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Design of an Autonomous Amphibious Robot for Surf Zone Operations: Part II - Hardware, Control Implementation and Simulation

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Abstract— **This paper describes on-going work at The Naval Postgraduate School (NPS) and Case Western Reserve University (CWRU) to create an autonomous highly mobile amphibious robot. A first generation land-based prototype has been constructed and field tested. This robot design, based on a tracked element, is capable of autonomous waypoint navigation, self-orientation, obstacle avoidance, and has the capacity to transmit sensor (visual) feedback. A water-resistant second generation amphibious prototype design, based around the biologically inspired Whegs^{TM} platform, has been completed. This design marries the unprecedented mobility of Whegs^{TM} with the autonomous hardware and control architectures implemented in the first generation prototype. Furthermore, we have also implemented a dynamic simulation capturing salient features of Whegs^{TM} for testing of robotic locomotion capabilities. The integration of these elements will lay the foundation for the development of a new generation of highly mobile autonomous amphibious robots.**

Index Terms— **Biologically inspired robotics, legged vehicles, micro-robots, reduced actuation.**

I. INTRODUCTION

There has been significant interest in the development of robots capable of autonomous amphibious operation within turbulent ocean surf zones. Of particular importance is the achievement of missions focused on the removal of shallow-water mines. Critical features include the ability to follow a search instruction plan, rigorous terrain mobility, and the capacity to classify and map underwater mines and other potential threats. Long term visions include the use of robots to scout and map potential approach lanes for amphibious naval operations. Control, navigation, communication, obstacle avoidance, and sensor payloads remain critical issues to be resolved for successful operation. Recent work [1], [2], [3] in this area has focused the construction of robots based on legged and/or crawling elements to address these issues.

A. Biologically Inspired Mechanisms

Cockroaches have remarkable locomotion abilities. One solution to the problem of producing highly mobile amphibious robots is to design a vehicle with the mechanisms responsible for the mobility of a cockroach [5]. In studies of cockroach movement, we have noted the following locomotion principles. A cockroach has six legs, which support and move its body. It typically walks and runs in a tripod gait where the front and rear legs on one side of the body move in phase with the middle leg on the other side. The front legs swing head-high during normal walking so that many obstacles can be surmounted without significant gait changes. However, its gait changes when it encounters larger barriers.

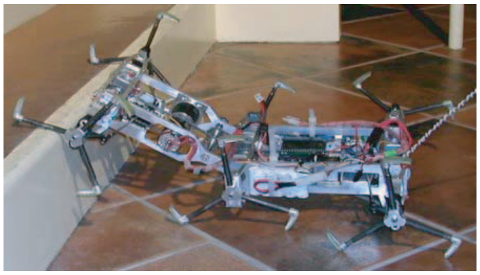

Fig. 1. Whegs^{TM} II rearing half of its body.

The cockroach turns by generating asymmetrical motor activity in legs on either side of its body as they extend during stance [6]. A cockroach enhances its climbing abilities by changing its body postures before and during a climb over an obstacle [7]. It uses its middle legs to pitch its body up, prior to climbing obstacles that are higher than its head. This behaviour enables its front legs to reach higher. Also, during a climb it uses its body flexion joints to bend the front half of its body down to avoid high centering. A cockroach enhances its climbing abilities by changing its body postures before and during a climb over an obstacle [7]. It uses its middle legs to pitch its body up prior to climbing obstacles that are higher than its head. This behaviour enables its front legs to reach higher. Also, during a climb it uses its body flexion joints to bend the front half of its body down to avoid high centering.

Whegs^{TM} (Fig. 1) is a proven rugged all-terrain line of vehicles capable of fast running and climbing through the incorporation of all of the aforementioned biologically inspired mechanisms to navigate terrain. In their design, a single drive motor powers six multi-spoked appendages called wheel-legs. Neighbouring legs are offset by 60 yielding a nominal tripod gait. The spokes allow Whegs^{TM} to climb over larger obstacles than a vehicle with similarly sized wheels.

Whegs^{TM} robots have compliant mechanisms in all six

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Fig. 2. Whegs^{TM} II flexing its body as it climbs over a curb

of their axles. These mechanisms cause them to run in a nominal tripod gait, but passively adapt their gaits to irregular terrain. This compliance captures much of what the cockroach accomplishes with actions of its distal leg joints. The use of a single large drive motor provides a high power-to-weight ratio, making Whegs^{TM} highly energetic, and compliant drive components enable passive gait adaptation over irregular terrain.

Additionally, Whegs^{TM} II, Fig. 1, incorporates a body flexion joint in addition to all of the mechanisms that were implemented in its precursor, Whegs^{TM} I [8]. This actively controlled joint enables it to perform both of the above posture changes used by the cockroach, thereby improving its climbing ability as seen in Fig. 2.

B. Objective

We summarize on-going efforts at NPS and CWRU aimed at the development of autonomous robotic devices capable of operations within the ocean surf zone. Part one of this project, the "Design of an Autonomous Amphibious Robot for Surf Zone Operation: Part I, Mechanical Design for Mulit-Mode Mobility" [4], deals with the mechanics of our platform. In this paper we report:

- The development of a first generation *autonomous* land-based robot which will serve as a model for hardware and control architectures for implementation on an amphibious platform.
- The development of a prototype mechanical platform designed for arduous terrain locomotion ideally suited for amphibious operation.
- The completion of a preliminary design integrating hardware and control architectures onto the proposed amphibious locomotion platform.
- The implementation of a dynamic simulation for robotic locomotive capability testing for design optimization.

Our first goal was to develop a platform that would operate autonomously under waypoint navigation and collision avoidance. This was done with a tracked vehicle. The Robot would need to communicate in an IEEE 802.11 wireless environment, return visual data and be able to respond to manual user input as required.

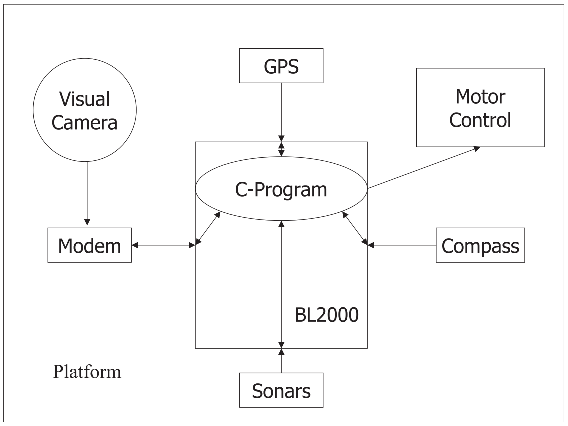


Fig. 3. Robot Architecture

II. FIRST GENERATION ARCHITECTURE

A. Hardware

Fig. 3 illustrates the architecture developed for the NPS autonomous robot. The heart of the system is based on the BL2000 WILDCAT microcontroller produced by Z-World. The BL2000 is programable in C and has a development environment with a library of functions available for its interface ports and Ethernet interface.

The GPS and compass components are connected via RS-232 ports. Ultrasonic sonars, with an analog voltage output, are used for collision avoidance. The modem is a Netgear 802.11g access point set up for UDP/IP communications. A standard RJ45 connection is used for this device. Motor control is realized with an analog voltage output to a PWM circuit interfaced to an RC motor controller, this gives the robot differential motor control capabilty. Finally, our visual sensor is a standard DLink Web Cam, set up with a unique IP address and connected directly to the modem. Table I gives a summary of the installed components.

The components are powered by a 15 and 6 volt (regulated) power-bus. These are supplied by a 15 volt, 11 amp-hour Lithium Polymer battery. The power bus and major components are displayed in Fig. 4.

The Robot was developed on a Foster-Miller *Lemming* tracked platform. Fig. 5 gives a forward view illustrating the layout of the key sensors. The camera is mounted forward of the Garmin GPS receiver while the sonar array is mounted in the robot superstructure as shown.

TABLE I
ROBOT PARTS SUMMARY

Components	**Model**	**Vendor**	**Comments**
Platform	Lemming	Foster Miller	Differential Drive
Micro-controller	BL2000	Zworld	Web Capable
GPS	GPS16	Garmin	WAAS Capable
Compass	HMR2300	Honeywell	+/- 1 Degree
Sonar	Ultra-30	Senix Corp	1-3 Meters
Modem	802.11g	Netgear	Access-point

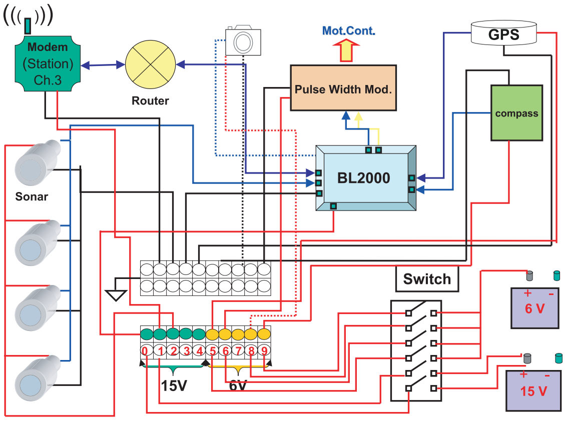


Fig. 4. NPS Autonomous Vehicle Power Bus [11]

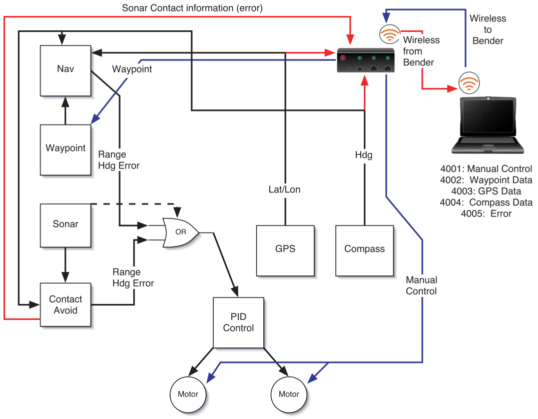


Fig. 6. Algorithm Information Flow [9]

B. Software

A 500 line C program anchors our system and is compiled to flash ROM on the WILDCAT. Z-World Dynamic C offers COSTATE capability and is invoked in our program. COSTATES provide for the ability for functions to operate cooperatively during runtime. We found that this helped optimize our code by allowing functions to give up CPU cycles while waiting for a response or input from internal or external devices.

The advantage is that the program uses CPU cycles more efficiently; the disadvantage is that the programmer loses some control over function implementation.

Algorithm logic is viewed in Fig. 6 and COSTATE functions are listed. Any valid sonar contact is serviced as an Interrupt Service Routine (ISR) and control is passed to the Sonar COSTATE. You will notice that the Manual Control COSTATE overrides all other COSTATES in the algorithm.

C. Communications

The wireless architecture was used for three purposes:

1) Pass waypoint data prior to transition to autonomous control
2) Take manual control
3) Send telemetry (GPS, Compass) and/or error data to the remote wireless station

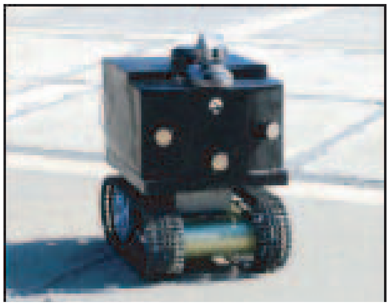
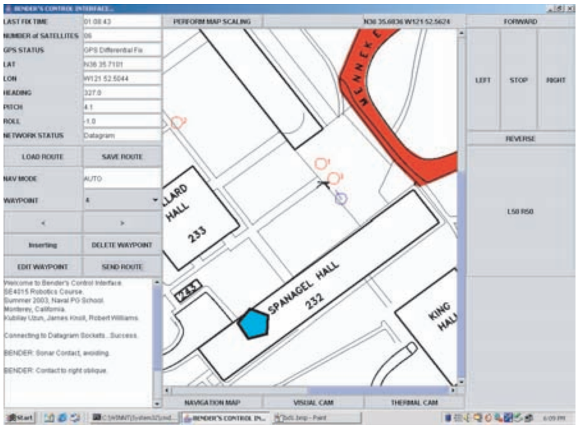


Fig. 5. Front View

Five UDP/IP communications sockets are established and bound to the ports shown, Fig 6. Ports 4001 and 4002 are set up one way from the remote station to the Robot and ports 4003, 4004 and 4005 from the robot to the remote station. The UDP protocol is preferred because we do not need a three-way handshake for communication.

A Java application, "MainApp", was developed for the remote station, Fig. 7, for the user interface. "MainApp", displays GPS, waypoint and compass data (on the left), a field for a scaled chart (center), manual control interface and a joystick pad (on the right). The scaled chart can be grid locked to GPS coordinates. Therefore selection of waypoints is simply a matter of double clicking a position on the chart and sending the waypoint to the Robot via the "Send Route" button.



LAST FIX TIME 01:08:43
NUMBER of SATELLITES 06
GPS STATUS GPS Differential Fix
LAT N36 35.7101
LON W121 52.5044
HEADING 327.0
PITCH 4.1
ROLL -1.0
NETWORK STATUS Datagram
NAV MODE AUTO
WAYPOINT 4

N36 35.6836 W121 52.5624

L50 R50

Welcome to Bender's Control Interface.
SE4015 Robotics Course.
Summer 2003, Naval PG School.
Monterey, California.
Kubilay Uzun, James Knoll, Robert Williams.

Connecting to Datagram Sockets...Success.

BENDER: Sonar Contact, avoiding.

BENDER: Contact to right oblique.

Fig. 7. Example of the Main Application Interface showing the Icons for waypoints in red and the robot in blue. Here we see the robot enroute waypoint 1 [10]

In Fig. 7 we see the robot en-route waypoint 1. The chart is a scaled version of the NPS quadrangle. Spanagel Hall is the Science and Engineering Building. You will notice that parsed GPS and compass data are sent to the remote station and displayed in the control panel. This gives the observer a quick view of the status of the robot while in auto (autonomous) mode, as indicated by the NAV MODE dialog box in fig 7. The icon for the robot is blue and shows a heading leader based on compass input. You can see that the heading is reported as 327 degrees magnetic. On this chart north is up, so we are confident that the heading is correct.

Communications and error data are displayed in the left hand box. Information about sonar contacts and waypoint navigation is also passed and reported here.

D. Control

To give the robot the ability to control it's heading during transit and turn rate during position corrections, a standard PID controller was invoked:

$$S = P_c e_{(t)} + I_c \int_{t_0}^{t} e_{(t)} dt + D_c \frac{de_{(t)}}{dt} \tag{1}$$

The control signal S is sent to the plant from the compensator as illustrated in Fig. 8.

For our architecture we chose to invoke the PID controller in software. The gain coefficients P_c, I_c and D_c where established empirically through field tests and were normalized to one. We summed the PID outputs as follows:

$$S = S_P + S_I + S_D \tag{2}$$

Where:

$$S_P = P_c e_{(n)} \tag{3}$$

$$S_I = I_c \sum_{n=0}^{5} e_{(n)} \tag{4}$$

$$S_D = D_c (e_{n+1} - e_n) \tag{5}$$

In our case, the error $e_{(n)}$ is the difference between desired and actual heading in degrees, $e_{(n)} = \theta_d - \theta_a$. The sensor for the feedback is the digital magnetic compass. Upon receipt of waypoint latitude and longitude coordinates, the robot calculates desired heading and distance and then determines error. The receipt of a valid route-plan also places the robot in autonomous mode. Error is passed to the compensator, invoked in software, as a dynamic COSTATE. The output of the compensator is a number, S, that is interpreted as a motor control voltage and is passed to the plant.

Proportional gain, and subsequently proportional control, dominates our equation. Little velocity feedback is required since our platform moves slowly. Integral control is needed to compensate for a DC offset that we often encounter as we near our desired heading. The unit is relatively heavy such that proportional control inputs from the compensator are not enough to overcome ground friction, motor friction and platform inertia. We needed to integrate over at least five program time counts to overcome this problem.

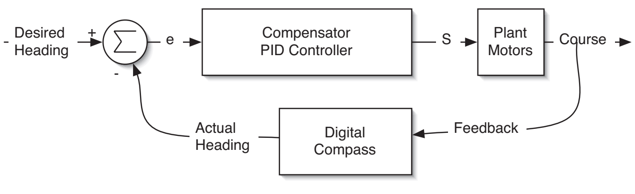


Fig. 8. Functional Control Loop

E. Results

The hardware, and control architecture provided the robot with the ability to conduct waypoint navigation and collision avoidance in the field. Fig. 9 shows the robot approaching from the right, enroute a waypoint avoiding an obstacle (person) by maneuvering to the right.

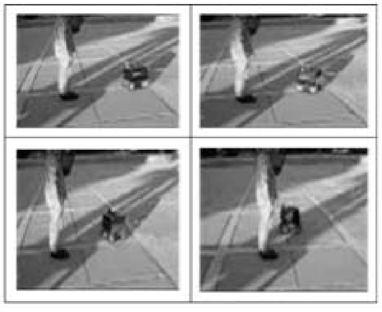


Fig. 9. The Robot Avoids

However the tracked vehicle does not operate nicely in rugged terrain environments. It is relatively heavy and slow and has difficulty traversing obstacles. As a Consequence, it has a tendency to high center on relatively small protrusions.

Therefore, this autonomous functionality will need to be used in a more versatile and rugged Platform and is planned for the Whegs^{TM} IV platform.

III. AMPHIBIOUS WHEGS^{TM} DESIGN

Whegs^{TM} IV is designed to have a fully enclosed chassis that is waterproof in up to 40 feet of water and dirt proof on land. This will allow the robot to autonomously navigate the ocean floor, surf zone and beach with little or no low-level control.

Previous Whegs^{TM} designs [8] have an open-frame, where all components are attached to one of the cross members. This allows for a lightweight chassis that is easy to service Fig. 10. However, dirt and debris can clog the drive train and damage the electronic components. Whegs^{TM} IV is completely encased, keeping dirt as well as water out. Each body segment is constructed from four aluminum side panels and carbon fiber tops and bottoms. Each set of four side panels is sealed to itself using a silicone liquid gasket, while the carbon fiber panels are sealed to the side panels using rubber gaskets. This will allow the robot to be easily serviced by removing the carbon fiber panels without breaking the seals between the side panels.

Special consideration is needed to accommodate the drive train as it passes through the body joint. The chain and sprocket running from the middle axle to the front axle needs

Fig. 10. Whegs^{TM} IV concept rendering

Fig. 11. Whegs^{TM} IIII body joint drive shaft (right) and middle axle (left) in coaxial arrangement

to be encased and sealed. There also has to be a way to actuate the body joint. Both of these goals are accomplished by extending the case of the front body segment around the whole chain and sprocket that connects the two body segments. This protrusion of the case then mounts to the rear body segment at the middle axle in a coaxial arrangement. The outer axle actuates the body joint and the inner axle attaches to the sprocket and chain to deliver torque to the front wheel-legs. By keeping all connections axial in nature, a standard rotary seal can be used to keep water and dust out.

Rotary axles must also penetrate the body of the robot in six other places, one for each wheel-leg. Several rotary shaft seals are in consideration for this task. One possibility is a mechanical seal, with two mating parts rotating against each other, one mounted to the shaft and the other mounted to the body. Another possibility is a single or double O-ring seal, which can be specialized for positive and negative pressure, but are more susceptible to leaking as grease wears off. Finally, a spring loaded graphite ring can mate with a polished shaft. All of these solutions may be complimented by pressurizing the hull to push air out, instead of pulling water in, if a leak occurs. Steering push rods that also penetrate the body of the robot and must be sealed. Since they have a limited range of motion, a flexible rubber bellows can be permanently affixed to the push rod and housing.

Because the robot is intended to be autonomous with little or no knowledge of small obstacles in its immediate path, it is best if these obstacles can be surmounted passively whenever possible. The aforementioned strategies implemented in Whegs^{TM} II are useful to this end. Whegs^{TM} IV has several advancements to this end.

A body joint on previous Whegs^{TM} allowed the robot to climb larger objects by giving the front wheel-legs higher reach and by preventing high centering. However, several designs have not survived field testing. The first version of Whegs^{TM}I with a body joint used a large backdrivable servo, which allowed the motor to absorb some of the shock of impact, but constant current draw quickly drained the batteries. To remedy this, Whegs^{TM} III used a non-backdrivable worm gear. However, the teeth of the gear sheared off under impact loading. The Whegs^{TM} IV body joint has a worm gear in series with the transmission and motor, like Whegs^{TM} III. However, the tooth face is twice as large and has been designed to withstand the frequent impact loads the robot experiences, Fig. 11.

The Interior view of component layout is seen in Fig 12. Whegs^{TM} IV will include space for the components used by the NPS first generation autonomous vehicle. With the exception of the motor and torsion devices, the front compartment is left free for electronics and sensors. Batteries, speed controllers, the body joint mechanism and motor, and additional electronics are stored in the rear body segment. With a microprocessor, GPS, compass and three sonar sensors, there is still ample room for additional equipment.

IV. SIMULATION FOR DESIGN OPTIMIZATION

Finally, we have constructed a basic environment such that our amphibious Whegs^{TM} design may be tested dynamically in simulation prior to construction. The results of one simulation run, in this environment, are shown in Fig. 13. In this simulation, a quadruped robot driven by 4 spoke wheel-legs approaches a plateau which it must climb. The height of the plateau in this simulation is exactly equal to the height of each wheel-leg (measured from the geometric center). The

Fig. 12. Another innovation in Whegs^{TM} IV is a clear acrylic front panel. This makes it possible to mount infrared sensors or a video camera internally in an area directly adjacent to the main electronics compartment. The rounded shape of the front Panel will have good hydrodynamic characteristics and will also allow it to push up and over irregularly shaped obstacles

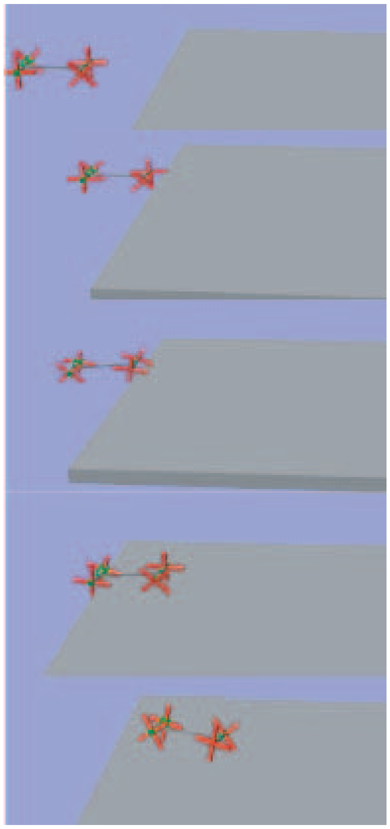


Fig. 13. Simulation

body of the robot was modeled as a rod attached to 2 revolute joints, each of which was connected to a shaft driving the wheel-legs. The weight of the rod was 10 kg representing the robot sensor payload, motors, and chassis.

The weight of each shaft was 1 kg, and the weight of each wheel-leg was 300 grams. As with the actual robot, each wheel-leg was also equipped with a compliant mechanism, in the form of a torsional spring with a constant of 0.2 N-m/deg. The robot was also designed to run in a diagonal gait where each wheel-leg was moving in phase with the wheel-leg diagonally opposite itself. From top to bottom, each snapshot in Fig. 13 shows phases of the dynamic simulation:

- The robot in motion at the beginning of the simulation
- The robot just prior to reaching the vertical step to the plateau. (Note: The robot has not reached the plateau, and is still moving in a diagonal gait, as can be seen from the gait.)
- The robot is beginning to climb the step

These results clearly demonstrate the capacity of Whegs^{TM} to passively adjust its gait to arduous terrain. This simulation testbed will be used extensively to dynamically examine the locomotive capability of our design to insure proper functionality for all manner of amphibious operations.

V. CONCLUSIONS AND FUTURE WORK

A. Conclusions

These design innovations will allow Whegs^{TM} IV to navigate on rough terrain and under water to accomplish tasks with little or no low-level control. This will greatly simplify the autonomous control problem and give the vehicle a versatility that no amphibious robot has yet enjoyed.

B. Future Work

A Dead Reckoning (DR) capability will be added to the system in the near future. Current position information is the sole result of the ability to receive accurate GSP data. However, GPS cannot and should not be relied upon as the only source for position. The concept of operations for the platform includes some time at, near or under the water and would preclude GPS reception.

VI. ACKNOWLEDGMENTS

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