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Multi-Limbed Locomotion Systems for Space Construction and Maintenance

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1. Abstract

Multi-limbed locomotion systems operating in a "hand over hand" fashion are attractive for the construction and maintenance of large structures in space. They offer much greater energy efficiency as compared to thruster based mobility systems. They also free the designer of the structure from the necessity to incorporate tracks or other elements necessary for construction robots into his structural design. This type of locomotion system also offers great flexibility for handling unexpected situations such as structural failures.

A well developed technology of coordination of multi-limbed locomotory systems is now available. ~~This presentation will include~~ results from a NASA sponsored study of several years ago. This was a simulation study of a three-limbed locomotion/manipulation system. Each limb had six degrees of freedom and could be used either as a locomotory grasping hand-holds, or as a manipulator. The focus of the study was kinematic coordination algorithms.

The presentation will also include very recent results from the Adaptive Suspension Vehicle Project. The Adaptive Suspension Vehicle (ASV) is a legged locomotion system designed for terrestrial use which is capable of operating in completely unstructured terrain in either a teleoperated or operator-on-board mode. Future development may include autonomous operation. The ASV features a very advanced coordination and control system which could readily be adapted to operation in space. An inertial package with a vertical gyro, and rate gyros and accelerometers on three orthogonal axes provides body position information at high bandwidth. This is compared to the operator's commands, injected via a joystick to provide a commanded force system on the vehicle's body. This system is, in turn, decomposed by a coordination algorithm into force commands to those legs which are in contact with the ground. The individual leg controls are mode ~~switched between~~ a force control mode, when the foot is on the ground, and a position velocity mode when the foot is being returned. This form of control is attractive for space applications of multi-limbed systems, whether for locomotion or manipulation, since the weight appears only as one of the forces acting on the vehicle body and the coordination algorithms are set up to minimize generation of loads by limbs pushing against one another.

2. Introduction

Multi-limbed systems can be used for locomotion over space structures as well as for manipulation. A proven technology of artificial limbed locomotion is now available [1,2]. A configuration which is well adapted both to locomotion and to manipulation is shown in Figure 1 and has been studied in simulation [3,4].

Limbed locomotion has several advantages for use over space structures. First, a limbed system can be wholly electrically actuated using only energy which is renewable via solar panels. The actuation system can be configured for regeneration minimizing energy requirements. Further, limbed locomotion requires only discrete hand-holds and should require no modification of many structures. Finally, limbed systems provide great flexibility permitting adaptation to unexpected situations caused either by failures within the locomotion system itself, or by damage to the structure it is negotiating.

Technologies which provide capability for autonomous identification of hand-holds in real time [5] are now under test at several centers [1,6]. This raises the possibility that a remote operator need only designate a path which would be traversed autonomously, in much the same way as is planned for a Mars rover [7]. In this manner, direct teleoperation would only be necessary when performing manipulative tasks.

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In this presentation the status of the technologies needed for realization of a limbed locomotion/manipulation system will be reviewed.

3. A Suggested Configuration

As is shown in Figure 1, the suggested configuration has three limbs. This will allow locomotion with two hands gripping hand-holds at all times. It will also allow use of two manipulation modes: a single armed mode in which two hands grip hand-holds leaving one free for manipulation, and a two armed cooperative mode with one hand gripping a hand-hold. It is expected that manipulation would be performed in a teleoperative mode. Locomotion would be performed in either a teleoperative mode, or autonomously with the remote operator designating path segments, as mentioned above. However, even in the teleoperative mode, the operator would command only direction and rate, individual limb movements would be fully automated.

The optimum geometry of a limb for locomotion [8] is quite compatible with that for manipulation [9]. In fact, if the first joint axis is placed parallel to the longitudinal axis of the body (the preferred locomotion direction), the second axis intersects the first and is normal to it, the third is parallel to the second and is placed exactly half way along the length of the limb, the fourth is also parallel to the second and third, the fifth intersects the fourth normally and the sixth intersects the fifth normally, as shown in Figure 2. The configuration is optimal for both purposes. However, a three limbed system lends itself better to a rotationally symmetric configuration which favors omni-directional motion without a preferred direction. In such a configuration it is preferable to place the first axis of each limb parallel to the axis of symmetry, as in the Odex, for example [2].

A four-legged system would have the attraction of allowing bilateral manipulation from a firmer base with two hands grasping handholds. It could also be configured as a bilaterally symmetric system with a preferred direction of motion, with some gains in locomotion speed and efficiency. This would, however, probably only be an advantage on very large structures. The cost would be the necessity of coordinating 24 degrees of freedom rather than 18, and the corresponding increase in system complexity.

4. Coordination

The primary problem in adaptive limbed locomotion is the automatic coordination of a relatively large number of actuated degrees of freedom to achieve a desired body motion. A great deal is now known about this problem as a result of the Adaptive Suspension Vehicle project [1]. In particular, the problem of using irregular, so-called "free gaits" to accommodate to sparse foot-holds or hand-holds is well understood. The architecture of a suitable free-gait algorithm is shown in Figure 3. With respect to gait, which is the phasing of limb movements, the situation in space is, in fact, much simpler than in terrestrial locomotion since there is no need to maintain stability against gravity. Thus, the sole determinant of the locomotion potential of a limb at a given instant is its kinematic margin [3]. This problem was examined in the simulation study described in references [3] and [4].

The Adaptive Suspension Vehicle [1], shown in Figure 4, uses an inertial local guidance system to detect body motion at high bandwidth. The actual body rate is compared to the operator's commands via a six axis joystick. The resulting error is converted into a commanded acceleration and, hence, a commanded inertia force system. This inertia force system is combined with the weight of the machine and decomposed via a force allocation algorithm into commanded leg forces [8,9]. Finally, these are decomposed via a Jacobian transformation into commanded actuator forces. The use of the legs as force generators in this fashion removes the necessity for sophisticated dynamic modelling of the legs.

The inertial sensing package is a relatively simple unit consisting of a vertical gyroscope, rate gyroscopes on three orthogonal axes, and accelerometers on the same axes. Drift and integration errors are corrected at low bandwidth by use of position information from joint position sensors on the leg joints.

Obviously, a substitute would have to be found for the use of gravity for a vertical reference in this scheme. However, the force control strategy is very applicable. In this manner the problem of limbs working against each other, which is characteristic of cooperative, multi-limbed operations, is avoided.

5. Sensing

Although it can be assumed that the geometry of the structure over which the machine will operate will be known, except for circumstances in which the structure is damaged, it is still necessary to provide on-board sensing to identify hand-holds and other features. This is necessary to correct location of the hand-hold for inertial system drift and other system errors. In fact, location of landmarks, perhaps combined with proprioceptive position sensor information, can be used to provide the necessary low bandwidth position data to update the inertial guidance system. As was mentioned above, technologies which will permit automatic, real-time identification of such features are being developed in the Adaptive Suspension Vehicle (ASV) [5] and Autonomous Land Vehicle (ALV) [6] programs. The scanning rangefinder described in reference [5] is being used to select footholds for the Adaptive Suspension Vehicle. It provides a range image in angle-angle coordinates scanning a 128 X 128 pixel field at two frames per second. In the ASV configuration the field scanned is 60° in the vertical plane and 80° in the horizontal. The ALV uses a scanning rangefinder with a slightly different field. Similar instruments are being used at several other centers.

The necessary technology for conversion of the range image into a continuously updated elevation map in Cartesian coordinates based on the vehicle, and for selection of footholds based on that map, has been developed for the ASV, and would be directly applicable to a limbed locomotion system in space. The scanner, in the ASV configuration, would be too heavy and bulky, and too expensive in power requirements for use in space construction. However, since this was the first operational unit, considerable development is possible. The mechanical scanning system could readily be redesigned into a much more compact, and much lower power system. The need for higher resolution at shorter range would allow use of a lower power laser.

Video based terrain modelling technologies are also being developed [6], particularly in the ALV program. At present, the emphasis is on identifying large features, such as roads. Further development of this approach might ultimately provide models at higher resolution than can be achieved with the laser scanner approach.

Another important feature of the sensing system is the need to sense both position and force at all actuated joints. In fact, joint rate sensing is easily added and is useful in limb control. Position, velocity, and force sensing are used on the ASV actuators [1]. Position/rate sensing is important for guidance of the limb when it is not gripping a hand- hold, and for inference of the position of the system from known hand-hold positions. Force sensing is needed for limbs gripping hand-holds, and for cooperative manipulation.

6. Controls

A number of features of the control system for the proposed machine have already been described. The proposed system has a hierarchical architecture shown in Figure 5. It is based on techniques proven in the ASV project. As is the case with that system, it is intended that the operator could interact with the system at several different levels [1,3]. At the highest level, the operator would designate path segments to be autonomously traversed, as suggested in Section 1. Figure 6 shows a composite photo of a three-legged robot walking over a series of path segments [4]. It might be noted that operation in this mode would require very little hardware or software added to that needed for continuous interaction. This is a result of the need for automated hand-hold selection and coordination for effective locomotion.

The next level of interaction would be one in which the operator continuously commands body velocity and angular velocity during locomotion via a joystick controller similar to that used on the ASV [1]. This is expected to be an effective control mode for relatively short traverses. Note that hand-hold selection and limb coordination would be fully automated in this mode.

At the next lower level of interaction, the operator would directly control the position, relative to the machine body, of one, or two hands. NASA has investigated six-axis controllers suited to this function [12]. This mode would be used both in teleoperated manipulation and in locomotion when the operator finds it necessary to directly control hand-hold selection and limb and body motion. This might happen, for example, when repairing damage.

It should be noted that the proposed system has a great deal of inherent flexibility of operation and redundancy. Locomotion is possible using only two limbs. Loss of function of several actuators could be accommodated to with degradation in performance, but without total loss of function. The use of differing mixes of automated and teleoperated function allows adaptation to a large variety of situations.

7. Conclusion

A technology of coordinating multi-limbed systems for locomotion, cooperative manipulation, and for manipulation with multi-finger, multi-degree of freedom hands is now available. It is here suggested that a manipulation system with at least three dual purpose limbs can provide an attractive mobility capability. Key features of the technology for this purpose have been discussed in this paper.

8. Acknowledgement

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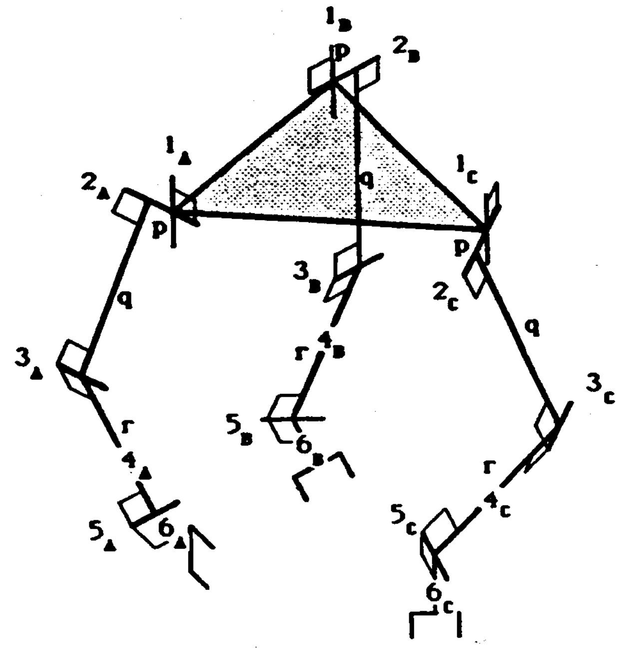

Figure 1. Proposed configuration of a limbed locomotion/manipulation system.

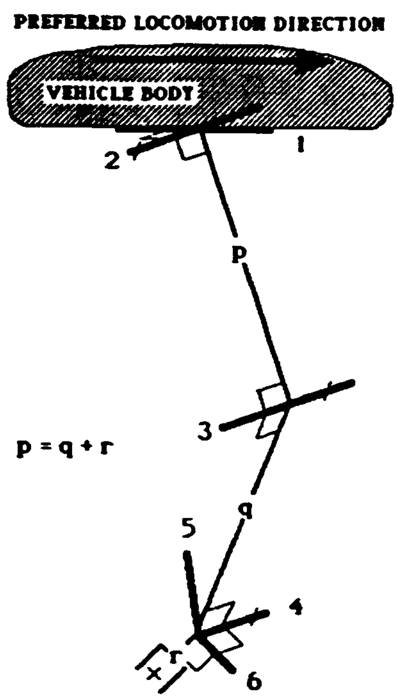

Figure 2. Optimal geometry for a dual purpose limb.

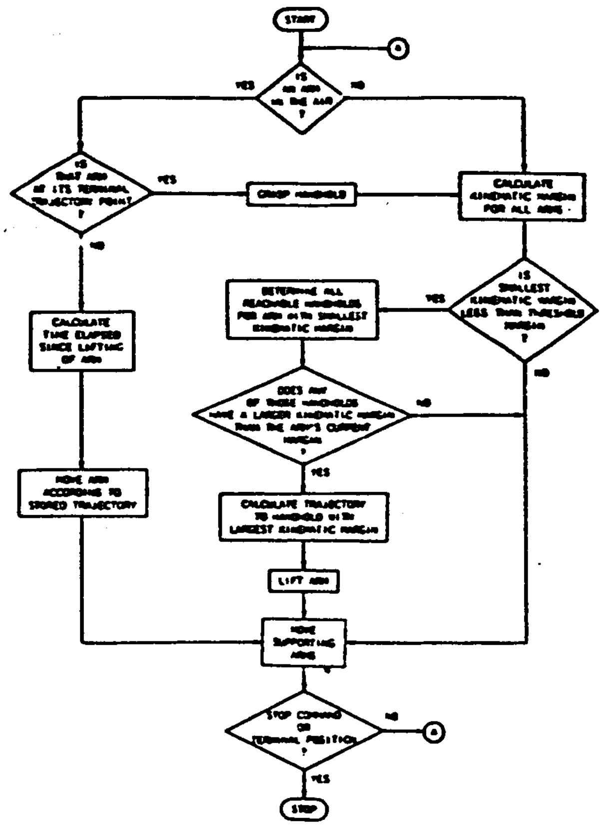

Figure 3. Architecture of free gait algorithm [3].

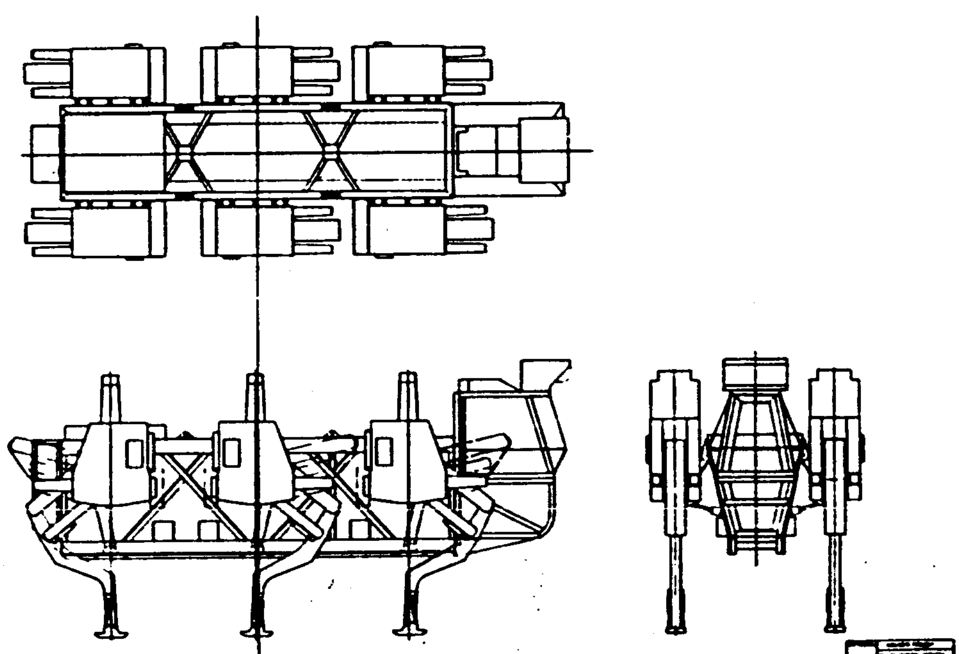

Figure 4. The Adaptive Suspension Vehicle.

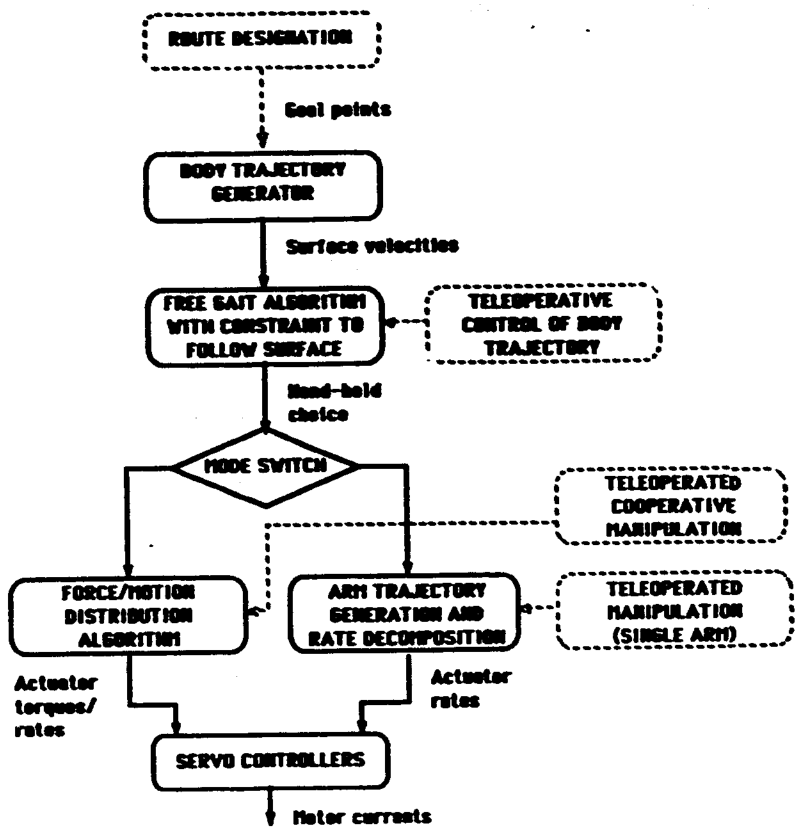

Figure 5. Control and coordination software architecture. The dotted boxes indicate operator interactions.

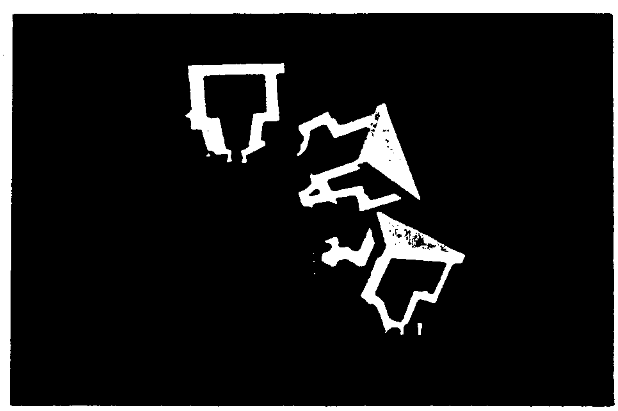

Figure 6. Photo of simulated space vehicle walking over a structural beam.