DYNAMIC STABILITY FOR MANIPULATORS USED IN CONSTRUCTION

Irving J. Oppenheim and Lyman J. Petrosky

Department of Civil Engineering

Carnegie-Mellon University

Pittburgh, Pennsylvania, 15213

1. Introduction

Humans and higher animals possess an efficiency of motion which far exceeds that of most machines. Future robotic tasks will demand motion and force capabilities which cannot be realized by conventional machines and which may require the dramatic improvement associated with human-like efficiencies; tasks in the construction environment are present day examples which may drive the adoption of these advanced technologies. A prevalent characteristic of animal motion is dynamic stability (active balancing) from which the basis of this research, and the title to this paper, is derived.

The germane physical characteristics of animal motion are described in the next section, under a more specific heading of *Motion Adaption*, with examples of salient efficiencies. A succeeding section discusses the pertinence of motion adaptive manipulation to some demands in construction. That is followed by a description of our experimental manipulator, developed expressly to pursue experiments in motion adaptive manipulation. The next section presents the experimental results to date and anticipated results within the present program.

2. Motion Adaption in Animals

2.1. Mobility

The *motion adaptation* of animals is dramatically demonstrated in mobility itself. Legged animals are extraordinarily effective at negotiating irregular terrain; our ability to compensate for elevation differences and to choose from a large zone of foot placements on any step permits us to cover terrain which because of its steepness or irregularity cannot be negotiated by machines. Machines which contend with some irregularity (such as tracked earthmoving machines or military armored tanks) achieve only limited success, and do so only at great expense in machine size, weight, and power consumption. Legged animals instead achieve motion and maintain travel over long distances with reasonable energy consumption and with moderately sized actuators. *The advantages of motion adaptation for mobility have been long recognized, and research into legged motion for robotics has a considerable background and history [3, 4, 5]. The departure in this present work is to carry motion adaptation to task-related conditions including position control, force control, and task planning.*

2.2. Geometry Control

Motion adaptation gives humans the capability to control stance and geometry in ways that are highly effective for task demands. Examples can be cited as follows:

- Humans can maintain a *stance* on uneven terrain or in relation to the irregular geometry of a workpiece.

- Humans can vary their stance to retain gross geometric stability under application of various forces or under the burden of payload/location demands.
- Humans can vary their posture for maximum reach; vertical reach, in particular, is fairly high compared to the small "base width" which a worker can assume in a constricted space.
- Humans can achieve fine position control by assuming a posture with temporary bracing against available supports; in most high precision tasks (such as writing) this capability is employed.

This set of motion adaptive capabilities form a group which are related expressly to *configuration*, or *stance*. Additional capabilities are recognized next in examining motion adaptation for *force* capabilities.

2.3. Force Development and Control

Animals and humans develop and control forces far more efficiently than do machines. "Efficiency" can be interpreted as the maximization of applied force per actuator torque, the minimization of overall energy consumption, the minimization of path traversal times in manipulation, the "smoothness" of motions, and so on. Consider the following examples of motion adaptive force development and control:

- Humans adjust their stance and the overall geometry of their limbs to apply quasi-static forces with best "leverage." We seek a body position which automatically uses the best-positioned and best-prepared muscles for such an application of force. (This is a subset of the geometry or stance control which is also needed to assure gross stability.)
- Humans use their body masses to develop dynamic and impulsive forces which are then harnessed and controlled to perform tasks. In opening doors we apply a resultant force developed by the inclined position (quasi-static force) and the motion (dynamic and/or impulsive forces) of our large body masses. This condition is also evident when we pull or tug on an object.
- Humans find paths representing highly efficient motions *for the dynamics of the body and payload masses, along the path,* and in so doing accomplish demanding tasks with limited actuator capacities. The weight-lifter's "clean-and-jerk" is an extreme example, and comparable examples are found in most human motions which carry a payload.
- Humans successfully utilize forces which interact with an uncontrolled external medium, as in the acts of digging, wedging, breaking, and so on.
- Humans find various temporary or local conditions to enhance the application of forces.
- Humans identify the preferred tactics for force application in uncontrolled environments; there is a "sense" as to where to pull, push, or bend in shaping an object.

3. Motion Adaptation for Construction Robotics

3.1. Geometric Stability

An obvious requirement for construction equipment is that it maintain its overall geometric stability; crane tipover and equipment rollover are dramatic examples of occasional instability in conventional equipment. The control of overall stability will become even more important as the following conditions apply:

- The stability of present equipment derives from its self-weight and its wheelbase, designed to provide a broad useful range of stable motion. If active control is utilized, lighter and narrower equipment can be developed.

- As autonomous manipulator motions are employed, the control of stability under *dynamic* forces is required as well.

From these considerations it is proposed that *dynamic stability*, in the form of *active balancing* as possessed by humans, is a compelling research objective for robots which will operate in general uncontrolled geometric domains, force environments, and under the effects of dynamics. It is not suggested that actual robots will rely solely or largely on dynamic stability, but rather that they possess the capability and utilize it as needed. For instance, a common forklift is generally stable, but it would be superior in its performance if it *also* possessed the capability to adjust its position under the effect of load eccentricity, as would a human.

3.2. Reach and Position Control

A variety of practical issues can be addressed in this category. A conventional solution to vertical reach for a machine requires a heavy, wide machine, and is particularly sensitive to ground conditions and pitch. In contrast, high vertical reach can be obtained (in all or in part) by employing active balance. Similarly, conventional machines are constrained in their ability to work in constrained spaces as compared to a human. A machine which balances actively will be capable of interacting with objects around it as would a human, with "live" response to contact, bearing, or impact. In this way it could safely be brought into proximity with such solids. Moreover, a machine which temporarily braces itself against stationary surfaces can achieve high precision manipulation as well as a general capability to work in such spaces. These constitute examples of machine advances which would require the technology of motion adaptive manipulation.

3.3. Forces and Tasks

Tremendous efficiencies in force capacity (per actuator capacity) can be achieved by employing and controlling the dynamic effects of manipulator masses. Existing construction equipment is sometimes used in this way *under the active control of a human operator.* A manipulator which can regularly and autonomously work in the force envelope developed by this technology would be a major contribution to robotics in general. Construction represents one driving application, and it is anticipated that space manipulation will also be strongly influenced by such a capability. A related technology is proper *force control* and the problem of *force cognitive* manipulation. We use the latter phrase to describe manipulation tasks in which the major sensing function is satisfied by forces reflected through the manipulator, and in which task cognition and control is maintained in a force environment. An example, under present investigation in our laboratory, is found in excavation:

- A human digs with a spade by varying a number of effector conditions (angle of attack, depth of penetration, angle of breakaway and removal) in response to soil conditions. *The adjustments are all made by feel.*
- A human conducts such excavation within rather tight constraints of actuator limit and capacity.
- A human maintains overall geometric stability and proper stance throughout the task, including the change in geometry effected by the removal act itself.
- At numerous points in the process the dominant sensing mode is that of the force environment, and task decisions are made on that understanding.

Finally, the general problem of task planning and contingencies should be recognized. The kinds of capabilities required for motion adaptive manipulation are appropriate for contingency response, and adaptive enough for a central role in task planning.

4. Manipulator Description

4.1. Research Statement

An experimental manipulator has been constructed expressly to support research into motion adaptation. The purpose is to develop an approach for *tactical planning* (or *path planning*) which generates the capabilities exhibited in human and animal motion. The experimental device which was designed for this purpose is stable (only) dynamically. While many of the advantages of motion adaptation could be utilized in conventional (statically stable) open chain manipulators, success would be "measured" in terms of actuator currents, traversal times, and so on. In contrast, experiments on a dynamically stable system yield a binary indicator of success/failure; the system falls if it fails, and experiments are therefore more challenging and more compelling. A dynamically stable experimental system was chosen for this study, but the results are intended for use in a broad family of robot manipulator applications.

4.2. Mechanical System and Sensors

The experimental manipulator, Figure 1, is a planar system supported solely on two wheels. It is a double inverted pendulum, constantly requiring active balance to prevent tipover. The manipulator consists of the servo driven wheeled base, a lower arm section, an elbow joint with drive servo, an upper arm, and an electro-magnet gripper at its tip. It is constructed primarily of aluminum and has a total weight of 29 pounds. The two wheels are mounted on a single shaft and there is effective out-of-plane stability. The tip of the manipulator can reach to a height of 6 feet when fully extended, and can be lowered to touche the floor.

The manipulator wheels and elbow joint are each driven by Aerotek 1050 servos powered by Aerotek 6020 amplifiers. The peak torque delivered by the amplifier-servo combination is 180 in-oz and the continuous rating is 50 in-oz. The servos weight 4 pounds each. The elbow joint has a chain reduction ratio of 57.6:1 and the drive wheels have a chain reduction of 4.8:1. The chain reduced servo arrangement was chosen over direct drive to save weight, and over gear-reduced or harmonic drive to mitigate costly damage in the event of a severe floor collision.

The sensors utilized for manipulator control are:

- Inclination RVDT - a rotary differential transformer measures the angle between the floor surface (via a feeler) and the lower arm.
- Motor Encoders - each servo has an optical encoder of 500 counts per revolution which runs a 4x hardware counter read by the parallel interface board.

Additional sensors are available for diagnosis and monitoring, but they are not required for the system control. They are:

- Load Cell - a load cell is mounted inline with the electromagnet gripper. It indicates the actual payload being realized.
- Motor Tachometers - the motor tachometers provide a direct indication of the motor rpm.

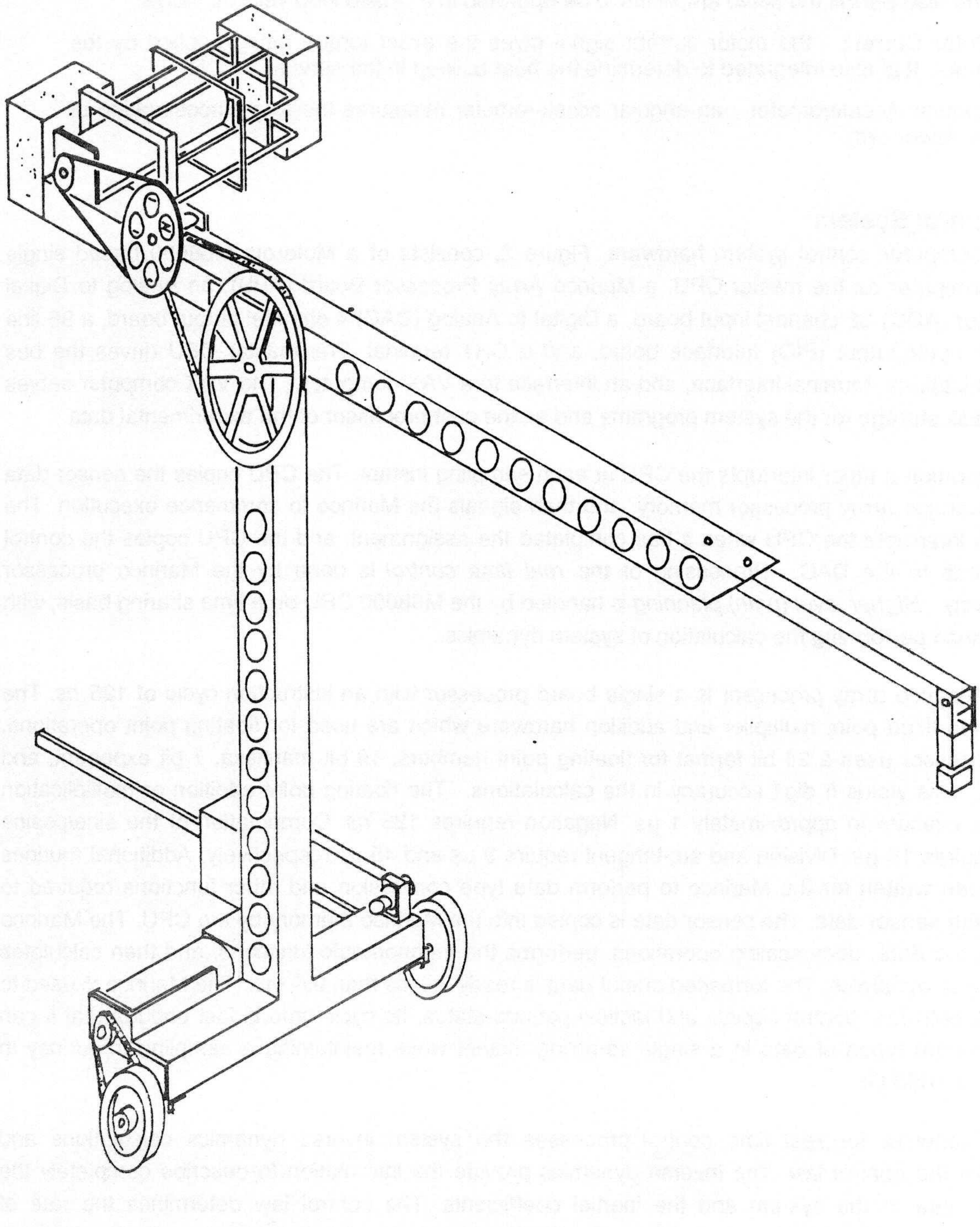

Figure 1. Experimental Manipulator

The also permit the servo amplifiers to be operated in a closed loop velocity mode.

- Motor Current - the motor current signal gives the exact torque being applied by the motor. It is also integrated to determine the heat buildup in the servos.
- Angular Accelerometer - an angular accelerometer measures the rotary acceleration of the lower arm.

4.3. Control System

The computer control system hardware, Figure 2, consists of a Motorola M68000 based single board computer as the master CPU, a Marinco Array Processor Board (APB), an Analog to Digital Converter (ADC) 32 channel input board, a Digital to Analog (DAC) 4 channel output board, a 96 line Parallel Input/Output (PIO) Interface board, and a CRT terminal. The master CPU drives the bus communications, terminal interface, and an interface to a VAX computer. The VAX computer serves as the disk storage for the system programs and as the post processor of the experimental data.

In operation a timer interrupts the CPU at each sampling instant. The CPU copies the sensor data to the Marinco array processor memory, and then signals the Marinco to commence execution. The Marinco interrupts the CPU when it has completed the assignment, and the CPU copies the control commands to the DAC. Processing of the *real time control* is done by the Marinco processor exclusively. *Higher level (path) planning* is handled by the M68000 CPU on a time sharing basis, with the Marinco performing the calculation of system dynamics.

The Marinco array processor is a single board processor with an instruction cycle of 125 *ns*. The board has fixed point multiplier and addition hardware which are used for floating point operations. The processor uses a 24 bit format for floating point numbers, 16 bit mantissa, 7 bit exponent, and sign bit. This yields 5 digit accuracy in the calculations. The floating point addition or multiplication routines execute in approximately 1 μs. Negation requires 125 *ns*. Computation of the sine/cosine pair requires 15 μs. Division and arc-tangent require 9 μs and 45 μs respectively. Additional routines have been written for the Marinco to perform data type conversion and other functions required to format the sensor data. The sensor data is copied into the Marinco memory by the CPU. The Marinco formats the data, does scaling operations, performs the trigonometric functions, and then calculates the inverse dynamics. The formatted output data is ready in less than 0.5 *ms*. The Marinco is used to process both real control signals and tactical pseudo-states. Its cycle time is fast enough that it can process both types of data in a single sampling instant while maintaining a sampling frequency in excess of 1000 Hz.

The software for *real time control* processes the system inverse dynamics calculations and executes the control law. The inverse dynamics provide the information to describe completely the current state of the system and the inertial coefficients. The control law determines the rate of correction of path deviations, and utilizes a method developed earlier in this research program [1, 2] which has been labelled a *partitioned control* approach. It is noteworthy for providing effective *non-linear* control of the manipulator as a double inverted pendulum. The *real time control* runs entirely on the Marinco processor except for necessary supervisory functions which are provided by the M68000 CPU. The software for *path planning* (also described as *higher level* planning) uses methods which mimic available "rules" for motion planning, and runs primarily on the M68000 CPU.

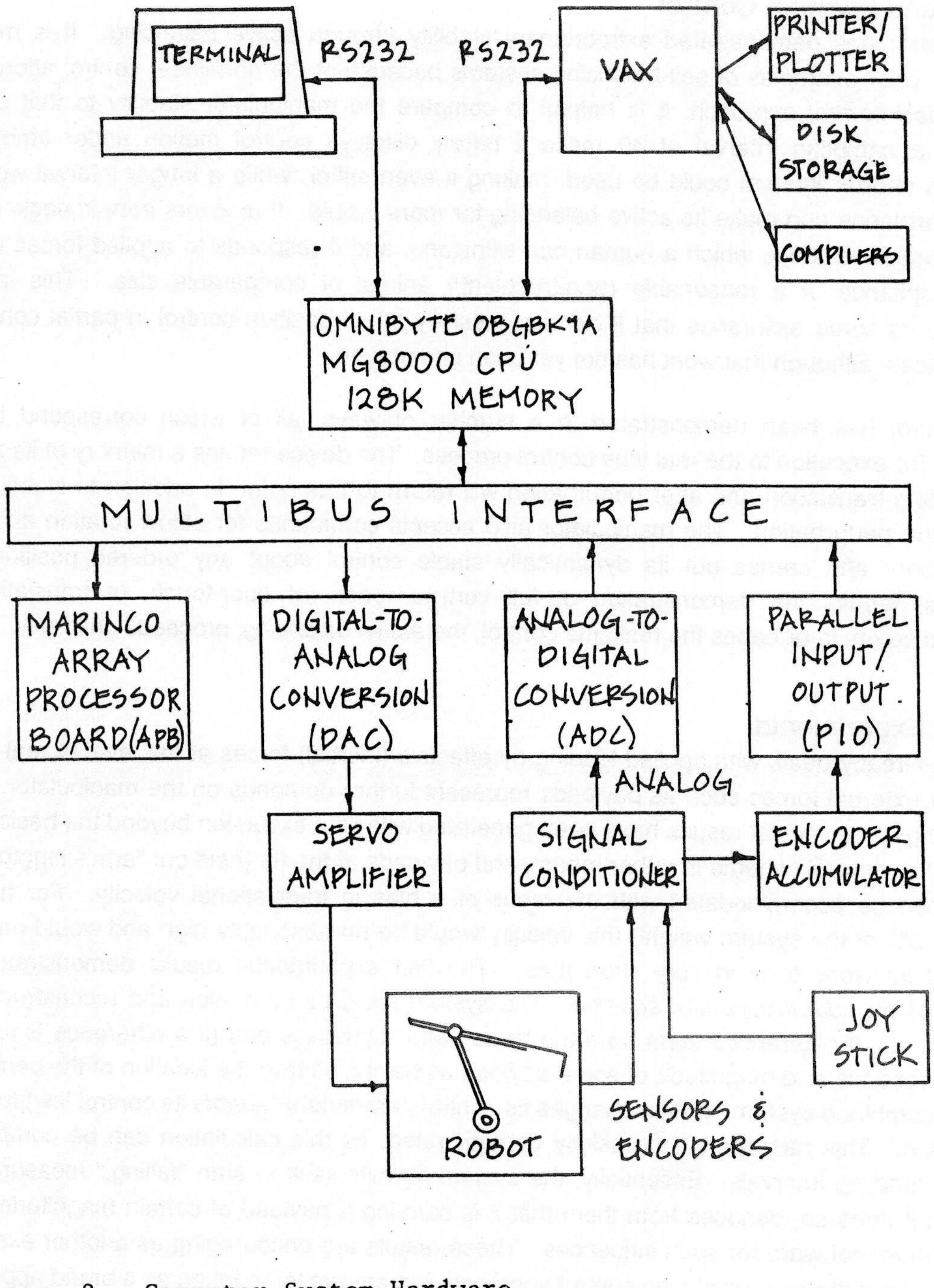

Figure 2. Computer System Hardware

5. Results

5.1. Stability and Position Control

The manipulator has demonstrated extraordinary stability through active balancing. It is more successful than prior examples of self-balancing systems because of the non-linear control afforded by the *partitioned control* approach. It is helpful to compare the manipulator stability to that of a human. With a sampling interval of 40 msec it barely displays control motion under ambient perturbations; a shorter interval could be used, making it even stiffer, while a longer interval would corrupt its performance and make its active balancing far more visible. It recovers from impacts and assaults comparable to those which a human can withstand, and it responds to applied forces with the gentle compliance of a reasonable (non-truculent!) animal of comparable size. This latter capability gives us some assurance that it can successfully attain position control in partial contact with other surfaces, although that work has not yet been undertaken.

Position control has been demonstrated in a number of ways, all of which correspond to a command sent for execution to the real time control process. The device retains a memory of its zero position regarding translation and after perturbation will return to that point, in addition to stabilizing the effects of the perturbation. The manipulator also accepts commands for elbow rotation and for overall translation, and carries out its dynamically stable control about any ordered position or velocity. This permits the demonstration of full vertical reach, of floor-touch, of translational placement, and so on; in all cases the real time control, the *active balancing*, proceeds uniformly.

5.2. Payload Experiments

The system already deals with applied loading by effective (inertial) forces at the level of real time control. Other external forces such as payloads represent further demands on the manipulator, and some interesting experimental results have been generated with little excursion beyond the basic real time control. The control scheme is rather robust, and payloads at the tip (held out "arm's length," as in Figure 1) can be accommodated with the result of a bias in translational velocity. For heavy payloads (say 5% of the system weight) this velocity would be unreasonably high and would run the system out of its work zone in very short time. The first experimental results demonstrate the effectiveness of an *adaptive control scheme*. The system samples its motion and reconstructs its system dynamics. It differences them from the "bare state" dynamics and (if a difference is found) deduces the presence and magnitude of some payload as having altered the location of the center of gravity of the combined system. It then changes its control parameters (*adapts* its control law) for this new information. This has been successfully demonstrated, as this calculation can be completed within a few sampling intervals. Essentially, the system permits itself to start "falling," measures its "velocities" as it does so, deduces from them that it is carrying a payload of certain magnitude, and corrects its control software for such influences. These results are encouraging as another example of the *robustness* of the basic real time control approach, but are not to be taken as a broad approach for greater capabilities. Rather, the preferred approach is for some kind of intelligent motion planner (to facilitate a wide range of useful task capabilities) which recognizes all system forces and dynamics. Such an approach constitutes the remaining work, described below.

5.3. Remaining Work Plan

The experimental results described above are current to the date of this conference. Remaining work under this research contract, to be completed by October 1987, will produce a *path planner* which takes cognition of the system dynamics in finding some preferred path; it is also a *task planner* in the sense that its statement of path will include statements in the force domain. The approach is to choose path characteristics from some general rules which have been derived from research into optimal path planning, and to perform a series of "look-ahead" path projections during the sampling interval for real time control. The path planning occurs at a *higher* level, generating path segment choices at a speed slightly less than real time, performed while the manipulator operates in real time. (The Marinco array processor is necessary in this implementation to provide the speed for this approach.) The analytical examination of paths and segments is aided by performing calculations in Riemann space and by generating geodesics. Employment of these procedures at such speeds is new; special techniques have been developed in this effort, and initial results are favorable.

The anticipated results should include the following:

- Manipulator selection of paths which (under appropriate boundary conditions or constraints) may vary from quasi-static to smoothly stable to "jump" stable. The planner is to generate these paths uniformly, with the particular regime being an incidental outcome of path requirements.
- Manipulator transition between conditions of free movement and conditions of temporary contact with abutting solids. This transition also surfaces in the "pickup" of payload from the floor.
- Development and control of forces generated by system mass movement, disproportionate to direct actuator power consumption. This includes the demonstration of payload capabilities greatly in excess of the nominal (quasi-static) limitations constrained by actuator capacities.

6. Conclusions

Our experimental results demonstrate that a motion adaptive system, in this case displaying dynamic stability by active balancing, can perform at a level of reliability which warrants further development of the technology for manipulation tasks. The remaining and intended future work is the development of a path planning capability which creates the advantageous manipulation skills possessed by humans: adaptability, high capacity with respect to actuator size, and exploitation of the work environment geometry for improved precision or force capacity. These capabilities can be exploited in conventional manipulator geometries as well, and transferability of the motion adaptive technology through control software is anticipated.

7. Acknowledgements

This program has been supported by the U. S. Department of Energy, Breeder Reactor Program, for university research into technologies to assist in the operation of advanced reactors. It is funded as contract DE-AC02-85NE37947, "Dynamic Stability for Robot Vertical Reach and Payload." The support is gratefully acknowledged, as is the particular interest and enthusiasm of the technical project manager, Clinton Bastin. Mr. Petrosky is an employee of Westinghouse Electric, Advanced Energy Systems Division, and has been on leave and on subcontract to the research effort at Carnegie-Mellon; the co-operation of Westinghouse is greatly appreciated.

8. References

[1] Petrosky, L.J.
Problem Substructuring Applied to the Design of a Controller for the Stabilization of a Double Inverted Pendulum.
Master's thesis, Carnegie-Mellon University, 1986.

[2] Petrosky, L. J. and I. J. Oppenheim.
A Substructured Controller for a Double Inverted Pendulum.
Technical Report, Submitted to ASME Jnl. of Dynamic Systems ..., 1986.

[3] Raibert, M.H., Brown, H.B., Jr., Chepponis, M., Hastings, E., Shreve, S.T., Wimberly, F.C.
Dynamically Stable Legged Locomotion.
Technical Report CMU-RI-81-9, Robotics Institute, Carnegie-Mellon University, 1981.

[4] Raibert, M.H., Brown, H.B., Jr., Chepponis, M., Hastings, E., E., Koechling, J., Murphy, K.N., Murthy, S.S., Stentz, S.S.
Dynamically Stable Legged Locomotion.
Technical Report CMU-RI-TR-83-20, Robotics Institute, Carnegie-Mellon University, 1983.

[5] Raibert, M.H., Brown, H.B., Jr., Chepponis, M., Hodgins, J., Koechling, J., Miller, J., Murphy, K.N., Murthy, S.S., Stentz, S.S.
Dynamically Stable Legged Locomotion.
Technical Report CMU-LL-4-85, Robotics Institute, Carnegie-Mellon University, 1985.