REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
10/27/95

3. REPORT TYPE AND DATES COVERED
Progress Report 5/20/95 - 10/1/95

4. TITLE AND SUBTITLE
Adaptive Dynamic Balance of Two and Four Legged Walking Robots

5. FUNDING NUMBERS
ARPA/ONR Grant
#N00014-95-1-1024

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10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for public release
Distribution Unlimited

19960821 038

13. ABSTRACT *(Maximum 200 words)*

Two-legged and four-legged walking are the most versatile forms of land locomotion in the sense of maneuverability and the ability to traverse irregular terrain. Unfortunately, the problem of practical bipedal walking with dynamic balance has so far eluded solution using classical and other control techniques. We have been investigating the use of neural networks for on-line gait modulation during walking, using a 10 degree-of-freedom biped robot and a 20 degree-of-freedom quadruped robot developed in our laboratory. The research in the current project involves extending our adaptive walking control architecture, developed in prior research, to provide good performance over a wider range of stepping lengths and rates, and to provide good stability during both minor and significant deviations from nominal behavior. This should result in a truly practical control structure for walking with dynamic balance. This is a project progress report for the research carried our prior to October, 1995.

14. SUBJECT TERMS
Neural Networks, Robotics, Legged Locomotion

15. NUMBER OF PAGES
3

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

UNH

19951031 072

Adaptive Dynamic Balance of Two and Four Legged Walking Robots

ARPA/ONR Grant #N00014-95-1-1024
5/20/95 - 12/31/96

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PROGRESS REPORT: 10/27/95

Two-legged and four-legged walking are the most versatile forms of land locomotion in the sense of maneuverability and the ability to traverse irregular terrain. Even in human designed spaces with horizontal floors and regular geometries, legged locomotion is more versatile than wheeled locomotion. Unfortunately, the problem of practical bipedal walking with dynamic balance has so far eluded solution using classical and other control techniques. We have been investigating the use of neural networks for on-line gait modulation during walking, using a 10 degree-of-freedom biped robot and a 20 degree-of-freedom quadruped robot developed in our laboratory. Results from our prior ARPA funded research indicate that our approaches to on-line gait adaptation are effective at automatically developing the detailed motions of dynamically balanced, phase-locked, feedforward gaits for two-legged and four-legged robots under nominal operating conditions, requiring very little a priori knowledge of the robot dynamics. The research in the current project involves extending our adaptive walking control architecture to provide good performance over a wider range of stepping lengths and rates, and to provide good stability during both minor and significant deviations from nominal behavior. This should result in a truly practical control structure for walking with dynamic balance.

Much of the effort during the most recent project period focused on the reallocation of primary control functions within the multi-processor control architectures of the biped and quadruped robots. This reallocation of software functions resulted in more efficient use of the computing resources, thus freeing computing time for the investigation of more complex dynamic balance and walking algorithms. In addition, the data rates on the serial communications channels between the high level control computers and the microcontrollers on the biped and quadruped robots were increased by an order of magnitude (from 50K baud to 500K baud) via modifications to the communications hardware. This significantly reduced the lag times in the high-level control, enhancing overall system stability.

A series of control experiments was also initiated using the biped robot. These experiments focused on improving the stability of the side-to-side swaying motion of the biped during walking with dynamic balance. The basic concept was to learn to modify the time at which the next foot is lifted off of the floor as a function of the sensed motion of the biped body (via feedback from the solid-state accelerometers). Lifting the foot earlier than nominal dampens the rhythmic side-to-side motion, while lifting the foot later than nominal increases the amplitude of the motion. In our previous control architecture, the nominal side-to-side swaying was adapted to provide good average performance as a function of desired stepping length and stepping rate. However, it was observed that for a given set of conditions and control inputs, the amount of swaying varied from one step to the next as the accumulated result of various uncertainties in the mechanical structure and the finite control update rate. These deviations from nominal occasionally led to falls, particularly for more aggressive stepping rates and lengths. In our most recent controller, we actively dampen these deviations from nominal by learning to adjust the time of foot lift as a function of the filtered time integrals of the body accelerometer signals. While some results have been achieved for the dynamics of side-to-side swaying, the overall effort targeted at learning to actively dampen deviations from nominal behavior will continue during the next project period.

Most recently we have begun the study of walking with quasi-static balance, and the smooth transition from quasi-static to dynamic balance. This is intended to increase the range of stepping rates at which the system can operate (dynamic balance implies walking at rates at or above the characteristic frequency of the effective "inverted pendulum" of the biped structure). As a first stage in this process, we have been making modifications to our two-dimensional biped dynamic simulator (developed in an earlier project) in order to improve the correlation between the simulator and the experimental biped as viewed independently in the frontal and lateral planes. This will allow us to more carefully evaluate alternative learning control architectures in simulations under controlled conditions prior to testing the controllers in experiments, where performance results can be more difficult to interpret.