tractable legs to walk on rough and smooth terrains, flippers to achieve 5DOF trajectories underwater, ninja legs to aid both the walking and swimming maneuvers. In our experiments, we compare the performance of ninja legs for walking with that of the semi-circular walking legs. We also compare the swimming performance of the robot with ninja legs against the performance with the flippers.

B. Data collected

The performance of newly designed ninja legs was evaluated by collecting the data over multiple runs of the robot fitted with the ninja legs. The data was collected on two kinds of terrains: tiled floor and carpeted floor. We make use of a 3-axis Inertial Measurement Unit (3DM-GX1TM), which possesses 3 Micro-Electro-Mechanical Systems (MEMS) acceleration sensors, 3 MEMS rate gyroscopes and 3 magnetometers for our data collection. The collected data is a mixture of many sensor measurements: the relative leg rotations measured using optical encoders attached to the leg motor shafts, leg motor electrical currents estimated using motor models, the linear accelerations of the robot measured by the acceleration sensors, and the angular velocities measured by rate gyroscopes. The data is collected from these sensors at a rate of 20 Hz, i.e. 20 readings of sensor data per second.

Multiple data collection runs were made by varying the leg-cycle frequency (f_c). The cycle frequency represents the number of leg rotations per unit time. The video of all the trials was recorded from a fixed distance to accurately measure the time taken by the robot to cover the experimental path distance.

For the swimming experiments, the thrust generated by the ninja legs was measured with a force gauge. The amplitude and the period of oscillations were varied to generate different thrust measurements. The thrust data was collected for both ninja legs and the flippers. A test bed assembly, explained in next sub-section, was used to measure the thrust of individual flippers.

C. Test Bed Assembly

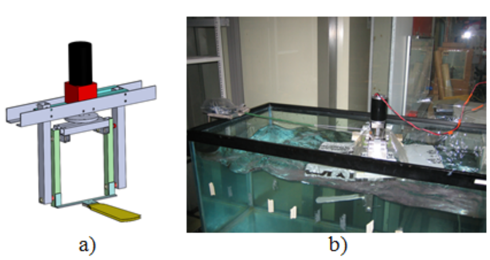

Fig. 9. a) Test-bed to measure the thrust of the flippers. b) Flipper being tested using the test bed.

A test bed was designed to measure the thrust exerted by a single flipper (Figure 9). The test-bed also helped in understanding the interaction of the flippers with vortex while oscillating for making a reverse Karman Vortex. The experiments reveal that the flippers perform poorly under turbulent flow; compliance is very important for power efficiency; and efficiency in the thrust increases with aspect ratio.

IX. Experimental Results and Observations

We conducted two sets of experiments to evaluate the effectiveness of the ninja legs for both terrestrial and underwater locomotion. Here we present the performance results of the Aqua robot when equipped with ninja legs for walking on terrains and swimming underwater. The performance for terrestrial walking is measured in terms of the physical speeds achieved and the power consumption per meter. The underwater performance is measured in terms of the thrust produced by the legs for swimming.

A. Terrestrial locomotion

In our experiments we have evaluated the walking performance of the Aqua robot when equipped with ninja legs and compared it with the walking performance of the robot equipped with the semi-circular walking legs.

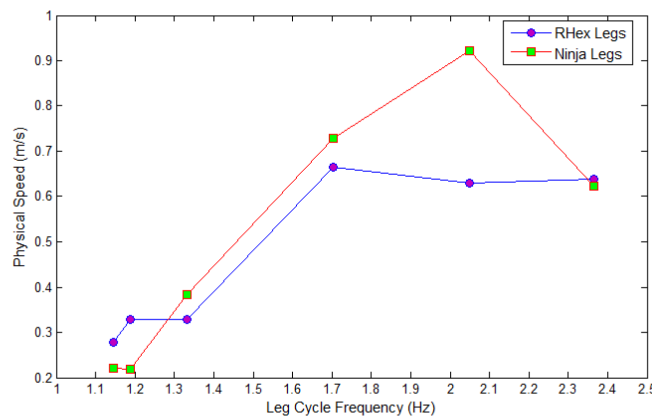

Fig. 10. The physical speeds for both RHex legs and Ninja legs plotted against the cycle frequency of the leg rotation.

The plot in Figure 10 shows the physical speeds achieved by the robot when run with varied leg-cycle frequencies. Ninja legs, due to the reduced compliance of their building materials, achieve better physical speeds at higher frequencies. Whereas the semi-circular walking legs make the robot's motion irregular (i.e. "bumpy") at higher frequencies because of higher compliance of their component materials. Figure 11 represents the power consumed per unit distance of walk plotted against the varying cycle frequency f_c of the robot legs. The plot indicates that the robot consumes more power when walking with the ninja legs than with the walking legs. We suspect this is because of the added weight of the ninja legs. Even though the power consumption is slightly higher than the usual semi-circular legs, the ninja legs achieve higher physical velocity when compared to the semi-circular walking legs.

As mentioned earlier, the robot was made to go from sit mode to stand mode and the leg motor current was measured. This experiment was done with both semi-circular walking legs and the ninja legs. We found that the ninja legs draw 0.65 Ampere of leg current which is much less than 1.96 Ampere drawn by the walking legs.

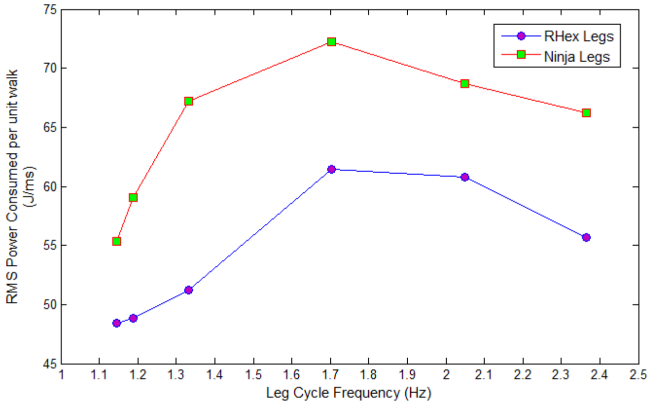

Fig. 11. The Power consumed per unit distance walk plotted against the cycle frequency of the leg rotation. The plot shows the readings for both RHex legs and ninja legs.

B. *Underwater locomotion*

A kick in water generates reactive forces against the water. Only those force components which are resolved parallel to the longitudinal axis of the swimmer's body contribute to the forward motion. These components are referred to as thrust. Thus by measuring thrust we can evaluate the performance of the flippers under water. In our experiments we observed the thrust exerted by the aqua robot when equipped with the swimming flippers and the ninja legs. We collected the thrust data over three different oscillation frequencies and oscillation amplitudes.

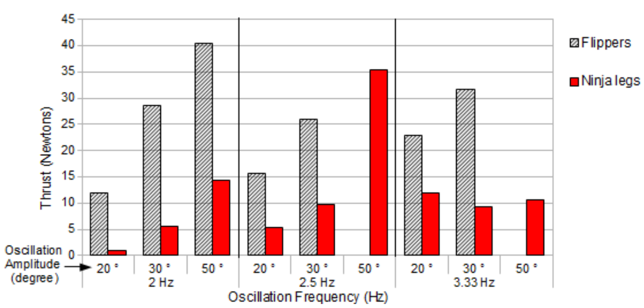

Fig. 12. The variation of thrust generated by the flippers against that by the ninja legs. The x-axis shows variation in the oscillation frequency and amplitude.

The plot in Figure 12 displays the thrust values observed over varied frequencies and amplitudes of oscillations of the robot's legs. As it is seen, the flippers generate more thrust compared to the ninja legs. The reduced thrust by ninja legs is due to the turbulent flow generated by the enclosure around the inner flippers. This turbulent flow in-turn increases the total drag of the ninja leg further affecting the thrust generated. However, ninja legs perform well at oscillation frequency of 2.5 Hz and oscillation amplitude of 50^0. The flippers could not operate at amplitude of 50^0 and oscillation frequencies higher than 2.5 Hz. This is because the flippers drain peak leg current at higher frequencies and the safety switch of the batteries shuts down the power supply of the robot. Hence, having lower leg motor currents helps in the smooth functioning of the robot. As the ninja legs continued to work at higher frequencies without shutting down the batteries it can be concluded that the ninja legs perform well with respect to the leg motor current peaks.

Thus from the results we observe that the ninja legs are capable of performing well both on land and underwater locomotion. The semi-circular walking legs for land and flippers for underwater are well established and proven designs. The ninja legs perform comparable to both these designs and are capable of achieving mobility in both land and underwater environments. The ninja legs were also successfully evaluated for walking on different kinds of terrains including dry sand, wet sand, concrete, tilled floors and carpeted floors. The swimming capabilities of ninja legs were evaluated in both controlled environment (swimming pool) and uncontrolled environments (sea water).

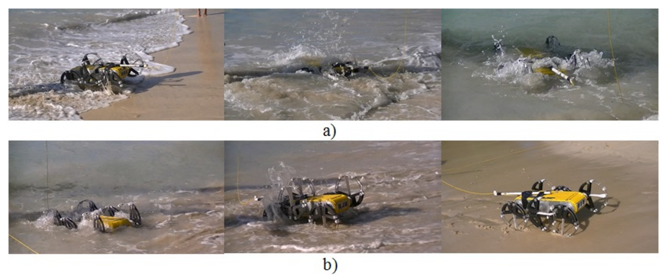

Fig. 13. a) Surf Entry-Aqua walks to the ocean and starts swimming once it is in water. b) Surf Exit-Aqua swims to shore and starts walking on the beach.

We also evaluated the qualitative performance of the robot using Ninja legs in terms of entering and exiting the open ocean through surf with a wave height of roughly 1 m (Figure 13). Under these circumstances we observed that the robot was able to swim to shore, switch (manually) to walking mode upon contact with the beach, and walk onto the shore. It was similarly able to walk into the surf, enter the water, and swim out in the open water. Executing this maneuver depended critically on a sequence of gait transitions to time various actions relative to wave action, and this challenging behavior was executed under manual control. The legs, however, were clearly sufficient to perform this activity.

X. Conclusion

In this paper we have described and evaluated the design of a new class of multi-purpose leg to be used for walking robots, and specifically for the Aqua hexapod vehicle. These legs allow amphibious operation: that is both swimming and walking, providing efficient swimming underwater on the surface, maneuverability underwater allowing 5 DOF motion and complex trajectories in 6 DOF, as well as efficient walking on land. We evaluated the effectiveness of these legs for both underwater swimming as well as for walking on a variety of terrain types. In the field, we also verified that these legs are suitable for swimming through moderate surf, walking through the breakers on a beach (and thus through slurry), and onto wet and dry sand. To our knowledge, this level of versatility is comparable to, and apparently exceeds, what has been previously demonstrated with walking vehicles.

The leg design we have proposed is based on a combination of a flipper and a circular cage which imparts some properties of legged locomotion with some properties of wheel locomotion. In fact, there is a space of alternative gaits that can be used on land that accentuate either the walking or rolling nature of the locomotion system, although in this paper we have only touched on the interesting issues of gait selection and optimization.

XI. Future Work

It was seen that the increased weight of the ninja legs caused an additional power consumption of the robot while walking. Hence, we would like to reduce the total weight of the ninja legs by considering the material used for the circular enclosure. Also the center of rotation is far from center of gravity for which the motor draws more current under "no load condition". By redesigning the support clips, the center of gravity could be shifted towards the center of rotation.

The walking supports were needed for walking in the sand or other soft terrains. They help in distributing the weight on ground, but they increase the drag while swimming. Also it generates turbulent flow in the stream of the flipper, which reduces the thrust. A proper placement of the walking supports might help reduce the turbulent flow. We would also like to study the flippers extensively to determine the critical flow direction where laminar flow is desired for optimal thrust.

We hope to fully examine the space of both available gaits as well as preferred gait transitions that can be used for locomotion on complex terrains and specifically on land/water interfaces.

Acknowledgment

We would like to acknowledge the NSERC Canadian Field Robotics Network (NCFRN) for its funding support.

References

[1] C. Georgiades, A. German, A. Hogue, H. Liu, C. Prahacs, A. Ripsman, R. Sim, L.-A. Torres, P. Zhang, M. Buehler, *et al.*, "Aqua: an aquatic walking robot," in *Intelligent Robots and Systems, 2004.(IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on*, vol. 4. IEEE, 2004, pp. 3525–3531.

[2] U. Saranli, M. Buehler, and D. E. Koditschek, "Rhex: A simple and highly mobile hexapod robot," *The International Journal of Robotics Research*, vol. 20, no. 7, pp. 616–631, 2001.

[3] G. Dudek, P. Giguere, C. Prahacs, S. Saunderson, J. Sattar, L.-A. Torres-Mendez, M. Jenkin, A. German, A. Hogue, A. Ripsman, *et al.*, "Aqua: An amphibious autonomous robot," *Computer*, vol. 40, no. 1, pp. 46–53, 2007.

[4] A. S. Boxerbaum, P. Werk, R. D. Quinn, and R. Vaidyanathan, "Design of an autonomous amphibious robot for surf zone operation: Part i mechanical design for multi-mode mobility," in *Advanced Intelligent Mechatronics. Proceedings, 2005 IEEE/ASME International Conference on*. IEEE, 2005, pp. 1459–1464.

[5] J. Yu, Y. Tang, X. Zhang, and C. Liu, "Design of a wheel-propeller-leg integrated amphibious robot," in *Control Automation Robotics & Vision (ICARCV), 2010 11th International Conference on*. IEEE, 2010, pp. 1815–1819.

[6] X. Liang, M. Xu, L. Xu, P. Liu, X. Ren, Z. Kong, J. Yang, and S. Zhang, "The amphihex: A novel amphibious robot with transformable leg-flipper composite propulsion mechanism," in *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*. IEEE, 2012, pp. 3667–3672.

[7] R. Altendorfer, N. Moore, H. Komsuoglu, M. Buehler, H. Brown, D. McMordie, U. Saranli, R. Full, and D. Koditschek, "Rhex: A biologically inspired hexapod runner," *Autonomous Robots*, vol. 11, no. 3, pp. 207–213, 2001.

[8] G. Hughes, "The co-ordination of insect movements i the walking movements of insects," *Journal of Experimental Biology*, vol. 29, no. 2, pp. 267–285, 1952.

[9] G. Clark Haynes and A. A. Rizzi, "Gaits and gait transitions for legged robots," in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*. IEEE, 2006, pp. 1117–1122.

[10] U. Saranli and D. E. Koditschek, "Template based control of hexapedal running," in *Robotics and Automation, 2003. Proceedings. ICRA'03. IEEE International Conference on*, vol. 1. IEEE, 2003, pp. 1374–1379.

[11] P. Giguere, *Unsupervised learning for mobile robot terrain classification*. McGill University, 2010.

[12] N. Plamondon, *Modeling and Control of a Biomimetic Underwater Vehicle*, 2010, vol. 72, no. 08.

[13] T. J. Allen, R. D. Quinn, R. J. Bachmann, and R. E. Ritzmann, "Abstracted biological principles applied with reduced actuation improve mobility of legged vehicles," in *Intelligent Robots and Systems, 2003.(IROS 2003). Proceedings. 2003 IEEE/RSJ International Conference on*, vol. 2. IEEE, 2003, pp. 1370–1375.

[14] E. Moore, D. Campbell, F. Grimminger, and M. Buehler, "Reliable stair climbing in the simple hexapod'rhex'," in *Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on*, vol. 3. IEEE, 2002, pp. 2222–2227.

[15] J. Spagna, D. Goldman, P. Lin, D. Koditschek, and R. Full, "Distributed mechanical feedback in arthropods and robots simplifies control of rapid running on challenging terrain," *Bioinspiration & biomimetics*, vol. 2, no. 1, p. 9, 2007.

[16] M. Ankarali, E. Sayginer, Y. Yazicioglu, A. Saranli, and U. Saranli, "A dynamic model of running with a half-circular compliant leg," in *Proceedings of the 15th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines*, vol. 23, 2012, p. 26.

[17] C. Georgiades, M. Buehler, and M. Nahon, "Simulation and control of an underwater hexapod robot," Ph.D. dissertation, McGill University, 2005.

[18] G. Dudek, M. Jenkin, C. Prahacs, A. Hogue, J. Sattar, P. Giguere, A. German, H. Liu, S. Saunderson, A. Ripsman, *et al.*, "A visually guided swimming robot," in *Intelligent Robots and Systems, 2005.(IROS 2005). 2005 IEEE/RSJ International Conference on*. IEEE, 2005, pp. 3604–3609.

[19] K. C. Galloway, J. E. Clark, and D. E. Koditschek, "Design of a multi-directional variable stiffness leg for dynamic running," 2007.

[20] C. T. Farley, J. Glasheen, and T. A. McMahon, "Running springs: speed and animal size," *Journal of experimental Biology*, vol. 185, no. 1, pp. 71–86, 1993.

[21] Y. Ö. Aydın, K. C. Galloway, Y. Yazicioglu, and D. E. Koditschek, "Modeling the compliance of a variable stiffness c-shaped leg using castiglianos theorem." ASME, 2010.

[22] K. A. Harper, M. D. Berkemeier, and S. Grace, "Modeling the dynamics of spring-driven oscillating-foil propulsion," *Oceanic Engineering, IEEE Journal of*, vol. 23, no. 3, pp. 285–296, 1998.

[23] J. O. Scherer, "Experimental and theoretical investigation of large amplitude oscillation foil propulsion systems," DTIC Document, Tech. Rep., 1968.

[24] J. Anderson, K. Streitlien, D. Barrett, and M. Triantafyllou, "Oscillating foils of high propulsive efficiency," *Journal of Fluid Mechanics*, vol. 360, no. 1, pp. 41–72, 1998.

[25] G. Dudek, P. Giguere, and J. Sattar, "Sensor-based behavior control for an autonomous underwater vehicle," in *Experimental Robotics*. Springer, 2008, pp. 267–276.

[26] M. Sfakiotakis, D. M. Lane, and J. B. C. Davies, "Review of fish swimming modes for aquatic locomotion," *Oceanic Engineering, IEEE Journal of*, vol. 24, no. 2, pp. 237–252, 1999.