The Adaptive Suspension Vehicle

Kenneth J. Waldron and Robert B. McGhee

ABSTRACT: This paper provides a description of the Adaptive Suspension Vehicle. The vehicle uses a legged, rather than a wheeled or tracked, locomotion principle, and is intended to demonstrate the feasibility of systems of this type for transportation in very rough terrain conditions. The vehicle is presently under test, with installation and validation of software modules for different operational conditions scheduled for completion by the end of 1986.

Introduction

The Adaptive Suspension Vehicle (ASV) is a six-legged vehicle designed for sustained locomotion on unstructured terrain. The ASV project, under its present sponsorship, was initiated in January 1981. The vehicle, shown in Fig. 1, was completed in May 1985. Subsystem testing, software installation, and tuning occupied the summer of 1985. Testing of the full system began in October 1985, and the machine took its first steps in December 1985. The first outdoor tests of this vehicle are scheduled for the end of 1986.

The Adaptive Suspension Vehicle is not, in its present configuration, an autonomous robot. It carries an operator, who provides supervisory-level commands and, specifically, performs long-range sensing, path selection, and navigation. However, the mechanical and control technologies used are the same as those needed for unmanned operation, and an intensive effort to realize this capability is currently in progress.

As the first computer-coordinated legged system designed to operate in completely unstructured terrain, the ASV is very ambitious when compared to earlier legged vehicles. The only previous system comparable to the ASV—General Electric's Quadruped [1]—used no computer. Instead, a human operator performed all coordination manually. Also, it never operated with a self-contained, onboard power supply. The Ohio State University Hexapod [2], Titan III [3], Carnegie-Mellon Quadruped [4], and a number of earlier machines are laboratory-scale vehicles operated only in very simple, structured environments. Reference [1] includes an extensive bibliography of the literature of artificial legged locomotion. The Odex I [5] is a prototype of a possible commercial unit, but its design is specialized for indoor environments. It, nevertheless, most closely approaches the ASV in potential capability. The Sutherland and Sproull Hexapod [6] was also a relatively sophisticated machine and was fully self-contained. However, its control architecture and mechanical configuration limited it to operation in easy terrain.

The ASV system will, in its fully developed configuration, have six operating modes. The *utility mode* comprises power up, power down, system test, and diagnostic functions. The remaining modes are walking modes. Leg coordination and foothold selection are completely automated in all but the *precision-footing mode*. In this *semiautomatic* mode, the operator can either control body translational and rotational velocity in body coordinates, with the feet fixed, or control any selected foot, in body coordinates, with the body fixed. All operating modes will be described subsequently.

The omnidirectional motion characteristics and the specialization of the vehicle planform for sustained locomotion are important features of the ASV system design. The leg geometry used is further specialized for efficient continuous locomotion predominantly in the longitudinal direction. The reasons for, and details of, this specialization are extensively discussed in [7], [8]. The overall design goals for the ASV are given in the table.

The fully terrain-adaptive characteristic of the ASV is another important design feature [9], since at a small scale, the body motion can be completely isolated from terrain variations. Of course, this is not true at a large scale. In all ASV walking control modes, body motion is determined by an algorithm, which maintains the body parallel to, and at constant distance from, a smoothed average of the terrain surface as perceived by foot positions and/or data from a scanning rangefinder mounted atop the vehicle (Fig. 1). This algorithm determines the behavior of the locomotion system in filtering out short-wavelength variations in terrain [10]. An advantage of a fully terrain-adaptive machine as a sensor platform is that body motions are, in principle, completely controlled. Hence, sensor position is completely determinate and can even be predicted to a time roughly equal to the leg-placement interval. In contrast, in a vehicle with a sprung suspension, vehicle motions must be sensed and sensor position computed, which must necessarily be done at a substantially higher bandwidth than that of the motions transmitted to the body by the suspension.

Operator Controls

The operator of the ASV interacts with the system via a joystick and a keypad. The joystick provides continuous rate control of three degrees of freedom: longitudinal, lateral motion, and heading. Two thumb-operated minijoysticks mounted on the main joystick provide intermittent rate control of the remaining three degrees of freedom. This system is shown in Fig. 2. The keypad is used to communicate with the operating system of the computer to select software modules corresponding to the operating modes of the machine and to set system parameters. It is also used to select functions in some of the operating modes. The operator receives information from the computer via two cathode-ray-tube (CRT) displays and a set of LED (light-emitting diode) bar gages. These are mounted on the ceiling of the cab, as shown in Fig. 3. One display, detailed in Fig. 4, provides a graphical representation of the vehicle stability status and the positions of the legs within their operating envelopes. The other is an alphanumeric display for operating system and vehicle status messages.

Sensing

Operation in unstructured terrain requires intensive environmental sensing. The ASV system senses 82 control variables, which are fed back to the control computer as analog signals. Six additional analog channels feed operator commands to the system via the joystick. A number of other analog channels monitor internal system status information. The actuator servo loops use feedback of position, velocity, and hydraulic actuator differential pressure.

The machine has an optical scanning rangefinder, which can be seen mounted atop the cab in Fig. 1. This system, built by the

Kenneth J. Waldron is with the Department of Mechanical Engineering, and Robert B. McGhee is with the Department of Electrical Engineering, The Ohio State University, Columbus, OH 43210.

0272-1708/86/1200-0007 $01.00 © 1986 IEEE

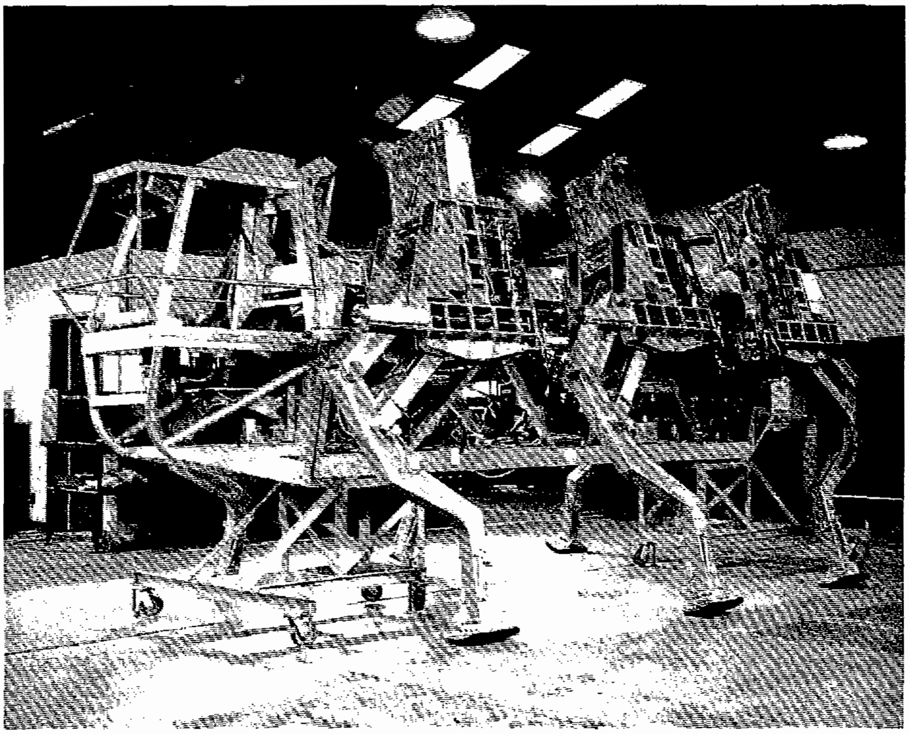

Fig. 1. The Adaptive Suspension Vehicle. The wheeled undercarriage provided support during assembly and individual leg tests, and was removed after initial tests of the complete system.

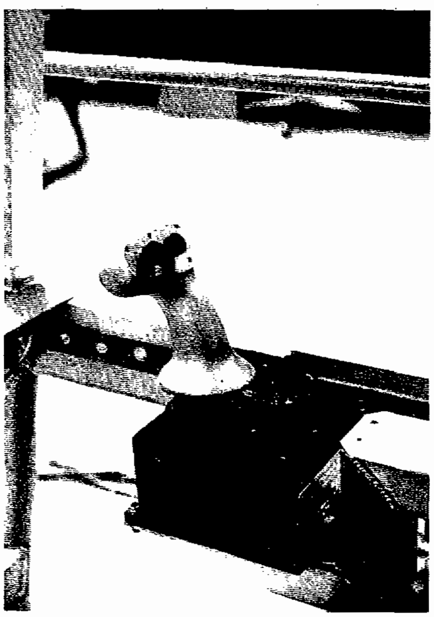

Fig. 2. Three-axis hand controller showing thumb-operated miniature force-sensing joysticks. The left joystick button provides two additional degrees of freedom; the right provides one.

Environmental Research Institute of Michigan [11], scans a 128 by 128 pixel field at two frames per second transmitting 32K eight-bit words per second over a parallel data link to the computer system. The rangefinder has a field of view of 40 degrees on either side of the body axis, and from 15 to 75 degrees below the horizontal. Its range is 10 m. No long-range sensing system is presently used, since the operator performs path selection and navigation. This being the case, additional sensors will be needed for all but the simplest types of autonomous operation.

A particularly important sensor package provides feedback of body movements. It consists of a vertical gyro, rate gyros for the pitch, roll, and yaw axes, and accelerometers in the corresponding directions. This system provides the feedback variables for the body force control loops.

Computer Architecture

The ASV computer system consists of 17 Intel 86/30 single-board computers [12]. The architecture is shown schematically in Fig. 5. Each board has an 8086 processor, 8087 coprocessor, 128K 8-bit bytes of memory, and an optional plug-in module with 16 A–D ports and 8 D–A ports. Each leg is coordinated and its actuator servos serviced by one of the 86/30 boards. Four boards generate commands to the legs based on the operator's control inputs and on the terrain model developed from the scanning rangefinder data. This system also computes stability information and guards against exceeding actuator motion limits. Two boards drive the cockpit displays and monitor the joystick controller. All of the boards previously mentioned are linked by a multibus. Five additional boards process the data from the scanning rangefinder. They are linked by a second multibus. The two multibus systems are connected by means of a parallel data link.

The output from the computer system consists of 18 analog channels, which deliver command signals to the actuator servos. There are also two data streams, which drive the cockpit displays. The mature system will have 18 switching channels, which will activate pyrotechnically released bypass valves allowing the actuators to be inactivated individually, or in groups, in system fault conditions.

Control Configuration

The ASV system is operated in a body force control mode with sensed body motion converted into force commands to the actuators of supporting legs. This mode of control has the advantage of largely eliminating the

Table
Design Goals for the Adaptive Suspension Vehicle

Length	5.2 m
Width	2.4 m
Height	3.0 m
Weight	2700 kg
Payload for Sustained Operation	220 kg
Cruising Speed	2.25 m/s
Maximum Speed	3.60 m/s
Leg Stroke	1.80 m
Vertical Foot Height Variation	1.22 m
Lateral Leg Swing	±20 degrees
Vertical Step Negotiation	2.1 m
Horizontal Ditch Negotiation	2.7 m

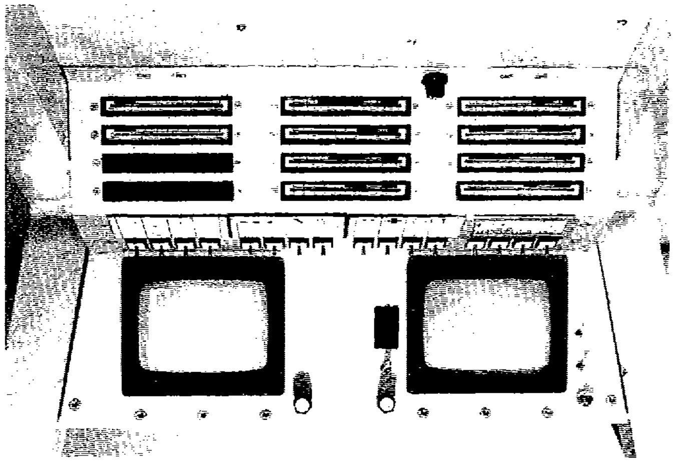

Fig. 3. Cockpit displays. The left CRT displays graphic information; the right displays alphanumerics. The LED bar gages allow monitoring of system health and status variables.

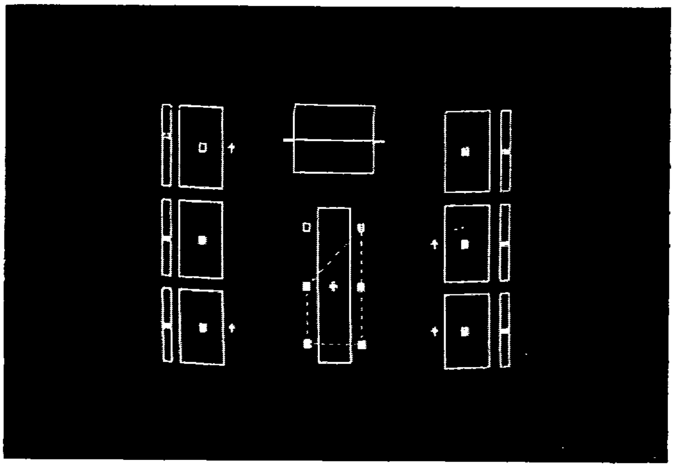

Fig. 4. Precision-footing graphical display on the operator's CRT. The central figure shows the support polygon and location of the vehicle's center of pressure on the terrain and, hence, stability status. It also shows the relative positions of the body and feet. The three displays on each side represent the positions of the feet within the working volumes of the legs. The rectangles show the foot position relative to the lateral and fore-aft motion limits. The bars show vertical foot position. The large box with a central line at top center is an artificial horizon display. The solid boxes indicate supporting feet; open boxes indicate lifted feet. The arrows indicate feet, which may be raised without loss of stability.

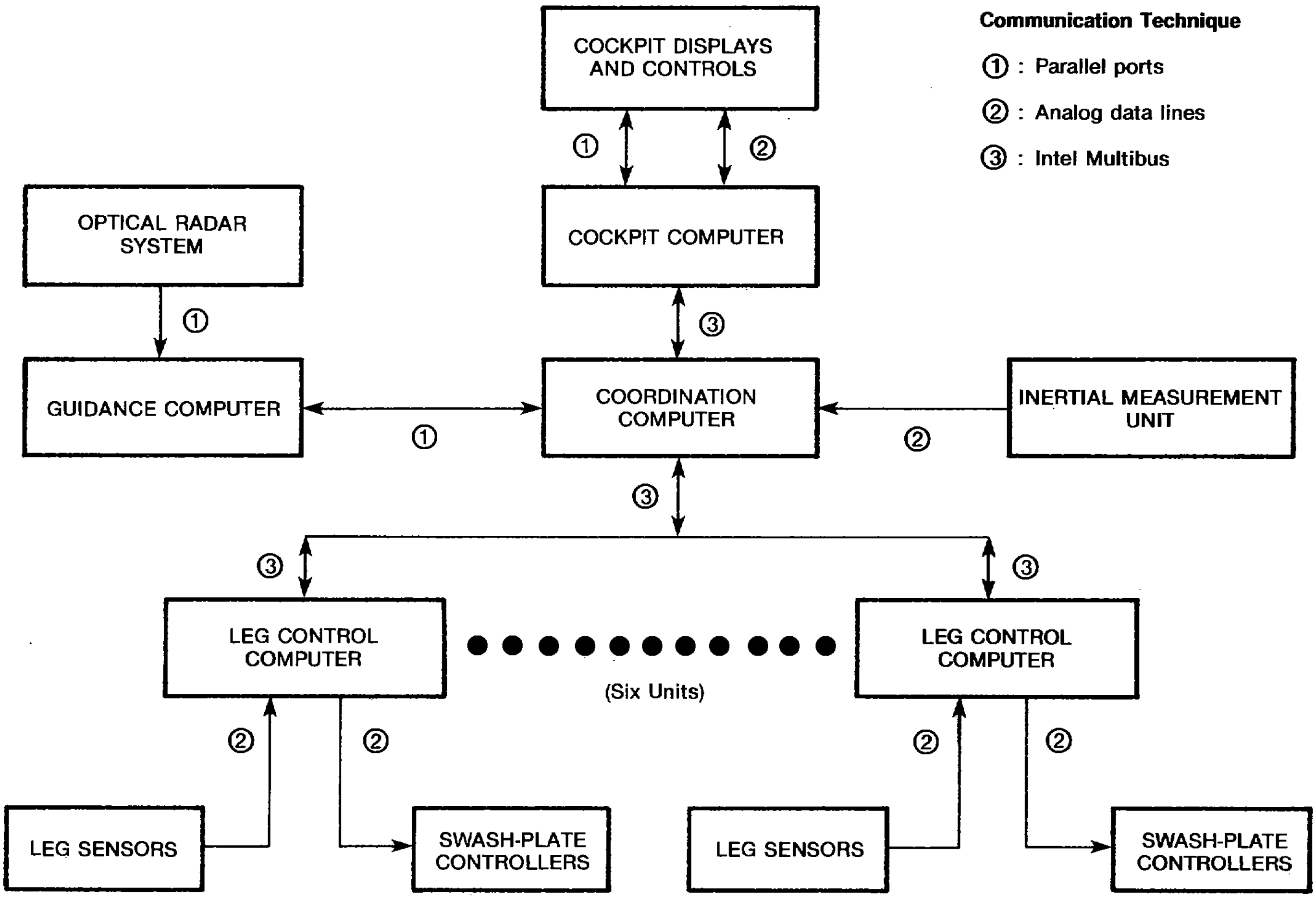

Fig. 5. Block diagram of ASV computer system showing three-layer hierarchical organization of hardware and software.

effects of leg dynamics and flexibility. However, it requires decomposition of the commanded vector force and moment (including inertia effects) on the body into commanded forces at each actuator. This turns out to be a demanding problem requiring new algorithmic and hardware approaches [13], [14].

Leg-position feedback is used from legs in support phase for the purpose of correcting for gyro and integration drift in the inertial reference system. The sampling rate for this function is chosen to be well below the mechanical system natural frequencies.

The leg control system uses a mode-switching scheme to employ different control laws during the portions of the leg cycle in which the foot is, respectively, in contact, and out of contact with the ground. When the foot is on the ground, the primary control variable of each actuator servo is the differential pressure across the actuator; that is, it is primarily a force servo. When the foot is off the ground, it is controlled to follow a preplanned path, and actuator position and rate become the important control variables.

Power Transmission and Actuation

The actuation system of the ASV is a two-stage hydraulic system in which the power stage is hydrostatic [7]. Specifically, each actuator is coupled to a variable-displacement pump in a closed system. Variation of the displacement of the pump varies the output flow and, hence, actuator rate. The primary stage for each actuator is a valve-controlled system operating off a pressure-regulated supply pump. It operates rotary actuators coupled to the control shafts of the variable-displacement pumps. Each rotary actuator is controlled by a servo valve via an analog control loop in which shaft position is fed back from an RVDT (rotary variable displacement transducer) sensor. The entire system is unique in several respects. Its bandwidth is of the order of 20 Hz, which is exceptional for a hydrostatic system. The output motion is also reciprocating, which is, again, unusual for a hydrostatic system. The high-response bandwidth is assisted by several unusual features of the actuator design, which are described in [15].

The power for the actuation system is provided by a 900 cubic cm, 68-kW peak power, four-cylinder motorcycle engine modified to run continuously at power levels of up to 50 kW in still air. This engine drives an energy storage flywheel of 0.25 kW-hr capacity. Power is distributed from the main shaft via toothed belts to three quill shafts, which run the length of the body of the vehicle. Two of these quill shafts run through the main lateral swing bearings at which the legs mount to the body. The third runs down the centerline of the body in the bottom of the frame. Power is taken off these shafts by means of toothed belts to each of the 18 variable-displacement pumps. For each leg, the drive and lift actuator pumps are mounted in the upper leg structure and powered by a belt from the shaft through the leg-mounting bearings. The pumps for the lateral swing actuators are located in the bottom of the body frame and are powered from the body shaft.

The vehicle flywheel is important for several reasons. First, it provides sufficient energy for an orderly shutdown in the event of engine failure. Second, it permits regenerative braking by reversing the roles of the actuators and pumps. Third, it provides an ability to draw very high-power densities for short periods to overcome obstacles. The output power of all hydraulic pumps, if used simultaneously at full power, is an order-of-magnitude higher than engine power. Fourth, the large flywheel isolates the engine from the strong torque fluctuations that the actuation system produces on the drive line.

Leg Mechanisms

The mechanism used in the legs of the ASV is a two-dimensional pantograph [7], [16]. See Fig. 6. This arrangement has the energetically important property of decoupling vertical and horizontal motions. It also facilitates coordination by providing a very simple leg Jacobian matrix [1], [16]. The third degree of freedom is provided by swinging the entire leg assembly laterally about an axis parallel to the longitudinal body axis. The sliding joints required by the pantograph mechanism are provided by vee-rail and conical roller assemblies, which have very low friction. The reflected inertia of the legs, as seen by the actuators, varies with leg position. However, the variation is sufficiently moderate to be handled by a small look-up table. This table is used by the leg

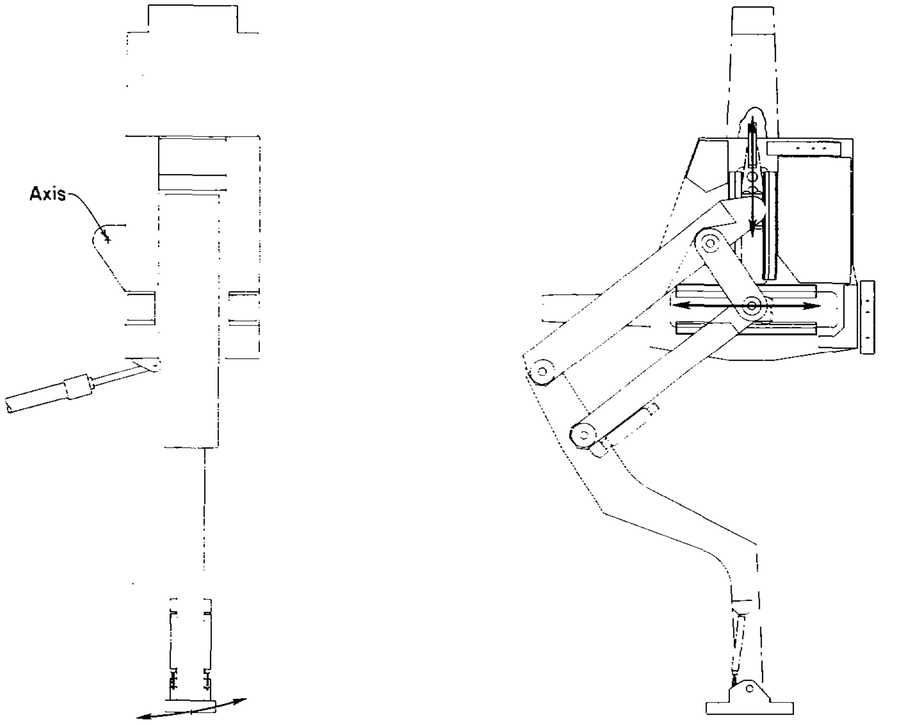

Fig. 6. ASV leg. The right-hand view is from the side with the outer guideway structure removed. The pantograph mechanism geometry provides true horizontal foot motion when the horizontal actuator is active. The arrows indicate the motions of the horizontal and vertical actuators. Roller and rail assemblies, which constrain the joints at which the actuator forces are applied to move linearly, are shown. The left-hand view is from the front and shows the location of the longitudinal axis about which the leg swings, and of the corresponding actuator. Thus, the three actuated degrees of freedom of foot motion are a horizontal motion parallel to the longitudinal axis of the vehicle body, a rectilinear motion orthogonal to that in the plane of the leg, and a rotation of the entire leg assembly about a horizontal axis.

control computers to determine the appropriate drive and lift actuator forces during the swing phase of leg motion.

The legs have an ankle hinge normal to the plane of operation of the leg. A passive hydraulic system operates across this hinge to maintain the foot parallel to the body when it is off the ground. This system operates from a pair of master cylinders, which act between the intermediate links of the pantograph linkage and the carrier of the drive roller assembly. A pair of slave cylinders controls ankle positions [17]. The kinematic relationship is not exact, but foot attitude varies by less than 3 degrees throughout the working volume of the leg. Accumulators in the system provide a controlled compliance for rotation out of the neutral position. Buffers limit foot angulation under load to 60 degrees on either side of the neutral position.

Operating Modes

As mentioned previously, the ASV has six operational modes: *utility*, *precision footing*, *close maneuvering*, *follow-the-leader*, *terrain following*, and *cruise/dash*. As previously explained, the utility mode is used for start-up, shut-down, and system testing. All of the other modes involve various forms of coordination. Precision footing is a mode of operation designed for particularly difficult terrain conditions. In this mode, the operator can select any of seven functions. One of these provides simultaneous rate control of body displacement and attitude via the joystick and minijoysticks. The other six functions allow selection and individual control of any of the six legs. The forward and lateral foot motion rate is then determined by the forward and lateral minijoystick movements, which normally control pitch and roll body rates. Foot height is controlled by the minijoystick, which normally controls body height. Computer coordination of motion is, of course, necessary to produce body displacement with six degrees of freedom from the cooperative action of the 18 leg-motion actuators.

The utility, precision-footing, and close-maneuvering modes were fully operational as of July 1986. The close-maneuvering mode is a low-speed operational mode designed for omnidirectional motion. The gait algorithm is a simplified *free gait* [2]. The scanning rangefinder is not used in this mode. since its fixed mount does not permit lateral or rearward vision. Consequently, speed of operation is limited, since force sensing must be used to govern leg descent. That is, the system will operate by "feeling" the terrain.

The follow-the-leader mode uses a gait in which the middle and rear feet are placed either in the footprints of the front feet or directly alongside them. The operator will control front-foot placement and body motion, as in the precision-footing mode. This mode will be used to cross large obstacles. It has the advantage that it relieves the operator of having to be able to see the middle and rear legs, and allows the operator to concentrate on selection of advantageous footholds.

The terrain-following mode is the most completely automated operational mode. It will be used in moderate to severe terrain. The operator in this mode, as well as in the other continuous locomotion modes, commands longitudinal velocity, lateral velocity, and rate of change of heading with the main joystick. One of the two minijoysticks controls pitch and roll rates; the other controls rate of change of walking height. In this mode, no predetermined gait will be used. Rather, a free-gait algorithm will be used to select and place feet, so as to optimize stability in terrain in which there are a relatively large number of areas unsuitable for foot placement. These are identified using the scanning rangefinder system. A further development of the terrain-following software will be used in the initial autonomous locomotion demonstrations of the ASV.

The sixth operational mode—the cruise/dash mode—differs from terrain following in using determinate gaits, specifically wave gaits [1]. This mode is designed for rapid and energetically efficient locomotion over moderate terrain. The need for shorter processing cycles will limit the utilization of scanning rangefinder data. Operation of the ASV at top speed (dash) involves sacrifice of efficiency and smoothness for speed over easy terrain. The use of scanning rangefinder data may be further reduced, and the highest speed wave gait—the tripod gait—will probably be used exclusively. Higher primary hydraulic system pressures and flywheel speeds will be used to provide greater speed at the expense of considerably increased power consumption.

Summary

The Adaptive Suspension Vehicle is the most sophisticated artificial legged locomotion system attempted to date. It will break new technological ground in operating over completely unstructured terrain. Of course, detailed discussion of the many technical features and capabilities of this machine is not possible in one paper. Rather, the reader is referred to a substantial number of publications on various aspects of the vehicle design, which are available in the literature. A number of these are cited in the present paper. A more complete list, along with a brief history of the project, is given in [18].

Acknowledgments

The work presented herein was supported by the Defense Advanced Research Projects Agency under Contracts MDA 903-82-K-0058 and DAAE 07-84-K-R001. The authors wish to acknowledge the contributions of numerous students and coworkers to the work presented here. The work of V. J. Vohnout, D. R. Pugh, and E. Ribble (all of Adaptive Machine Technologies, Inc.) has been of particular importance to the hardware and software design of the ASV as well as to its subsequent testing.

References

[1] R. B. McGhee, "Vehicular Legged Locomotion," *Advances in Automation and Robotics*, edited by G. N. Saridis, Greenwich, CT: Jai Press, Inc., 1985.

[2] R. B. McGhee and G. I. Iswandhi, "Adaptive Locomotion of a Multilegged Robot Over Rough Terrain," *IEEE Trans. on Systems, Man, and Cybernetics*, vol. SMC-9, no. 4, pp. 176–182, Apr. 1979.

[3] S. Hirose, et al., "Titan III: A Quadruped Walking Vehicle," *Proceedings of the 2nd ISRR Symposium*, Tokyo, Japan, pp. 247–253, Aug. 1984.

[4] M. H. Raibert, et al., "Dynamically Stable Legged Locomotion," Rept. CMU-R1-TR-83-20, The Robotics Institute, Carnegie-Mellon University, Dec. 1983.

[5] T. Bartholet, "Odetics Makes Great Strides," *Nuclear Engineering*, vol. 31, no. 381, pp. 43–44, Apr. 1986.

[6] I. E. Sutherland and M. K. Ullner, "Footprints in the Asphalt," *International Journal of Robotics Research*, vol. 3, no. 2, pp. 29–36, Summer 1984.

[7] K. J. Waldron, V. J. Vohnout, A. Pery, and R. B. McGhee, "Configuration Design of the Adaptive Suspension Vehicle," *International Journal of Robotics Research*, vol. 3, no. 2, pp. 37–48, Summer 1984.

[8] S. M. Song, K. J. Waldron, and G. L. Kinzel, "Computer-Aided Geometric Design of Legs for a Walking Vehicle," *Mechanism and Machine Theory*, vol. 20, no. 6, pp. 587–596, 1985.

[9] K. J. Waldron, "The Mechanics of Mobile Robots," *Proceedings of 1985 International Conference on Advanced Robotics*, Tokyo, pp. 533–544, Sept. 1985.

[10] K. J. Waldron, "Mobility and Controllability Characteristics of Mobile Robotic Platforms," *Proceedings of 1985 IEEE International Conference on Robotics and Automation*, St. Louis, MO, pp. 237–243, Mar. 1985.

[11] D. Zuk, F. Pont, R. Franklin, and M. Dell'Eva, "A System for Autonomous Land Navigation," *Proceedings of Active Systems Workshop*, Naval Postgraduate School, Monterey, CA, Nov. 6, 1985.

[12] R. B. McGhee, D. E. Orin, D. R. Pugh, and M. R. Patterson, "A Hierarchically-Structured System for Computer Control of a Hexapod Walking Machine," *Theory and Practice of Robots and Manipulators, Proceedings of ROMANSY-84 Symposium*, edited by A. Morecki, et al., London: Hermes Publishing Co., pp. 375-381, 1985.

[13] R. B. McGhee and D. E. Orin, "A Mathematical Programming Approach to Control of Joint Positions and Torques in Legged Locomotion Systems," *Proceedings of ROMANSY-76 Symposium*, Warsaw, Poland, pp. 225-232, Sept. 1976.

[14] K. J. Waldron, "Force and Motion Management in Legged Locomotion," *Proceedings of 24th IEEE Conference on Decision and Control*, Fort Lauderdale, FL, pp. 12-17, Dec. 1985.

[15] A. Pery, K. J. Waldron, and J. F. Gardner, "Synthesis, Analysis and Design of a Hydraulic Actuation System for a Six-Legged Walking Machine," *Proceedings of 1985 American Control Conference*, Boston, MA, June 10-12, 1985, vol. 2, pp. 730-736.

[16] S. M. Song, J. K. Lee, and K. J. Waldron, "Motion Study of Two- and Three-Dimensional Pantograph Mechanisms," *Proceedings of 9th Applied Mechanisms Conference*, Kansas City, MO, Oct. 1985, Sess. III.A, Paper I.

[17] S. M. Song, "Kinematic Optimal Design of a Six-Legged Walking Machine," Ph.D. Dissertation, The Ohio State University, Columbus, OH, 1984.

[18] R. B. McGhee and K. J. Waldron, "The Adaptive Suspension Vehicle Project: A Case Study in the Development of an Advanced Concept for Land Locomotion," *Unmanned Systems*, vol. 4, no. 1, pp. 34-43, Summer 1985.

Kenneth J. Waldron obtained the B.E. and M. Eng. Sc. degrees in 1964 and 1965, respectively, from the University of Sydney. He received the Ph.D. degree from Stanford University in 1969. He was Acting Assistant Professor at Stanford (1968-1969); Lecturer, then Senior Lecturer, at the University of New South Wales (1970-1974); Associate Professor at the University of Houston (1974-1979); and Associate Professor, then Professor, then John B. Nordholt Professor at The Ohio State University (1979-present). His research interests include the kinematics and dynamics of mechanisms, application of computer-aided engineering techniques to mechanism design, and mechanical design of robots and computer-coordinated mechanical systems, with particular emphasis on mobile robotic systems. He has authored over 70 journal articles and conference proceedings. He is Codirector of the Adaptive Suspension Vehicle Project.

Robert B. McGhee received the B.S. degree in engineering physics from the University of Michigan in 1952. After three year's service in the U.S. Army Ordnance Corps in the area of guided-missile electronic maintenance, he entered graduate school at the University of Southern California, where he subsequently received the M.S. degree in 1957 and the Ph.D. degree in 1963, both in the field of electrical engineering. During this period, he was also a member of the technical staff of Hughes Aircraft Company, where he worked on the design of guidance systems for antiaircraft and antitank missiles. In 1963, Dr. McGhee became a member of the faculty of the Department of Electrical Engineering at the University of Southern California. In 1968, he joined The Ohio State University, where he now holds a joint appointment as Professor of Electrical Engineering and Professor of Computer and Information Science and is, in addition, Director of the Digital Systems Laboratory, The Ohio State University Research Foundation. His teaching and research interests center around computer control of complex mechanical systems in general, and mobile robots in particular. He has also worked extensively in the fields of biomechanics and neural control. For the 1985-1986 academic year, Dr. McGhee is the recipient of the Commodore Grace Hopper Visiting Research Chair at the Naval Postgraduate School, Monterey, California, where he is involved in research relating to applications of artificial intelligence to the control of mobile robots. He is codirector of the Adaptive Suspension Vehicle Project.

Out of Control

"Sorry, Monsieur Bezout ... but I'm afraid this proof of your identity is just not acceptable. Perhaps you should carry American Express!"