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ABSTRACT

The goal of this research was to investigate the performance of the Articulated Transporter and Manipulator System (ATMS) during various tasks relative to the choice of wrist/end-effector configuration. The approach taken was to generate computer graphics-aided three-dimensional interactive application (CATIA) system-based models of four wrist/end-effector combinations and consider the volumetric reach of each of these configurations based on the capacity of the ATMS. The results indicate that a simple, lightweight end-effector provides a greater volumetric reach. The greatest variation presented herein is ~40% when comparing a 7-degree-of-freedom (DOF) dexterous arm with a simple 3-DOF arm; however, the benefit of increasing volumetric reach by only 40% by using a simple arm may be outweighed by the loss of dexterity.

INTRODUCTION

As part of the Nuclear Engineering (NE) program funded by the Department of Energy (DOE), a unique transporter system, called the Articulated Transporter and Manipulator System (ATMS), is being studied as a possible mobile platform for manipulators intended for maintenance in nuclear facilities. The ATMS was designed jointly by Odetics, Inc., (Anaheim, California) and The University of Florida, Department of Mechanical and Nuclear Engineering (Gainsville, Florida).

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It is a unique teleoperated robot designed for remote maintenance and surveillance in a highly unstructured and possibly hazardous environment. Possible environments include, but are not limited to, nuclear power plants, chemical processing plants, and waste disposal and storage facilities. This study addresses the choice of an end-effector system for the ATMS based solely upon consideration of the total volumetric reach of each candidate.

The ATMS, shown in FIG. 1, is a snake-like manipulator designed to navigate in an unstructured and crowded environment. The ATMS is comprised

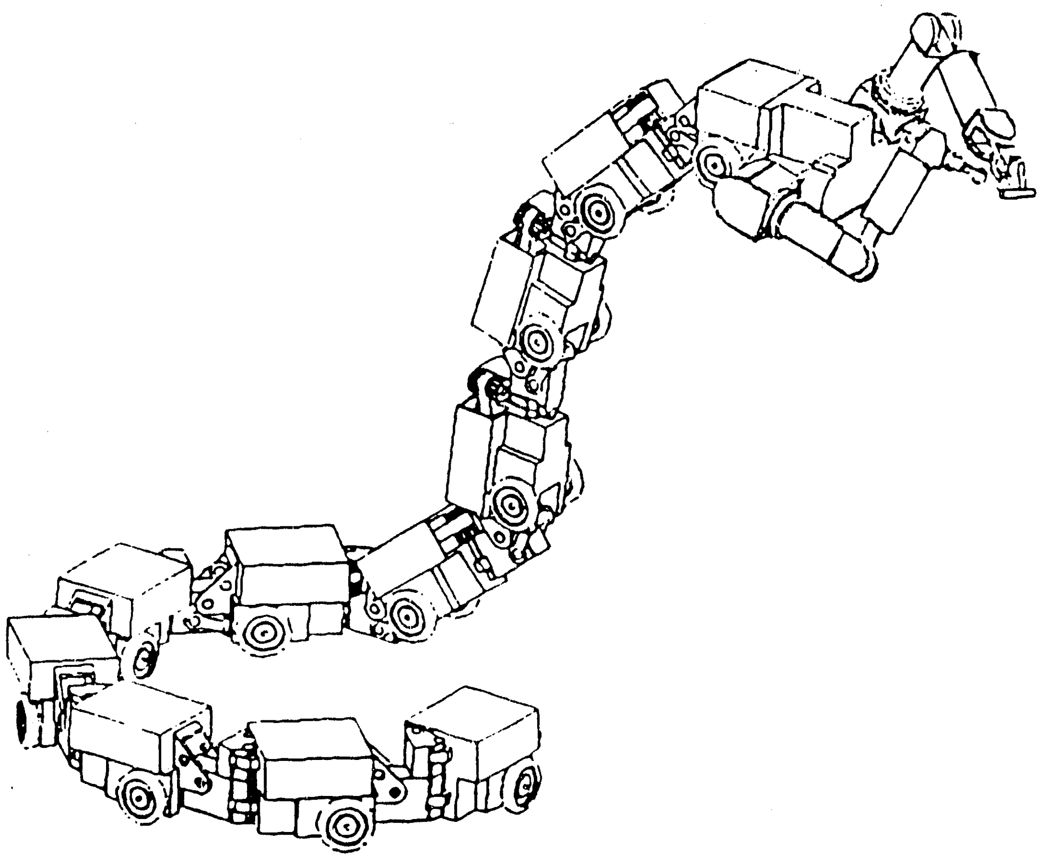

FIG. 1. Articulated Transporter and Manipulator System (ATMS).

of 18 segments, each with a pitch joint on one end, a yaw joint on the other end, and two drive wheels. Each segment is 0.292-m (11.5 in.) wide × 0.330-m (13 in.) high × 0.610-m (24 in.) long. The wheels are 0.178 m (7 in.) in diameter [1]. Maneuvering the ATMS will be accomplished by an operator who establishes the direction and velocity of the front segments and subsequent segments follow one another. Horizontal and vertical navigation algorithms are presently being studied that will allow the ATMS to move along a plane and to move over and under obstacles. The ATMS is controlled through a 6-degree-of-freedom (DOF) joystick. Each DOF of the joystick can be locked to reduce the DOFs.

The most significant feature of the ATMS is its ability to cross horizontal gaps of several feet and move vertically over obstacles. The extent of this capability is determined by the choice of manipulator system used as the ATMS end-effector; however, this capability is unique and is far in excess of the capabilities of traditional platforms employed in the nuclear industry (e.g., bipeds [2] and wheeled platforms [3,4]). If the ATMS is to perform any useful work, a wrist/end-effector (or arm/end-effector) must be attached to the final link. With this basic concept, the final link or links become the slave manipulator of a telerobot.

The first design requirement guiding the selection of candidate wrist/end-effectors was to achieve modularity. The wrist/end-effector must be remotely detachable from the final section of the ATMS. A second requirement was that the wrist/end-effector be an independent module so that different wrists/end-effectors could be used with different tasks.

When the ATMS reaches its work area, the final link or links may be required to rise so that the manipulator(s) may access the component requiring maintenance. In this event, the maximum number of links that can be lifted determines the overall reach of the ATMS/manipulator system and is a function of the total mass of the manipulators. Computer graphics-aided three-dimensional interactive application (CATIA)-based models of several different wrist/end-effector combinations were constructed and used to geometrically determine the volumetric reaches of each of the systems. The first three systems considered were

1. Oak Ridge National Laboratory (ORNL)/Human Engineering Laboratory (HEL) 3-DOF wrist with parallel-jaw tong;

2. dual arm, 6-DOF RM-10A [5,6]; and

3. dual arm, gear-driven, electronically counterbalanced 7-DOF Laboratory Telerobotic Manipulator (LTM) [7].

As in the design of any manipulator system, the choice of gripper/hand for the ATMS is determined by the particular task environment envisioned for the system. The ATMS will be able to navigate around, over, and through many obstacles; however, the effectiveness of the ATMS in completing a particular task is directly tied to the choice of wrist/end-effector mounted on the first link of the chain. Each of these three candidate systems already listed uses a simple parallel-jaw-type gripper. Multiple-DOF hand designs exist today [8,9]. At least one design needed to consider the possibility of implementing a multiple-DOF hand. Thus, an additional candidate system was considered;

4. ORNL/HEL 3-DOF wrist with ORNL-designed three-finger hand.

APPROACH

Volumetric reach is defined as the volume accessible by the manipulator. It is a function of arm length and mass; joint design, placement, and limits; actuator design; and gripper/hand design. Volumetric reach is an important parameter in describing any manipulator designed for work in an unstructured environment; however, the successful completion of most tasks requires the manipulator system to maneuver around obstacles while accessing (in appropriate orientations) objects connected with the maintenance task. Other measures of manipulator performance exist (e.g., a dynamic simulation); however, volumetric reach is a simple, basic way to compare manipulator systems.

Volumetric reach was calculated for each system in the following manner. For the ATMS to rise, each link must be capable of lifting the mass of the successive links as well as the end-effector. For static conditions, the sum of the moments about any of the ATMS links must be zero. This condition is illustrated in FIG. 2 for the ATMS with two links elevated.

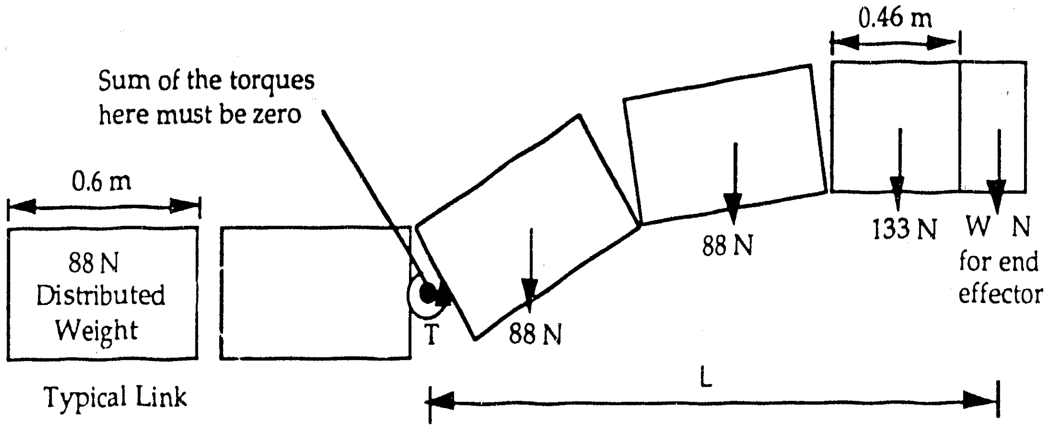

FIG. 2. ATMS elevated for task.

Note that the end-effector is connected to the last complete link by an end-interface link having a weight of 133 N (30 lb_f) and a length of 0.46 m (18 in.). This static system is solved for the number of links capable of being elevated. The solution is given by Eq. (1):

$$T = \left[\frac{N}{2} + \sum_{i=1}^{N} (i-1)\right] Wd + W_E(Nd + 0.23) + (Nd + 0.46)W_{Arm} , \quad (1)$$

where

- T = Torque developed by the joint (Nm),
- W = Weight of each ATMS segment (88 N),
- W_E = Weight of the end ATMS segment (133 N),
- W_{Arm} = Weight of the end-effector system (N),
- d = Length of the ATMS segments (0.6 m),
- L = Total length lifted in Fig. 2 (m),
- N = Number of segments elevated.

The maximum torques that can be developed by the ATMS pitch and yaw joints are 4067 Nm (3000 ft-lb_f) and 2034 Nm (1500 ft-lb_f), respectively. Assuming that the ATMS is positioned in a worst-case orientation, which would require the yaw joint to oppose gravity, then 2034 Nm is the limiting torque. The reachable volume is determined by using both side and top views of the area enclosed by the manipulator system when the ATMS joints and the arm joints are moved through their maximum ranges of motion.

An important point to consider is that the working reach may be very different from the volumetric reach. The working reach is defined as the volume in which the manipulator not only can reach a point but also can achieve a usable orientation. (A usable orientation will be determined by the task under consideration.) The working reach is, therefore, a task characteristic as well as a manipulator characteristic. To simplify this analysis, it is assumed that the working volume is equal to the volumetric reach.

RESULTS

Results are presented for each of the wrist/end-effector combinations. The "a" part of each table has joint ranges of motion, and the "b" part has volumetric reach data. The volumetric reach data are presented for all of the possible configurations; that is, from "no segments elevated" (arms only) to the "maximum number of segments elevated."

ORNL/HEL Wrist with Parallel-Jaw Tong

The mass of the HEL wrist system, shown in FIG. 3, is 34 kg. Its motion ranges are given in TABLE Ia. Solving Eq. (1) for d translates into four segments as liftable. Volumetric reach data are summarized in TABLE Ib.

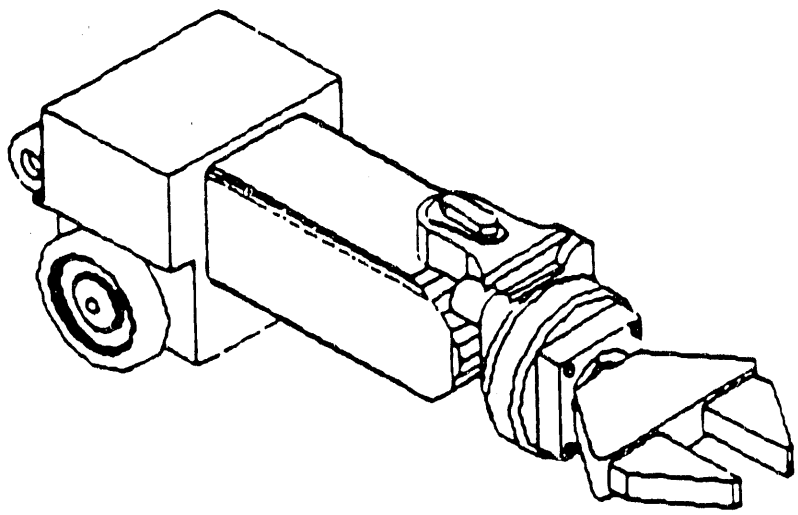

FIG. 3. The HEL wrist.

TABLE Ia. Joint ranges of motion for the HEL wrist.

Joint	Description	Motion Range (rad)
1	Pitch	$+\pi/4$ $-3\pi/4$
2	Yaw	$+\pi/2$ $-\pi/2$
3	Roll	$+\pi$ $-\pi$

Source: ORNL Dwg. X3E12651-001

TABLE Ib. Volumetric reach for the HEL wrist.

No. of ATMS segments elevated	Volumetric Reach (m^3)
0	0.76
1	6.65
2	29.14
3	80.93
4	171.88

RM-10A System

The mass of the RM-10A system, shown in FIG. 4, is 57 kg. Its motion ranges are given in TABLE IIa. Solving Eq. (1) for d translates into three segments as liftable. Volumetric reach data are summarized in TABLE IIb.

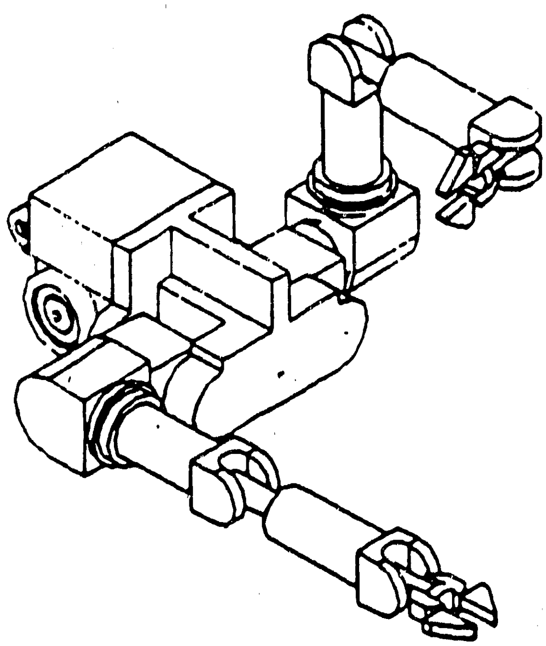

FIG. 4. The RM-10A system.

TABLE IIa. Joint ranges of motion for the RM-10A system.

Joint	Description	Motion Range (rad)
0[a]	Arm Roll	$+\pi/2$ -0-
1	Shoulder Pitch	$+2\pi/3$ $-2\pi/3$
2	Shoulder Roll	$+2\pi/3$ $-2\pi/3$
3	Elbow Pitch	$+5\pi/9$ $-5\pi/9$
4	Elbow Roll	$+5\pi/2$ $-5\pi/2$
5	Wrist Pitch	$+11\pi/36$ $-11\pi/36$
6	Wrist Roll	$+5\pi/2$ $-5\pi/2$

Source: White [6]

[a] Property of ATMS.

TABLE IIb. Volumetric reach for the RM-10A system.

No. of ATMS segments elevated	Volumetric Reach (m^3)
0[a]	5.69
1	21.95
2	66.77
3	147.08

[a] This is the arm only.

LTM System

The mass of the LTM system, shown in FIG. 5, is ~100 kg. Its motion ranges are given in TABLE IIIa. Solving Eq. (1) for d translates into two segments as liftable. Volumetric reach data are summarized in TABLE IIIb.

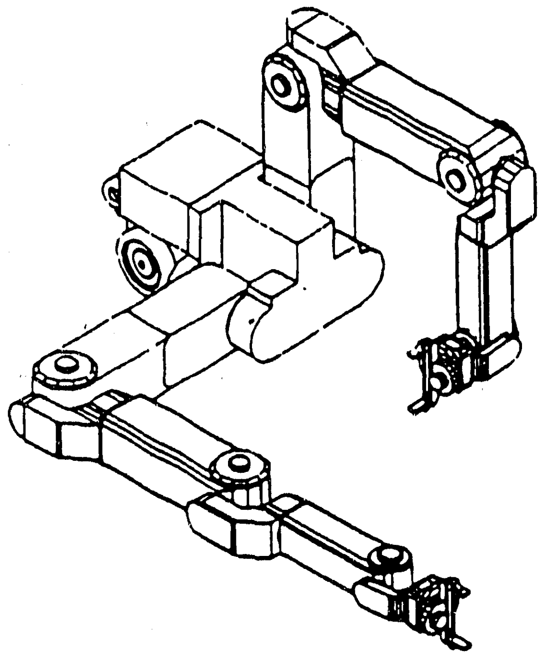

FIG. 5. The LTM system.

TABLE IIIa. Joint ranges of motion for the LTM.

Joint	Description	Motion Range (rad)
0[a]	Arm Roll	$+\pi/2$ -0-
1	Shoulder Pitch	$+3\pi/4$ $-\pi/4$
2	Shoulder Yaw	$+\pi$ $-\pi$
3	Elbow Pitch	$+3\pi/4$ $-\pi/4$
4	Elbow Yaw	$+\pi$ $-\pi$
5	Wrist Pitch	$+3\pi/4$ $-\pi/4$
6	Wrist Yaw	$+\pi$ $-\pi$
7	Wrist Roll	$+\pi$ $-\pi$

Source: ORNL LTM Critical Design Review, Dec. 8–9, 1987.
[a]Property of ATMS.

TABLE IIIb. Volumetric reach for the LTM.

No. of ATMS segments elevated	Volumetric Reach (m^3)
0[a]	16.68
1	51.34
2	124.23

[a]This is the arm only.

ORNL/HEL Wrist with ORNL-designed three-finger hand

The mass of the HEL wrist with the ORNL-designed three-finger hand is assumed to be approximately the same as its mass with the parallel-jaw tong; therefore, the volumetric reach data are the same as TABLE Ib for the HEL wrist with parallel-jaw tong.

DISCUSSION

This study illustrated some general concepts about the selection of an end-effector for the ATMS. One important consideration is that the choice of end-effector is determined not only by the ATMS mechanical capabilities but also by the task requirements and the environment in which the task will be performed. For example, the ORNL/HEL wrist is the lightest of the candidate systems, which means that, mechanically, the ATMS can be more flexible with this end-effector than with the others. This end-effector is restricted, however, to tasks requiring little or no dexterity because it is only 3-DOF, as opposed to 6- or 7-DOF. It must rely on the ATMS to provide the other DOFs. Note that even though more of the ATMS links are liftable for the lighter end-effector, it should not be inferred that the lighter, fewer DOFs end-effectors have more dexterity than the heavier, 6- or 7-DOF end-effectors resulting from the added DOFs of the ATMS links. The ATMS links have large cross-sectional areas (0.096 m^2, or ~1 ft^2) and large volumes (0.059 m^3, or ~2 ft^3); therefore, they are not as maneuverable as a link of an RM-10A or LTM arm (e.g., 0.023 m^2, or 0.25 ft^2 in cross section for the LTM). The added mobility of being able to lift additional links is helpful, but it is not as important as the dexterity gained by having additional arm segments. For more details, see Kress et al. [10].

CONCLUSIONS

The work cited in this report is only a small portion of the basic design effort required to complete the design of a wrist/end-effector for the articulated transporter and manipulator system. It does, however, compare and summarize the basic properties of some candidate end-effector systems. Clearly, the choice of end-effector depends upon the desired task; however, based on the results of this study, the general conclusion can be made that a lightweight, redundant manipulator with a dexterous hand seems best suited for the ATMS end-effector. Light weight and redundancy are usually conflicting requirements and is the case for all of the systems presented herein. The development of a lightweight, high-capacity, dexterous, multi-finger hand could extend the set of tasks performable by the ATMS; however, the tasks would still be limited by the size and dexterity of the ATMS segments.

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