CONF-970464--10

HYDRAULIC MANIPULATOR RESEARCH AT ORNL*

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To be presented at the
ANS SIXTH TOPICAL MEETING
on Robotics and Remote Systems
in Augusta, Georgia
April 27 - May 1, 1997

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*Oak Ridge National Laboratory, managed by Lockheed Martin Energy Research Corp. for the U.S. Department of Energy under contract number DE-AC05-96OR22464.

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ABSTRACT

In the early developmental stages of robotics, hydraulics played an important role. Many of the early high-payload capacity manipulators were actuated by hydraulic cylinders and hydraulic rotary actuators. As the power-to-weight ratio of electric motors increased, they eventually came to be the preferred form of actuation for robotic manipulators because of the relative ease of operation, control, and maintenance for general cleanliness. Recently, however, task requirements have dictated that manipulator payload capacity increase to accommodate greater payloads, greater manipulator length, and larger environmental interaction forces. General tasks such as waste storage tank cleanup and facility dismantlement and decommissioning require manipulator lift capacities in the range of hundreds of pounds rather than tens of pounds. To meet the increased payload capacities demanded by present-day tasks, manipulator designers have turned once again to hydraulics as a means of actuation. Hydraulics have always been the actuator of choice when designing heavy-lift construction and mining equipment such as bulldozers, backhoes, and tunneling devices. In order to successfully design, build, and deploy a new hydraulic manipulator (or subsystem), sophisticated modeling, analysis, and control experiments are usually needed. Oak Ridge National Laboratory (ORNL) has a history of projects that incorporate hydraulics technology, including mobile robots, teleoperated manipulators, and full-scale construction equipment. In addition, to support the development and deployment of new hydraulic manipulators, ORNL has outfitted a significant experimental laboratory and has developed the software capability for research into hydraulic manipulators, hydraulic actuators, hydraulic systems, modeling of hydraulic systems, and hydraulic controls. The purpose of this article is to describe the past hydraulic manipulator developments and current hydraulic manipulator research capabilities at ORNL. Included are example experimental results from ORNL's flexible/prismatic test stand.

I. GENERAL COMMENTS ON HYDRAULICS

Hydraulically actuated manipulators play an important role in real applications because of their high payload-to-mass ratios compared with those of conventional electrically actuated manipulators. Comparable power-to-mass ratios range from 3.3 kW/kg (2 hp/lb_m) for hydraulic systems to 50 W/kg (0.03 hp/lb_m) for electric systems.[1] The best electric motors are now getting as high as 1 kW/kg (0.6 hp/lb_m) power-to-mass ratios.

In many industrial applications where a high power capacity is desired, hydraulics is the general form of actuation. Hydraulics provides a number of unique features. First, the fluid provides a natural method of lubrication and cooling. There is no

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phenomenon in hydraulic components that is equivalent to the saturation and concomitant losses in magnetic materials as is associated with electric motors. Torque output from a hydraulic machine is limited only by safe stress levels. Furthermore, hydraulic actuators have a high stiffness compared to other drive devices. In addition, they have a higher speed of response as well as large torque-to-inertia ratios, providing high acceleration capacity. Hydraulic components may be operated in continuous, intermittent, reversing, and stalled conditions without damage. In addition, rotary and linear hydraulic actuators are available for many different sizes and power ranges.[2]

Hydraulics technology is not without its disadvantages. For example, hydraulic power is not as readily available in most industrial settings as is electric power, and most stationary applications must have a hydraulic power supply installed. Hydraulic components are expensive. Hydraulic fluids are sometimes flammable and/or considered to be hazardous waste. Hydraulic systems almost always leak and are therefore considered messy. Hydraulic fluids must be filtered and in some cases filtered thoroughly for high-performance applications like those found in servovalves. Contaminated oil is one of the primary reasons for component failure in hydraulic systems. Finally, hydraulic actuators are not generally as flexible and easy to use for low-power applications as are electric actuators.

II. RECENT HYDRAULIC MANIPULATOR RESEARCH

The recent focus on hydraulics and hydraulics controls in the open literature highlights the importance and relevance of hydraulics in today's applications. Examples of current hydraulics-related controls research and other hydraulics efforts relating to automation can be found in recent literature. Examples range from controllers for basic positioning systems such as the work by Plummer and Vaughan[3], to system identification such as when Vossoughi and Donath[4] describe a globally linearizing feedback controller for electrohydraulic servo systems, to work done on the development of grasping control laws for use with hydraulically actuated fingers in a robotic hand by Pfeiffer.[5] In another example Conrad[6] discusses the development of a mechatronic test facility with a transputer controlled hydraulic robot. Other less recent publications also highlight hydraulics and hydraulics controls for automation applications. Tsao and Tomizuka[7] present the development of a robust controller for an electrohydraulic servo-actuator for machine tool positioning. Jinghong, Zhaoneng, and Yuanzhang[8] present a short paper considering the variation of oil effective bulk modulus with pressure in a hydraulic system. They develop a model and compare it to experimental results. Variation of bulk modulus is one parameter that greatly affects the system performance for hydraulic systems, which is one of the topics of focus of ORNL hydraulics research.

III. PAST HYDRAULIC MANIPULATORS AT OAK RIDGE NATIONAL LABORATORY

The applied nature of the projects at Oak Ridge National Laboratory (ORNL) and the direct results of the value of hydraulics have made hydraulics the power source of choice in many ORNL projects. Consequently, ORNL has had considerable experience with hydraulic manipulators and movable systems over the past decade. This section briefly describes some of the hydraulic hardware systems developed at ORNL.

Except for some very early work with commercially available teleoperated manipulators, one of the first hydraulic systems developed at ORNL was the Soldier Robot Interface Platform (SRIP) vehicle shown in Fig. 1.[9]

The SRIP vehicle was designed and built with the assistance of the Tooele Army Depot in Utah. The SRIP has a hydrostatic-drive transmission and was fitted with an electric arm and numerous sensor systems. It was designed for two purposes; the military developed it as a platform for research into unexploded ordinance disposal, and the Department of Energy (DOE) supported it for buried waste site characterization and remediation. One of the particularly challenging aspects of the SRIP development was providing it with the ability to maintain an accurate trajectory necessary for complete coverage of an area during a waste characterization survey in spite of limited accuracy wheel position sensors and a hydrostatic transmission. At the time of the development of SRIP, low-cost and accurate Global Positioning System (GPS) sensors were not readily available.

Another hydraulic system developed at ORNL is the Future Armor Rearm System (FARS), shown in Fig. 2.[10,11]

The FARS was designed and built with the assistance of the Tooele Army Depot. The FARS was developed to allow the Army to rearm its new M1A1 tanks without exposing the soldier to the hazards of the battlefield. The FARS hydraulically actuated arm served several purposes: (1) to dock with the empty tank; (2) to be a communication link between the tank and the FARS rearm vehicle; and (3)

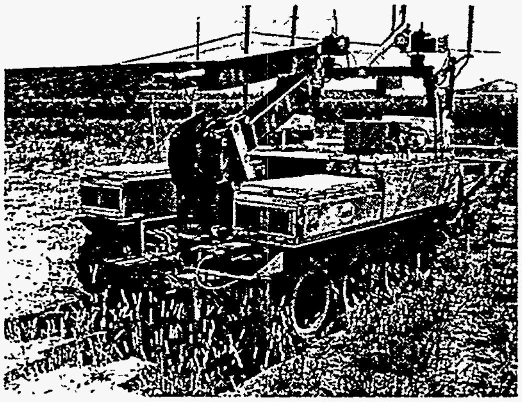

Figure 1. The Soldier Robot Interface Platform (SRIP) vehicle

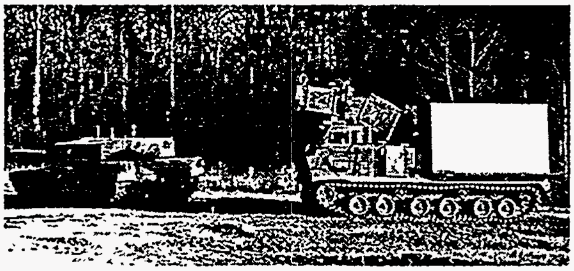

Figure 2. The Future Armor Rearm System (FARS)

to transfer the ammunition between the tank and the FARS vehicle. Control of the FARS arm proved to be a challenge in achieving the fine motion required to dock with the tank rearm port. Management of the interaction forces between the arm and the docking port during contact proved to be a hydraulic system challenge. Ultimately, interaction forces were controlled by developing a compliant rearm port on the tank. Flexibility and low natural frequency would be a problem with the FARS arm if it were moved quickly. To avoid exciting the arm's structural dynamics, however, the joints are moved slowly.

The next hydraulic system developed by ORNL was the Telerobotic Small Emplacement Excavator (TSEE), shown in Fig. 3.[12,13] Like the SRIP, this system was developed as a dual-use system. The military supported development as a platform for research into unexploded ordinance disposal, and DOE supported development for buried waste site characterization and remediation. One of the particularly challenging aspects of the TSEE development was providing it with the ability to be remotely operated as well as be operated as it was originally designed with no interference to the operator from the modifications for remote operation.

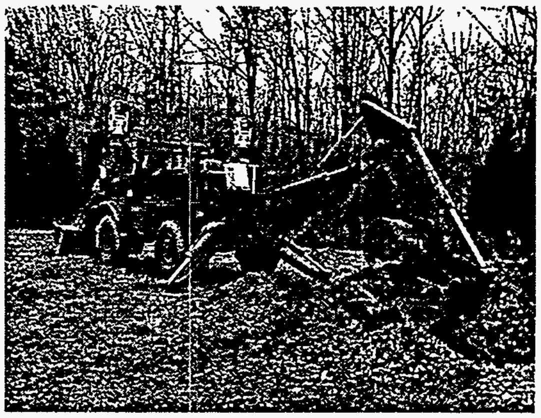

Figure 3. The Telerobotic Small Emplacement Excavator (TSEE)

In addition, the TSEE control panel was made to be portable with an intuitive operator interface. Arm and bucket motions were controlled by a single joystick where the direction of the joystick motion matched the physical direction and motion of the arm and bucket. The control system provided an adjustable dig floor to prevent the operator from inadvertently digging below a desired level. These intuitive features made the TSEE easy and simple to use; in fact, over half of the soldiers surveyed in an operational experiment comparing the use of the remotely operated TSEE with a conventionally operated version preferred the remotely operated TSEE. Low-cost and reliable proportional valves were used in the TSEE vehicle. The TSEE has also been operated over the network with operator and vehicle separated by thousands of miles.

As part of the DOE Robotics Technology Development Program's support of decontamination and dismantlement (D&D) efforts, the Dual Arm Work Module (DAWM) was developed at ORNL.[14-16] This system is the most current manipulator in the evolutionary development of telerobotic manipulators at ORNL.[17] The DAWM, shown in Fig. 4, features two 6-degree-of-freedom (D.O.F.) hydraulically actuated, Schilling manipulators and a 5-D.O.F., hydraulically actuated base. It is currently deployed off a 4-D.O.F. electrically actuated, gantry-like transporter; however, it can be deployed from a mobile platform as well. Each of the Schilling arms is capable of lifting 250 lb fully extended. A similar system will be used to support the D&D activities at the CP-5 reactor at Argonne National Laboratory (ANL). The ORNL DAWM is used for support of the D&D effort at ANL in the areas of operator training, tool and fixture testing and development, control algorithm development and testing, cost/benefit experimental analysis, and operator interface design and evaluation.

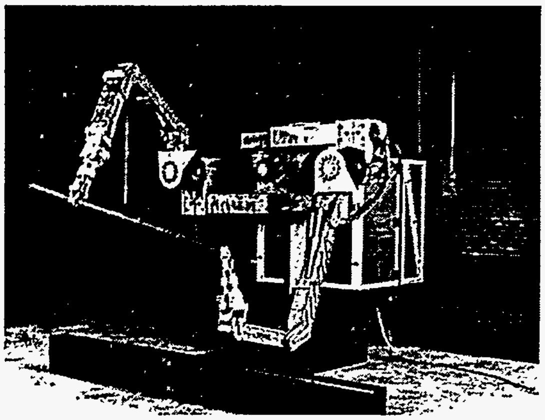

Figure 4. The Dual Arm Work Module (DAWM)

Another hydraulic manipulator system at ORNL is the Schilling 7F, 6-D.O.F., multiplaner, teleoperated, flexible controls test bed used for controls and teleoperator research for hydraulically actuated, flexible-link manipulators. This system is shown in Fig. 5.

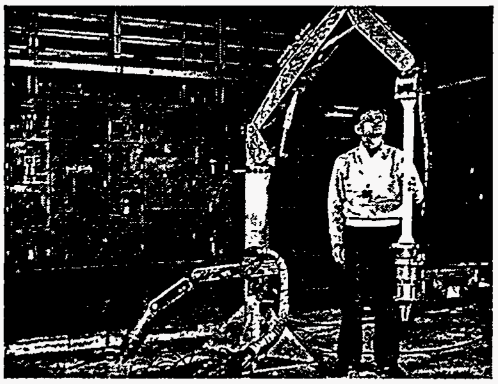

Figure 5. The Schilling 7F, 6-D.O.F., multiplaner, teleoperated flexible controls test bed

This system is presently being used for event-based controller integration in support of ORNL's Gunite And Associated Tanks (GAAT) cleanup effort. This system has also been used for mockup of larger arms and for preliminary demonstrations of hardware that is normally deployed off of larger manipulators. This system is normally teleoperated, but it has been converted to run robotically. Limited accuracy and low reliability remain a problem.

IV. NEW HYDRAULIC MANIPULATOR SYSTEMS

A. Human Extender/Amplifier

A human extender (also called a human amplifier system) is a device that amplifies the lifting capacity of a person and allows a preselected amount of force feedback to the operator (e.g., the operator can feel any desired portion of the load). This type of manipulator system is similar to a teleoperated system in that a human operator is coupled directly to the mechanical system; however, it is fundamentally different from the traditional teleoperated manipulator system in the sense that the master and slave manipulators are one integral unit. Applications of a human extender system include the following:

1. Material handler in an unstructured environment where manipulating and orienting large objects while transmitting back to the operator a fraction of the object's dynamics (i.e., its weight, contact forces, slippage, etc.) could significantly enhance productivity, quality, and safety (e.g., missile loader and rearming tanks/heavy artillery for the military).
2. Rescue operations (e.g., Oklahoma bombing rescue, firefighting).
3. Material handler in the construction industry (i.e., taking large loads off trailers as is typically done by a large crane; moving large pipes; putting up sheet rock; etc.).
4. Medical (e.g., patient manipulation).
5. Material handler in the mining industry.
6. Material handler in the forestry industry.

The human extender problem was first addressed in the 1960s by General Electric during the Hardyman project.[17] More recently, H. Kazerooni has been working on a scaled-down version of a similar concept.[19-21] These systems have always had difficulties because of profound stability issues associated with varying dynamics and gross nonlinearities in the fluid power system (e.g., nonlinear pressure-flow relationship, time–varying fluid properties, large quantities of nonlinear friction, and time–varying system dynamics).

The goals of the ORNL human amplifier system are to achieve high lift capacity (around 500 lb), force amplification (from 1 to 500), and tracking performances (submillimeter range). The effects of human dynamics must be minimized to achieve these goals.

Detailed hydraulic models that include most of the nonlinear fluid and mechanical dynamics have been generated for a 1–D.O.F. human extender test stand. Fundamental stability limits and how they relate to the mechanical device have been analytically developed and experimentally evaluated on the hydraulic test stand. The ORNL human extender/amplifier is shown in Fig. 6.

B. Flexible/Prismatic Test Stand

The flexible/prismatic test stand, shown in Fig. 7, was developed as a research manipulator for the ORNL hydraulics laboratory.

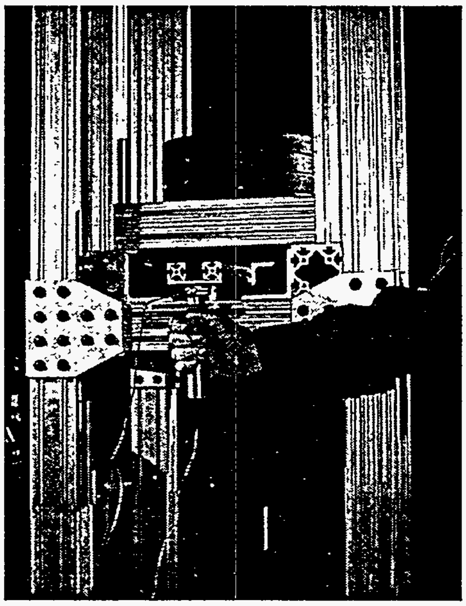

Figure 6. The ORNL 1–D.O.F. human amplifier

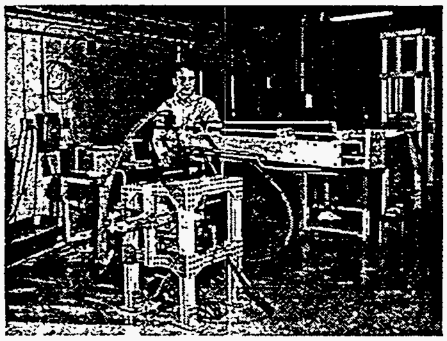

Figure 7. The flexible/prismatic test stand in the ORNLhydraulics laboratory

Its main objective is to serve as a hydraulic manipulator controls research test bed for studying the effects of hydraulics and link flexibility on manipulator design and control. The goal of the design is to have a realistically sized actuator and payload. The prismatic joint of the flexible/prismatic test stand consists of a hardened steel tube with 1–in. OD and a 0.6–in. ID. This tube can extend from 12 to 60 in. In addition, the payload can vary from 10 to 75 lb. With this range of payload and displacement, the arm can match the natural frequencies expected with current designs of waste tank cleanup manipulators such as the Modified Light Duty Utility Arm (MLDUA).[22-24] In addition, small displacements in the position can provide dramatic variations in the natural frequency, as illustrated in Kress.[25] With the speed capacity of the prismatic joint, the natural frequency of the arm can vary by an order of magnitude over a very short range of motion in a very short time. The stroke of the cylinder is 1.22 m (48 in.) with the link length varying from 0.30 to 1.52 m (12 to 60 in.).

The rotary actuator on the flexible/prismatic test bed is a Parker HTR30 hydraulic rack and pinion rotary actuator. At 13.8 Mpa (2000 psi), this actuator has a maximum torque capacity of 2260 N-m (20,000 in.-lb_f). The prismatic joint is powered by a Parker Series EH hydraulic cylinder with a 5-cm (2–in.) bore. Its force capacity at 13.8 Mpa (2000 psi) is 27.9 KN (6280 lb_f). Moog 760 series valves control the fluid flow. These high-bandwidth valves are relatively popular in the aircraft and robotics community. The valve on the rotary joint has a rated flow of 0.32 liters/s (5 gpm), while the prismatic joint's flow is rated at 0.95 liters/s (15 gpm).

C. Flexible/Prismatic Test Stand Amplitude Variation Experiments

This section briefly shows one of the research results from the hydraulics laboratory. For hydraulic systems there is a nonlinear relationship between the valve opening and resulting fluid flow. Figures 8 and 9 illustrate the effect of different magnitudes of input commands on the frequency response of a typical hydraulic system; that is, the joints of the flexible/prismatic test stand. The input command ranged from 100 mV to 1 V. This produces a magnitude and phase shift up to 8 dB and 30°.

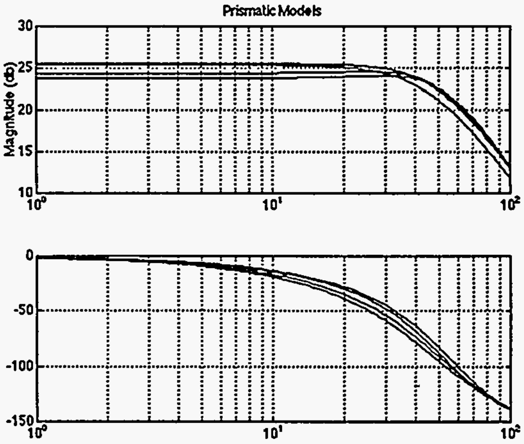

Figure 8. Amplitude sensitivity on

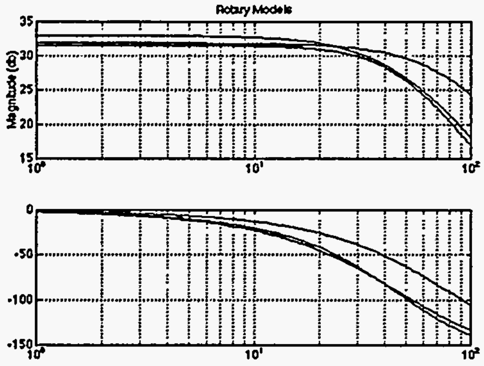

Figure 9. Amplitude sensitivity on rotary joint

The goal of the these experiments was to illustrate the potential variations in the plant dynamics during operation. The selection of a joint controller must be robust to these variations. Frequency domain design of robust controller for these highly nonlinear hydraulic manipulator systems will be the topic of future research efforts in ORNL's hydraulics laboratory.

V. CONCLUSIONS

ORNL has extensive experience in the design, analysis, and control of hydraulic manipulators. ORNL has over a decade of experience in developing hydraulic systems for a number of applications, including mobile robotics, robotic arms, and new concept systems. To support the development and deployment of the new hydraulic manipulators, ORNL has outfitted a significant experimental laboratory and has developed the software capability for research into hydraulic manipulators, hydraulic actuators, hydraulic systems, modeling of hydraulic systems, and hydraulic controls. This paper has shown ORNL's history of hydraulic automation projects including mobile robots, teleoperated manipulators, and full-scale construction equipment This paper has discussed two recent manipulator systems in ORNL's hydraulics laboratory that are currently being used to characterize the performance of hydraulic components in a manipulator environment. Applications of the fundamental knowledge obtained through these experiments will be the subject of future articles.

ACKNOWLEDGEMENTS

Research sponsored by the Department of Energy sponsored Robotics Technology Development Program and the Laboratory-Directed Research and Development Program of the Oak Ridge National Laboratory, managed for the U.S. Department of Energy by Lockheed Martin Energy Research Corporation, under contract DE-AC05-96OR22464.

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