Paper:

Design, Simulation, Fabrication and Testing of a Bio-Inspired Amphibious Robot with Multiple Modes of Mobility

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[Received January 18, 2012; accepted May 2, 2012]

Surf-zone environments represent an extreme challenges to robot operation. A robot that autonomously navigates rocky terrain, constantly changing underwater currents, hard-packed moist sand and loose dry sand characterizing this environment, would have significant utility in a range of defence and civilian missions. The study of animal locomotion mechanisms can elucidate specific movement principles that can be applied to address these demands. In this work, we report on the design and optimization of a biologically inspired amphibious robot for deployment and operation in an ocean beach environment. We specifically report a new design fusing a range of insect-inspired passive mechanisms with active autonomous control architectures to seamlessly adapt to and traverse a range of challenging substrates both in and out of the water, and the design and construction of SeaDog, a proof-of-concept amphibious robot built for navigating rocky or sandy beaches and turbulent surf zones. The robot incorporates a layered hull and chassis design that is integrated into a waterproof Explorer Case in order to provide a large, protected payload in an easy-to-carry package. It employs a rugged drivetrain with four wheel-legs and a unique tail design and actuation strategy to aid in climbing, swimming and stabilization. Several modes of terrestrial and aquatic locomotion are suggested and tested versus range of mobility metrics, including data obtained in simulation and hardware testing. A waterproofing strategy is also tested and discussed, providing a foundation for future generations of amphibious mobile robots.

Keywords: biologically inspired robotics, legged vehicles, field robotics, amphibious operation, advanced mobility

1. Introduction

The ability to employ autonomous robots in difficult terrain continues to be a rich area for research. There has been significant interest, in particular, in the development of amphibious robots capable of autonomous operation within beach and turbulent ocean surf-zone environments. Potential utilities for such a robot include mine clearing, terrain mapping and scouting potential approach lanes for amphibious naval and marine operations [1].

A number of research groups have constructed platforms with the eventual goal of facilitating operations of this nature. These efforts have included wheeled and tracked variants such as the Foster-Miller LEMMING [2], legged and crawling robots [3–6], snake robots [7] and walking-platforms such as AQUA [8] based on the RHex [9] platform, which, with manual adjustment, may be transitioned from walking to swimming locomotion. To date, however, a rugged robot capable of robust autonomous locomotion has yet to be fully developed for operations such as beach mine detection and clearing.

Foremost among the challenges impeding this goal remains the locomotive capacity of robotic devices in both terrestrial and aquatic media. Additional challenges include uneven substrates, rocks, boulder fields, shoals, wave surge, tidal currents and algal beds [10, 11]. A robot operating in this region will be expected to navigate based on a specified compass heading, with GPS signals accessible when not submerged. Its controller must traverse terrain obstacles (e.g., large and small rocks, wet sand, etc.) without disrupting higher-level navigation sequences. Our long-term research is driven by unresolved issues in this arena related to remote sensing, search and mapping and mine countermeasures in the ocean littoral and/or rivers and streams.

We report the development of a new robotic platform addressing these issues based on a hybrid wheel-leg concept that draws inspiration from cockroach mobility principles. It has been shown [12] that mobility is optimized for robots in this series through a single drive motor that powers six multi-spoked appendages called wheel-legs. Neighboring legs are typically offset, yielding a nominal tripod gait. These wheel-legs allow the robots to climb over larger obstacles than a vehicle with comparably sized wheels. Whegs^{TM} robots have compliant mechanisms in all of their axles. These mechanisms allow passive adaptation of a nominal tripod gait to irregular terrain. This compliance captures much of what the cockroach accomplishes with actions of its distal leg joints. Robots in this series have also incorporated a body flexion joint [13, 14] scaled based on a cockroach. This actively controlled joint enables them to model cockroach behavior, extending to reach its legs higher preceding a climb and flexing them to control the robot's center of gravity, thereby improving climbing ability. Recent robots in the series have successfully navigated complex and varied terrain with both full [15–17] and partial autonomy [18].

This work extends and modifies this concept toward the design and fabrication of a new amphibious vehicle, SeaDog, designed for multiple terrestrial and aquatic modes of mobility in the turbulent surf zone. Its design integrates recent work in autonomous control with rugged waterproofing of the robot, allowing it to walk on the ocean floor and swim. A novel concept based on insect-inspired body flexion joint is introduced through the development of a tail that enables several benefits during locomotion, including climbing stabilization and aquatic propulsion capabilities. A simpler and more customizable torsion device is also presented for wheel-legs, with new steering and control strategies. These design changes are examined in a 2D simulation environment, which is used to optimize design parameters for robot performance. Obstacle climbing using the tail is compared to results from a previous robot with a posterior body segment and body flexion joint. Actual results are presented of the fabricated robot crawling over challenging terrain and moving through land and water substrates. These results provide the foundation for a new generation of robotic vehicles with the capacity to navigate challenging terrain in the ocean surf zone and locomote in both terrestrial and aquatic settings with complete autonomy. **Fig. 1** shows the concept rendering the robot design and a photograph of the actual robot transitioning from land to water.

This paper is organized as follows: the first sections of this paper focus on the design and simulation of the robot, outlining critical parameters for optimization prior to fabrication, followed by descriptions of the construction of the robot. The paper closes with facsimile field experiments examining its performance through challenging terrestrial (climbing) and aquatic substrates. Section 2 presents an overview of the design approach and outlines the design methodology, focusing on delivering multiple modes of mobility to the robot, and defines operational issues. Section 3 details specifics of the mechanism design for the robot. Section 4 describes the insect-inspired tail mechanism enabling enhanced terrestrial mobility and elementary aquatic locomotion, and presents climbing simulation results establishing the veracity of the design. Section 5 details the final design and construction of the robot, while Section 6 presents the aquatic locomotion strategies of the robot. Results and discussion from robot testing follow in Sections 7 and 8, with final conclusions and future work in Section 9.

Fig. 1. (Top) Rendering of SeaDog with its water-tight case open. Two drive motors power the left and right sides independently via a chain drive for differential steering. (Bottom) The fabricated robot in transition from land to water.

2. Overview and Design Approach

2.1. Overview and Design Approach for Multiple Modes of Locomotion

Recent research in robotic locomotion particularly in efforts drawing upon inspiration from biology, has resulted in remarkable progress toward mobile platforms with the capacity to traverse challenging environments. There remain significant issues, however, that have impeded the development of truly robust ambulatory platforms capable of locomotion in more than one medium; this dearth has resulted in a plateau in the present utility of autonomous and semi-autonomous vehicles. Specifically, the challenges of transitioning between combinations of aquatic and terrestrial modes of locomotion present an array of issues in sensor development, energy consumption, mechanical design, sensor integration, perception and planning and control system development. At this time, system design issues involved in creating a hybrid vehicle capable of transforming locomotion modalities have yet to be fully clarified by the research community.

In animals, the synergistic interaction of mechanical structure, e.g., muscles, bones, and tendons, of an organism and its neural control centers play a critical role in enabling adaptability in balance, locomotion and virtually all facets of movement control. This is particularly true for higher frequency disturbances such as maintaining posture over varying substrates and in transitional regions between two locomotive media [19]. In legged locomotion, for example, a fundamental role is played by passive stiffness and damping that stabilizes the body in an intrinsic fashion and thus greatly simplifies higher-level control. It is these intrinsic properties of the musculoskeletal system that augment the neural stabilization of the body.

It is now irrefutably accepted that biological inspiration offers a wealth of promise for robot mobility; however the current generation of power supplies, actuation technology and other fabrication materials are not yet at a point where they may lend animal-like capabilities to mobile robots. An approach focusing on this issue, known as abstracted biological inspiration [12], centers on the delivery of critical robot performance characteristics for near-term field use. Abstracted biological inspiration attempts to capture as much of salient biological principles as possible, yet implements them using currently available technologies. The aim is to achieve the best balance between desired and realistically deliverable capabilities. This approach founded the basis of the design methodology in this work aimed at enabling capacity for locomotion in both land and water, and the critical transitional regions between the each substrate.

2.2. Scope

Within the context and goals of this research, mechanisms for multiple modes of locomotion may be viewed in consideration of three principal factors: 1) complexity in design and control, 2) capacity to adapt to variable terrain and different media, and 3) energetics of locomotion. Abstracted biological inspiration relates complexity in design to the realistic possibility of fabricating a field-ready prototype for targeted utility. Terrain adaptability is of vital importance for effective functionality in the beach/surf-zone region. Performance in this region demands the capacity to navigate various obstacles when transiting dramatically different terrain. Mobility tuned for soft sand, for example, is often not optimal or even functional for hard packed sand, rocky beaches and aquatic settings. A platform calibrated to operate smoothly in wet hard-packed sand may be impaired in dry sand and will not address balance, e.g., high centering, on a rocky beach. Stability in water will not be achieved without the capacity to adapt to fluctuations in terrain [7]. Energy efficiency in locomotion correlates directly with the autonomous capacity of the robot. This remains a critical optimization parameter in natural locomotion systems.

We report a rigorous design methodology, relying on biological study for terrestrial locomotion, biological inspiration for locomotive mechanisms capable of transiting in multiple media, extensive simulation, and eventual fabrication and testing of an amphibious robot. Simulation results leading to robot balance optimization and mobility are detailed. The robot, dubbed 'SeaDog,' is shown to be capable of crawling over difficult terrain, moving through deep water, and navigating non-turbulent transitional regions (e.g., river and lake banks) between terrestrial and aquatic media.

3. Mechanisms of Locomotion for Multi-Modal Mobility

3.1. Gate and Tail Design

Demands of multi-modal locomotion motivated a quadruped design for SeaDog. Drawing parallels from smaller robots [15], SeaDog will have a diagonal gait instead of the more stable tripod gait but will be much larger. A multifunction tail will provide increased stability on land and will prevent high centering during climbing, similar to the function of the body joint in the American cockroach. In surf-zone environments, the tail can be used to convert constantly changing currents into downward force, thus increasing stability and keeping the robot on the seabed in the same way that lobsters use their tails (as shown by Ayers et al. and implemented RoboLobster [20]). The tail can also be used as a propulsion method while under water, similar to a flipper. In the future we may use the tail in conjunction with a mounted thruster to steer while swimming.

Careful studies of how robots with insect-inspired body joints (e.g., [14]) climb suggest that the rear body segment functions primarily as a tail when large obstacles are climbed by preventing the robot from falling backward off of the obstacle. Simulation and multiple trials verified that it was advantageous to have a center of gravity forward from the center of geometry [14]. Using a tail instead of a rear body segment simplifies waterproofing design requirements and adds stability both on land and in water.

This new morphology is well suited to four-wheel-leg design. The diagonal gait is not as stable, however, as a tripod gait. The number of spokes per wheel-leg has therefore been increased from three to four and the tail can be lowered when the robot senses strong rolling.

3.2. Differential Steering

Other wheel-legged robots have used differential (tank) steering [9, 10, 21]. In past Whegs^{TM} robots, differential steering has generally been avoided due to the burden of controlling multiple motors and keeping wheel-legs in correct phase alignment. It also reduces one of the strengths of Whegs^{TM}, i.e., the design using one propulsion motor. Differential steering, however, permits a zero turn radius and eliminates problematic steering mechanisms and steering motors. Servo-based steering mechanisms were exposed to repeated impact loading and required careful design to implement a robust solution [14, 16]. By using differential steering, we simplify the system by eliminating the need for steering servos and U-joints.

In this work, we propose two drive motors, one each for the left and right wheel-legs. We use a novel method of synchronizing the left and right wheel-legs that is not computationally intensive and that allows for the zero turning radius typical of differential steering. We also incorporate torsionally compliant devices in drive shafts to allow each wheel-leg to rotate back under heavy loads. This greatly increases stability against rolling by transitioning out of a diagonal gait during climbing [11, 17]. Differential steering requires, however, that outside wheel-legs travel farther and faster than inside wheel-legs. As a result, the robot can only turn in set increments such that after a turn, wheel-legs are back in proper phase alignment. Whereas robots such as RHex overcome this problem by changing the velocity of the wheel-leg in the swing phase [9], this is not possible in this design due to the mechanical coupling of the wheel-legs. As an alternative method of synchronization, we propose making one foot on each side of the robot slightly longer in arc length. This means that during each gait cycle, there will be brief periods where three feet are touching the ground, two on one side and one on the other. Having two feet down on one side will naturally resist turning. During these brief periods, the motor on the side with just one foot down accelerates forward to align the left and right sides. Instead of turning, this causes the single foot that is down to wind its torsionally compliant device. On toe-off, the device unwinds and phase alignment is completed.

3.3. Passive Torsionally Compliant Devices

Whegs™ robots have compliant mechanisms in all four axles. These mechanisms allow them to passively adapt their gait to irregular terrain by allowing the wheel-leg to rotate out of phase with the axle when it experiences threshold torque. While surmounting an obstacle, a wheel-leg experiences a large amount of torque and, through the passive compliance of this device, is able to match the phase of the opposite wheel-leg, thereby providing a better climbing stance.

The torsionally compliant mechanism on SeaDog improves on previous models, introducing several advantages over past designs. Most Whegs™ torsion devices use torsional springs. SeaDog incorporates an enclosed circular track that guides compression of a linear spring along the perimeter of the torsion device. This design has a larger radius than previously but is integrated entirely into the wheel-leg assembly (**Fig. 2**). This reduces overall weight, eliminates problems with misalignment in torsion devices and reduces the number of keyed shafts from six to two. Axial loads on the wheel-leg are transferred directly to the main axle while torque is transferred to a preloaded linear spring within the device.

The current design allows for extensive customization that is easy to implement. Mechanical stops can be installed to define an allowed angle of rotation while springs can be quickly swapped to experimentally optimize desired characteristics such as threshold torque and maximum torque. It is also easily adaptable to wheel-legs with three, four or five spokes. All changes regarding stiffness and a range of motion for torsion device can be made without even opening the robot case. This allows us to optimize these settings while conducting field experiments.

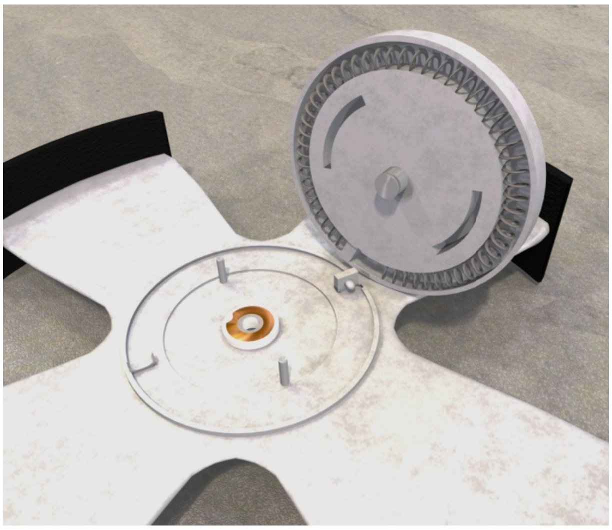


Fig. 2. Rendering of an open torsion device showing a linear spring in its groove. When assembled, the slider attached to the wheel-leg applies a compressive force on the spring.

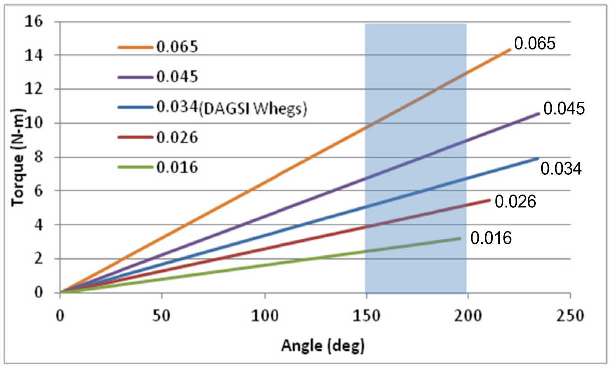
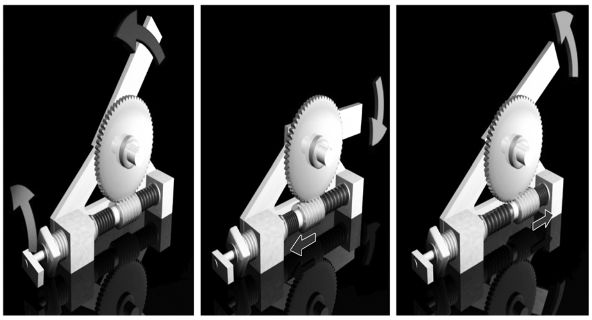


Fig. 3. Characteristics of five springs with designated torsional stiffness (N-m/deg). The shaded area indicates an example 50° range of motion which will be used with a four spoke wheel-leg to achieve in-phase climbing (the further to the right, the more preloading). The left edge defines the breakaway torque, while the right edge defines the final torque, where the device becomes rigid again. The mechanical design of the torsion device is such that we can tune its properties over a wide range of robots.

There is a limited range of adjustability inherent in any design. The circular track that guides compression springs, for instance, limits the size and stiffness of the spring. We have centered that range of adjustability on settings intended to replicate the characteristics of most desirable to gait adaptation. After a threshold of 6.2 N-m, a torque of 1.7 N-m results in the desired 50° phase shift (**Fig. 3**).



(a) (b) (c)

Fig. 4. A Simplified diagram of the tail transmission demonstrates its multiple functions. When the worm is driven by a motor (light arrow in (a)), the tail changes position similar to a standard worm gear (dark arrow in (a)). When a force is applied to the driven gear (light arrows in (b) and (c)) the worm slides axially on the drive shaft, where Bellville springs cushion the blow (outline arrows in (b) and (c)).

3.4. Sealing the Body

Efforts at sealing previous generations of robots [14] resulted in the need for time consuming maintenance and burdensome field adjustments. Because of these issues, we propose using a commercially available Pelican case as the clamshell that keeps water out (hence the namesake). An aluminum chassis inside the case provides a structure for mounting motors and electronic components, as well as transmitting force to adjacent sides of the case during dives in deeper water. This structure could be removed in one piece for maintenance and the robot could operate outside of its clamshell during initial land testing. Through implementation of rotary axles and U-cup seals, the finished robot will have easily removable wheel-legs that will fit inside the Pelican case. This means that, prior to deployment, the robot will function as a self-contained heavy-duty suitcase.

4. Unique Actuation of Tail

The actuation mechanism for the tail of SeaDog demands a non-backdrivable motor with compliance for preventing breakage during unexpected heavy loading. We introduce a unique modified worm gear recently developed to provide such a mechanism. A motor with a transmission is connected to a worm that drives the worm gear. In this modified design, the worm can slide axially but not radially on the shaft and is cushioned on both sides by Belleville springs. A large axial bolt holds bearings in place and tensions the Bellville springs. When the front wheel-legs impact on an obstacle, the front body segment rotates up and back, rotating the driven worm gear, which then pushes the driving worm in a fashion similar to a rack and pinion, allowing the Belleville springs to cushion the blow (**Fig. 4**). Regardless of the passive state of the body joint, the motor can actuate the body joint in either direction.

This design essentially puts a spring in a series with an actuator and is similar to a series elastic actuator used in several robotic applications [19]. Unlike a series elastic actuator, which also measures actuator force, the joint is partially passive, acting like a car suspension independent of actuation. This non-backdrivable design is also inherently rotary, eliminating the need for cables.

This design also allows the passive stiffness of the body joint to be independently tuned in clockwise and counterclockwise directions by changing the number and stiffness of the Belleville springs on either side of the worm. When run autonomously, it may be advantageous to have a very low stiffness body joint that works entirely passively to overcome obstacles. When in radio control mode, body joint stiffness can be higher to allow more responsive user control.

4.1. Simulation of Tail Versus Body Joint in Climbing

Two-dimensional dynamic simulation of both the previous robot with a body joint and the proposed new design with a tail was done to test design and to optimize critical performance parameters. During climbing the left and right wheel-legs slide into phase with each other due to torsional compliance. This allowed us to simplify the 2D model as a robot with only three wheel-legs, and fundamentally stable in rolling. We also assumed that all wheel-legs moved together at a constant velocity. We did not include the torque limit of the motor in the model, which allowed us to safely predict the maximum height of the obstacle that the robot can overcome given its dimensions and weight distribution (**Fig. 5**). Future work will be done with a 3D simulation package to assess the stability of this new diagonal gait.

Both the body joint model and the tail have a torsional spring and damper at the middle drive axle. The rest point can be changed in real time during simulation either by an observer or based on an autonomous control algorithm. For this work it was controlled by the user in real time in order to recreate the current testing environment.

Examination of the climbing of past robots in the series showed that that high centering was the primary mode of failure. From close examination of robot performance, it appeared that the position of the center of mass relative to middle foot placement when the top of the obstacle was reached is critically important. If the center of mass appeared to be behind the foot, the robot falls back and high-centers off of the obstacle; if the center of mass is in front of the foot, the robot falls forward onto the top of the obstacle and successfully completes the task.

We extensively tested the veracity of these hypotheses in our simulation. Simulations confirmed that weight distribution has significant impact on climbing ability, particularly with an active body joint (**Table 1**). By moving the 4.7 kg mass from the center of the robot to the front of the robot, the maximum height obstacle it could repeatedly overcome was increased from 32 cm to 38 cm. By redistributing 6 kg to the front of the robot, a 40 cm obstacle was consistently overcome. Obstacles as high as

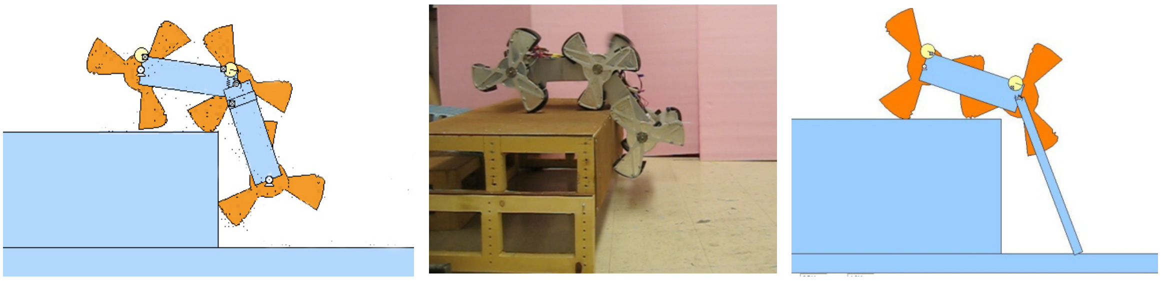


Fig. 5. Screen shot from dynamic simulation of a six wheel-legged Whegs robot with a body joint successfully climbing a 40 cm obstacle; frame from a video of the DAGSI Whegs successfully climbing an obstacle of the same height; dynamic simulation of a four-wheel-legged Whegs robot with a tail climbing a 48 cm obstacle. The middle wheel-leg reaches much further onto the obstacle, even at this greater height, decreasing the chances of high centering.

Table 1. Summary of climbing ability of with a body joint in simulation and experiment. In simulation, successful climbing was considered three successful climbs in a row. In experiment, successful climbing was limited to two climbs in a row, in order to limit the risk of damaging the platform. The center of mass dimension is the distance from the center of geometry to the center of mass, positive values; it is forward of the center of gravity.

Experimental /Simulated	Total body weight (kg)	Center of Mass (cm)	Body Joint	Max Height (cm)
Simulated	21	0	Locked	30
Simulated	21	7.4	Locked	30
Simulated	21	0	Active	32
Simulated	21	7.4	Active	38
Simulated	21	11.2	Active	40
Experimental	20	0	Locked	27
Experimental	20	0	Active	33
Experimental	21	7.4	Active	40

46 cm were overcome, but not repeatedly.

In simulation of a robot with four wheel-legs and a tail, the tail length was chosen to be as long as the rear segment of the robot with the body joint. This design was able to surmount obstacles as high as 48 cm in simulation, higher than its six wheel-legged counterpart (**Table 2**) due to the fact that the rear wheel-legs in the six wheel-leg model often prevent the robot from getting its center of mass on top of the obstacle in those critical moments before the middle wheel-legs push off from the top of the obstacle. The tail, however, does not get in the way and, instead, provides a foot on the lower platform until the last possible minute.

Interestingly, the robot with the tail does not benefit from moving the center of mass forward. This is because the center of mass is already very far forward relative to the full length, including the tail. Moving it further forward prevents the robot from developing enough traction to lift its body up the vertical face in the first stage of climbing. Last, a robot with four wheel-legs and no tail performed significantly worse than any other model. This is in agreement with tests performed with a four-wheel-leg robot that flips over backwards when trying to climb obstacles higher than 1.5 times its leg length [15].

Table 2. Comparison of climbing ability in simulation of a Whegs robot with six wheel-legs and body joint to one with four wheel-legs and a tail. The robot with the body joint climbs well with the body joint active and the center of mass moved forward. The robot with only a tail can climb the highest, but does not significantly benefit from moving the center of mass any further forward.

Simulations	C.O.M. Forward	C.O.M. Neutral
Tail	48	46
Body Joint	40	32
No Tail	17	16
No Body Joint	30	30

4.2. Robot Design and Simulation Conclusions

A robust amphibious biologically inspired robotic platform, SeaDog, has been designed based on abstracted biological inspiration. Several design innovations allow it to navigate on rough terrain and under water to accomplish tasks with little or no low-level control. This greatly simplifies autonomous control and gives the vehicle unprecedented mobility and versatility. With the ability to swim, it could be deployed offshore and then walk along the ocean floor through the surf zone and onto the beach. It could search for objects on land or on the ocean floor and swim over obstacles that pose a risk of trapping it, making it ideal for mine sweeping, surveying and civilian utility.

5. Robot Construction

Rigorous design and focused simulation provided a foundation for the fabrication and testing of a prototype robot that will serve as a basis for a future generation of robots with the capacity to traverse the ocean surf-zone. Design and testing are detailed in this section.

Fig. 6. Layered chassis design. Two latches expose the inside of the robot allowing for easy access for maintenance.

5.1. Chassis

SeaDog is designed to work in challenging, rugged environments such as the surf-zone and sandy and rocky beaches. In such environments, small failures can have large consequences: any exposure of internal components to salt water or sand can result in damage to the payload and electronics and, ultimately, loss of control of the robot. In an offshore setting, this would make it very difficult or impossible to retrieve the robot. Under these circumstances, a rugged body and chassis design with multiple levels of redundancy are necessary.

5.1.1. Layered Chassis Design

SeaDog has a layered hull and chassis design that utilizes a water-resistant aluminum inner chassis enclosed in a rugged waterproof case. The outermost layer consists of commercially available Explorer Case model 5117. Designed for diving, yachting and military applications, the case provides an extremely durable, waterproof exterior at a small cost in both money and machining time. Although we considered making a custom carbon fiber outer shell, the Explorer Case provides many conveniences, e.g., easy access to internals via jam-free latches, a removable lid, an integrated padded handle for easy carrying and field-tested waterproof seals (**Fig. 6**).

The inner chassis is constructed from 6061 structural aluminum alloy. A six-sided box shape was chosen for the chassis for structural support and another layer of water resistance. Offset in each corner is a short structural wall to support the drivetrain and add rigidity to the chassis. To study the effects of depth pressure on the chassis, finite element analysis was undertaken and stress concentration was addressed.

5.1.2. Volume and Weight Concerns

The coupling of this robot's weight and volume are of great concern due to gravity and the buoyant force of water. Due to the fixed volume of the Explorer Case, the buoyancy of the robot is predetermined. Testing in a pool showed that approximately 30 kg is required to make the Explorer Case slightly negatively buoyant. The robot is currently designed to weigh significantly below 30 kg, giving us the freedom to add ballast to both adjust the location of the center of gravity and to switch between positive and negative buoyancy.

5.2. Drivetrain

5.2.1. Differential Steering

SeaDog uses two drive motors to power its four wheel-legs, each motor controlling a different side of the robot. With this arrangement, the robot can be controlled using differential steering methods. This reduces mechanical complexity, making the sealing process easier and more reliable. It also provides zero-turn radius, improving the robot's maneuverability in highly unstructured environments.

5.2.2. Drivetrain Components

Axle diameter and motor power were calculated based on a worst-case scenario in which the robot supported its entire weight and survive a fall from the maximum height of the robot. Several falls of this nature were observed during testing with no observed damage.

The axles of the current robot only span 20% of the robot's width, necessitating larger bearings and axles to balance moment in the shaft. This additional weight in bearings is offset by shorter drive shafts and by a large increase in the unobstructed payload volume.

Drivetrain components for each wheel-leg, including bearings, gears, axles and support structures, have been separated into easily assembled and disassembled subunits. By loosening just three screws and removing the drive chain that couples same-side wheel-legs, each subunit is maintained independently. Complete assembly or disassembly of one of these subunits takes less than one minute.

Tapered roller bearings are a compact and lightweight way to support both radial and axial loads on the drivetrain. We used them in all instances where a bearing was needed except for the motor, where a bearing was already integrated to support radial loads; a thrust bearing was added here to support axial load.

With axial load already being supported, it was decided to use helical gears in place of spur gears. Noise emission from spur gears can be considerable in high speed robotic applications. Helical gears have a smoother overlap between teeth, reducing noise significantly. They also provide extended life and a slight improvement in strength over spur gears with similarly sized teeth.

5.2.3. Removable Concentric Shaft Design

One aim of this project is to make a robot that can be easily transported by a single field technician. To realize this, it is necessary to be able to quickly remove or attach the wheel-legs and tail. Once these were detached, the robot would assume the shape and function of the easy-to-carry Explorer Case that comprises its outer shell.

Implementing the concept of removable wheel-legs has been attempted previously [11] using small crenellations to transmit torque from the motor and to support any axial

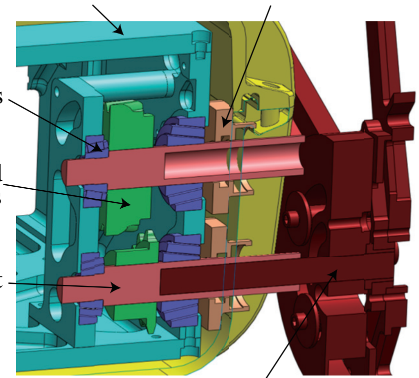


Fig. 7. Cross section of the drive train highlighting the concentric shaft configuration. Components are laid out as such: blue – chassis; purple – bearings; green – gears and sprockets; orange – shaft seal retainers; pink – outer shaft; red – inner shaft and wheel-leg (colors are in original image).

force that creates moment on the wheel-leg. This method worked well when torque was transmitted from the motor, but the wheel-legs were somewhat wobbly because the crenellations were too short to support moment caused by ground reaction force. We have improved on this approach by using concentric shafts to support the moments on the wheel-leg. Here, the smaller shaft attached to the wheel-leg slides into a larger hollow shaft that is coupled to the motor (**Fig. 7**). Using this method, the inner shaft is supported along the entire length of the outer shaft, enabling it to support moments and to prevent wheel-legs from wobbling. Torque is transmitted from the outer shaft to the inner shaft with a key that is "double-trapped," thus preventing axial force from pulling the inner axle out of the robot. The key is kept in place with a clamp that can be removed quickly. Once the clamp and key are removed, the wheel-leg and inner shaft assembly slide out, leaving an Explorer Case easily carried by a field user. The wheel-legs and tail can be carried in a backpack or similar rugged case.

5.3. Seal Testing

5.3.1. Explorer Case Seal

One of the two ways water and dirt can get into the robot is via the neoprene strip that seals the opening between the lid and the main compartment of the Explorer Case. We field-tested two similar cases, the alternative being Hardigg Storm Case model iM2500. We submerged them in progressively deeper water while videotaping them with an underwater camera. After each trial, the inside was checked for leaks. At a depth of 5 meters, large deformations were observed in both cases. As the pressure on the case increases, the strength of the seal also increases due to increased pressure between the neoprene and the plastic rim. This increased pressure advantage may reach a limit, however, because the case deforms so much that it peels the rim away from the neoprene seal,

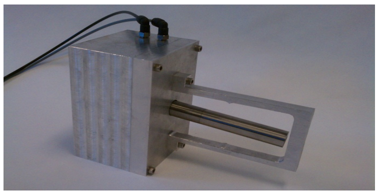


Fig. 8. Apparatus for testing shaft seals at simulated depths. The main chamber is filled with water and then pressurized with air. The shaft is free to spin and become misaligned to test for leaking.

thus allowing water to enter. This deformation is mitigated by the introduction of the aluminum inner chassis.

The Storm Case allowed water in, although at a slow rate, whereas the Explorer Case did not leak. The location of the Storm Case's leak appeared to be at the seam where the neoprene O-ring was bonded to itself. Upon returning to the surface, bubbles were seen escaping from the Storm Case due to added internal pressure caused by the introduction of water. This shows that sealing this case does not resist positive internal pressure, precluding the possibility of pressurizing it to avoid leaks.

5.3.2. Shaft Seals

Whereas the previously discussed seal is a static seal, the seals that prevent water and dirt from entering through openings for shafts must account for the rotational and translational motion of shafts. Larger pressure on the seal results in an increase in friction between the seal and the shaft, which leads to wear on the seal and also wastes energy from the motor. Too little pressure on the seal, however, allows it to leak.

In order to test specific designs, we constructed a small aluminum box with a removable lid. A hole with various grooves for different seals was machined into the lid. A shaft was inserted into the hole and secured from translating axially but remained free to rotate or enable a small amount of misalignment. The box was finally filled with water and a small pneumatic hose pressurized the water to a specified amount. This inverted test method, in which the box is filled with liquid rather than surrounded by it, allowed us to test several solutions in the laboratory at different simulated depths (**Fig. 8**).

Using this in vitro method, we found that a U-cup seal combined with an O-ring prevents leaking during rotation and small misalignments up to at least 689 kPa, which is the approximate pressure at 70 meters under water. The U-cup seal is rated up to 2068 kPa, far beyond any expected field condition.

5.4. Tail Construction

In Section 4, we proposed a method to actuate the tail that was based on a modified worm gear, preloaded with Bellville springs to achieve a passively compliant yet actively controlled body joint. This mechanism was well suited to a robot consisting of two rigid body segments that remained at a constant relative angle to each other during the majority of its operation, yet needed to absorb large impact experienced while traversing rough terrain. SeaDog, in contrast, has a flexible tail instead of a rigid rear body segment. This flexibility fills the role of the Belleville springs in the aforementioned body joint by filtering out impact force when the tail is held in a fixed position. Where a body joint will remain relatively rigid except during climbing, SeaDog will also constantly adjust its tail for various applications, such as flapping the tail as a means of propulsion, maintaining stability while walking on land by dragging the tail on the ground, and actuating the tail to climb over obstacles. We thus eschewed the worm gear assembly for a lower-reduction back-drivable spur gear.

The tail is a simple rectangular aluminum frame that is attached to both sides of an axle that passes through the entire width of the robot. Encoders in the motor allow for position control of the tail, which will be necessary as more autonomous capabilities are added to the robots repertoire. As we attempt more underwater mobility testing, a neoprene sleeve can slide over the tail and be secured in place to act as a control surface for various purposes.

6. Aquatic Locomotion Strategies

Three modes of aquatic locomotion are being available to SeaDog.

The first involves a positively buoyant robot floating at the surface while its wheel-legs are actuated to provide forward thrust and steering. This is possible due to the fact that the lower legs of the wheel-leg pass through the water while the upper legs emerge from the water and pass through the air. This creates a paddleboat-like effect allowing the robot to move along the surface of the water in a manner similar to the RHex and ASGAURD robots [8, 18, 22]. Travelling at the surface makes communication with the robot easier, allows for visual servoing and makes the robot easier to retrieve in the event that control is lost. The robot is left, however, to toss in the waves at the surface.

In the second mode, the robot is negatively buoyant and sinks to the ocean floor. Here, the robot is still subject to surges. However, it can use its tail as a control surface to convert these traversing waves to downward force, giving it more traction and stability much like Ayers' robotic lobster [10]. It is hypothesized that the robot's wheel-legs will be less effective underwater due to increased drag and decreased normal forces while maintaining a large inertia. For this reason, the tail will be used to aid in propulsion.

The third method of locomotion combines the previous two by including a variable buoyancy mechanism, examples of which are described in [5]. In this manner, the robot is free to explore three-dimensional space under the surface of the water and to locomote using either of the previously described methods. In calmer waters, reduced drag and better use of wheel-legs for propulsion can be used at the surface. In surf-zones and heavier seas, added stability found at the ocean floor will be more advantageous.

Table 3. Specifications and performance characteristics.

	Chassis	Overall
Length	56 cm	114.5 cm
Width	30 cm	44.5 cm
Height	18.5 cm	38 cm
Wheel-Leg Radius	19 cm	
Tail Length (short/long)	48 cm	58 cm
Mass w/o Batteries	23.8 kg	
Total Mass	25.1 kg	
Drive Motor Rated Stall Torque	2.28 N-m	
Gear Reduction	38 : 1	
Max Speed	2 body lengths per second (2.23 m/s)	
Turning Radius	0 m	
Max Obstacle Height Tested	48 cm	
Max Pressure Tested (in vitro)	689 kPa ($\sim$70 m underwater)	

Table 4. Obstacle climbing height.

Configuration	Simulated (cm)	Experimental (cm)
Tail	48	48
Body Joint	40	40
No Tail	17	21.5
Body Joint Locked	30	27

Comparison of climbing ability in simulation of a Whegs robot with six wheel-legs and body joint to one with four wheel-legs and a tail.

7. Results

SeaDog was tested in several environments, including a natural body of water with a gravel beach, a grassy field and a steep stairwell. It also completed several stepping tests to evaluate maximum obstacle climbing height. General measurements and performance characteristics were recorded and are presented in **Table 3**, with obstacle height data presented in **Table 4** alongside data from simulation. **Fig. 9** shows video snapshots of SeaDog climbing an object taller than itself in an experiment similar to that simulated in **Fig. 5** with the action of its tail.

8. Discussion

8.1. General Mobility and Stair Climbing

Maximum speed and turning radius compare favorably to our past Whegs^{TM} robots. It should be noted that maximum speed was measured on grass. Previous Whegs^{TM}

Fig. 9. SeaDog climbing a 48 cm high obstacle. In frame 3, the tail helps to prevent high centering by applying counterclockwise moment to the robot. In frame 4, the tail rotates the robot counterclockwise and acts as a support while the robot is off the ground.

robots designed for sandy substrates showed a 58% reduction in speed when transitioning from grass to loose grit sand when using concave "feet" [14]. We expect similar performance for SeaDog.

Climbing three or more stairs is difficult for the robot. The robot's zero turn radius and the intermittent nature of the wheel-legs make it difficult to ascend stairs while maintaining a straight approach. Once the robot rotates on the stairs, maneuverability decreases drastically and usually results in the robot rolling down the stairs. Fortunately, MCM operations differ from standard search and rescue scenarios in that stairs are not encountered. Large unstructured obstacles such as rocks or logs are more likely to be found. Testing in this type of environment is forthcoming.

8.2. Obstacle Climbing

Climbing simulation showed that replacing the rear body joint with a tail of similar length actually increased maximum climbing height from 40 cm to 48 cm. These results were verified using actual robots, as can be seen in **Table 2**. We hypothesize that this increase in height is due to reduced interference that was previously caused by the rear wheel-legs and body joint. The tail allows the robot to approach the obstacle more closely, placing its center of mass in a better position. The lack of the rear body segment also places the center of mass forward, which agrees with data that a more forward center of mass results in better climbing ability and less high centering [23].

Climbing trials at 48 cm were attempted with tail lengths of 48 cm and 58 cm using suggested climbing strategies developed in [12] and [24]. During the climbing sequence (**Fig. 9**), the robot exerts downward force with its tail to transition from vertical to horizontal orientation at the top of the climb. If the tail is too short, it will actually slide underneath the body resulting in a sudden loss in this righting moment, which leads to high centering. The addition of 10 cm in length to the tail eliminated this problem, resulting in the successful ascent of a 48 cm obstacle (2.5 times the leg height). It is also to be noted that current wheel-legs were not able to grip the front surface of the step sufficiently. When the front surface was removed, wheel-legs gripped the underlying scaffolding while climbing. A flat surface will be attempted with improved feet.

Fig. 10. SeaDog using its wheel-legs to swim at the surface of the water.

8.3. Mobility in Water

Figure 1 (p. 630) shows a snapshot from a video taken of robot transitioning from land to water. Preliminary water mobility testing was done at the surface with positive buoyancy using the wheel-legs as paddles (**Fig. 10**). Even without wheel-legs designed for paddling, the robot was able to move forward and backward and turn with reasonable success in water. Speed was much slower than land-based locomotion, as was expected. It is believed, however, that improved wheel-leg design with paddling in mind would greatly help with this. (See http://faculty.nps.edu/ravi for videos.)

9. Conclusions

SeaDog shows promise as a dual mobility land-water vehicle targeted for mine detection, and as the precursor to an entire line of amphibious robotics devices. It builds on previous designs by integrating a large payload capacity with the ability to traverse sand and mud, climb obstacles and swim, making it an ideal candidate for mine detection and neutralization. Further extensions of this work include optimizing tail design for both climbing and swimming, wave pool testing and the development of autonomous navigations techniques.

Acknowledgements

The authors gratefully acknowledge the continued support of Dr. David Olwell, Dr. Clifford Whitcomb and the Department of Systems Engineering, the Center for Robotics and Unmanned Systems Education and Research (CRUSER), and the Office of Research at the US Naval Postgraduate School. This research was supported by the Temasek Defence Systems Institute (TDSI) and National University of Singapore under Grant TDSI/06-006/1A.

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