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Algorithm Development and Computer Graphic Simulation of an Articulated Transporter/Manipulator System

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ABSTRACT

The University of Florida is part of a multi-university research effort, sponsored by the U.S. Department of Energy, which is underway to develop and deploy an advanced semi-autonomous robotic system for use in nuclear power stations. The robotic system being designed by the Florida/Odetics team can be described as an Articulated Transporter/Manipulator System (ATMS) which has several unique motion and transport capabilities. The ATMS will be capable of performing tasks in radioactive hazardous environments to reduce occupational radiation exposure of plant personnel and to increase the availability of the plant. This paper will describe the key design and control features of the ATMS with emphasis placed on the implementation of specific motion control algorithms.

INTRODUCTION

The nuclear industry is actively seeking ways to reduce the radiation exposure of workers at nuclear power plants to as low as is reasonably achievable. In addition, the operational up-time of nuclear plants must be increased in an effort to reduce the total life-cycle costs associated with the plant. The use of advanced robotic technologies can directly impact both of these important operational areas. The Advanced Technology Development Division of the U.S. Department of Energy (DOE) is currently sponsoring a research consortium of four universities (University of Florida, University of Michigan, University of Tennessee, and University of Texas) and the Oak Ridge National Laboratory to develop the next generation of robots to service and maintain existing nuclear power plants as well as the innovative nuclear reactor plant designs now being developed in companion DOE programs.

The Florida/Odetics contribution to the DOE research team has primarily been in the areas of (1) data base modeling of nuclear power plants and (2) the transportation and mobility of a robotic system throughout the plant. The complex obstacle strewn environment of a nuclear power plant (numerous pipes, dykes, cables, stairways, etc.) requires that the robotic system be capable of crossing or jumping over substantially sized obstacles. Transport mechanisms consisting of combinations of wheels, tracks, and legs were considered as candidates, but the inherent mobility limitations of these mechanisms led to the selection of a transporter comprised of multiple articulated segments. The resulting ATMS design is shown in Figure 1.

The ATMS is comprised of eighteen individual segments which provide both maneuverability and locomotion. Each segment is 11.5 inches wide, 13 inches high, and 24 inches in length, and has a pair of motor driven wheels to provide traction for forward and

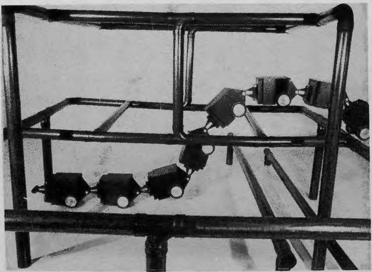

Fig. 1: ATMS Model

backward motion. Segments are connected in series by a pair of revolute joint axes. Initial control of the system will be accomplished by an operator who establishes the direction and velocity of the lead segment of the system. Subsequent segments of the ATMS will follow the path of the segment directly in front of it.

The significant feature of the design is that the ATMS will be able to cross over horizontal gaps of up to twelve feet in length. This is accomplished by guiding the lead segment through the air until the twelve foot mark is reached. At this point, torque limitations require that the lead segment touch ground again. In a similar fashion, the ATMS can cross over obstacles by 'flying' through the air, until operational constraints require that the lead segment come in contact with some flat support structure.

Research in the design and control of articulated, multi-link manipulators has been previously conducted in Japan, Germany, and England. The works of Tomizawa [1] and Wakahara [2] have shown that it is possible to control a multi-link manipulator by having segments successively follow the path of a lead segment. The German concept is being jointly developed by the Princeton Plasma Physics Laboratory and Karlsruhe Laboratory and is composed of six links with a total extension of ten meters (Bohme, et al. [3]). The English at the Marchwood Laboratory of the Central Electricity Generating Board (Langford [4]) have been developing a multi-link manipulator for the Sizewell Reactor which is comprised of nine links, each about two feet long. The linkage is controlled by steering the tip with each pivot point of the mechanism following the same path. Each of these programs have that it is possible to control the motion articulated manipulator system. Florida/Odetics research aims to furt advance these developments by achieving articulated robot device which has mobility characteristics.

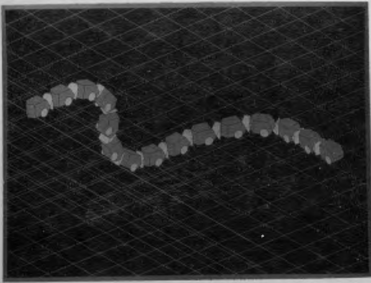

Fig. 2: Animated Representation of ATMS

CONCEPT OF OPERATION

As previously stated, the ATMS will the ability to cross horizontal gaps of up twelve feet in length before the lead seg must again contact a firm support. Since eighteen segments are connected in series two revolute joints, at every instance a to of thirty four joint angle parameters must specified in order to define the configurat of the system. Effective operation of the requires that a control and guidance strat be developed to reduce the number of degrees freedom that an operator must consider control.

Four control strategies are be developed as follows:

(1) joystick control with operatio
constraints
(2) X,Y planar control
(3) Previewed motion
(4) High level motion specification

The simplest method of control for ATMS will require the operator to 'fly' lead segment via a joystick device. operator will point the lead segment desired direction by controlling the two jo angles between the lead and second segmen The lead segment will be propelled forw along this direction with all subsequ segments following the same path. The comput controller will monitor the ATMS to ensure no operational constraints are exceeded. example, the computer controller automatically warn the operator when the twel foot horizontal 'jumping' distance is about be exceeded and will then autonomously land lead segment if necessary. Similarly, computer controller will not allow the opera to exceed maximum vertical jumping distan nor to command any motion which would produc static instability of the ATMS.

The second operational control strateg X,Y planar control, will require an operator guide the lead segment of the ATMS as if were operating on a smooth horizontal surfa An accurate geometric description of environment will allow the computer control to identify vertical obstacles which obstr the ATMS path. Required take-off points be calculated and the computer controller wi perform all required vertical motions in ord to jump over or across the obstacle.

During previewed motion control, operator will be able to observe the ATMS its environment on an animated graphics disp (see Figure 2). The operator will be able guide the animated transporter in previously described joystick control mode while the actual ATMS remains stationary. If the operator performs a successful task, the actual ATMS will be commanded under computer control to perform the operator's previously specified commands. If the operator is not successful in performing some desired motion, he can repeat the attempt by returning the animated system to the location of the actual system. This scenario serves to ensure successful task performance as well as serve to train inexperienced operators. Similar methods have been applied to the control of remote manipulators and to the development of telepresence systems [5].

The final control strategy allows the operator to perform high level motion specifications. In this mode, the operator will be provided with an interactive animated representation of the environment. The operator will be able to point to specific locations in the environment via a mouse input device. The computer controller will generate a path through these specified points. The operator will be able to watch the animated ATMS perform the motion and modify the path if desired before the actual ATMS begins its motion.

A fifth operational mode will be developed which will allow for the autonomous planning of ATMS motions between user specified positions. This work is strongly coupled to the effort underway to model the nuclear plant and will not be discussed in this paper.

MOTION CONSTRAINTS

Each of the operational modes described above requires that the ATMS be capable of performing two basic types of motion, i.e. horizontal and vertical navigation. As each name implies, horizontal navigation is concerned with the movement of the ATMS along some smooth flat surface while vertical navigation deals with the motion of the ATMS as it jumps over and across obstacles (see Figure 3). During vertical navigation the ATMS is presently restricted to remain in a vertical plane. This paper will detail the development of system constraints and 'follow-the-leader' algorithms for the case of vertical navigation. Vertical motion of the ATMS can be classified into three types:

(1) jump and land on top of obstacle
(2) jump over an obstacle
(3) descend from a higher to a lower level

For each type of vertical motion, certain constraints must be considered. These constraints are basically due to the designed torque capacity of the ATMS joints and to stability considerations.

As the ATMS performs vertical motion, torques are applied at certain of the joints due to the cantilever effect caused when the lead segments leave the ground. The torque experienced by any joint must never be allowed to exceed the designed torque for that joint. The relationship between the required torque and jumping height for each of the three types of vertical motion has been established and the results for the first type of vertical motion will be described in detail.

Shown in Figure 4 is an example of the first type of vertical motion. As shown, the path is comprised of circular segments with a radius of twenty four inches together with straight line segments. Any desired vertical

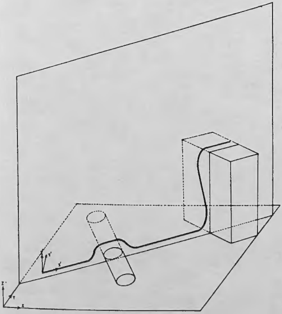

Fig. 3: Vertical Navigation

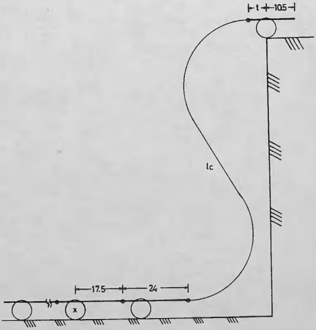

Fig. 4: Type I Vertical Navigation

motion can be accomplished with these three primitives. Figure 5 shows a computer generated path over several different obstacles. It should be noted that a straight line segment must be inserted between the two curved sections only when the height of the vertical jump exceeds 89.57 inches.

As expected, the maximum vertical jump is directly dependent on the torque which can be generated and sustained at each of the joints of the ATMS. Shown in Figure 6 is a plot of the maximum torque that an individual joint must generate versus the height of the obstacle. Two curves, T0 and T2, are shown in the figure. The T0 curve represents the maximum torque experienced by any joint as the front of the ATMS is about to land on top of the obstacle. The T2 curve represents the maximum torque experienced by any joint as the last segment of the ATMS leaves the ground. The abrupt change in the shape of the torque curves when the height of the obstacle exceeds 89.57 inches is due to the fact that the shape of the vertical path now includes a straight line segment between the two curved sections. The design torque for each joint of the ATMS is 38,880 in-lbs. From Figure 6 it can be seen that the ATMS will thus be able to jump to a height of approximately 180 inches.

The maximum vertical height that the ATMS can jump is also governed by stability considerations. For example, in Figure 4 the lead segment of the ATMS is about to contact the top of the obstacle. At this instant, the sections of the ATMS which are off the ground produce a moment about the axis of the forwardmost wheel which is still on the ground. This moment must be balanced by the ATMS sections which are behind this pivot point or the ATMS will lose stability and the rear segments will be lifted off the ground.

Shown in Figure 7 are balancing moment curves when the rear sections of the ATMS are in a straight line as shown in the path of Figure 4. The curve M0 represents the moment about the wheel pivot point just before the lead segment touches the top of the obstacle. The curve M0b represents the moment about the same pivot point due to the last segments of the ATMS which are in a straight line. If for any given obstacle height, the value of M0b is less than M0, then stability will be lost. In a similar fashion, the curves M2 and M2b represent the case where the last segment of

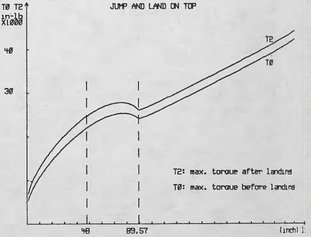

Fig. 6: Required Torque vs. Obstacle Height

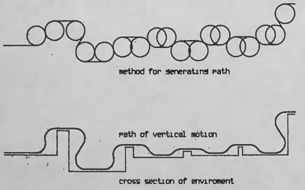

Fig. 5: Computer Generated Path

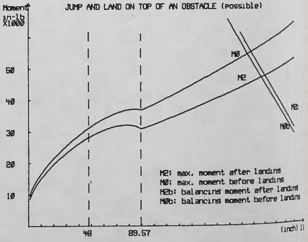

Fig. 7: Stability Moments vs. Obstacle Height (Case

the ATMS has just left the ground and where the lead segments are stretched out in a straight line to provide counter balancing. If M2b is less than M2, then the ATMS will fall back off of the obstacle. From Figure 7 it is apparent that the ATMS can jump a vertical distance of 175 inches without losing stability if the rear sections are straight before the jump and the lead sections remain straight after the jump.

As shown in Figure 5, it may often be the case that the rear sections of the ATMS may not be straight before a jump. Such a case is shown in Figure 8 with corresponding moment balancing curves shown in Figure 9. Since the rear segments were not straight before the lead segment attempted the first jump, the curves M0b and M2b in Figure 9 have been shifted significantly when compared to Figure 7. For the type of motion shown in Figure 8, the maximum vertical height of the next obstacle can be only 25 inches. This case has shown that it is important for the computer controller to continuously monitor the system stability to ensure that the operator does not attempt to exceed the capabilities of the system.

FOLLOW-THE-LEADER ALGORITHM DEVELOPMENT

A vertical motion path can be generated by knowing the size of the obstacles along the desired route. Such a path was shown in Figure 5. In order for the ATMS to move along the planned path, the following information must be known at every instant:

(1) the position and orientation of the lead segment
(2) the thirty four joint angles of the ATMS

A tremendous amount of computation would be required in order to continuously calculate this information.

In order to reduce the number of computations, a follow-the-leader algorithm has been developed which stores the data that has been previously calculated for the preceding segments and passes this data to the following segments. In other words, after a certain amount of time, segment j+1 will be in the exact position and orientation as segment j which immediately precedes it.

In the algorithm, the first three segments form a unit for the generation of data. Each subsequent three segments are also treated as a unit. The data generated by the first three segments are stored and passed back in time to subsequent units. An important feature of the algorithm is that the data is generated without any discontinuity at any of the joint angles. Basically, this is done by calculating the information for the first three segments (the first unit) from the vantage point of the fourth segment. This approach has produced smooth, continuous motion of the ATMS as it moves along the path (see Figure 10). Further, the algorithm has been implemented on a VAX 11-750 computer in real time at discreet intervals of 0.2 inches.

CONCLUSIONS

The key feature of this development is that the ATMS will have the ability to maneuver through obstacle strewn areas which are impossible with conventional transporter systems. The multiple freedoms of the ATMS design (34 joint angle parameters) which allow for the impressive mobility of the system require, however, that detailed control

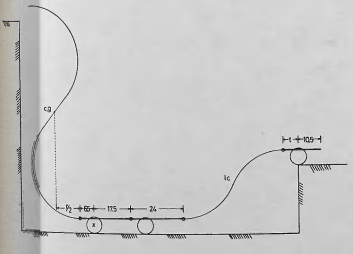

Fig. 8: Maneuvering Over Multiple Obstacles

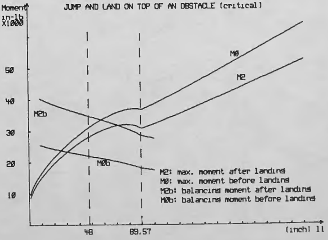

Fig. 9: Stability Moments vs. Obstacle Height (Case 2)

strategies be developed to simplify the task of the operator. Operational concepts have been presented which minimize the cognitive processing that the operator must perform by requiring that the computer controller ensure that operational constraints are not violated.

Results to date from all demonstrations and simulations show that the ATMS offers promise both from a mobility standpoint and from a control standpoint. The system has been modeled in simple form and found to meet all projected capabilities.

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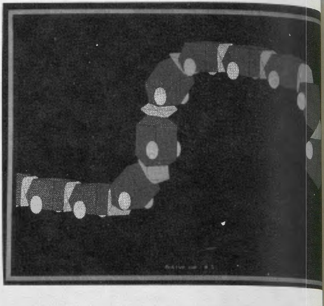

Fig. 10: Animated Representation of ATMS