Design and Testing of an Autonomous Highly Mobile Robot in a Beach Environment

Richard Harkins, Thomas Dunbar, Alexander S. Boxerbaum, Richard Bachman, Ravi Vaidyanathan, and Roger D. Quinn

***Abstract*— The capability of autonomous platforms to function on beaches is critical for a wide range of military and civilian operations. Of particular importance is the ability to autonomously navigate through rocky terrain, hard-packed moist sand, and loose dry sand typically found in these environments. The study of animal locomotion mechanisms provides specific movement principles that can be applied to address these demands. In this work, we report the design, fabrication, control system development, and field-testing of a biologically inspired autonomous robot for deployment and operation in a surf-zone environment. The robot successfully fuses a range of insect-inspired passive mechanisms with active autonomous control architectures to seamlessly adapt to and traverse through a range of challenging substrates. Field testing establishes the performance of the robot to navigate semi-rugged terrain in the surf-zone environment including: soft to hard packed sand, mild to medium inclines, and rocky terrain. Platform autonomy is shown to be effective for navigation and communication. The fusion of passive mechanisms and active control algorithms enables the robot with the mobility of a legged vehicle with a control system as simple as that of a wheeled robot.**

***Index Terms*— biologically inspired robotics, legged vehicles, field robotics, advanced mobility, autonomous control**

I. Introduction

The ability to employ autonomous robots in difficult terrain continues be a rich area for research. In particular, there has been significant interest in the development of robots capable of autonomous operation within beach and turbulent ocean surf-zones environments. Potential utilities for such a robot include: mine clearing, terrain mapping, and scouting potential approach lanes for amphibious naval operations [2].

A number of research groups have constructed platforms with the eventual goal of facilitating operations of this nature. These have included wheeled and tracked variants such as the Foster-Miller LEMMING [1], legged and crawling robots [8, 9], snake robots [15], and walking-platforms such as AQUA [10] (based on the RHex [14] platform), which, with manual adjustments, 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. A major hindrance to this realization is the tradeoff between complex mechanical designs facilitating mobility over several substrates, verses the difficulty of controlling these structures with enough rigor for full autonomous operation.

Our on-going research has attempted to address this issue through the development of a hybrid wheel-leg (dubbed Whegs^{TM} [6]) platform drawing inspiration from cockroach mobility principles. In past work, our laboratory demonstrations and limited field testing [2, 3] have shown intriguing potential for combining active and passive control mechanisms to achieve the autonomy and robustness necessary for operation in the rocky terrain, hard sand, and soft sand that characterize the surf-zone environment. In this work, we report the development of a robot capable of traversing all these terrains with no input from a human operator. The robot design, incorporation of passive mechanisms for traversing variable challenging terrain, autonomous control system (hardware and software), and communication system are detailed. Results culminate with a full field demonstration of mobility and autonomy (waypoint navigation) on the beach in Monterey, California.

II. Autonomy and Challenging Terrain

Vehicle operation over rugged terrain without operator intervention poses many unique challenges. The surf-zone, in particular, presents a host of distinctive environmental issues. Paramount among these is the capacity to navigate various obstacles while transiting dramatically different terrain. For example, mobility tuned for soft sand is often not optimal, or even functional, for hard packed sand or a rocky beach. A platform tuned to operate smoothly in wet hard-packed sand might be impaired in dry soft sand and would have trouble maintaining balance (e.g. 'high center') on a rocky beach unless endowed with the capacity to adapt to fluctuations in terrain. Another critical challenge is to provide reasonable path control, obstacle avoidance, and the capacity to forward communications and data while in autonomous mode.

Figure 1 illustrates a potential operational scenario for a surf-zone robot with wheel-leg appendages moving over terrain typified by this region.

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Figure 1 Image rendering for a robot moving from the water to the beach

III. Biologically Inspired Mobility

Cockroaches have remarkable locomotion abilities that provide a wealth of inspiration for robot design (Figure 2). This capacity can provide specific inspiration to address challenges of surf-zone operation. In studies of cockroach movement, we have noted the following [12]:

- A cockroach has six legs that support and move its body
- It typically walks and runs in an alternating tripod gait wherein the front and rear legs on one side of the body move in phase with the middle leg on the other side
- Although the front legs swing head-high during normal walking so that many obstacles can be surmounted without significant gait change, the animal changes its gait when it encounters larger barriers
- The cockroach turns by generating asymmetrical motor activity in legs on either side of its body as they extend during stance [11]
- A cockroach enhances its climbing abilities by changing its body posture before and during a climb over an obstacle [4]
- It uses its middle legs to pitch its body up prior to climbing obstacles that are higher than its head, which enables its front legs to reach higher (Fig. 2, lower left)
- During a climb it uses flexion joints to bend the front half of its body down to avoid high centering (Fig. 2A, 2B)

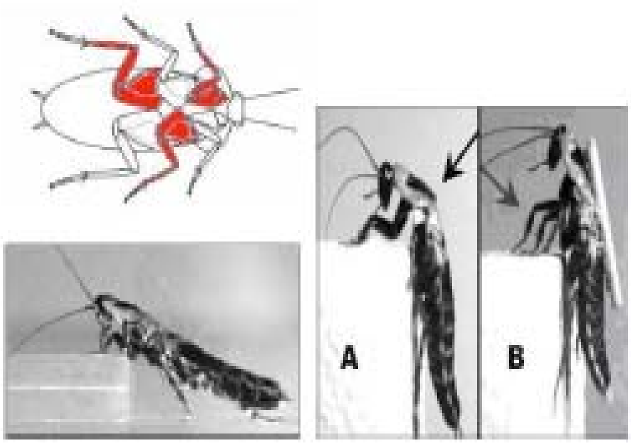

Figure 2: Cockroach climbing and tripod gait locomotion [13]: graphic of tripod gait (top left), change of posture to climb (lower left), body flexure while climbing (A), and difficulty in climbing with flexure restricted (B)

IV. Design of Surf Zone Robot

The CASE/NPS Beach Whegs™ robot is designed with active and passive mechanisms for maximum mobility and terrain adaptability. Specifically, the robot is propelled by a single motor to move in a cockroach-like tripod gait normally, but passively adapts to obstacles by implementing a mechanically compliant axle within each wheel-leg. Its integrated body houses electronics for autonomous GPS waypoint navigation. Figure 3 shows the prototype constructed in this work.

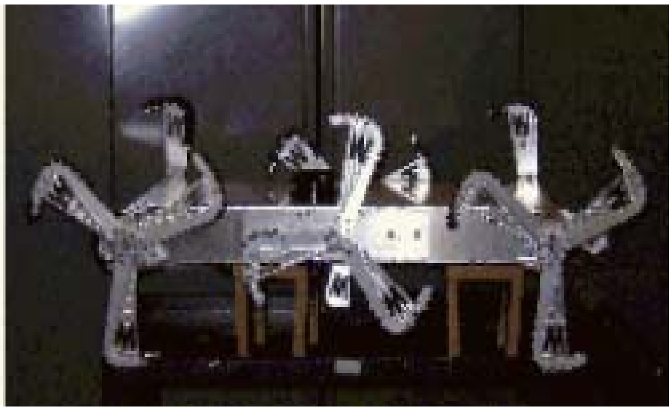

Figure 3: The Prototype Beach Whegs™

A. *Mechanical Design*

Similar to all Whegs™ robots, a single drive motor powers six multi-spoke appendages, called wheel-legs. Neighboring legs are offset by 60°, yielding a nominal cockroach-like tripod gait (Figure 3). The spokes allow the robot to climb over larger obstacles than a vehicle with similarly sized wheels. The robot is equipped with compliant mechanisms in all six of its axles (Figure 4). These mechanisms allow the robot to passively adapt its tripod gait to irregular terrain. This compliance captures much of what the cockroach accomplishes with its local neuromechanical system and greatly simplifies the robot's control system.

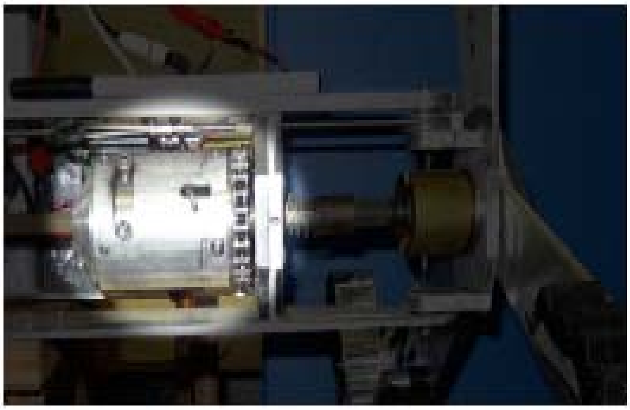

Figure 4: Passive Compliance Mechanism in an Axle

Additional features of this robot implemented to accommodate its size, payload, and capacity for surf-zone operation include:

Cable Steering: Whegs™ hexapod robots are steered by rotating their front and rear wheel-legs in opposite directions. Previous versions of Whegs™ use a hobby servo to drive a four-bar mechanism through a tie-rod. For the surf-zone robot, we used a more powerful servo linked to the wheel-legs with a cable. This allows for a more compact design, consistent torque, and a larger-range of motion, which provides a smaller turning radius. We have also found that the elasticity of the cable insulates the servo from the harsh impacts the wheel-legs experience on rocky terrain. Several materials for the cable design were tested, including Spectra, Kevlar and aircraft steel. The reoccurring problem was breakage of the cable due to fraying at the attachment points. Spectra did not fray when used with knots instead of screw plates; yet tension was inconsistent. Ultimately, a thicker steel cable with nylon coating was used with success.

Foot design: Two kinds of feet were tested for maximum terrain adaptability. One was designed for grassy fields and soil, consisting of an aluminum spike or claw offset from the spoke. This design performed well on those substrates. The spike penetrated the top layer of grass, giving it excellent traction on an otherwise slippery surface. Using these feet, the robot was able to climb up a 32 degree slope hill. However, these feet were not suited for hard or sandy surfaces. There was no damping and the wheel radius was highly discontinuous. Furthermore, this foot had insufficient surface area to keep the robot from sinking into the sand. An alternate design was developed for more general use. It consisted of a one-inch wide aluminum and rubber foot with wave treads. This was tested in the Nevada desert and demonstrated excellent performance on rocks, gravel, packed dirt, and even indoor carpeting. This design also added the benefit of a 'zero-scrub' radius; *i.e.* the 1" wide foot was arranged to locate the center of the foot directly below the steering axis of rotation. This eliminates any moment about the steering axis caused by ground reaction forces. The design enabled stronger controllability, particularly at high speeds, and less wear on the steering servos.

Partially enclosed body: The field-tested robot design has a partially closed body with small openings along the seams. While not fully enclosed, the robot casing protected interior components from the environment. Future work will involve a fully sealed body for in-water operation.

Heat: The robot's sealed body inhibited heat dissipation, which became a problem in certain environments. The speed controllers and batteries were particularly vulnerable to issues with overheating. We installed a fan and several air filters to reduce box temperature. Furthermore, the interior was designed to separate heat producing from heat sensitive components and custom heat sinks were built to transfer heat from the motor and speed controller to the outer aluminum wall of the robot.

Wide body and steering mechanism: The robot had a toe-to-toe width of 50cm (20 inches) with a wheel-leg radius of 19cm (7.5 inches). A wide body steering mechanism had to be designed to support robot turning. In rocky terrain, rocks small enough to pass between the legs had to be accounted for in design.

Weight: With GPS equipment and all-terrain feet, the mass of Beach Whegs™ is 16.8kg (37 lbs). When the drive electronics were running properly, giving full torque, this weight appeared to be acceptable. The robot could climb steep slopes and full size stairs.

B. Electronic Hardware

To realize autonomy, the robot was populated with various controllers and sensors. The heart of the platform was based on the Z-World Wildcat BL2000 microcontroller. The BL2000 uses a 22 Mhz Rabbit processor that is programmed in C and comes with a ready function library and development environment.

A Garmin GPS unit was used for land based positional awareness. An HMR2100 Honeywell digital magnetic compass with a built in inclinometer was also installed on the vehicle. GPS and compass data update rates were on the order of 4 Hz. A Netgear Access point was used for communication and data telemetry. A Crossbow accelerometer was also incorporated into the design.

For motor speed and direction control, a pulse width modulation (PWM) circuit was designed and constructed. For this circuit, a 555 timer chip was used to create a saw-tooth signal that was fed into the non-inverting side of an operational amplifier in comparator mode. Input from the DA converter on the micro-controller was fed to the inverting input based on calculated control requirements. The result was a PWM signal for direction and speed control to the motors. The turn direction was implemented by the servos attached to the forward and aft wheel-legs. Figure 5 illustrates the output of the comparator as a function of the inputs.

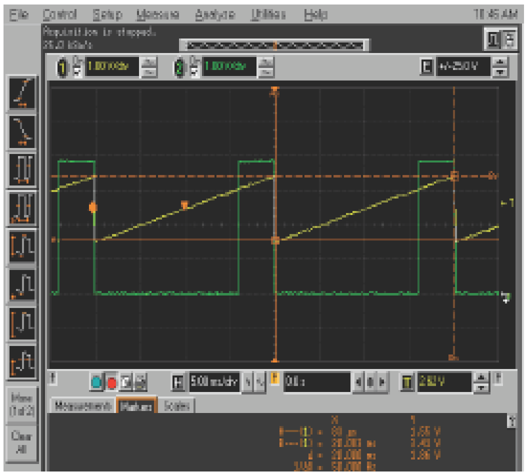

Figure 5: The PWM Signal

C. Communications

The communications design for our platform was anchored on a UDP/IP stateless 802.11b/g protocol. A stateless protocol is preferred so that communication would not hang on a failed 3-way handshake inherent in full state communications. Data to the robot included up to 10 waypoint latitude and longitude positions and an ability to drive the platform manually. The latter was a necessity for in-field experiments. A way to manually stop and maneuver the robot was essential to protect the robot during testing and integration. Figure 6 shows the communications ports as they relate to robot algorithms. Waypoint data is processed by the waypoint handling function, while manual control strings are passed directly to the PWM for direct control of the robot.

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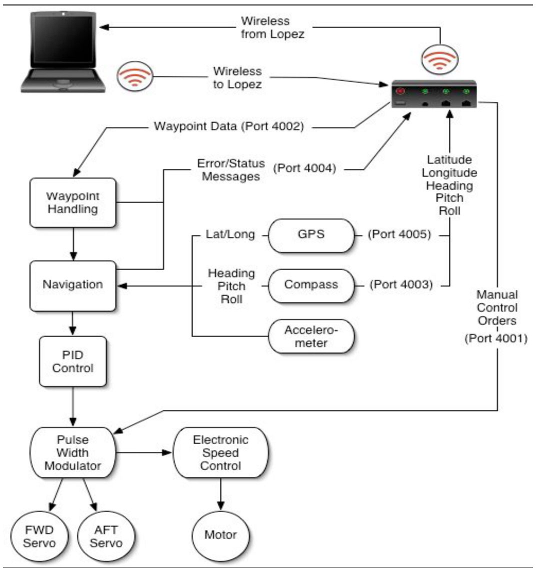

Figure 6: Robot Communications Architecture

Outgoing data included real-time position and heading information and any error messages from the robot to the control station while in autonomous mode.

D. Control

The robot is placed into autonomous mode when the control station sends waypoint route data to the platform on UDP port 4002. Figure 7 illustrates the functional and hierarchical relationships for the robot co-statements while autonomous. Co-statements are a Z-World implementation for cooperative multitasking (shared CPU time) between the control functions. As waypoint, compass, and GPS data are fed to the navigation function, plant signals are calculated and sent to the PWM which signals the motor-controllers to maneuver the robot.

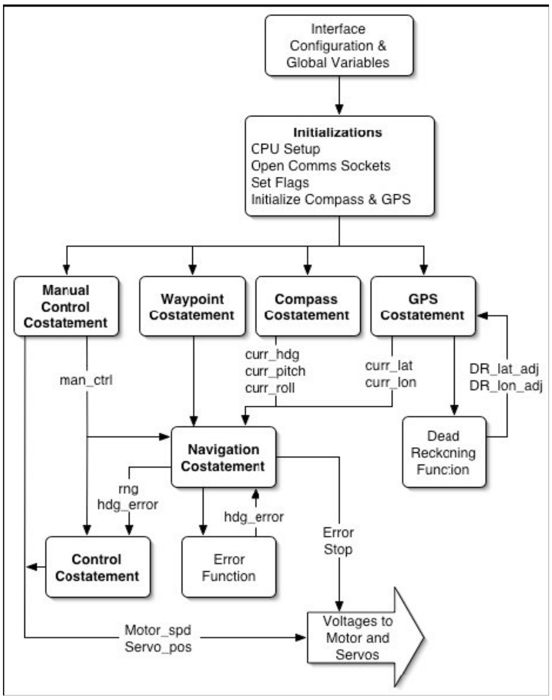

Figure 7: Robot Autonomous Control Logic

E. PID Heading Control

Robot course and heading control is realized with PID control. The feedback loop is depicted in Figure 8. Upon receipt of waypoint data, the robot calculates a desired course and range and figures error which is passed to the compensator. The compensator operates on the error and determines a signal (S) that is sent to the plant. The objective is to drive the error (difference between desired and actual heading) to zero in an optimal (critically damped) way. The feedback loop, through the digital compass, is used to monitor the desired outcome and continuously update the calculated error. The proportional, integrative, and derivative gain coefficients were established through an in-field tuning process using a modified Ziegler-Nichols Method.

Figure 9 shows the robot with all these features, including the new foot design, steering linkage, integrated autonomous GPS navigation hardware, and all sensor components.

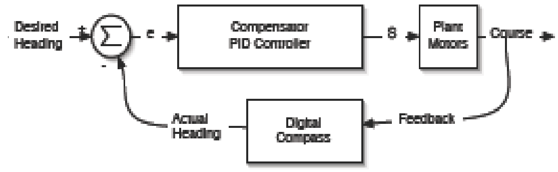

Figure 8: Functional Control Loop for Heading

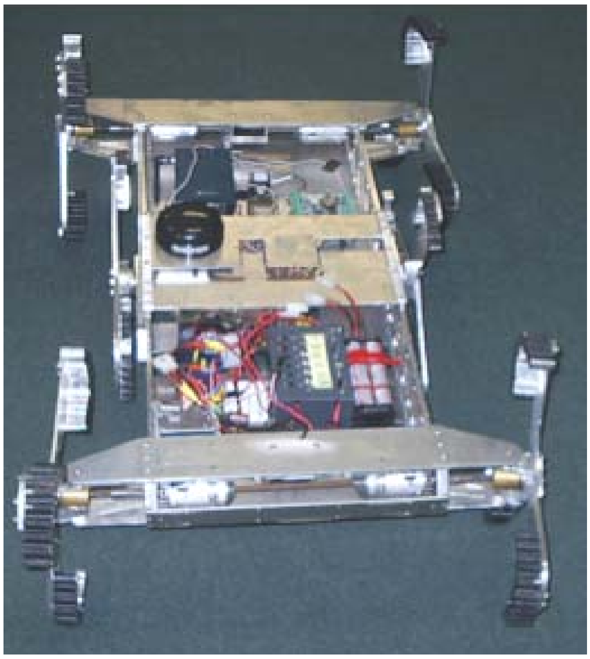

Figure 9: Surf-Zone Robot with Mechanical and Electrical Components

V. Results

A. Locomotion

In a series of field experiments, Beach Whegs™ was tested in hard packed sand with a transition to soft dry sand in 20° to 30° inclines. In the hard packed sand, with minor exceptions, the robot maintained the tripod gate. Passive compliance was observed in the transition to soft sand without any loss of mobility or control. In contrast, wheeled robots were tested in this terrain and observed to 'bog down' in the exact same soft sand conditions. Inclines over approximately 30° in soft sand proved challenging for the robot, yet mobility was maintained with some loss of speed due to slippage of the feet slipped. Passive gait change was also observed more frequently over higher inclines. Figure 10 shows a snapshot of one experiment of the robot maintaining mobility under autonomous control over soft sand. Note the depth of the footprints left by the feet in the soft sand, indicating the actions of the feet and additional forces provided by the passive mechanisms of the robot.

Figure 10: Robot crawling over soft sand

B. *Control*

Autonomous waypoint navigation was demonstrated in a facsimile de-mining mission on the beach in the non-submersed surf-zone region. In the facsimile mission (Figure 11), a series of waypoints were given to the robot (representing possible mines). The robot was to navigate autonomously over any obstacles or change in substrate to each waypoint, circle the waypoint to inspect the possible threat, and move to the next location. The robot recovered from all terrain perturbations in the field environment while in transit to multiple waypoints. Navigation was based on GPS data. Figure 11 (a-f) shows progressive snapshots of the robot walking autonomously on the beach over both hard and soft sand to reach a series of waypoints (designated by flags in the snapshots).

Figure 11 (a-f): Progressive snapshots of the robot walking autonomously on a beach in Monterey, CA to reach waypoints

VI. Conclusions and Future Work

The objective of this research was to develop a prototype beach robot capable of navigating complex terrain and changing substrates seamlessly and autonomously. A secondary goal was to determine if the Whegs™ platform was robust enough and mobile enough to operate in this environment to justify future work in this area. A third goal was to demonstrate how simplified, implementable robust control can enable complex locomotion over varying terrain through synergistic interaction with passive mechanisms in mechanical design. It is our opinion that our data confirm all these objectives.

We report the successful design, construction, and implementation of communication and autonomous control systems on a robot capable of navigating the challenging terrain of the non-submersed surf-zone region. The robot benefits from insect inspired mechanisms of locomotion for movement over various and different terrains. The robot's mechanics are an integrated and essential part of its control system. It does not have (or need) sensors and control circuits to actively change its gait. Instead, its mechanics cause it to passively adapt its gait appropriately to very different terrains. Therefore, its motor control circuits are reduced to controlling only speed and heading of the robot – much like that of a wheeled vehicle. Its navigational system is a higher-level circuit that communicates desired speed and heading to the local control system. Therefore, Beach Whegs™ has a control system with the simplicity of a wheeled vehicle which nevertheless facilitates the mobility of a legged vehicle.

In extending this work we intend to develop a lighter, carbon fiber or Kevlar, water tight vehicle that can be tested in the water and in transit to the beach to reproduce these results while transitioning from aquatic to terrestrial environs. This platform will have the ability to swim or walk in the transit towards the beach. We are also in the process of developing a new multi-modal locomotion mechanism combining aquatic propeller propulsion with terrestrial locomotion capacity provided by Whegs™. Propeller wheel-legs will propel the next generation robot in both land and aquatic modes.

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