An International Joint Research Project on an Autonomous Underwater Walking Robot *

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Abstract

This paper describes the objectives, organizations and research results of an international joint research project on an autonomous underwater walking robot conducted at the Naval Postgraduate School in the US and the Port and Harbour Research Institute in Japan. The main purpose of this project has been to investigate several scientific research questions in the US side and to enhance the capability of the existing six-legged underwater walking robot, AQUAROBOT. The period of this project is three years beginning in February 1992. Almost two dozen researchers have been involved in this project. The research results briefed in this paper include smooth motion planning for rigid body robots, versatile extended gait planning, dynamic foot motion planning, experiments with the real AQUAROBOT, linkage

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dynamics, virtual reality simulation model, and task and mission level control architecture. In order to conduct these subprojects, there have been frequent and close communications between two countries.

1 Introduction

The importance of coastal ocean space has been continually increasing for shipping, fisheries, marine-mining, leisure activities, and so on. Therefore we need to investigate methods of developing underwater space without damaging the natural circumstances. Numerous situations have been recognized where underwater walking robots are more desirable than human divers, submersible underwater vehicles, or underwater bulldozers. Especially, walking robots are considered the best for underwater civil engineering work.

Underwater inspection work is currently carried out by human divers' labor, but efficiency and safety are problems because of the severe underwater working conditions. Also, inspection is the simplest one among other civil engineering tasks.

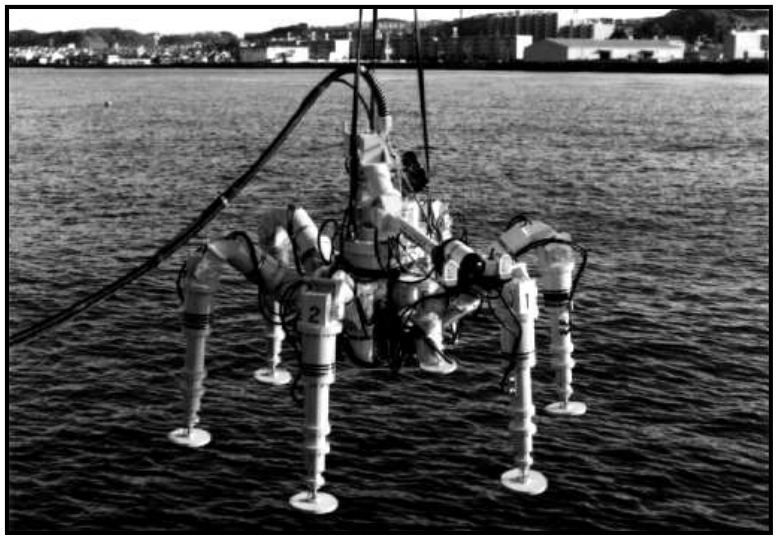


Figure 1: AQUAROBOT

Through the evaluation of several aspects including the aforementioned ones, the Port and Harbour Research Institute (PHRI) of the Ministry of Transport in Yokosuka, Japan has constructed three experimental six-legged underwater walking robots, AQUAROBOT (Fig. 1). The second version was tested for an inspection task of the evenness of a rubble mound of size of 42×77 meters at an average depth of 24 meters in the caisson yard for Kamaishi Bay Breakwaters [2, 3]

The purpose of this research is to improve the performance of these underwater walking robots through international collaboration. One of the goals was to make its walking speed

faster. The research activities in the US have been mostly supported by the National Science Foundation for three years beginning in February 1992 (Grant No: BCS-9109989, Computer Simulation and Control of Autonomous Underwater Walking Robots). Activities in Japan have been partially supported by the Science and Technology Agency for the Japanese fiscal year of 1993 (Grant Title: High Speed Walking Control of Underwater Inspection Robot) [4, 5, 8].

2 Objectives of the Research Project

The purpose of this project was to investigate the following scientific hypotheses with respect to computer simulation and control of autonomous underwater walking robots: [1]

1. There is an analytical method for optimizing the cycling of the legs of a walking vehicle for an arbitrarily given motion specification while moving over rough terrain.
2. In the application of the motion control method described in Item 1 on a real vehicle, the use of inertial sensing to separate lateral acceleration from inclination data enhances performance significantly.
3. Real-time computer simulation of vehicle dynamics, including both viscous and attached mass forces, and the effects of ocean currents, will permit effective estimation of the vehicle state with a corresponding increase in navigational accuracy during autonomous underwater operation.
4. There is an algorithm to extend a legged vehicle's functionality, (i) to negotiate an unknown terrain if its roughness is moderate, (ii) to avoid obstacles if they are not negotiable, and (iii) to generate an elevation map while executing such motions.

An important boundary condition in this project was that the AQUAROBOT hardware system was at PHRI in Japan and the major computer equipment, including the simulation capability, was at NPS in the US. Therefore, our natural decision was that the hardware tasks were done in Japan and the software and simulation tasks in the US.

3 Project Members and Activities

The project team of the US side consists of, mainly, four faculty members, two staff members, three Ph.D. students, and seven MS students. They are Yutaka Kanayama, Robert B. McGhee, Kan Yoneda, Scott McMillan, Chuck Lombardo, Shirley Pratt, Kenji Suzuki, Ron B. Byrnes, David McPherson, Jim Alexander, Carl J. Grim, Sandra L. Davidson, Charles A. Schue III, John R. Goetz, and Wrus Kristiansen.

The project team of the Japan side consists of, mainly, two faculty members, one Ph.D. student, and four researchers. They are Hidetoshi Takahashi, Kan Yoneda, Kenji Suzuki, Tomoyoshi Takeuchi, Mineo Iwasaki, Shigeki Shiraiwa, and Katsuei Nakagawa. Yoneda and Suzuki belong to both teams.

Both parties made individual efforts to accomplish research goals in Monterey and Yokosuka respectively. In addition, both parties tried hard to keep good contacts for the latest developments. We have communicated by e-mail almost every day and and by fax frequently. Without these high-tech communication tools, this much research results could not have been attained. All the members in this research project visited the other sides of the ocean at least once, including the one year stay of Suzuki at NPS.

4 Smooth Motion Planning

In order to specify the rigid body robot's motion, Kanayama has been developing the high-level language Model-based Mobile robot Language (MML) with a smooth motion planning algorithm "steering function" [6, 7]. Although this concept and algorithm was originally developed for non-holonomic vehicles, we have proved it effective for walking robot's motion specifications.

5 Extended Gait Planning and Dynamic Foot Motion Planning

Generalizing this algorithm, we have establish the concept of "extended wave gaits." A generalized wave gait seems to be the optimal one in the sense that the number of supporting legs is maximized in a given situation and the stability margin is larger than other gait planning algorithms previously proposed (this is the same advantage that a wave gait for a longitudinally symmetric robot possesses). Furthermore, we are able to design a generalized wave gait in a situation which the original wave gait algorithm could not handle. If the commanded motion slightly changes in its speed and/or motion direction, the new algorithm generates a slightly changed solution gait accordingly. This algorithm computes the best duty factor and the best combination of relative phases for each leg. The gait class improves the performance in several ways: The gait changes continuously with the body speed. A higher speed can be attained with a statically unstable gait. When the robot's dynamics model is incorporated, we will be able to use the higher speed gait planning effectively. In underwater operation, the water dragging effect adds a more advantage to it. The body motion direction can be smoothly changed, i.e., the robot is able to follow a curve. The body motion can be any combination of translational and rotational motions with smooth motion speed and direction changes. This algorithm generated the conventional tripod gait as a special case. For more detailed description of this theory, see [8].

Figure 2 shows the supporting leg combination at a kinematic phase ϕ for a given duty factor β. During its motion, a robot's state corresponds to a point with the current β and ϕ in the chart. If a robot is walking at a constant translational speed u without rotation, the robot's state is moving along the horizontal line at a duty factor β corresponding to the speed. In a special case of $\beta = 1/2$, this extended wave gait becomes the well-known tripod gait as this figure shows.

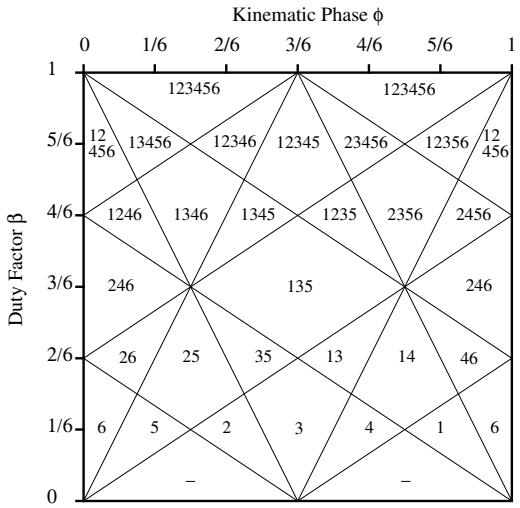


Figure 2: Supporting leg chart of extended wave gait ($\alpha = \pi/6$).

The features of the foot trajectory planning algorithm investigated are (i) smooth foot trajectories are adopted, (ii) omnidirectional motion commands are allowed, and in order to deal with the omnidirectional motions, (iii) footholds are dynamically determined. The problem to be solved here is finding six leg's motion when the kinematic phase ϕ, the duty factor β and relative phases ψ_is are given.

Figure 3 shows an example of the executing a extended wave gait with the dynamic foot motion planning algorithm. The robot follows first a line, second a parabola, and third the original line. In this simulation, we use the smooth motion planning algorithm as well [6, 10, 9, 10]. At the top portion of this figure, the supporting period of each leg is shown by broken lines. This figure shows how the gait/foot planning algorithm coordinates to make smooth motions possible.

6 Experimental Results

The implementation work of the gait/foot planning algorithm on AQUAROBOT started at PHRI in the summer of 1994. The project members for this experiment were Suzuki,

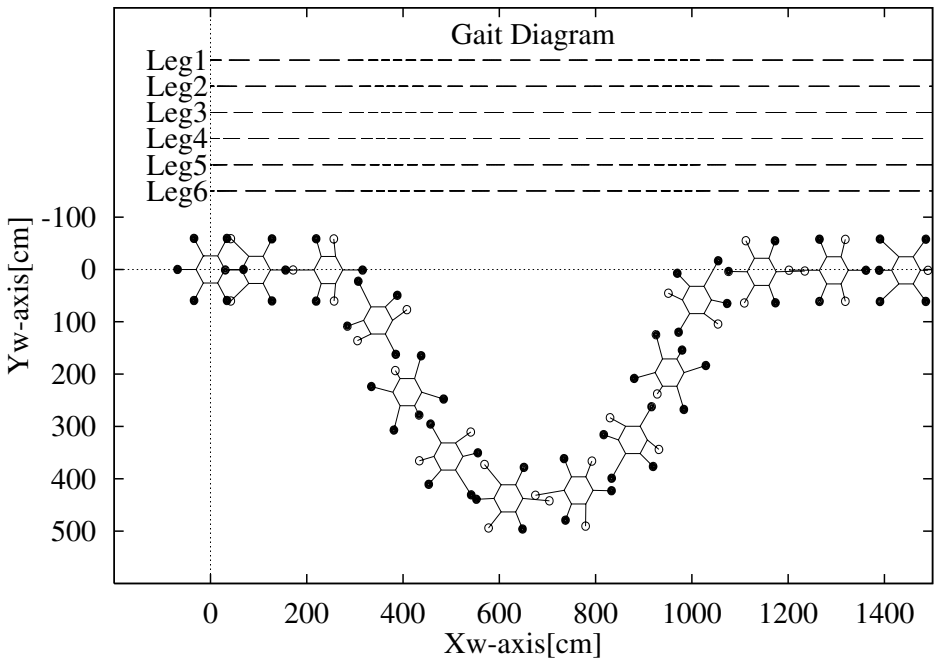


Figure 3: Execution of a extended wave gait.

Takahashi, Yoneda, Nakagawa, and Kanayama.

All the experiments have been successful. Figure 4 shows an example of the experimental results in which AQUAROBOT1 tracks a circular path with a radius of 1 meter. During this motion, the robot's body orientation is kept constant and the crab angle changes at a constant rate. This photograph tells the trajectories of the body and a foot. The robot has two miniature light bulbs: one on the body and the other on the leg1.

Real-time walking experiments over uneven terrains were also conducted successfully. Thus the correctness of the gait/foot motion planning algorithms were demonstrated through these experiments.

The walking speed of AQUAROBOT was 7.5 meters/minute with the old software system in 1990 or earlier. With the new software system, its speed become 15 meters/minute. Therefore, at least one goal of this project was clearly attained. Since the motors are driven at its fastest speed, this improvement has been obtained through the improvement in gait algorithms. For instance, the body is moving at a constant speed independent of the leg positions in the new algorithm.

Figure 4: Circular Motion of AQUAROBOT Showing Body and Foot Trajectories.

7 Comparison of $O(N)$ and $O(N^3)$ Linkage Dynamics for Subsea Robots

It is generally recognized that the use of articulated body inertias leads to a formulation of the direct dynamics problem for open chain linkages in which the complexity of the calculations grows only linearly with the number of links. It is also known that earlier approaches based on composite rigid body inertias exhibit cubic computational complexity. This result makes it clear that for a large number of links (large N), $O(N)$ methods should be used. However, practically, it is necessary to have an exact formula for the number of additions and multiplications required for each method in order to determine which is best for simulation of a given robotic system.

Until now, the computational requirements of $O(N)$ and $O(N^3)$ methods have been derived only for terrestrial or space-based manipulators or vehicles. In [12, 13], this work is for the first time extended to the underwater domain by inclusion of hydrodynamic and hydrostatic effects in an $O(N)$ method. It is found that the amount of computation required in this case is increased by approximately seventy-five percent over the corresponding requirement for a single chain serial manipulator mounted on a mobile base and operating in space or air. A detailed example is presented in the Ph.D. dissertation of Dr. Scott McMillan [14], using the parameters of the 12 degree of freedom *Tiburon* unmanned submarine currently under development by the Monterey Bay Aquarium Research Institute. Figure 5 shows a typical image from this simulation. This dissertation also includes an extension of $O(N)$ methods to tree structured mechanisms as exemplified by AQUAROBOT. A summary of these results is contained in [15, 16].

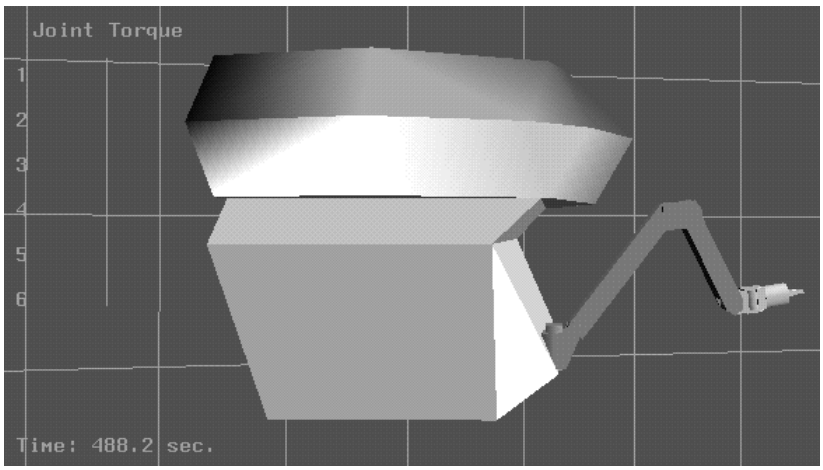
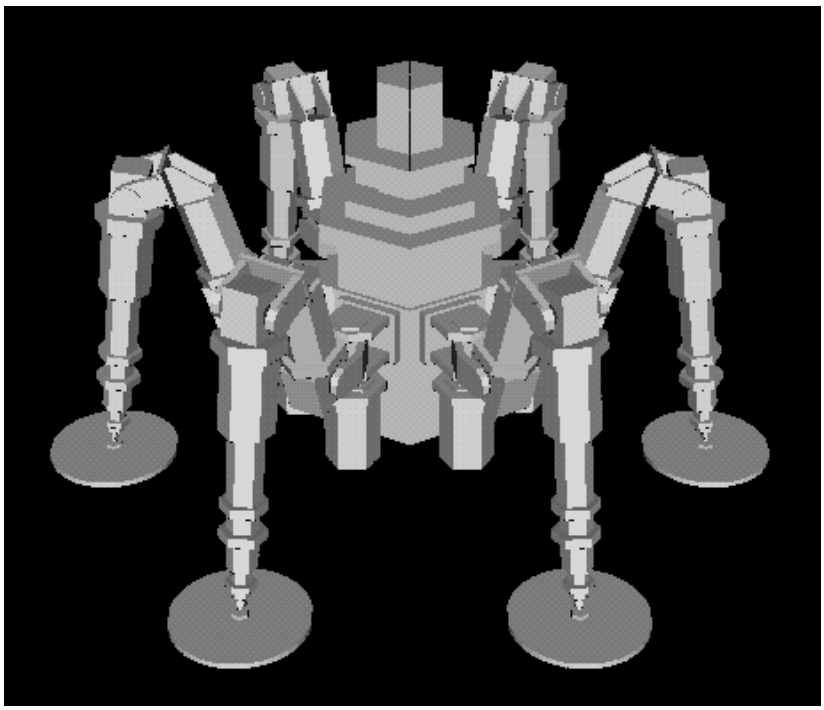


Figure 5: Tethered Underwater Robotic Vehicle "Tiburon"

8 Virtual Reality Simulation Model for AQUAROBOT

As a first step toward a virtual reality model for AQUAROBOT, we developed a purely kinematic simulation [17, 18]. This model assumes a level sea bottom, and proved to be very useful in supporting the development of an initial version of AQUAROBOT motion coordination software. Figure 6. presents an example of an image from this simulation. The current version of this model makes use of the *Performer* software package provided by Silicon Graphics Inc. (SGI) to compute the collision of cylindrical feet with uneven terrain [18]. Another simplified model [19], provides a single rigid body representation for AQUAROBOT in which the mass of the legs is concentrated in the body. Both of these simulations have the advantage of running in real time on low-end SGI graphics workstations. An exact $O(N)$ articulated rigid-body graphical simulation model running slower than real-time [14] has been delivered to PHRI and will, in future work, allow evaluation of the accuracy of a real-time virtual reality model, derived from [18, 19]. A further possibility is to attempt to increase the efficiency of the simulation in [14] by the use of multiple processors and by replacing homogeneous transform representation of orientation with a more efficient quaternion formulation [20].

9 Task and Mission Level Control for Autonomous Walking Robots

While AQUAROBOT currently incorporates a human operator in its control loop, and is thus an example of a remotely operated vehicle (ROV) rather than an autonomous underwater vehicle (AUV), unlike most ROVs, it is capable of autonomous survey missions in which the operator functions as an observer who intervenes in the mission only in the event of