UST-ID Robotics

Wireless Communication and
Minimum Conductor
Technology, and End-Point
Tracking Technology Surveys

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Abstract

This report is a technology review of the current state-of-the-art in two technologies applicable to the Underground Storage Tank (UST) program at the Hanford Nuclear Reservation. The first review is of wireless and minimal conductor technologies for in-tank communications. The second review is of advanced concepts for independent tool-point tracking.

The basis for this study is found in TTP No. SF213204, entitled *Robotics UST*. This study addresses the need to provide wireless transmission media or minimum conductor technology for in-tank communications and robot control. At present, signals are conducted via contacting transmission media, i.e., cables. Replacing wires with radio frequencies or invisible light are commonplace in the communication industry. This technology will be evaluated for its applicability to the needs of robotics. Some of these options are radio signals, leaky coax, infrared, microwave, and optical fiber systems. Although optical fiber systems are contacting transmission media, they will be considered because of their ability to reduce the number of conductors. In this report we will identify, evaluate, and recommend the requirements for wireless and minimum conductor technology to replace the present cable system.

The second section is a technology survey of concepts for independent end-point tracking (tracking the position of robot end effectors). The position of the end effector in current industrial robots is determined by computing that position from joint information, which is basically a problem of locating a point in three-dimensional space. This has several serious problems. First, the robot structure must be very rigid because any flexing or bending of the arms causes errors in the robot controller's ability to locate the end effector. This requirement for rigidity increases the cost and weight of the robot and limits the payload. A second problem is that, even with precision encoders and stiff members, the accuracy of large robots is very poor. This makes most large robots unacceptable for tasks requiring precise knowledge of the position of the end effector. As the demand for better accuracy performance grows, so grows the need for innovative systems and methodologies that can provide accurate information about the position of robot end effectors. Several approaches are presently being used in industrial robotics, including: stereo-triangulation with a theodolite network and electrocamera system, photogrammetry, and multiple-length measurement with laser interferometry and wires. The techniques that will be evaluated in this survey are advanced applications of the aforementioned approaches. These include laser tracking (3-D and 5-D), ultrasonic tracking, vision-guided servoing, and adaptive robotic visual tracking.

1.0 Wireless Communication and Minimum Conductor Technology Survey

1.1 Background

The U.S. Department of Energy is currently involved in the environmental restoration of the Hanford Site, located in southeastern Washington State. This site restoration presents a series of remediation problems that challenge the state of the art for equipment and procedures. The most serious challenge involves the 177 large, underground storage tanks that were used since 1943 to contain by-products of the nuclear production process that supplied plutonium for the nation's nuclear weapons program. The contents of the storage tanks are primarily reprocessed solid waste from the chemical separation process that extracted plutonium from irradiated reactor fuel. The waste material is chemically complex and includes physical forms ranging from thick, sticky sludge to a crystalline salt cake. The sludge has the consistency of soft mud, and the salt cake approximates low-grade concrete. There is a small amount of interstitial or supernatant liquid in most tanks.

One hundred and forty-nine of the tanks are of an early design consisting of a single reinforced concrete shell with a carbon-steel liner. There are four sizes of these single-shell tanks, built between 1943 and 1964. The smallest is a nontypical tank with a capacity of 55,000 gallons. This small tank has a diameter of 20 feet and a height of about 25 feet. Only 16 of these tanks were built. The most common configuration is a tank with a diameter of 75 feet and a wall height of either 18, 24, or 32 feet. The different wall heights give the tanks capacities of 500,000 gallons, 750,000 gallons and 1,000,000 gallons, respectively (see Figure 1-1). There are sixty 500,000-gallon tanks, forty-eight 750,000-gallon tanks, and twenty-five 1,000,000-gallon tanks. As shown in Figure 1-1, the tanks are buried from 5 to 12 feet underground to provide radiation shielding.¹

1.2 Technology Background

The environmental restoration and final disposal of the radioactive contents of the underground storage tanks at the Hanford site will require removing and treating the tank contents. Since the contents are in the form of various residues from the nuclear separation operations, radioactivity levels far exceed those that permit suitable manned operations.

Studies have been carried out since the 1970s on proposed methods for a control and monitoring signal transmission system for communicating with stationary and mobile equipment within high radiation areas. Various wireless technology concepts have been developed to meet these criteria. Based on recent evaluations, a wireless or minimum conductor transmission system has been identified for further engineering evaluation, study, and demonstration.

1.3 Previous Work

Extensive work has been done by the Oak Ridge National Laboratory (ORNL) on microwave signal transmission systems for in-tank use. The ORNL work is based on decades of experience in optimizing contactless communication for use in the ORNL Remote Systems Development Facility at the Thorium-Uranium Recycle Facility. Their work will be referenced and summarized where appropriate.

1.4 In-Tank Environment

The in-tank radiation environment assumed by ORNL as the design point were radiation-dose rates from 10^3 to 10^5 (Si) rad/h.^{1,2} According to Westinghouse Hanford Corporation (WHC) document WHC-SD-TD-TI-001, entitled, *A Description of the Hanford Single-Shell Tanks and Their Contents*, the

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Fig. 1-1. Typical configuration of the 75-foot diameter single-shell tanks.

radiation levels at the surface of the waste vary from a few rads/h in some tanks, to up to about 5000 rads/h in others. In a significant portion of the tanks, the radiation levels will be between 200 and 2000 rads/h at the surface. Other properties of the in-tank environment are summarized below in Table 1-1. This data is for Tank 106-C, specifically.³

Table 1-1. Properties of the in-tank environment.

Temperature	100° F at waste surface
Radiation	300° F in waste
	Total: 10⁶ rad–10⁷ rad
	270 rad/h above waste
	540 rad/h @ hot spots in waste
Chemical	pH: 7–13
Humidity	5–100%
Pressure	+/- 2491 Pa (+/- 10 inches of H₂O)

1.5 Technology Requirements

Based on the aforementioned ORNL work and preliminary WHC Long Reach Manipulator (LRM) system specifications, signal transmission requirements can be defined. According to the most current information from Pacific Northwest Laboratory (PNL), the control requirements for the LRM will include control of a six degree-of-freedom arm with a dexterous end effector. This manipulator will require high performance, closed-loop servomechanisms, and a high-rate of error-free, bi-directional data transmission capability. It will also require the following end-effector utility services (see Table 1-2).

Table 1-2. End effector service requirements.

2 hydraulic connectors	Working @ 45 gpm @ 2000 psig
2 hydraulic connectors	Working @ 8 gpm @ 5000 psig
1 pneumatic connector	400 scfm @ 500 psig
1 high-pressure water connector	20 gpm @ 55 ksi
1 low-pressure water connector	8 gpm @ 80 psi
One abrasive supply connector	0.5 in. I.D. rated @ 200 psi
One three-conductor as power supply connector	120 V, 60 Hz, 25 A
One dc power supply & instrumentation connector	16 contacts; 5 A each
30	Shielded twisted pairs
6	RG 174 Micro coaxial cable connectors
3	75 ohm coaxial cable connectors
1	CO₂ abrasive pellet supply @ -60 psi
Services for 3-D viewing system	

Sensor requirements for the LRM have been preliminarily defined and are divided into the following categories:

1. Joint control sensors.
2. Manipulator strain and acceleration sensors.
3. Force-torque sensors.
4. Remote viewing cameras and microphones.

1.5.1 Joint Control Sensor Requirements (Table 1-3)

Also note that these sensors should have control algorithm compatibility for position, velocity, and force/torque data, as well as an ability to measure absolute position after a robot restart.

1.5.2 Strain and Acceleration Sensors (Table 1-4)

Note that the number of strain gages and accelerometers is unknown at this time, but it is known that they will be used.

1.5.3 Force Torque Sensor (Table 1-5)

This sensor will be at the end-effector exchange plate.

1.5.4 Remote Viewing Cameras & Microphones (Table 1-6)

These sensory system support requirements show that high-bandwidth communication systems are necessary for LRM control. As stated in the LRM specifications, communication between controllers and sensory systems should be no slower than 200 Hz.³

Table 1-3. Joint control sensor requirements.

Sensor type	Specifications
Position sensor	16-bit/0.01% linearity
Velocity sensor	12-bit/0.01% linearity
Joint force torque sensor	12-bit (able to measure to 0.1% maximum load)

Table 1-4. Strain and acceleration sensors.

Sensor type	Function
Strain gages	Identify vibratory link modes
Accelerometers	Measure acceleration at distal end of each link

Table 1-5. Force torque sensor.

Six-axis force-torque sensor	12-bit resolution
Maximum load of the sensor—1000	

Table 1-6. Remote viewing cameras and microphones.

Camera/Microphone	Location
Hardened CCD/microphone	Identify vibratory link modes
3-D microphone	GPM
Hardened CCD/microphone	DM

1.6 Microwave Signal Transmission Systems (MSTs)

As stated earlier, ORNL has done extensive work on MST systems for use in nuclear fuel reprocessing facilities. The operating environment that ORNL used for their studies is similar to that of the UST tanks but with some differences; therefore, where the ORNL results are applicable, they will be used and where they differ, those differences will be pointed out.

ORNL evaluated many signal transmission methods in 1987 and published their work in early 1988 and in follow-on work in 1991.^{4,5} The methods included confined-path radio frequency systems and free-space radio frequency systems, as well as optical and inductive systems. Because of the intrinsic radiation hardness demonstrated by high-frequency semiconductors, ORNL concluded that a free-space-launched microwave signal transmission system greatly reduced the mechanical and maintenance problems associated with slotted-line or leaky coax systems. An additional advantage was the fact that microwave-frequency transmission accommodates the wide information bandwidths and the great number of discrete information channels required to control complex in-tank hardware. Frequency modulation techniques applied to microwave carriers can mitigate the effects of multipath interference, which in this case can be caused by tank-wall reflection.

Two techniques considered for signal transmission in a reprocessing cell, but not investigated at ORNL because of inherent technical limitations, included free-space radio-frequency and inductive-loop transmission techniques. There are problems with free-space radio-frequency transmission in metal-lined cells. Specifically, there is a high probability of signal interference produced by radio waves repeatedly reflected by the cell wall. Also, at a frequency of 12 MHz, the maximum data rate is limited to 160 baud. Inductive-loop transmission has severe bandwidth limitations and also could not provide the data rate necessary for servomotor control or video signal transmission. For these reasons and because alternative transmission methods are more attractive, free-space radio frequency and inductive loop were not considered further.

A technical survey of the signal transmission methods considered for hot cell applications by ORNL is presented in Table 1-7. Desirable technical properties of each of these methods are identified and arranged in descending order of importance. Each property is also assigned a numerical ranking, or weight, corresponding to its importance in achieving overall system goals. This weight factor (WF) ranges in value from 1 to 5, where 5 represents a very critical parameter. Each transmission method surveyed is then scored, also on a scale from 1 to 5, in its ability to meet the technical requirements of the specified property. In this rating scheme, a 5 represents a high ability of the given system to meet these requirements. Finally, by summing the products of the property ratings and scores for each system, a single system score is obtained for making system comparisons.

The first transmission method listed in Table 1-7, focused infrared light, has very good data-rate capabilities, but it is penalized because most of the better semiconductor optoelectronic devices that are commercially available are sensitive to gamma radiation damage. In addition, nearly all optical detectors will respond to nuclear radiation. This will result in undesirable electronic noise on the data and television links and, ultimately, errors in the data.

The confined-path slotted-line and confined-area, leaky-coax systems both received fairly high ratings in the survey and, at first glance, appear to be strong candidates. Nevertheless, these two systems have major drawbacks when remote maintenance requirements are considered. These transmission lines must be remotely segmentable into removable short sections. The connectors for these segments must be

Table 1-7. Signal transmission methods survey.

Property	Weight factor ^a	Systems					
		Focused infrared	Slotted line rf	Lossy coax	Fiber optics	Focused microwave	Omni-directional microwave
Data Rate	5	5 ^b	3	3 ^c	5	5	2 ^c
Data-error rate	5	3	5	5	5	5	5
Bidirectional	5	4	3	3	5	5	5
Radiation hardness	4	1	3	3	1	4	4
Ease of remote maintenance	4	4	1	2	1	4	4
Reliability in an emergency	4	1	5	5	5	5	5
Low maintenance	3	2	3	3	2	3	4
Ease of redundancy	3	4	2	2	2	4	4
Available technology	3	2	3	3	1	3	3
Mechanical size	3	4	2	2	2	3	5
Biological hazard	2	2	5	5	5	4	5
Power requirement	1	4	3	3	5	4	4
Total score		128	134	138	139	198	174
Weighted score (normalized)		0.72	0.75	0.78	0.78	1.0	0.98

^a 5 = absolutely necessary, critical; 1 = desirable but not necessary.

^b 5 = very good, very desirable; 1 = poor, very undesirable.

^c Data rate is not great enough for servomanipulator control but may be great enough for sampling vehicle control.

very positive, or excessive signal losses would be experienced. For very long cell applications, the design for the connections must be extremely good with very low losses. It appears that use of the slotted line for transporters should be avoided unless multipath problems render no other concept tenable. Use of the leaky-coax should be avoided for the maintenance system transporters and should be used where other criteria demand its use. The limited data-rate capability of the leaky-coax prohibit its use for real-time control of servomanipulators but is adequate for control of other types of equipment, like the sampler vehicle transmission rate of 1200 baud. The transmission limits of a leaky-coax system have not yet been experimentally determined but are believed to be less than 9600 baud because of standing wave-type interference problems.

Fiber-optic cable is capable of transmitting high rates of error-free data, but is susceptible to radiation browning and also presents remote maintenance problems. Fiber optics also require in-cell electronics that need to be hardened or shielded, although this problem is not unique to fiber optics and is shared by other types of signal transmission techniques, e.g., microwave, leaky-coax. Another problem is the mechanical failure of the cable caused by fatigue from power track operation as experienced with metal-conductor coaxial cabling. Further, it is doubtful that fiber-optic cable connections can be remotely maintained; a fiber-optic cable connection is difficult to make, even by hand, because of the precision and quality required in the process. If a nearly flawless optical connection is not achieved, the transmission rate is significantly reduced. Some losses are experienced with even the best connection, and for these reasons the number of connections between the in- and out-of-cell transmitter/receivers must be minimized. However, to allow for maintenance of the cabling and cable-handling tracks, several connections would be required. ORNL maintained that the use of fiber-optic cabling for reprocessing cell applications presented significant risks that were difficult to justify when compared to the alternative microwave transmission techniques.

Focused-beam microwave systems operating in the >10-GHz range have much more than adequate bandwidth for the real time control of servomanipulators and the transmission of many video channels. Omnidirectional microwave has a limited bandwidth, but it could possibly be used for low-transmission applications where focusing of the beam is difficult because of nonlinear movement of the controlled device. Based on theory and bench-scale experiments conducted to date, it is believed that both focused and nonfocused systems can successfully operate in large, metal-lined cells without interference. Also, radiation hardness is not expected to present problems because the intrinsic radiation hardness of properly selected high-frequency microwave devices is very good. Furthermore, remote maintenance problems will be minimal because of the lack of "proximity-type" position-tolerancing requirements that are encountered with many other systems, such as the slotted-line method. A microwave transmitter/receiver system is very localized and can be modularized for maintenance using standard design practices. For these reasons, ORNL selected and pursued the development of microwave signal transmission techniques for reprocessing cell applications.^{4,5}

1.7 Commercial Systems

The above stated conclusions are somewhat dated due to advancements in specific technology. For example, the disadvantages noted for fiber optics such as susceptibility to radiation browning have been mitigated by hardened fiber-optic cable and transmitter and receiver components now commercially available. Also, the concerns raised about the mechanical failure of fiber caused by fatigue have been addressed by commercial vendors and are discussed below.

1.8 Reliability of Optical Fiber in Hazardous Environments⁸

Optical fibers are valued for both military and space applications because of their low mass and small size as well as their immunity to electromagnetic interference (EMI) and electromagnetic pulse (EMP), and their low loss and high-bandwidth properties. These fibers can provide communications for a wide range of unique systems.

The reliability issue has two main facets, mechanical and optical. The former deals with the strength and the fatigue properties of the glass component of the fiber and the protection available from the design and materials used in the cable structure. The latter deals with all the internal or external factors that can vary the optical signal transmission over time, such as increasing its loss.

Much work has been done on the characterization of optical fiber properties and their changes under specific environmental conditions, e. g., fatigue of fibers immersed in water, the effects of hydrogen ingression on optical loss, or the effects of microbending on optical loss. The effects of radiation on fibers for commercial, simulated military environments and some hazardous industrial environments have been documented for many fibers, especially under the auspices of the NATO (RSG-12) study group.

Reliability concerns arising from environmental conditions other than radiation will be dealt with in this section, with radiation hardness discussed in the following section.

1.8.1 Fiber Strength and Fatigue

Optical fiber strength is limited by two generally accepted failure mechanisms—instantaneous fracture controlled by defects in the fiber or surface flaws and delayed failure caused by fatigue. Fatigue is the weakening to failure of materials under loads well below their inert strength. In the fatigue of silica-based glass fibers atmospheric moisture, or water, reacts with a flaw on the glass surface which is under stress; defects, flaws, and stress-corrosion reactions reduce the strength of fiber from the glass theoretical strength of 18 GPa (2.6 Mpsi) to typically <3 GPa (450 ksi).⁶ The main variables are stress level, exposure time, exposure temperature, and the moisture (or other corrosive agent) level.

In most practical industrial applications, moisture and stress will be standard aspects of the operating environment. Tensile stress, which facilitates the fatigue of glass fibers, is found in bending stress and torsional stress as well as in direct tension. For example, in bending, the outer surface of the fiber experiences tension while the inner surface is compressed. The maximum stress of a bent fiber is located within a small area at the apex of the bend while the remainder of the fiber experiences lower tensile, or compressive, stresses.

Fiber-optic cables can be designed so that optical fibers are protected from direct tension, but with only a possibility of minimizing the bending stress they are subjected to in an application. For this reason, bending stresses are more important for applications using cables, while both bending and direct tensile stresses must be considered for applications employing simple fibers.

If silica did not fatigue in moist environments, then a simple bend or direct tensile stress test at the highest stress to be encountered in practice would suffice to guarantee against breakage (failure) in use. When tensile stress is present, fatigue does occur and reduces the fiber's strength upon extended exposure to moist environments, thus fatigue as a function of time under stress must be known or evaluated.

Fatigue testing has become the primary way to estimate mechanical reliability and predict lifetimes. The fatigue behavior of fibers has been measured using several techniques, both dynamically and statically. Since these can yield different results and predictions, it is important to understand when and where the differences arise. This will be discussed in subsection 1.8.2.

Furthermore, as recent research has demonstrated strong correlations between fiber coating properties and fiber fatigue behavior,⁶ it is also important to take the coating properties into consideration when evaluating the long-term reliability of optical fibers.

A power law model was developed by Charles to describe the fatigue of glass.⁶ The basic equation is as follows:

$$\log t_f = -N \log \sigma + \log k \quad (1)$$

where N (fatigue parameter) and k are characteristic constants for the materials, geometry and the environment of the samples tested, and t_f is the time to failure under the given stress, σ . This relationship is illustrated in Figure 1-2, where the static fatigue of a standard Hard Clad Silica (HCS) fiber in ambient water is shown.

In dynamic fatigue testing, the entire fiber is stressed to failure at several different stress (strain) rates while exposed to an appropriate environment—typically moisture or water. The average strength for each testing rate is determined from a Weibull Failure Probability plot. This strength is then plotted

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Fig. 1-2. Static fatigue of a standard Hard Clad Silica (HCS).

versus the rate on a log-log plot. The slope of the resultant graph is inversely related to the fatigue constant, N . The testing rates should cover at least two orders of magnitude for meaningful results.

1.8.2 Fiber Requirements

Military/government applications span a very large range of environments, from extremely harsh to relatively mild indoor conditions. Considering the harsher end of the spectrum, where critical operation and reliability may be needed the most, the preferred fiber would have the following mechanical and assorted properties. The fiber should have high initial strength, good fatigue resistance, low sensitivity to environmental conditions, low sensitivity to prior handling and environmental exposure, good radiation resistance, and assorted application-specific optical properties.

Since failure in ceramic materials, like silica, is a statistical process, the strength of optical fibers is normally obtained from a Weibull plot of 10–20 strain to failure tests. The results for a high-strength fiber are depicted in Figure 1-3. There are three major points which offer important information about the fiber's strength. First, only one mode of failure is indicated when all the data points fall on a straight line. Second, the higher the slope, the tighter the distribution of flaws in the fiber. Slopes (m value) >70 indicate that the distribution is essentially flaw-free, after allowing for diameter fluctuations in the

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Fig. 1-3. Weibull plot for a high strength fiber.

sample lengths tested. Finally, the mean Weibull strength is the value of the failure stress with a $50 \times$ failure probability. Obviously, the higher the mean value, the stronger the fiber, but the slope must be high and there should be only one mode of failure evident in the data if this strength value is to have any real value in practical applications.

Good fatigue resistance is very important to the design and reliability of fiber-optic installations. The environment and exposure time of the application define the conditions that the fiber must meet. The fatigue constant, N , measures the sensitivity of the fiber's strength to these parameters; for a plot of static fatigue data such as in Figure 1-3, the larger the value of N , the steeper the slope, and the smaller the change in failure stress with time. For example, when $N=15$, a fiber would fail in 40 years at its 1-second failure stress (the x-intercept in a plot such as Figure 1-2). When $N=20$, this rises to 0.34 times this value and at $N=30$, it rises to 0.5 times this value. This means that the design stress for the lifetime of the application can be much closer to the strength of the fiber as measured by the Weibull plot when N is higher.

A fiber with a very high tensile strength and a high fatigue parameter will be able to handle quite stringent mechanical requirements. The change in these values with handling, temperature, or aging are equally important in providing a safe, reliable fiber. HCS fibers, whose silica surfaces have been passivated, show little or no adverse effects from exposure to moisture even at moderate stresses and exposure times. At elevated temperatures the N values are somewhat higher than ambient, although the failure strength level is slightly lower.

1.9 Radiation Hard Fiber-Optic Cable Performance

The transmission performance in a Co-60 radiation environment of a polymer clad/pure silica core fiber has been evaluated near both the 850 and 1300 nm telecommunication windows, and at +22°C and

–55°C. The evaluation included an in situ measurement of a radiation-induced loss of up to 10 krad and a fading of this loss of up to 105 seconds after cessation of exposure. It is found that at room temperature superior radiation resistance is afforded near 850 nm. However, in spite of larger intrinsic losses, it was found that at –55°C, lower total attenuation, during irradiation and up to several hundred seconds after exposure, is available at the longer-wavelength window. Furthermore, as average transmitted power increases, the doses during irradiation increase and the times during recovery decrease for this period of superior performance. These results suggest the longer wavelength may be better suited for shorter transmission links intolerant of momentary interruptions.

Some early, multimode optical fibers, with cores fabricated from low-OH-content silica preforms, demonstrated higher radiation-induced transmission losses near 85 nm than those fabricated from OH-containing silicas. However, more recent work has demonstrated counterexamples, with an approximate dependence of the radiation-induced loss upon the square root of the drawing-induced band near 630 nm. Fibers with a weak 630-nm band will have less radiation-induced loss near 850 nm, and, since the induced-loss spectrum of pure silica fibers decreases with wavelength, these fibers are expected to have less induced loss at 1300 nm. However, for many military, aerospace, and other applications in harsh environments where ionizing radiation and low temperatures may be encountered, the total link attenuation, intrinsic plus radiation-induced, is of primary concern. Here, it is not clear whether the added intrinsic loss due to the presence of the first OH overtone band at 1380 nm, caused by the few ppm OH present, would compensate for reduced radiation sensitivity at 1300 nm.

1.9.1 Experimental Procedure

The sample used in testing was a fiber with a 200-micron core of pure silica clad with a 12-micron thick fluoropolymer, enclosed with a 500-micron diameter extruded teflon buffer. Silica soot for the core material was deposited in an Ar plasma, and in order to lower the OH content before consolidation, soot blanks were treated with chlorine compounds. Consequently, the concentration of Cl has been confirmed to be about 7000 ppm. On the other hand, intrinsic loss measurements discussed below suggest 3 to 5 ppm OH.

Samples were irradiated in a J. L. Shepherd and Associates Model 81-22 Irradiator, fitted with a Model 484 Radiation Tunnel and presently supplied with 6.8 kCi of Co-60. The total dose in all cases was 10 krad (SiO_2), and the dose rate was 1300 rad/min. Separate and previously unexposed samples were used for each irradiation. Samples were loosely wrapped on a 3.50-inch (8.89-cm) diameter aluminum spool. The spool was cooled with chilled dry nitrogen gas. The temperature was monitored with a thermocouple taped to the outer fiber layer. Temperature and optical signal stability was established for 1 to 2 hours prior to commencement of irradiation. Fifty-meter sample lengths were exposed for 865-nm measurements and 100-meter lengths used at 1300 nm. Temperature- and current-stabilized light-emitting diodes were used as light sources; the wavelength of the shorter wavelength device was centered closer to 865 nm. A portion of this output (taken from one output of a fiber optic, multimode, 1×2 splitter) was monitored; this served to normalize source-related intensity fluctuations.

These sources were current-modulated to provide a 2-kHz square wave with a 50% duty cycle. Power exiting the test fiber, measured with a commercial fiber-optic power meter, is given as average power. Other experimental details may be found elsewhere.

Intrinsic loss spectra were taken by the cut-back method from 600 to 1600 nm with a commercial optical spectrum analyzer and from 300 to 900 nm with an in-house spectrophotometer adapted for this use. Spectral resolution with both instruments was 0.5 nm. Fiber lengths ranged from 58 to 863 meters.

1.9.2 Results

In order to determine the loss before irradiation near both 850 nm and 1300 nm, the intrinsic loss of the fiber was measured. Figure 1-4 shows this loss from 350 nm to 1600 nm. A minimum of about 4 dB/km appears at 850 nm. The second window near 1300 nm has an approximate loss of 25 dB/km. These will be used later to calculate the total loss experienced in a radiation environment. The drawing-induced band near 630 nm, present in some low-OH silica fibers, is here conspicuously absent. The bands near 720, 945, and 1380 nm are the fourth, third and second OH stretch overtones, respectively; from their intensity, 3 to 5 ppm OH is determined. The bands near 905, 1020, 1185, and the broadened long wavelength tail of the 1380-nm OH band extending from about 1440 to 1500 nm are normally not

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Fig. 1-4. Intrinsic loss in a fluoropolymer clad/low-OH, pure silica core fiber.

associated with overtones of OH stretching or combinations of OH stretch with the fundamental SiO_4 tetrahedron vibration near 12.5 μm . These bands have not been observed in all-glass waveguides. As they have been observed, indeed with very similar proportions, in other polymer-clad, low-OH silica fibers whose core material has been fabricated somewhat differently and processed under different conditions, they likely are associated with C-H stretching vibrations of the cladding material.

1.9.3 Radiation-induced Loss

Radiation-induced loss, as a function of dose, at room temperature and -55°C for 1.0 mW at both 865 nm and 1300 nm is shown in Figure 1-5. The salient features include: (1) the onset of loss saturation between 1 and 3 krad; (2) a large-loss dynamic range extending from 2 dB/km to 110 dB/km depending upon temperature and wavelength; (3) a larger increase in loss between 22°C and -55°C at 1300 nm than at 865 nm; and, (4) the attenuation at 1300 nm showing proportionally more recovery (15%) after saturation during irradiation than the loss at 865 nm (6%). The fiber does demonstrate an increased response to radiation at low temperature, and this response is different for different wavelengths and can be dose dependent. For example, at 10 krad, and at 865 nm, the induced-loss increases from 15 to 105 dB/km when the temperature drops from 22°C to -55°C , a seven-fold increase; at 1300 nm, the increase is from 2 to 43 dB/km, a 21-fold increase. Similarly, at 3 krad again, a 7-fold increase is observed at 865 nm, while a 25-fold increase is observed at 1300 nm.

Figure 1-5 shows the fading of radiation-induced loss after exposure to 10 krad, again at both wavelengths and temperatures. The curves drawn through the data points here serve only to guide the eye. One characteristic feature of the low-temperature recovery is the wavelength-dependent shape. Attenuation at the shorter wavelength late in the recovery, after a few hundred seconds, progresses proportionately slower than at the longer wavelength.

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Fig. 1-5. Fading of radiation-induced loss after a total dose of 10 krad delivered at 1300 rad/min with an average power of 1 μ W.

As an example of the implications of Figure 1-5 for the system designer, after 10 krad of exposure, the induced loss never exceeds 45 dB/km at 1300 nm, while at 865 nm, 70 seconds is required for the induced loss to fade to 50 dB/km. Such an induced loss is typical of loss budgets (≈ 5 dB) assigned to radiation effects for the fiber transmission portion (< 100 meters for most airborne platforms) of a photonic data/communication system operational in harsh environments. Therefore, operation near 1300 nm appears to afford greater radiation resistance at low temperature.

However, what is more meaningful to the photonic system designer is total link loss—the sum of intrinsic and radiation-induced losses. This is shown in Figure 1-6 as a function of dose for both wavelengths and temperatures. At room temperature, it is clear that operation near 850 nm always affords lower total loss, at least up to this dose and dose rate. However, this is not always true at low temperature. With 1.0 mW, lower total loss is found near the shorter wavelength up to about 430 rads, above which lower loss is available at the longer wavelength. Furthermore, because the radiation-induced attenuation decreases with a power increase (proportionately more for the short wavelength than for the longer wavelength, at least in this power density region),⁷ this dose crossover value, from short to long preferred wavelength, increases with optical power. For example, transmitting with 10 mW power increases this dose crossover to about 1200 rads.

The total loss picture during recovery is shown in Figure 1-7. Here, operation at low temperature near 1300 nm is preferred for about 600 seconds during recovery. For longer times, lower total loss is available at the shorter wavelength. Again, because of proportionately faster recovery with increased power at the shorter wavelengths, this crossover recovery time is a function of optical power, decreasing to about 200 seconds at 10 mW, while increasing to 1600 seconds at 0.1 mW.

Therefore, the two wavelengths may find application in two classes of fiber-optic communications systems for harsh environments. The longer wavelength is preferred at lower temperatures for shorter length transmissions where data interruptions cannot be tolerated, while the shorter wavelength may be

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Fig. 1-6. Total loss during irradiation at 1300 rad/min with 1 μ W power at either wavelength and at 22 and -55°C .

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Fig. 1-7. Fading of total loss after 10 krad delivered at 1300 rad/min with 1 μ W transmitted.

more applicable to transmission over longer paths where short interruptions are not catastrophic and for links that operate near room temperature.

In Figure 1-8, the different low-temperature attenuation versus dose behavior exhibited at the two wavelengths suggests the presence of somewhat different defect production and annihilation dynamics. For example, at -55°C with a 22 rad/s dose rate, there is more recovery from 3 to 10 krad at 1300 nm (15%) than at 865 nm (about 6%). This observation supports a similar notion concluded elsewhere based upon the different photobleaching characteristics at the two wavelengths.⁸

1.10 Fiber-Optic Links

The Hewlett Packard (HP) HFBR-1414 and the HFBR-2416 fiber-optic links have been tested from up to 300 krad with no significant drop in performance. The HFBR-2406 and HFBR-2416 are high-speed low-cost linear light-to-voltage converters with typical bandwidths of 125 MHz. This bandwidth more than adequately meets the 200-Hz requirements documented in a draft version of the Tank Waste Retrieval System technical specification. These components can be used to make fiber-optic links for both analog and digital applications.

The addition of the HFBR-24X6 receiver to the low cost 0400 component family opens new avenues for designers. The wide bandwidth of the HFBR-24X6 allows high-speed fiber-optic links to be built at lower prices than was formerly possible. The wide bandwidth of the linear light-to-voltage converter can be reduced by a low-pass filter to improve the sensitivity of the fiber-optic receiver lower-speed applications. The HFBR-24X6 accommodates a larger optical signal than other HFBR-0400 fiber-optic receivers before it begins to overload. This improvement in the overload characteristics of the 24X6 was achieved with no significant reduction in the ultimate sensitivity when compared to the existing HFBR-24X4 receiver. The increased optical input power tolerated by the HFBR-24X6 allows it to function at short fiber lengths with large values of launched optical power. When the receiver can tolerate higher optical power, a longer cable is possible before attenuation reduces the light to the sensitivity limit of the receiver. The increased dynamic range of the HFBR-24X6 will thus permit greater optical link length for any given fiber attenuation.

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Fig. 1-8. Co-60 irradiation-induced loss versus dose at 1300 rad/min and with 1 μ W average power at the indicated wavelengths and temperatures.

The 820-nm LED technology used in the HFBR-0400 family of components can be used in conjunction with the HFBR-24X6 receiver to construct digital fiber-optic links that transmit data at speeds up to 150 MBd. The length of the fiber-light guide that can be used with the HFBR-24X6 is restricted by the receiver sensitivity at low data rates. As the data rate is increased, a phenomenon known as chromatic dispersion begins to limit the maximum distance. This distance restriction results from the interaction of the 60 nm-wide spectrum emitted by the LED and the various velocities of light at wavelengths near 820 nm in silica. Since the velocities of light at various wavelengths near 820 nm are different, the optical pulses sent by the LED are dispersed or spread out in time as they travel down the light guide. A chromatic dispersion null exists at a wavelength of 1300 nm in silica glass. If an LED were operated at the chromatic dispersion null, the pulses would experience minimum broadening as they travel through the fiber. This is due to the nearly equal propagation velocity for all the wavelengths transmitted through the silica light guide by the long-wavelength emitter. As Figure 1-4 illustrated the effect of the LED center wavelengths and spectral width on the chromatic dispersion. An 820-nm LED with a 60-nm emission spectrum is shown to produce a larger change in the arrival time of the light pulses than a 1300-nm LED with a 100-nm spectral width.

1.10.1 EMI Issues

It is important to note that the optical fibers themselves are immune to EMI and it is only the associated electronics that are potentially susceptible. The potential problems caused by EMI for electronics exposed to the radiation fields can be mitigated if additional attention is paid to minimizing crosstalk between the transmitter that is switching hundreds of milliamps, and the receiver, whose optical detector will have photocurrents as small as hundreds of nanoamps. Individual ground planes are recommended for the transmitter and the receiver if they are to be laid out next to one another as is typically done in transceivers. The receiver designs shown in Figures 1-9, 1-10 and 1-11 use a balanced power supply filter that eliminates noise conducted by both the power and common sides of the voltage source used to power the circuit. This filter should be located between the two power-bus and ground planes of the transceiver to keep transmitter noise out of the receiver. The voltage source used to power the optical transceiver should be connected to the transmitter side of this filter since this half of the circuit is much less sensitive to power supply noise.

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Fig. 1-9. 155 MBd fiber-optic receiver for -5.2 V ECL interface.

5 0 0003 F17a p40

Fig. 1-10. 155 MBd fiber-optic receiver for +5 V ECL interface to Am 7969.

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Fig. 1-11. 155 MBd fiber-optic receiver for TTL interface.

Another factor that could degrade the performance of a fiber-optic receiver is environmental noise. The HFBR-2406 combines the PIN diode optical detector and the current-to-voltage converter in a small hybrid package. This minimizes the antenna lengths of the HFBR-2406/2416 at the high-impedance input of the transimpedance amplifier that converts the photocurrent to a voltage. This small geometry allows the light-to-voltage converter to have a high electromagnetic interference immunity in excess of 10 V/m. Caution must be exercised, however, to ensure that the metal ferrule of the fiber-optic connector does not act as an EMI source by contacting electrically noisy parts of the system into which it is integrated. If the system in which the fiber-optic link is used is extremely noisy it is recommended that a spring contact be used to ground the metal connector as shown in Figure 1-12. Another method that reduces the effects of EMI picked up by the fiber-optic connector is to use a connector with a nonconductive plastic or ceramic ferrule. In some extremely noisy applications, the fiber-optic components were enclosed in a metal box to eliminate noise coupled into the receiver from adjacent parts of the system into which they were designed. Systems that require metal shielding have proved to be unusual. Thus, in the majority of applications the inherent noise immunity of the components, combined with the shielding provided by the receiver ground plane, have provided sufficient noise immunity.

1.10.2 Radiation Hardness

These fiber-optic components have been radiation tested with no significant change in the performance of HFBR-1414 and HFBR-2416 after exposure to a total dose of 300 krad. The radiation was provided by a 6-megavolt gamma-ray source with a dose rate between 400 to 600 rad/min.

Testing was done by measuring the fiber-optic link's probability of error against the clock position at a symbol rate of 100 MBd. A symbol rate of 100 MBd implies that the system can send 80 Mbits/s if the AMD TAXIchip's 4B5B encoder is used. A symbol rate of 100 MBd also implies that each symbol sent through the fiber-optic link will have a 10-ns duration.

Three fiber-optic transceivers were tested prior to radiation exposure to determine initial performance. The same three transceivers were subsequently tested at progressively higher total dose levels of up to 200 krad. Two of the transceivers (#1 and #2) were tested to 300 krad, with no discernible change in performance. A pseudo random serial-bit stream was used to measure the

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Fig. 1-12. ECL output of the transceiver shown in Figure 1-10 and 1-13. Data rate—155 MBd; data pattern— $2^{23}-1$ PRBS; fiber type—Siecor 62.5/125 μm ; fiber length—500 m; typical peak-to-peak jitter = 760 ps; time scale is 2 ns/DIV.

performance of the three transceivers and a bit-error-rate tester was used to determine if the data at the receiver's output matched the data applied to the transmitter. BER is 1×10^{-10} for 6 ns of every 10-ns symbol in the pseudorandom test pattern used to measure the performance of the transceivers.

These results suggest that less than 1 error in 10^{10} bits will occur if the AMD TAXIchip samples the data over a 6-ns time window. The probability of error will actually be much lower when using the TAXIchip because the timing recovery circuit (PLL) in the AM-7969 typically clocks the received serial data in a window that is ± 1 ns from the center of each 10-ns symbol.

Another important discovery made during these tests was that the HFBR-1414 LED light output remained constant as total dose was increased to 300 k rads. Table 1-8 shows the optical power launched into a 1 m length of 62.5/125 μ m fiber-optic cable at various total dose levels between 0 and 300 k rads.

All test results were measured using the transmitter and receiver shown in Figure 1-10, and in 1-13.⁹

For radiation-hardened applications, it is recommended that the 74F3037 be substituted for the 74ACTQ00 quad nand gate recommended in Figure 1-13, from the revised version of AB-78. The 74ACTQ00 is a CMOS gate with a TTL threshold. The 74F3037 is an NPN Bi-polar gate which will provide the same function as the 74ACTQ00 but with better radiation immunity.

1.11 Fiber-Optic Connections

The difficulty of maintaining fiber-optic connections remotely has been addressed by new FDDI connectors. These connectors are as easy to use as standard electrical outlets that plug in and pull out.

1.12 Commercial Robotic Systems

There are several robot manufacturers that employ fiber optics as the data link for robot control. One company that uses fiber optics for robot control is PAR Systems, in Shoreview, Minnesota. Its CimCorp robot has a robot controller that utilizes a fiber-optic data link to interconnect the robot control computers with the robot interface and power electronics, allowing the control console to be located hundreds of feet from the robot.

The fiber-optic link is a master/slave arrangement, with the master-link controller initiating all communications. The master-link controller electronics are located on the robot-controller digital signal processor (DSP) board, which is a PC-AT (ISA bus) style board performing the robot-servo control tasks. The slave-link controller electronics are located on a PC-AT style board that resides on a passive backplane in the remote robot interface cabinet. The slave-link controller acts as a bus master, controlling the other I/O cards mounted in the remote cabinet.

When the robot controller DSP board needs to read data from or write data to the remote robot interface cards, it initiates communication by loading a 32-bit command word in the input registers of the master-link controller. The command word consists of a control bit that indicates (1) whether the command is a data read or a data write, (2) the desired I/O address, and (3) the data to be sent (in the case of a data write). The master then sends the 32-bit command word to the slave unit. The slave unit, upon receiving the command word, performs the desired I/O read or write cycle to the remote bus. If

Table 1-8. Optical power launched into 1 m of 62.5/125 μ m cable at $I_f = 60$ mA.

LED Ser. #	P_T @ 50 k rads (dBm)	P_T @ 50 k rads (dBm)	P_T @ 100 k rads (dBm)	P_T @ 150 k rads (dBm)	P_T @ 250 k rads (dBm)	P_T @ 300 k rads (dBm)
1	-17.1	-16.8	-17.1	-17.2	-16.9	-17.3
2	-15.5	-15.5	-15.5	-15.3	-15.2	-15.7
3	-15.2	NA	-15.4	-15.4	-15.6	NA

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Fig. 1-13. 155 MBd transmitter for +5 V ECL interface to Am 7968.

the slave received a data read command, the 16-bit data read from the robot I/O card is transmitted to the master-link controller. Upon receiving the data, the master-link controller places the data in output registers and sets a flag to notify the DSP that the requested data is available.

The master- and slave- link controllers use Advanced Micro Devices (AMD) TAXIchip integrated circuits, the AM 7968 TAXIchip transmitter and the AM7969 TAXIchip receiver, to encode and decode the data passed over the fiber-optic link. These components utilize an 8-bit parallel interface and operate at 4–12.5 Mbytes/s. Hewlett-Packard (HP) 820-nm low-cost fiber-optic components (the HFBR-1414 LED fiber-optic transmitter and the HBFR-2416 fiber-optic receiver) perform the conversion between the electrical signals used by the TAXIchip integrated circuits and the optical signals transmitted over the data link. Standard commercial duplex 632.5/125 mm multimode fiber-optic cables are used to carry the optical signals.

1.13 Conclusions

The state of the art in wireless and hardened minimum conductor technologies has been presented. It is clear that advanced microwave communication systems have been well characterized by ORNL; and it is also clear that commercially available hardened fiber-optic technology that can meet the potential harsh in-tank environmental conditions does exist.

The main advantage of a microwave transmission system is that it is truly wireless; however, potentially bulky signal-transporter links must be set up in the tank in close proximity to the robots being controlled. A summary of the ORNL results points to the following conclusions. First, the multipath reflections in a fully metal-lined cell can cause significant problems, and special circuits and techniques are necessary to overcome the effects of the electromagnetic reverberation (echo) present in the cell. Fortunately, the use of higher frequencies for the RF transmission tends to mitigate the multipath effects. Specific results were as follows.

1. The W-band (88/94-GHz) configuration was significantly more effective at maintaining video and digital quality data than the more conventional K-band (10/12-GHz) configuration.
2. The greater the antenna directivity (i.e., the tighter the signal beam), the better the immunity to fading and other multipath-induced effects. At 88/94-G-Hz, the 0.3-m-diameter dish antennae outperformed the 0.15-m dishes.
3. The lower the modulating signal bandwidth, the greater its immunity to multipath in the FM system context. The advanced MPST form of digital modulation is far more stable and reliable than the biphase format, because it required only half the bandwidth of the latter method.
4. High-density, multichannel, bidirectional communications for the reprocessing cell environment is realizable via microwave transmission systems. Large bandwidths, suitable for high-definition television cell viewing systems and/or high-speed data communications, are readily achievable with little additional circuit complexity.^{4,5}

The mechanical reliability of optical fibers has been a research topic for many years. Recently, as users outside the telecommunications field began trying optical fibers in their applications, the need for strong, fatigue-resistant, environmentally stable fibers has become an increasing necessity.

The more stringent environments of many industrial applications, as well as the requirements of fail-safe operations, are causing increased concern about the mechanical reliability as well as optical reliability of optical fiber systems. This is especially true because of the latter's great desirability due to higher bandwidths, EMP invulnerability, radar invisibility, more secure signal transmission, and light weight. Fiber producers have been working to establish and improve reliability through applying protective coatings on the fibers, be they passivating, hermetically sealed, or with very low permeability.

In conclusion, the wavelength that allows for the best performance in a fiber link in a harsh environment depends upon temperature, dose, and optical power, in addition to system tolerance for data interruption. For the Ensign-Bickford radiation-hardened fiber, the multimode fiber discussed here, lower total loss at room temperature is attained near 850 nm, when operating at 1 mW, and in exposures of up to 10 krad at dose rates of up to 22 rad/s. However, at -55°C, lower total loss is available at 1300 nm for exposures above a few hundred rads and for recovery times up to a few hundred seconds after a 10-krad exposure.

2.0 End-Point Tracking Technology Survey

Requirements exist in the technical specification draft document for the Tank Waste Retrieval Test Manipulator System that dictate end-point tracking performance for the LRM.³ These requirements are specified in Section 4.5.1.5 of the document, entitled, *Tracking Performance Using End Effector Sensors*. It states: "The capability of trajectory tracking using end-effector sensors shall be provided. Using end-effector mounted proximity sensing and feedback, trajectory tracking error shall be less than 0.5 inches for constant speed tracking and shall be 0.5 to 4.0 inches during acceleration of the commanded trajectory."

2.1 Technology

Currently there are several techniques used for end-point tracking. They will be presented and evaluated based on their robustness and their readiness to be deployed in a test-bed system. The position of the end effector of current robots is determined by computing that position from joint information. This has several serious problems. First, the robot structure must be very rigid because any flexing or bending of the arms causes errors in the robot controller's ability to locate the end effector. This requirement for rigidity increases the cost and weight of the robot, and limits the payload. A second problem is that, even with precision encoders and stiff members, the accuracy of large robots is very poor. In a robot with a reach of 2 m, carrying a variety of loads, an absolute accuracy of 1-2 mm is typical. This makes most large robots unacceptable for tasks requiring precise knowledge of the position of the end effector. As the demand for better accuracy performance grows, so grows the need for innovative systems and methodologies that can provide accurate information about the position of robot end effectors. The basic problem that needs to be solved is that of locating a point in three-dimensional space. Several approaches are being used, including: stereo-triangulation with a theodolite network and electrocamera system, photogrammetry, and multiple-length measurement with laser interferometry and wires. These approaches all suffer because either (1) they are more complex and costly than is feasible to consider as an integral part of a robotic system, or (2) they are too slow to operate in real-time.

2.1.1 Laser Tracking¹⁰

The National Bureau of Standards (NIST) in 1985 performed tests that specified a laser tracking system that can be used in real-time to determine the three-dimensional static and dynamic positioning accuracy of a robot end effector to a few parts in 100,000 (i.e., 12.5-50 mm for a medium- to large-size robot), and wrist orientations to within 2 seconds of arc. Both systems are simple and compact enough to be considered as a general-purpose portable calibrating tool for robots (or CNC machines), or as an integral part of a robotic system providing real-time position feedback of the end effector independent of the position and angle feedback of joint members. The ability to dynamically and statically measure the position of an end effector to the above accuracy has significant ramifications with regard to both meaningful robot performance measurements and to the potential of these systems in other industrial and engineering applications. NIST has developed two automatic single-beam laser tracking interferometer systems (LTIS). Preliminary tests indicate that both tracking systems are capable of determining the end-effector position (in either point-to-point or continuous-path mode) to about one part in 100,000 (i.e., 12.5 mm for a robot with 2 m of reach), which is about 100 times better than an industrial robot.

5-D LTIS. The automatic five-dimensional laser tracking interferometer system (5-D LTIS) is a dynamic tracking system designed to measure the position of a moving target in five axes; namely, x , y , z , plus pitch and roll. Figure 2-1 illustrates a 5-D LTIS which comprises three major components: a microcomputer, a portable tracking unit, and a target unit. The tracking unit, which includes a laser interferometer system, a dual-axis servo-controlled tracking mirror, and tripod, is firmly located at some convenient position away from the robot. The target unit, which consists of a dual-axis servo-controlled partial mirror (15% transmission), two bilateral-effect photodiodes (installed at the back of the mirror) mounted on the robot wrist, and a tripod, is firmly located at some convenient position away from the robot. The control objective of the laser tracking system is to accurately servo the angles of the tracking

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Fig. 2-1. 5-D laser tracking interferometer system (5-D LTIS).

mirror and direct the laser beam to the center of the target mirror. In the meantime, the target mirror is also servoed to stay perpendicular to the incoming beam and return the beam precisely to the source. The laser system, therefore, measures the change in radial displacement between the target mirror and the tracking mirror. An initial absolute distance calibration process is required in order to obtain the absolute position of the target from the tracking mirror. The two photodiodes at the back of the target mirror are used to supply information about the beam position on the photodiodes to the microcomputer through four A/D converters to close the servo-loop.

The measuring origin of the system is point A, which is defined by the intersection of the vertical (θ_A) and horizontal (ϕ_A) axes of the tracking mirror. Similarly, the measuring point is B, which is defined by the intersection of the vertical (θ_B) and horizontal (ϕ_B) axes of the target mirror. Each rotating axis is coupled with a high-precision encoder. Hence, by incorporating the angle outputs of θ_A and ϕ_A , and the absolute distance between points A and B, the X, Y and Z positions of the target mirror (and the position of the robotic end effector) can be computed in spherical coordinates. Since the target mirror stays perpendicular to the incoming beam during the tracking process, the pitch and roll orientations of the target mirror, relative to the measuring origin, can be readily related to the measurements of θ_B and ϕ_B angles.

3-D LTIS Concept. The 5-D LTIS has basically been proven as an advanced, flexible, and accurate multidegree-of-freedom measuring system, which has the potential of offering a variety of application opportunities. However, it is also recognized that there are applications where measurements of the X, Y, and Z positions of the target are considered adequate. In these cases, the 3-D LTIS, which employs a

passive target (i.e., a "cat's eye" or a "corner reflector," generally referred to as a retroreflector in this text) instead of a servoed target, becomes more economical and practical. The property of a retroreflector is that for a collimated beam striking the retroreflector off-center (Figure 2-2), it will emerge parallel to the incoming beam with twice the amount of lateral offset. Thus, for a beam striking the center of a precision retroreflector, it will be returned to the source literally on the same path.

3-D LTIS Theory of Operation. Unlike the 5-D system, which utilizes a "pseudo-single-beam plane mirror interferometer" for distance measurements, the 3-D system, shown in Figure 2-3, employs a "dual-frequencies single-beam interferometer." Two orthogonally polarized beams (referred to as the reference and measuring beams) at narrowly spaced frequencies are provided by the laser. The reference beam is immediately reflected off the polarizing beamsplitter of the interferometer and returned to the fringe counter. The measuring beam passes through the interferometer and a 50% beamsplitter, where half of its intensity is lost. It is then directed to the center of the passive target (i.e., retroreflector) through the dual-axis servoed tracking mirror. The beam is then returned (without offset) to the tracking mirror and the interferometer, and enters into the fringe counter where it is optically combined with the reference beam. On its return path to the fringe counter, half of its intensity (25% of the original) is deflected to the bilateral-effect photodiode DA by the beamsplitter. The magnitude of the bilateral offset of the beam from the centroid of DA is indicated by the X and Y voltage outputs of the DA. The information is fed to the microcomputer, which determines and issues the appropriate servo-commands to the tracking mirror to null the DA outputs.

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Fig. 2-2. Properties of a retroreflector.

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Fig. 2-3. Configuration of a 3-D LTIS.

Prior to the tracking process, the DA outputs are nulled by aligning the measuring beam with the optical center of the retroreflector. The residual outputs are fed into the computer through two A/D converters and stored as the control references. As soon as the target is driven sideways, a lateral offset between the incoming and the returning beam is immediately introduced and sensed by the photodiode. The information is fed to the computer for processing; the computer then determines and issues the appropriate "error-correcting" servo-commands for the θ_A and ϕ_A axes of the tracking mirror. On the other hand, if the target mirror is to move along the measuring axis of the beam, no offset is observed by the DA and no control action will be implemented. However, the laser system will continue to update the change in radial displacement of the target.

2.1.2 Ultrasonic Tracking¹¹

At the University of Sheffield, UK, ultrasonic position measurement and tracking systems have been developed that use a spark gap located at the point of interest and that time the transmission of energy from this point to three orthogonally placed microphones. In this system, ultrasonic receivers are mounted on the robot and rotated by a motor drive. Measurement of the phase differences between the signal received yields the range and bearing of the transmitter. However, measurement errors of 50 mm were reported and since computation times of 90 ms per measurements were required, such a system would be unable to satisfy current requirements. Ultrasonic measurement systems are clearly attractive in terms of their relative simplicity and low cost. However, previous work has failed to provide a system

of sufficient accuracy, and the current program of work at Sheffield was embarked upon to search for an adequate system.

Development of Measurement System. The use of single ultrasonic elements in the transmitter and three ultrasonic receivers, as indicated by Figure 2-1, only gives a very limited position measurement capability. The directivity of ultrasonic energy emission means that signals are only detected when the end effector is within a small subset of its possible range of orientations and when none of the three paths between the ultrasonic source and receivers are obstructed by the robot arm. The least harmful effect of obstruction in one or more of these paths is the absence of a measurement signal for the path(s) affected. However, the receiver associated with an obstructed path may in some circumstances receive a signal by reflection and generate an entirely incorrect path measurement.

The characteristics of various types of ultrasonic elements are shown in Table 2-1. Ultrasonic energy is emitted as a sinusoidal waveform, and the accuracy of measurement of each distance d_i is governed by the distance between successive peaks in the waveform (i.e., d_i depends on the nominal frequency of the emitter). This suggests that high frequency elements should be used. However, as shown in Table 2-1, the angle of spread and effective range of the emitted energy wave both decrease rapidly as the nominal resonant frequency is increased. Because of this, 40-kHz elements were used, as the range and angle of spread of higher frequency units is inadequate.

As mentioned earlier, a single ultrasonic transmitting element only emits energy within a limited conical volume. In order to provide a measurement capability over the whole robot working volume, for the end effector in any orientation, a transmitter composed of five ultrasonic elements inserted in five sides of a small aluminum cube was designed. Using 40-kHz elements with a $\pm 50^\circ$ spread gives a spherical volume of emitted energy apart from small 'dead zones' close to the transmitter, which extend up to 100 mm from the center of the transmitter. It is possible to reduce the size of these dead zones by increasing the number of ultrasonic elements in the transmitter to accommodate the extra elements, but the extra problems that this generates will rarely be justified.

In order to solve the problem of obstructed signal paths, the number of ultrasonic receivers has been expanded to eight, positioned at the corners of a 4-m-sided cubic volume surrounding the robot, as shown in Figure 2-3. This, together with the five-element transmitter, guarantees at least three energy path measurements for any position of the robot arm, providing that the working volume is otherwise unobstructed. Where obstructions, other than the robot itself, exist in the work volume, the system is usually able to provide three valid energy path measurements.

System Hardware. The maximum sampling rate of the position tracking system is governed by the transmission speed of ultrasonic energy through air and the length of the path. For a 5.6-m transmission path (the diagonal across a 4-m-sided cubic working volume) and a velocity of 340.17 m/s (at 20°C), the transmission time is 16.6 ms.

The ultrasonic transmitter is excited by a 40-kHz oscillator gated with a train of pulses repeating at a rate of 60 Hz and synchronized such that the high-frequency oscillator is always gated on a positive rising edge. This provides bursts of ultrasonic energy every 16.6 ms. This allows for a 16.6-ms energy transmission time and caters for transmission paths that can be accommodated by gating the 40-kHz oscillator at a slower rate, although this obviously degrades the data rate and tracking accuracy.

Table 2-1. Characteristics of ultrasonic elements.

Nominal frequency kHz	Angle spread (deg)	Detectable range (m)	Resolution (mm)
23	80	0.2-6	14.9
40	100	0.2-4	8.6
75	7	0.5-5	4.6
400	7	0.06-0.3	0.9

The output of the ultrasonic element in each receiver circuit is connected to amplification stages and a further state which rectifies and smoothes the signal. The final circuit element is a comparator, for which a signal output level greater than 1.5 volts defines the reception of the ultrasonic energy burst emitted by the transmitter.

Transmission times of the energy along the paths between the emitter and receivers are measured by a set of eight 12-bit counters. Measurement is achieved by incrementing the counters by pulses derived from a separate 340-kHz clock between the instants of energy emission and detection. Count-starts are synchronized with the gating of each 40-kHz burst of energy emission and each counter is stopped when its associated ultrasonic receiver first detects energy. The input 340-Hz oscillations to the counters give a path transmission time measurement resolution of 1mm. The hardware is summarized schematically in Figure 2-4.

Future Work. The system developed offers a relatively low-cost means of monitoring the position of a robot end-effector within a 4-m-sided cubic working envelope. At present, the accuracy is only a modest 3 mm. However, further work is proceeding, which is expected to either eliminate or at least substantially reduce the various error sources identified.

2.1.3 Vision-Guided Servoing⁷

Sensor integration is becoming a key element in today's flexible automated robotic workcells. With sensors, an automated robotic system can compensate for changes in the environment and uncertainties

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Fig. 2-4. Schematic diagram of experimental ultrasonic tracking system.

in its control model. In the field of robotics, sensors allow robots to go beyond simple pick-and-place operations, giving them the ability to manipulate parts with uncertain characteristics and locations. Vision is an especially useful sensor in robotics, as it may be used to close the feedback loop around the robot end effector's position and orientation (pose) rather than around the robot's joint angles, as in conventional robot control. This visual feedback allows for more accurate retrieval and placement of items within a workcell.

Most systems require specialized hardware with fixed image sampling times. An important and often overlooked system constraint is that the image processing time may be slow and usually varies with the size and complexity of the image. One technique concentrates on a control structure for an eye-in-hand robot with off-the-shelf image processing equipment.

In the past, vision feedback has taken many forms. Visual servo-control structures can be categorized by (1) choice of feedback representation (either position-based or image-based); (2) class of control structure (either closed-loop or open-loop joint control); and, (3) timing of image processing and manipulator control (either static or dynamic). The block diagram in Figure 2-5 illustrates the traditional, position-based, visual servoing structure which is used in most static "look-and-move" (closed-loop joint controlled) systems. Because the vision routines and the robot control routines are performed in a sequential manner, the robot must come to a complete stop before the camera can acquire a new image. This pause makes it difficult for the robot to track moving objects. In addition, by using position coordinates as the feedback variable, an exorbitant amount of on-line computation is necessary to determine the pose of a workcell component from its image features.

The other extreme is the dynamic, feature-based "visual tracking" (open-loop joint controlled) system. In this system, the vision routines and the robot control routines are performed in parallel. This allows the camera to acquire images while the robot is moving. In addition, by using image features as the feedback variable, on-line computation is reduced since the reference image features could be taught off-line either through teach-by-showing techniques or through CAD simulation. Although the proposed control appears theoretically sound, this system poses a number of difficulties when implemented with existing image-processing hardware. First, the system model assumes that the vision sampling time and delay time are constant. Second, using current video rate systems, the smallest cycle time possible would be 33 ms. This is substantially slower than the submillisecond sampling period currently used to control the dynamics of most robots. Third, the single-input single-output model reference adaptive controller (SISO MRAC) requires that coupling is minimized in the transformation from features to joint coordinates. This means that one feature must be selected to control each joint.

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Fig. 2-5. Traditional static "look-and move" control system.

The visual feedback control structure was designed to be a dynamic feature-based system, with the stability of a closed-loop joint controller. In addition, allowance for the variable delay time-of-vision feedback was included. The result is a dynamic, feature-based "look-and-move" control structure (see Figure 2-6). Independent proportional-integral-derivative (PID) controllers are used to position the joint angles. Above these joint controllers is a feature-based trajectory generator which plans a smooth path from the actual image features to the desired image features. Since the distance between the actual and desired features is often too large to be compensated for in a single robot control cycle, the trajectory generator is needed to break up the motion into realizable segments. A resolved motion rate scheme is used to transform the small changes in image features into changes in the robot's joint angles with a series of Jacobian transformations. By using this double rate control structure, the 0.875-ms sampling period required to control the robot's joints can be maintained while allowing the vision feedback to have variable sampling and delay times.

Feature-Based Trajectory Generation. The method of trajectory generation in joint and Cartesian spaces is well known. The general motion scheme is to move the robot at a constant velocity, in either joint or orthogonal coordinates, from one position to the next. The positions are normally queued up on a motion queue and popped off one at a time as the robot reaches each position. A small transition period exists between constant velocity segments to allow the robot to change velocities. The maximum velocity of each robot joint and the minimum transition time to reach this maximum velocity from rest are assumed to be known *a priori*.

For sensor feedback, this method poses three problems. Often with sensor feedback, sensor updates occur before all positions are popped off the motion queue. The result is an overshoot caused by the robot because it did not perform the new motion as specified by the updated sensor information. The second problem is how to move the robot within the sensor's constraints. The traditional method has been to first interpret the pose of an object from the sensor information and then to use a joint or Cartesian trajectory generator to perform a desired motion.

2.1.4 Adaptive Robotic Visual Tracking¹²

Papanikolopoulos and Khosla have proposed an adaptive visual tracking technique for the robotic (eye-in-hand configuration) visual tracking and servoing problem. The problem of visual tracking is stated as a problem of combining control with computer vision. The sum-of-squared differences (SSD) optical flow for the computation of the vector of discrete displacements is used. The measurements can be derived either from a single big window or from multiple small windows. These displacements are fed to

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Fig. 2-6. Feature-based look-and-move control structure.

an adaptive controller (self-tuning regulator) that creates commands for a robot control system. The whole algorithm is based on the on-line estimation of the relative distance of the target with respect to the camera. An important contribution of this work is that it requires only partial knowledge of the relative distance of the target with respect to the camera. This fact obviates the need for off-line calibration of the eye-in-hand robotic system. Three different adaptive control schemes have been implemented, both in simulation and in experiments. The computational complexity and the experimental results demonstrate that the proposed algorithms can be implemented in real time.

Robots can be made flexible and adaptable by incorporating sensory information from multiple sources in the feedback loop. Sensor-based robots can adapt quickly to the evolving requirements of an unknown task, can recover successfully from task failures, and can react properly to sudden changes in the environment. While there are many different types of sensors, such as force, tactile, and vision, Papanikolopoulos and Khosla are focusing on the use of a vision sensor for dynamically servoing a manipulator for object tracking. This work provides a bridge between traditional vision techniques for determining motion and control theory.

Specifically, they address the visual servoing problem which is a special case of the Controlled Active Vision framework. The underlying philosophy of this framework is that controlled motion of the camera can improve the performance of tracking and servoing algorithms, as well as enhance the power of vision algorithms. Combining control and vision strategies results in more robust algorithms, such as determining structure from motion and active calibration. Thus, the amount and quality of sensory information is increased.

The problem of robotic visual tracking/servoing can be defined as: "moving the manipulator in such a way that the projection of a moving or static object is always at the desired location in the image."¹² In accomplishing visual servoing, the camera may either be mounted on the end effector of the manipulator (also known as eye-in-hand configuration) or it may be statically located. In both of these instances, the traditional approach to visual servoing (the look-and-move approach) has been to decouple the problems of obtaining information about the target (from the camera image) and manipulator control. Since initial work in this area was typically hampered by the available computational power, it was obvious in physical experiments that a manipulator was looking and then moving. Recent advances in computers have made enough computational power available so that look-and-move is not very obvious in physical experiments, even though the basic philosophy of separating the vision and manipulator control problems still persists. It is also worth mentioning that in visual servoing, emphasis has been typically placed either on the vision processing component or the manipulator component.

Research has also been conducted on using vision information in the dynamic feedback loop. Weiss has proposed a model reference adaptive control scheme for robotic visual servoing. In this work, servoing is performed with the goal of reducing the error between desired image attributes (center-of-mass, first or second moment of the image) and the current image attributes. The verification of the proposed algorithms has been limited to simulations. Others have proposed an adaptive scheme for visually servoing a manipulator based on the information obtained by a static sensor. In this instance, the adaptation compensates for the unknown dynamic parameters of the manipulator.

Unlike previous approaches, this one assumes only a partial knowledge of the mapping between the target and the camera (which the adaptation mechanism is used to determine). It is not used to determine the unknown dynamics of the manipulator. This approach is dynamic because it incorporates the target's dynamics and kinematics in the system model as compared to the look-and-move approach, which is static. In addition, the camera model and the noise characteristics of the vision measurements are included in the design of the robotic and visual tracking strategy.

Algorithms that address real-time robotic visual tracking of moving objects are proposed. To achieve this objective, computer vision techniques for detecting motion are combined with appropriate control strategies to compute the actuating signal for driving the manipulator (see Figure 2-7). The problem is formulated from the system's theory point-of-view. An advantage of this approach is that the dynamics of the robot device are taken into account without changing the basic structure of the system. The proposed scheme is modular, allowing for different vision and control techniques to be implemented for calculation of the vector of discrete displacements and calculation of the control signal.

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Fig. 2-7. Structure of the adaptive algorithm for tracking 3-D translational motion.

2.2 Conclusions

Much of the state-of-the-art end-point tracking work is in the research phase and will take some development before it is deployable. However, the concepts mentioned above are all workable given resources dedicated for technology development.

The potential measuring accuracy of the LTIS is generally 10–100 times better than most industrial robots built today. One of the tasks which needs to be addressed is how to exploit this accuracy. For inspection, the robot can pick up a touch probe with a target reflector assembly mounted onto the probe; the tracking system will continuously compute the coordinates and orientations of the probe of origin. For robot accuracy enhancement, the system can be used to generate a static or dynamic error map of the robot which can be used later by the robot controller to compensate for the measured errors.

In areas such as robot performance measurements and standardization, the laser tracking system can offer speed, accuracy, flexibility, and range that no single system can. The designed accuracy of the 5-D LTIS system in 1985 was two parts per 100,000, with a measuring volume of $3 \times 3 \times 3 \text{ m}^3$ and a maximum tracking speed of 300 mm/s. These performance numbers have been exceeded (by how much it not known), but this system is certainly one that could be readied for test and deployment.

The main emphasis for further work in ultrasonic tracking is the introduction of an element of intelligence into the computer measurement processing. One potential use of this intelligence would be the ability to choose the three most suitable path measurements for coordinate computation when (as is usually the case) more than three measurements are available. Obvious candidates for elimination would be any measurements which fall within the ambiguous range where the receivers switch from detecting the first cycle of ultrasonic energy to detecting the second one. The problem of error amplification in the subtraction of quantities (e.g., $d_1^2 - d_2^2$ in the calculation of x) also dictates that those measurements where such differences are greatest should be used if possible.

Joint-position-measurement signals from joint transducers could also be used to an advantage. Approximate calculation of the end-effector spatial coordinates from joint angle measurements permits the angles between the transmitter and the receivers to be calculated. This would enable the correct correction factor to be used in compensating for the distances between the point sources of ultrasonic energy and the center of the transmitter block. Approximate knowledge of end-effector position would also enable false ultrasonic signals to be rejected.

A further improvement could be made by using counters with a greater number of bits. The use of 16-bit counters gives a measurement resolution of 1 part in 128×10^6 and would reduce the counter-resolution-induced errors in the calculated values of the x , y and z coordinates to 0.1 mm.

There are several advantages in using a feature based trajectory generator. First, the feature-based trajectory generator is achronous which allows sensor inputs at any time. Second, by performing the trajectory generation in feature space, it can be assured that the sensors will remain active throughout the motion. A smooth and continuous trajectory is maintained even for discontinuous sensor data by matching the velocity, acceleration and jerk of the features, but not the feature position. Another important characteristic of the feature-based trajectory generator is that features from other sensors with different sampling times could also be used, thereby allowing unified sensor integration.

Disadvantages of this technique are that the differential transformations from feature space to joint must be generated manually before the task begins. Also, in-depth knowledge of the robot kinematics and camera modeling is required. Further research needs to be done to determine a controllable set of features based on task and system constraints.

For adaptive visual tracking, the need for explicitly computing the depth map of the target is circumvented, and adaptive control techniques are used. Their algorithms do not require accurate knowledge of the camera model and of the environment. Additionally, contrary to previous research efforts, there is no need for continuous calibration of the hand-eye system. The adaptive control schemes estimate depth-related parameters of the robot model.

It is important to note that for all these end-point tracking techniques, radiation and environmentally hardened versions of the sensors would have to be developed for these systems to work in the in-tank environment. That issue is beyond the scope of this study, but does deserve further attention in future work.

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