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THE EVOLUTION OF TELEOPERATED MANIPULATORS AT ORNL*

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ABSTRACT

Oak Ridge National Laboratory (ORNL) has made significant contributions to teleoperator and telerobotics technology over the past two decades and continues with an aggressive program today. Examples of past projects are: (1) the M2 servomanipulator, which was the first digitally controlled teleoperator; (2) the Advanced Servomanipulator (ASM), which was the first remotely maintainable teleoperator; (3) the CESARm/Kraft dissimilar teleoperated system; and (4) the Laboratory Telerobotic Manipulator (LTM), a 7-Degree-of-Freedom (7-DOF) telerobot built as a prototype for work in space. More recently, ORNL has become heavily involved with Environmental Restoration and Waste Management (ERWM) robotics programs funded by the Department of Energy (DOE). The ERWM program requires high payloads and high dexterity. As a result, a hydraulically actuated, dual-arm system comprised of two 6-DOF arms mounted on a 5-DOF base has been constructed and is being used today for various research tasks and for decontamination and dismantlement activities.

All of these teleoperated manipulator systems build upon the experiences gained throughout the almost two decades of development. Each system incorporates not only the latest technology in computers, sensors, and electronics, but each new system also adds at least one new feature to the technologies already developed and demonstrated in the previous system(s). As a result of this building process, a serious study of these manipulator systems is a study in the evolution of teleoperated manipulator systems in general. This provides insight not only into the research and development paths chosen in the past, but also into the appropriate directions for future teleoperator and telerobotics research. This paper examines each of the teleoperated/telerobotic systems developed at ORNL, summarizes their features and capabilities, examines the state of the most current telerobotic system (the Dual Arm Work Module), and provides direction for a Next Generation Telerobotic Manipulator system.

I. INTRODUCTION

A. Historical Perspective

According to Raimondi **[Raimondi,88]**, "The telemanipulator is a device which allows an operator to perform a task at a distance, in a hostile environment where human access is impossible or inadvisable." Hot cells for the nuclear power field have been the primary application area for teleoperator

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systems because of the hazardous radioactive environment involved and because cost is not the primary concern. A teleoperator system is composed of two manipulators—a master manipulator that is held by a human operator and a slave manipulator that will perform (or try to perform) the desired task. The master manipulator is located in a safe, clean environment where information (typically visual, sound, and force information) is fed back from the slave manipulator to the human operator. Human-machine interface concepts are critical to the successful utilization of such systems but will not be addressed in this paper. The slave manipulator is located at the intended task typically at some distance from the human operator. In the late 1940s, Goertz and his colleagues at Argonne National Laboratory (ANL) developed one of the earliest recognizable mechanical master/slave manipulators without force reflection and later with force-reflecting capabilities **[Goertz,52]**. Force reflection refers to the capability of reflecting the external forces experienced by the slave manipulator to the master manipulator and is typically described as bilateral control: force on the slave (master) will cause the master (slave) to move. In the early 1950s, Goertz and his colleagues developed an electric master/slave manipulator in which each slave joint servo was tied directly to the master joint servo since both the master and slave were kinematically similar **[Goertz,54]**. Carl Flateau **[Flateau,65]** made major contributions to teleoperator development in the 1960s. Hydraulics, too, have been used from almost the beginning of this field, starting with the Handyman system developed by Mosher and his team at General Electric in the late 1950s **[Johnsen,67]**. Today, hydraulic actuators are not usually selected for high radiation environments because the hydraulic fluid and its associated seals suffer from radiation-induced degradation, but some examples of high radiation applications have been found **[Kaye,92]**. These two problems are ignored when significant payload to overall weight ratios are required, in which case, hydraulics are almost always selected. Interested readers can consult with Vertut **[Vertut,85]** for a detailed discussion of the history of teleoperator systems.

B. Telerobots

A telerobotic system is a system that is capable of performing as either a telemanipulator (master/slave mode) or with the slave manipulator performing alone as a robotic manipulator. In the latter case, the slave's trajectory and forces/impedance are determined by computer commands rather than master-arm inputs. The advantage of having a merger of these two capabilities is that repetitive tasks have the potential of being automated, thereby diminishing the physical demands placed on the human operator. Table 1 compares teleoperators with industrial manipulators.

Table 1. Distinction between a telemanipulator and an industrial robotic manipulator.

Good force-reflecting teleoperator	Good industrial robot
1. End effector speed 0.91 m/s (36 in./s)	1. End effector speed 30 to 50 in./s
2. Friction 1-5% of capacity (at expense of increased backlash)	2. Friction 30 to very large
3. Medium to low backlash	3. No backlash (at expense of increased friction)
4. Replica master control	4. Teach pendant, keyboard
5. 2.5- to 5-cm (1- to 2-in.) deflection at full load	5. Minimal deflection at full load (0.010 to 0.05 in.)
6. 6 DOF and end effector	6. 4 to 6 DOF and end effector
7. Bilateral position-position control for force reflection with man in the loop	7. Force feedback with 6-axis end effector sensing
8. Relative low inertia for minimum fatigue	8. High stiffness designs yield high inertia
9. Kinematics approximately manlike	9. Kinematics mission dependent
10. Accuracy and repeatability not important	10. Accuracy and repeatability very important
11. 1:40 to 1:10 capacity/weight ratio	11. 1:40 to 1:10 capacity/weight ratio
12. Universal end effector	12. Interchangeable end effector

II. DESCRIPTION OF PAST AND EXISTING ORNL MANIPULATOR SYSTEMS

This section includes a brief description of the teleoperated/telerobotic systems developed and used at ORNL. Systems discussed in the past tense are no longer in service at ORNL.

A. SM-229 Servomanipulator

The SM-229 servomanipulator system was manufactured by TeleOperator Systems. It is a 6-DOF (7 as when some authors count the gripper closure; note that in this paper only arm joints are counted when determining DOF), force-reflecting, electrically actuated manipulator system. It has an elbows-up configuration. The SM-229 had a continuous lift capacity of 10 kg and a reach of 1.23 m. It was mounted on a 3-axis positioner in the Remote Systems Development Facility at ORNL. It had a two-camera, pan/title-mounted viewing system and is shown in Fig. 1. The SM-229 was one of the first manipulator systems at ORNL and was used for human factors studies **[Clarke,83]**, for the development of human-machine interface concepts **[Stoughton,84]**, and for control system development **[Killough,86]**.

B. M2 Servomanipulator

The M2 servomanipulator was developed in a cooperative effort between Central Research Laboratories (CRL) and ORNL **[Herndon,84]**. The mechanical systems including motors and amplifiers were designed and fabricated by CRL, and the control system and system software were done by ORNL **[Saterlee,84]**. The M2 is a 6-DOF, force-reflecting, electrically actuated manipulator system. Actuators are connected to joints via cable drives. Position sensing is done with potentiometers. The M2 was installed in ORNL's Integrated Equipment Test Facility in the Remote Operations and Maintenance Demonstration area and was used for research into remote handling for fuel reprocessing, human factors studies, development of remote tools, and operator assessment and training. The M2 has a continuous lift capacity of 23 kg, a peak lift capacity of 46 kg, and a reach of 1.26 m. The primary evolutionary contribution of the M2 was the ORNL-developed digital control system that was awarded an IR100 award in 1984. In addition, the M2 was considered to be the benchmark teleoperated system for many years. It is shown in Fig. 2.

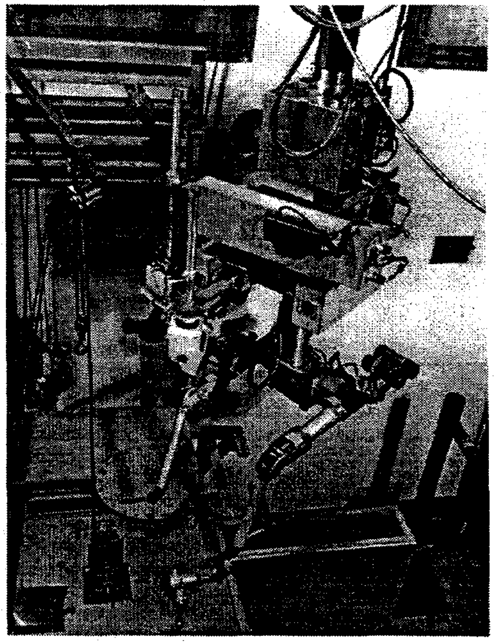

Fig. 1. SM-229 manipulator system

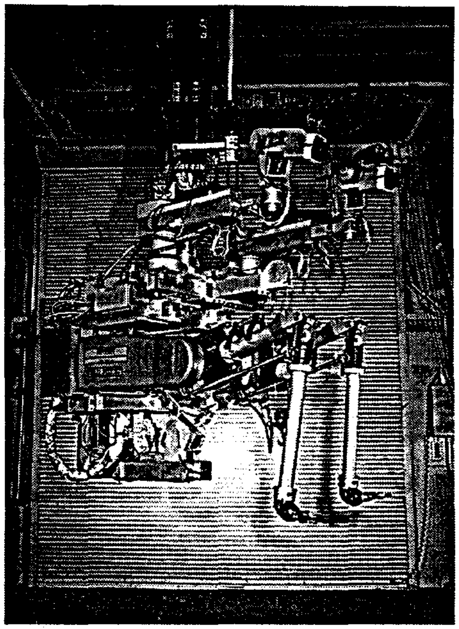

Fig. 2. M2 servomanipulator

C. Advanced Servomanipulator

The Advanced Servomanipulator (ASM) was designed and built at ORNL **[Kuban,87]**. It is a 6-DOF, force-reflecting, electrically actuated manipulator system. Actuators are connected to joints via torque tubes. Position sensing is done with optical encoders **[Martin,84]**. The ASM was used for research into remote handling for fuel reprocessing, human factors studies, development of remote tools, and operator assessment and training. The ASM has a continuous lift capacity of 23 kg, a peak lift capacity of 46 kg, and a reach of 1.40 m. The ASM had two primary evolutionary contributions. First was its modular design. It was made to be completely remotely maintainable so that it could be serviced in place by another manipulator system. Second, it was connected to an innovative human-machine interface used to evaluate state-of-the-art operator interface concepts and enhancements including pop-up control menus, selectable manipulator characteristics and performance, ORNL custom-built master manipulator, and multiple machine operators. The ASM is shown in Fig. 3.

D. Laboratory Telerobotic Manipulator

The Laboratory Telerobotic Manipulator (LTM) was designed and built at ORNL **[Herndon,89]**. It is a 7-DOF, force-reflecting, electrically actuated manipulator system. Actuators are embedded in separate links and are connected to joints via high-reduction (150:1 or 200:1) gear boxes. Position sensing is done at the actuators with optical encoders, velocity sensing is done with tachometers, and drive-train torque is measured with in-line torque sensors **[Kress,89]**, as was done by **[Luh,83]** and **[Pfeffer,89]**. Joint position and velocity are measured with 16-bit resolvers. The LTM was used for ground-based research into space telerobotic activities, including controller development for manipulators with joint torque sensors **[Jansen,90a][Kress,92]**. A very unique feature of the LTM was its traction-drive differential that provided 2-DOF with perpendicular intersecting axes on each link. The LTM has a continuous lift capacity of 20 kg, a peak lift capacity of 30 kg, and a reach of 1.40 m. The LTM had numerous evolutionary contributions. First was its modular design. For maintenance and/or for reconfiguration, each of the links could be removed and interchanged with a new link within minutes. Second, it was a redundant teleoperator system having master and slave, each with 7-DOF. Third was the distributed electronics **[Rowe,91]**. The LTM had processors in each link to collect and interpret all of the raw data associated with the drive trains and joints on that link as well as separate computer systems for the master and slave systems. Fourth was the traction drive differential designed in an attempt to strike a balance between backlash and joint friction. The LTM is shown in Fig. 4.

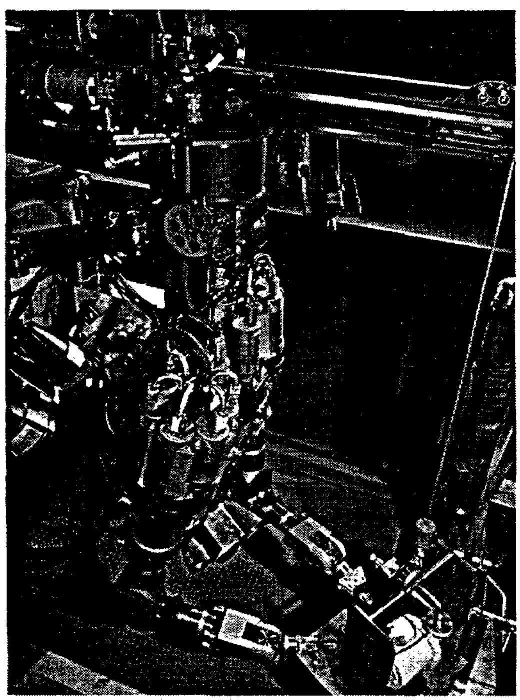

Fig. 3. Advanced Servomanipulator system

Fig. 4. Laboratory Telerobotic Manipulator

E. CESARm/Kraft Dissimilar Teleoperated System

The Center for Engineering Systems Advanced Research Manipulator (CESARm) was designed and built at ORNL as a research manipulator **[Babcock]**. It is a 7-DOF, force-reflecting, electrically actuated manipulator system. (Note that 6-DOF are all that are needed to arbitrarily position and orient an object in space; therefore, a 7-DOF manipulator has one redundant DOF.) The base, shoulder pitch, and shoulder yaw actuators are connected directly to the joints through gears. The elbow pitch actuator is connected to the forearm and a counter-balance weight through a unique five-bar linkage. The wrist pitch, yaw, and roll actuators are connected via cables. Position sensing on the CESARm is done with optical encoders, whereas velocity is sensed with tachometers. The CESARm was connected to a 6-DOF force-reflecting master manufactured by Kraft Telerobotics. (Only five of the DOF on this Kraft model are force reflecting.) The Kraft master is actuated by ac servomotors, and position sensing is done with potentiometers. The CESARm/Kraft redundant and dissimilar teleoperator system was used for research into dissimilar teleoperator control algorithms **[Jansen,90b,91,92][Kress,90]**, stiffness and impedance control **[Jansen,90c]**, and path planning. The CESARm has a continuous lift capacity of 13 kg and a reach of 1.52 m. The CESARm/Kraft system had two primary evolutionary contributions. It was one of the world's first dissimilar and redundant teleoperated manipulators. Second, it was one of the first teleoperated systems employing stiffness/ impedance control of the types pioneered by **[Salisbury,80]** and **[Hogan,85]**. The CESARm/Kraft is shown in Fig. 5.

F. Dual Arm Work Module

As part of the Robotics Technology Development Program's support of Decontamination and Dismantlement (D&D) efforts within DOE, the Dual Arm Work Module (DAWM) was developed at ORNL **[Noakes,95]**. This system is the most current manipulator in the evolutionary development of telerobotic manipulators at ORNL and is presently deployed in the Robotics Technology Assessment Facility at ORNL. The DAWM is shown in Fig. 6.

The DAWM features two 6-DOF, hydraulically actuated, Schilling manipulators and a 5-DOF, hydraulically actuated base, and is currently deployed off of a 4-DOF gantry-like transporter. Each of the Schilling arms is capable of continuously lifting 109 kg fully extended and has a reach of 1.99 m. A similar dual arm system will be used at the CP-5 reactor at ANL to support the D&D efforts there. The ORNL DAWM is used for support of the D&D effort at ANL. Typical other uses are for operator training, tool and fixture testing and development, control algorithm development and testing, **[Jansen,96]** cost/benefit experimental analysis, and operator interface design and evaluation. Besides being deployable from the 4-DOF gantry transporter, the DAWM can be operated from a mobile robot such as RedZone Robotics Rosie vehicle **[Conley,95]** or from other platforms such as the crane deployable Dual Arm Work Platform. The primary evolutionary contribution of the DAWM is the use of hydraulics for heavy lift capacity and the ability to operate from different work platforms.

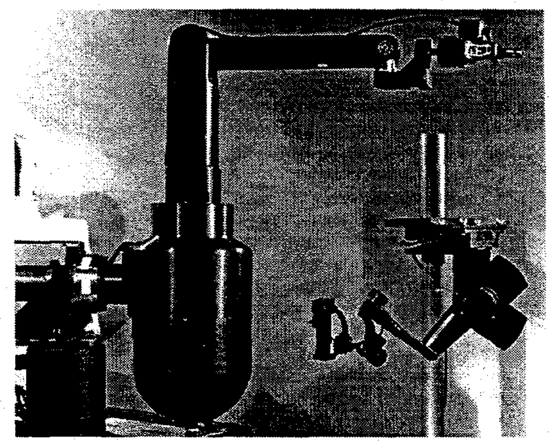

Fig. 5. CESARm/Kraft dissimilar teleoperated system

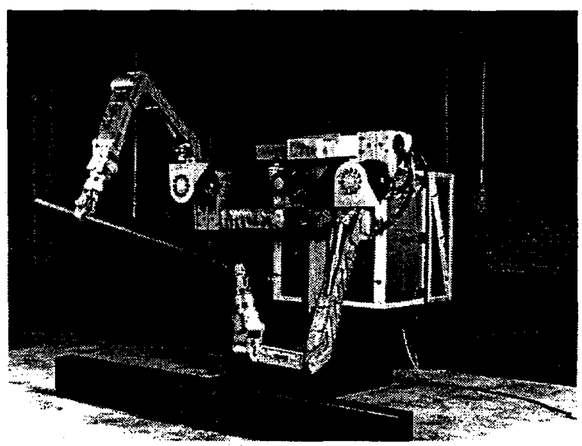

Fig. 6. The Dual Arm Work Module

III. SUMMARY OF EVOLUTION OF ORNL TELEOPERATOR SYSTEMS

The following tables summarize the major features of the ORNL teleoperator and telerobotic manipulator systems. Table 2 provides the mechanical and control system specifications, Table 3 provides the computer specifications, and Table 4 details the major evolutionary contribution of each system.

Table 2. ORNL manipulator specifications.

System	Elbow Config.	DOF*	Type of DOF	Lift Capac. (kg)**	Reach (m)	Tip Speed (m/s)	Act. Type	Force-Reflecting Ratios	Date
SM-229	up	6,6	PRPRPR	10	1.23	~1	ELE	1:1	1981
M2	up	6,6	PRPRPR	23;46	1.26	1.5	ELE	1,2,4,8, ∞:1	78-83
ASM	down	6,6	PRPPYR	23;46	1.40	~1	ELE	1:1 to 1:16	83-89
LTM	down	7,7	PYPYPYR	20;30	1.40	>1	ELE	1,2,8,16:1	87-89
CESARm	up	7,6	YPRPPYR	13	1.52	3.0	ELE	1:1 to ∞:1	1990
DAWM	either	6,6	YPPPYR	109;544	1.99	>1	HYD	1,2,8,64 ∞:1	1993

* Master, Slave

**Continuous; Peak.

Table 3. ORNL manipulator computer specifications.

System	CPU	Bus	Language	Operating System	Loop Rate (Hz)
M2 Master/Slave	(37) Intel 8031	Custom	Assembly	N/A	53
M2 Operator Interface	Z80	S100	Basic	CPM	N/A*
ASM Master/Slave	(15) Motorola 68000	(7) Multibus-I	FORTH	Poly FORTH	100
ASM Operator Interface	(1) Motorola 68000	Multibus-I	FORTH	Poly FORTH	N/A*
LTM Master/Slave	(9) Motorola 68020	VME	C	0S-9	250/500
LTM Operator/Interface	Macintosh 68020	NuBus	C	Mac OS	N/A*
CESARm	(3) Motorola 68020	VME	C	OS-9	100
DAWM Master/Slave	(5) Motorola 68030	VME	C/C++	VxWorks/ Control Shell	120
DAWM Operator Interface	Sun Sparc? R4000?	Sparc 5 SGI	C/C++	UNIX	N/A*

* Event-driven processes so loop rate is not applicable.

Table 4. Major evolutionary contribution of ORNL manipulator systems.

System	Major Evolutionary Contribution
M2	Digital controls for teleoperated manipulators
ASM	Modular construction, Advanced human machine interface
LTM	Modular construction, Redundant master, Distributed electronics, Traction drive differential
CESARm	Dissimilar master/slave, Stiffness/Impedance control
DAWM	Large lift capacity, Multiple deployment platforms

VI. FUTURE TELEROBOTIC SYSTEMS

Consider the Next Generation Telerobotic Manipulator (NGTM) system. It is anticipated that a successful system should have some or possibly all of the following: impedance reflecting capability; torque and/or pressure feedback for friction compensation; a Remote Compliance Center (RCC) **[Whitney,82]** for assembly tasks; modular construction for simplified remote maintenance and possible reconfiguration; and hybrid analog/digital electronics for low-cost and efficient controller design.

Another possibility for the NGTM is to develop human amplifier telerobotic systems **[Kazerooni,89a,89b,93]**. These new machines amplify the lifting capability of the operator. They may not be acceptable for certain hazardous environments (e.g., radioactive or high temperature), but they may be very applicable to other environments (e.g., rescue, mining, or construction). A future human amplifier system should have some or all of the following: integrated master/slave units; hydraulic actuation and possibly even water-based hydraulics for heavy lift capacity; an RCC for assembly tasks; and hybrid analog/digital electronics for low-cost and efficient controller design.

V. CONCLUSIONS

Teleoperators have evolved to telerobots out of a need to improve efficiency. ORNL's teleoperator systems have evolved into telerobots as well. Telerobots have moved from simple implementations using kinematically similar, joint-to-joint controlled master/slave manipulators with incremental automated enhancements to dissimilar teleoperated systems with impedance-based control, sophisticated human/machine interfaces, and highly developed world models. Fundamental robotics developments are also applicable to telerobots, for example, RCCs and joint torque sensors.

All of the teleoperated manipulator systems described herein built upon the experiences gained throughout almost two decades of development. This paper has examined each of the ORNL-developed teleoperated/telerobotic systems and summarized their features and capabilities. As with other advanced technology products, for example, computers and automobiles, telerobotics adds technical enhancements to existing base technologies to produce a slowly evolving system. Major leaps come from the introduction of entirely new classes of machines and in the case of telerobotics, this might well be the human amplifier.

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THE EVOLUTION OF TELEOPERATED MANIPULATORS AT ORNL*

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ABSTRACT

Oak Ridge National Laboratory (ORNL) has made significant contributions to teleoperator and telerobotics technology over the past two decades and continues with an aggressive program today. Examples of past projects are: (1) the M2 servomanipulator, which was the first digitally controlled teleoperator; (2) the Advanced Servomanipulator (ASM), which was the first remotely maintainable teleoperator; (3) the CESARm/Kraft dissimilar teleoperated system; and (4) the Laboratory Telerobotic Manipulator (LTM), a 7-Degree-of-Freedom (7-DOF) telerobot built as a prototype for work in space. More recently, ORNL has become heavily involved with Environmental Restoration and Waste Management (ERWM) robotics programs funded by the Department of Energy (DOE). The ERWM program requires high payloads and high dexterity. As a result, a hydraulically actuated, dual-arm system comprised of two 6-DOF arms mounted on a 5-DOF base has been constructed and is being used today for various research tasks and for decontamination and dismantlement activities.

All of these teleoperated manipulator systems build upon the experiences gained throughout the almost two decades of development. Each system incorporates not only the latest technology in computers, sensors, and electronics, but each new system also adds at least one new feature to the technologies already developed and demonstrated in the previous system(s). As a result of this building process, a serious study of these manipulator systems is a study in the evolution of teleoperated manipulator systems in general. This provides insight not only into the research and development paths chosen in the past, but also into the appropriate directions for future teleoperator and telerobotics research. This paper examines each of the teleoperated/telerobotic systems developed at ORNL, summarizes their features and capabilities, examines the state of the most current telerobotic system (the Dual Arm Work Module), and provides direction for a Next Generation Telerobotic Manipulator system.

I. INTRODUCTION

A. Historical Perspective

According to Raimondi **[Raimondi,88]**, "The telemanipulator is a device which allows an operator to perform a task at a distance, in a hostile environment where human access is impossible or inadvisable." Hot cells for the nuclear power field have been the primary application area for teleoperator

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systems because of the hazardous radioactive environment involved and because cost is not the primary concern. A teleoperator system is composed of two manipulators—a master manipulator that is held by a human operator and a slave manipulator that will perform (or try to perform) the desired task. The master manipulator is located in a safe, clean environment where information (typically visual, sound, and force information) is fed back from the slave manipulator to the human operator. Human-machine interface concepts are critical to the successful utilization of such systems but will not be addressed in this paper. The slave manipulator is located at the intended task typically at some distance from the human operator. In the late 1940s, Goertz and his colleagues at Argonne National Laboratory (ANL) developed one of the earliest recognizable mechanical master/slave manipulators without force reflection and later with force-reflecting capabilities **[Goertz,52]**. Force reflection refers to the capability of reflecting the external forces experienced by the slave manipulator to the master manipulator and is typically described as bilateral control: force on the slave (master) will cause the master (slave) to move. In the early 1950s, Goertz and his colleagues developed an electric master/slave manipulator in which each slave joint servo was tied directly to the master joint servo since both the master and slave were kinematically similar **[Goertz,54]**. Carl Flateau **[Flateau,65]** made major contributions to teleoperator development in the 1960s. Hydraulics, too, have been used from almost the beginning of this field, starting with the Handyman system developed by Mosher and his team at General Electric in the late 1950s **[Johnsen,67]**. Today, hydraulic actuators are not usually selected for high radiation environments because the hydraulic fluid and its associated seals suffer from radiation-induced degradation, but some examples of high radiation applications have been found **[Kaye,92]**. These two problems are ignored when significant payload to overall weight ratios are required, in which case, hydraulics are almost always selected. Interested readers can consult with Vertut **[Vertut,85]** for a detailed discussion of the history of teleoperator systems.

B. Telerobots

A telerobotic system is a system that is capable of performing as either a telemanipulator (master/slave mode) or with the slave manipulator performing alone as a robotic manipulator. In the latter case, the slave's trajectory and forces/impedance are determined by computer commands rather than master-arm inputs. The advantage of having a merger of these two capabilities is that repetitive tasks have the potential of being automated, thereby diminishing the physical demands placed on the human operator. Table 1 compares teleoperators with industrial manipulators.

Table 1. Distinction between a telemanipulator and an industrial robotic manipulator.

Good force-reflecting teleoperator	Good industrial robot
1. End effector speed 0.91 m/s (36 in./s)	1. End effector speed 30 to 50 in./s
2. Friction 1-5% of capacity (at expense of increased backlash)	2. Friction 30 to very large
3. Medium to low backlash	3. No backlash (at expense of increased friction)
4. Replica master control	4. Teach pendant, keyboard
5. 2.5- to 5-cm (1- to 2-in.) deflection at full load	5. Minimal deflection at full load (0.010 to 0.05 in.)
6. 6 DOF and end effector	6. 4 to 6 DOF and end effector
7. Bilateral position-position control for force reflection with man in the loop	7. Force feedback with 6-axis end effector sensing
8. Relative low inertia for minimum fatigue	8. High stiffness designs yield high inertia
9. Kinematics approximately manlike	9. Kinematics mission dependent
10. Accuracy and repeatability not important	10. Accuracy and repeatability very important
11. 1:40 to 1:10 capacity/weight ratio	11. 1:40 to 1:10 capacity/weight ratio
12. Universal end effector	12. Interchangeable end effector

II. DESCRIPTION OF PAST AND EXISTING ORNL MANIPULATOR SYSTEMS

This section includes a brief description of the teleoperated/telerobotic systems developed and used at ORNL. Systems discussed in the past tense are no longer in service at ORNL.

A. SM-229 Servomanipulator

The SM-229 servomanipulator system was manufactured by TeleOperator Systems. It is a 6-DOF (7 as when some authors count the gripper closure; note that in this paper only arm joints are counted when determining DOF), force-reflecting, electrically actuated manipulator system. It has an elbows-up configuration. The SM-229 had a continuous lift capacity of 10 kg and a reach of 1.23 m. It was mounted on a 3-axis positioner in the Remote Systems Development Facility at ORNL. It had a two-camera, pan/title-mounted viewing system and is shown in Fig. 1. The SM-229 was one of the first manipulator systems at ORNL and was used for human factors studies **[Clarke,83]**, for the development of human-machine interface concepts **[Stoughton,84]**, and for control system development **[Killough,86]**.

B. M2 Servomanipulator

The M2 servomanipulator was developed in a cooperative effort between Central Research Laboratories (CRL) and ORNL **[Herndon,84]**. The mechanical systems including motors and amplifiers were designed and fabricated by CRL, and the control system and system software were done by ORNL **[Saterlee,84]**. The M2 is a 6-DOF, force-reflecting, electrically actuated manipulator system. Actuators are connected to joints via cable drives. Position sensing is done with potentiometers. The M2 was installed in ORNL's Integrated Equipment Test Facility in the Remote Operations and Maintenance Demonstration area and was used for research into remote handling for fuel reprocessing, human factors studies, development of remote tools, and operator assessment and training. The M2 has a continuous lift capacity of 23 kg, a peak lift capacity of 46 kg, and a reach of 1.26 m. The primary evolutionary contribution of the M2 was the ORNL-developed digital control system that was awarded an IR100 award in 1984. In addition, the M2 was considered to be the benchmark teleoperated system for many years. It is shown in Fig. 2.

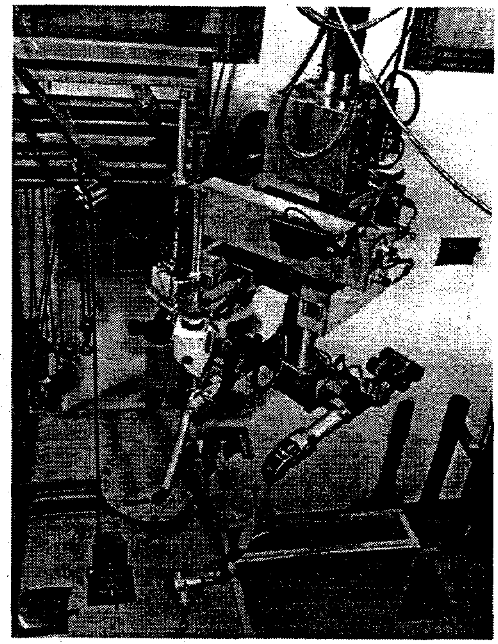

Fig. 1. SM-229 manipulator system

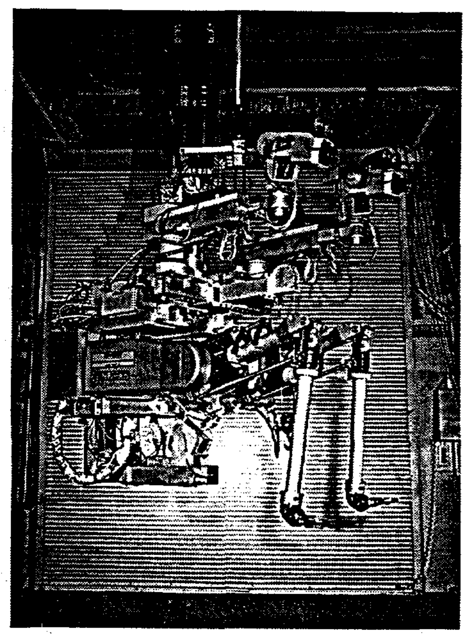

Fig. 2. M2 servomanipulator

C. Advanced Servomanipulator

The Advanced Servomanipulator (ASM) was designed and built at ORNL **[Kuban,87]**. It is a 6-DOF, force-reflecting, electrically actuated manipulator system. Actuators are connected to joints via torque tubes. Position sensing is done with optical encoders **[Martin,84]**. The ASM was used for research into remote handling for fuel reprocessing, human factors studies, development of remote tools, and operator assessment and training. The ASM has a continuous lift capacity of 23 kg, a peak lift capacity of 46 kg, and a reach of 1.40 m. The ASM had two primary evolutionary contributions. First was its modular design. It was made to be completely remotely maintainable so that it could be serviced in place by another manipulator system. Second, it was connected to an innovative human-machine interface used to evaluate state-of-the-art operator interface concepts and enhancements including pop-up control menus, selectable manipulator characteristics and performance, ORNL custom-built master manipulator, and multiple machine operators. The ASM is shown in Fig. 3.

D. Laboratory Telerobotic Manipulator

The Laboratory Telerobotic Manipulator (LTM) was designed and built at ORNL **[Herndon,89]**. It is a 7-DOF, force-reflecting, electrically actuated manipulator system. Actuators are embedded in separate links and are connected to joints via high-reduction (150:1 or 200:1) gear boxes. Position sensing is done at the actuators with optical encoders,

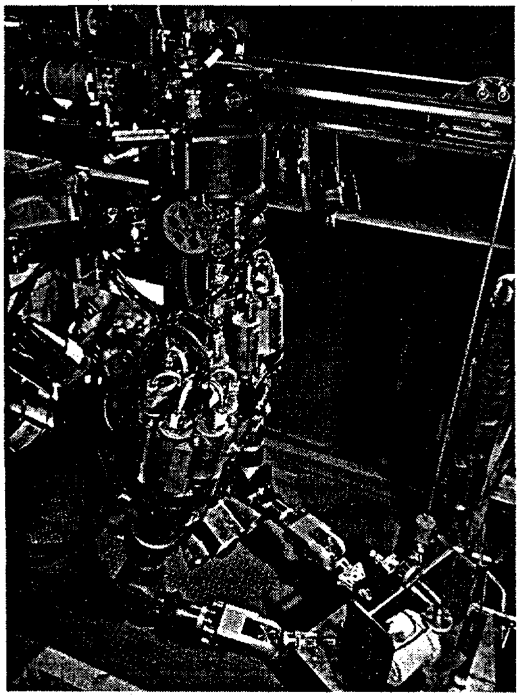

Fig. 3. Advanced Servomanipulator system

velocity sensing is done with tachometers, and drive-train torque is measured with in-line torque sensors **[Kress,89]**, as was done by **[Luh,83]** and **[Pfeffer,89]**. Joint position and velocity are measured with 16-bit resolvers. The LTM was used for ground-based research into space telerobotic activities, including controller development for manipulators with joint torque sensors **[Jansen,90a][Kress,92]**. A very unique feature of the LTM was its traction-drive differential that provided 2-DOF with perpendicular intersecting axes on each link. The LTM has a continuous lift capacity of 20 kg, a peak lift capacity of 30 kg, and a reach of 1.40 m. The LTM had numerous evolutionary contributions. First was its modular design. For maintenance and/or for reconfiguration, each of the links could be removed and interchanged with a new link within minutes. Second, it was a redundant teleoperator system having master and slave, each with 7-DOF. Third was the distributed electronics **[Rowe,91]**. The LTM had processors in each link to collect and interpret all of the raw data associated with the drive trains and joints on that link as well as separate computer systems for the master and slave systems. Fourth was the traction drive differential designed in an attempt to strike a balance between backlash and joint friction. The LTM is shown in Fig. 4.

Fig. 4. Laboratory Telerobotic Manipulator

E. CESARm/Kraft Dissimilar Teleoperated System

The Center for Engineering Systems Advanced Research Manipulator (CESARm) was designed and built at ORNL as a research manipulator **[Babcock]**. It is a 7-DOF, force-reflecting, electrically actuated manipulator system. (Note that 6-DOF are all that are needed to arbitrarily position and orient an object in space; therefore, a 7-DOF manipulator has one redundant DOF.) The base, shoulder pitch, and shoulder yaw actuators are connected directly to the joints through gears. The elbow pitch actuator is connected to the forearm and a counter-balance weight through a unique five-bar linkage. The wrist pitch, yaw, and roll actuators are connected via cables. Position sensing on the CESARm is done with optical encoders, whereas velocity is sensed with tachometers. The CESARm was connected to a 6-DOF force-reflecting master manufactured by Kraft Telerobotics. (Only five of the DOF on this Kraft model are force reflecting.) The Kraft master is actuated by ac servomotors, and position sensing is done with potentiometers. The CESARm/Kraft redundant and dissimilar teleoperator system was used for research into dissimilar teleoperator control algorithms **[Jansen,90b,91,92][Kress,90]**, stiffness and impedance control **[Jansen,90c]**, and path planning. The CESARm has a continuous lift capacity of 13 kg and a reach of 1.52 m. The CESARm/Kraft system had two primary evolutionary contributions. It was one of the world's first dissimilar and redundant teleoperated manipulators. Second, it was one of the first teleoperated systems employing stiffness/ impedance control of the types pioneered by **[Salisbury,80]** and **[Hogan,85]**. The CESARm/Kraft is shown in Fig. 5.

F. Dual Arm Work Module

As part of the Robotics Technology Development Program's support of Decontamination and Dismantlement (D&D) efforts within DOE, the Dual Arm Work Module (DAWM) was developed at ORNL **[Noakes,95]**. This system is the most current manipulator in the evolutionary development of telerobotic manipulators at ORNL and is presently deployed in the Robotics Technology Assessment Facility at ORNL. The DAWM is shown in Fig. 6.

The DAWM features two 6-DOF, hydraulically actuated, Schilling manipulators and a 5-DOF, hydraulically actuated base, and is currently deployed off of a 4-DOF gantry-like transporter. Each of the Schilling arms is capable of continuously lifting 109 kg fully extended and has a reach of 1.99 m. A similar dual arm system will be used at the CP-5 reactor at ANL to support the D&D efforts there. The ORNL DAWM is used for support of the D&D effort at ANL. Typical other uses are for operator training, tool and fixture testing and development, control algorithm development and testing, **[Jansen,96]** cost/benefit experimental analysis, and operator interface design and evaluation. Besides being deployable from the 4-DOF gantry transporter, the DAWM can be operated from a mobile robot such as RedZone Robotics Rosie vehicle **[Conley,95]** or from other platforms such as the crane deployable Dual Arm Work Platform. The primary evolutionary contribution of the DAWM is the use of hydraulics for heavy lift capacity and the ability to operate from different work platforms.

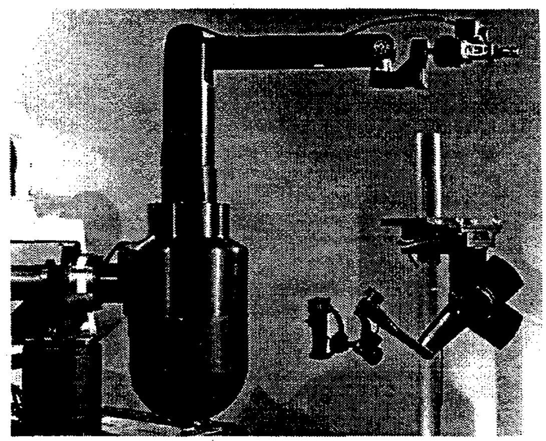

Fig. 5. CESARm/Kraft dissimilar teleoperated system

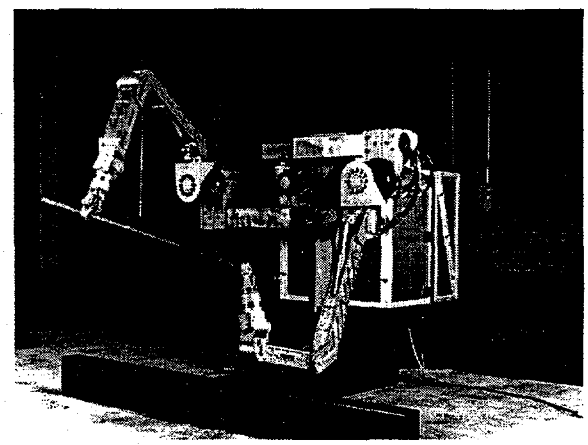

Fig. 6. The Dual Arm Work Module

III. SUMMARY OF EVOLUTION OF ORNL TELEOPERATOR SYSTEMS

The following tables summarize the major features of the ORNL teleoperator and telerobotic manipulator systems. Table 2 provides the mechanical and control system specifications, Table 3 provides the computer specifications, and Table 4 details the major evolutionary contribution of each system.

Table 2. ORNL manipulator specifications.

System	Elbow Config.	DOF*	Type of DOF	Lift Capac. (kg)**	Reach (m)	Tip Speed (m/s)	Act. Type	Force-Reflecting Ratios	Date
SM-229	up	6,6	PRPRPR	10	1.23	~1	ELE	1:1	1981
M2	up	6,6	PRPRPR	23;46	1.26	1.5	ELE	1,2,4,8, ∞:1	78-83
ASM	down	6,6	PRPPYR	23;46	1.40	~1	ELE	1:1 to 1:16	83-89
LTM	down	7,7	PYPYPYR	20;30	1.40	>1	ELE	1,2,8,16:1	87-89
CESARm	up	7,6	YPRPPYR	13	1.52	3.0	ELE	1:1 to ∞:1	1990
DAWM	either	6,6	YPPPYR	109;544	1.99	>1	HYD	1,2,8,64 ∞:1	1993

* Master, Slave
**Continuous; Peak.

Table 3. ORNL manipulator computer specifications.

System	CPU	Bus	Language	Operating System	Loop Rate (Hz)
M2 Master/Slave	(37) Intel 8031	Custom	Assembly	N/A	53
M2 Operator Interface	Z80	S100	Basic	CPM	N/A*
ASM Master/Slave	(15) Motorola 68000	(7) Multibus-I	FORTH	Poly FORTH	100
ASM Operator Interface	(1) Motorola 68000	Multibus-I	FORTH	Poly FORTH	N/A*
LTM Master/Slave	(9) Motorola 68020	VME	C	0S-9	250/500
LTM Operator/Interface	Macintosh 68020	NuBus	C	Mac OS	N/A*
CESARm	(3) Motorola 68020	VME	C	OS-9	100
DAWM Master/Slave	(5) Motorola 68030	VME	C/C++	VxWorks/ Control Shell	120
DAWM Operator Interface	Sun Sparc? R4000?	Sparc 5 SGI	C/C++	UNIX	N/A*

* Event-driven processes so loop rate is not applicable.

Table 4. Major evolutionary contribution of ORNL manipulator systems.

System	Major Evolutionary Contribution
M2	Digital controls for teleoperated manipulators
ASM	Modular construction, Advanced human machine interface
LTM	Modular construction, Redundant master, Distributed electronics, Traction drive differential
CESARm	Dissimilar master/slave, Stiffness/Impedance control
DAWM	Large lift capacity, Multiple deployment platforms

VI. FUTURE TELEROBOTIC SYSTEMS

Consider the Next Generation Telerobotic Manipulator (NGTM) system. It is anticipated that a successful system should have some or possibly all of the following: impedance reflecting capability; torque and/or pressure feedback for friction compensation; a Remote Compliance Center (RCC) **[Whitney,82]** for assembly tasks; modular construction for simplified remote maintenance and possible reconfiguration; and hybrid analog/digital electronics for low-cost and efficient controller design.

Another possibility for the NGTM is to develop human amplifier telerobotic systems **[Kazerooni,89a,89b,93]**. These new machines amplify the lifting capability of the operator. They may not be acceptable for certain hazardous environments (e.g., radioactive or high temperature), but they may be very applicable to other environments (e.g., rescue, mining, or construction). A future human amplifier system should have some or all of the following: integrated master/slave units; hydraulic actuation and possibly even water-based hydraulics for heavy lift capacity; an RCC for assembly tasks; and hybrid analog/digital electronics for low-cost and efficient controller design.

V. CONCLUSIONS

Teleoperators have evolved to telerobots out of a need to improve efficiency. ORNL's teleoperator systems have evolved into telerobots as well. Telerobots have moved from simple implementations using kinematically similar, joint-to-joint controlled master/slave manipulators with incremental automated enhancements to dissimilar teleoperated systems with impedance-based control, sophisticated human/machine interfaces, and highly developed world models. Fundamental robotics developments are also applicable to telerobots, for example, RCCs and joint torque sensors.

All of the teleoperated manipulator systems described herein built upon the experiences gained throughout almost two decades of development. This paper has examined each of the ORNL-developed teleoperated/telerobotic systems and summarized their features and capabilities. As with other advanced technology products, for example, computers and automobiles, telerobotics adds technical enhancements to existing base technologies to produce a slowly evolving system. Major leaps come from the introduction of entirely new classes of machines and in the case of telerobotics, this might well be the human amplifier.

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