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VIBROTACTILE FEEDBACK FOR INDUSTRIAL TELEMANIPULATORS

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ABSTRACT

Industrial applications of haptic feedback systems that add dexterity to telemanipulators have been limited due to their complexity, low reliability, and high cost. A promising and attractive alternative technology for industry is vibrotactile feedback. These systems are simple and can be added at low cost to existing telerobotic systems to provide robust contact information. We have developed a single channel prototype vibrotactile sensor and display system for a high capacity deep sea remote manipulator, the Schilling Robotic Systems TITAN-II. The vibration sensor consists of a pair of steel plates machined to fit inside the gripper jaws. Embedded between the plates are piezoelectric film strips molded into a rugged silicone rubber layer. Impact and frequency response tests indicate the sensor is durable to the extreme loading and sensitive to a large range of vibration frequencies of the industrial setting. Tests of the prototype system on the TITAN-II again proved the sensor to be rugged and durable while also being sensitive. In informal tests, operators found the system enhanced operation of the robot.

1 Introduction

Teleoperated manipulation has long been an important capability for the nuclear power and weapons production industries and more recently, it has become essential for offshore oil production. Oil rigs now operate in waters over 2000 m deep, well beyond the range of human divers. While much of the equipment used on the sea floor has been automated, human intervention is required for inspection, maintenance, repairs, and equipment retrieval, and to deal with unanticipated events and emergency situations. Remotely-operated submersible vehicles are used for these purposes, equipped with high capacity teleoperated robotic manipulators. Typically, these manipulators are powered hydraulically with 2 m reach and 100 kg payload capacity.

Due to the high costs and harsh conditions of the offshore environment, system reliability is at a premium: untimely manipulator failure can hold up drilling operations at a cost of hundreds of thousands of dollars per day. Although force feedback has been proven to enhance productivity in many types of tasks encountered in this application (Sheridan 1992), force feedback greatly increases system complexity. The master manipulator becomes a force-controlled robot, and the required communications and control algorithms become far more complicated. Reliability is thus reduced and cost is increased, which has precluded industrial adoption of haptic feedback, despite the availability of commercial force feedback systems. As a result, feedback to the operator from the subsea manipulator is exclusively visual.

Unfortunately, visual feedback is often less than optimal in the offshore setting. Drilling operations and vehicle thrusters stir up sediments from the sea bottom, reducing visibility. The number of cameras and lights is often restricted by the long cable distance to the surface, and viewpoints are limited to locations on the vehicle and arm. Under these circumstances, it is often difficult to determine visually the spatial relationship between the remote robot arm and the objects to be manipulated. The absence of contact information is detrimental in key tasks such as grappling cables, mating connectors, and placing inspection probes.

1.1 Vibrotactile feedback

One promising means of providing contact information to the operator with minimal cost and complexity is vibrotactile feedback. Vibrations signal key events during manipulation, and people make explicit use of this information. For example, contact between hard surfaces is accompanied by copious vibrations, such as the clatter of aligning a steel wrench with a bolt. Vibrations are also important in many perceptual tasks, as when a finger is stroked over a surface to determine roughness. Neurophysiological experiments show that vibration information is an essential part of our tactile sensory experience. Humans have highly specialized nerve endings for the perception of vibrations, which can detect vibrations to over 1 kHz in frequency and less than 1 micrometer in amplitude (Johansson, Landstrom and Lundstrom 1982).

A few previous studies have examined the display of vibrations in a task-related context. Hawkes (1987) used an acceleration sensor to detect vibrations in the finger tips of a remote manipulator, but displayed the resulting signal to the teleoperator in audio form through a loudspeaker. Crab and Richter (1996) developed an electromechanical vibratory tactile stimulus glove that can be customized for specific telerobotic and virtual reality applications. Minsky et al. (1990) developed a system that can provide vibratory information in virtual environments. Another vibrotactile display device which has recently become available is the CyberTouch™ option for the CyberGlove from Virtual Technologies, Inc. (Palo Alto, CA) This device tracks the position and posture of the hand and has small vibrators on each finger and the palm. The device offers no force feedback, however, and includes no software or electronics to aid the synthesis of meaningful stimuli.

In previous work, we have developed a laboratory system for relaying vibrotactile information in telemanipulation (Kontarinis and Howe 1995). Sensors in the gripping surfaces of the robot manipulator detect vibrations at the remote site, and a tactile display device recreates these vibrations on the finger tips of the human operator. Experiments have shown that this vibration feedback can improve performance in telemanipulation, particularly tasks where vibrations reveal the mechanical state of the hand-object interaction. Design guidelines for vibration display devices, based on simple mechanical models, have also been developed. The initial development of a custom designed vibrotactile stimulation system has been discussed by Crabb and Richter (1996)

Although these laboratory experiments concerned precision manipulation tasks with low forces, vibrotactile feedback is well suited to high-capacity subsea telemanipulation applications. By using piezoelectric vibration transducers, the vibration sensor can be integrated with the gripper jaw as a solid unit, able to withstand the high hydrostatic pressures and 10,000 Newton mechanical loads to which it will be subjected. This construction also allows high dynamic range, which is essential for detecting both the small forces at the first instant of contact, and the large force transients generated when a grasped object collides with other surfaces in the environment. Unlike force feedback, vibrotactile feedback can be configured as a separate system, completely independent of the kinematic control function of the master. If the vibrotactile feedback system fails, operation of the manipulator system is not compromised. This also facilitates adding vibrotactile feedback to existing manipulator systems.

In this paper, we describe the vibrotactile feedback system we are developing for industrial teleoperated manipulators. Among the challenges of moving this technology from the laboratory to the real world are developing sensing hardware with sufficient robustness, sensitivity, and bandwidth; development of a display device ergonomically integrated with the master controller; and definition of a user interface, including appropriate controls. We describe initial testing of the prototype feedback system on a hydraulic teleoperated arm, the lessons from these tests, and implications for vibrotactile feedback systems in a range of practical applications.

2 SYSTEM DESIGN

2.1 Application requirements

Our testbed for development of practical vibrotactile feedback is the TITAN-II remote manipulator (Figure 1) manufactured by Schilling Robotic Systems Inc. of Davis, California. This robot is widely used for subsea applications in offshore oil development,

TITAN III remote manipulator

Master controller

Figure 1. Schilling TITAN III remote manipulator arm (left) and master controller (right). This six degree-of-freedom arm is capable of lifting 250 lb. at its full reach of 75 inches. It is used in deep sea and dry land operations. The master controller consists of a replica master arm and a control panel with LCD display**.**

marine salvage, and oceanographic exploration, and for terrestrial applications in nuclear materials and hazardous waste handling. The TITAN is capable of lifting over 9800 N at full 1.8 m arm extension and applying grip forces of over 4000 N with the standard parallel-jaw gripper. Forces on the gripper can exceed this level due to collisions with surfaces in the environment and torques generated by levering with tools and other gripped objects.

The range of tactile sensitivity required for this application is broad. At the lowest level, it is important to detect the small forces that indicate the first instant of contact between the gripper and an object. Task examples include grasping dangling cables and delicate objects on the sea floor. Failure to determine that contact has occurred can lead to application of large forces that may disturb or damage the object before it can be acquired; a sensitivity of a few N is probably optimal for this type of task. At the other extreme, the system must relay the large forces that are produced when large and massive grasped objects come into contact with hard surfaces in the environment. A typical example is "hot stab" hydraulic connector mating, where a 15 cm diameter, 60 cm long steel peg must be inserted into a tight-fitting steel hole. Gripper forces can exceed 10,000 N, and transmitted vibrations at a fraction of this force level can indicate the progress of the task, from the initial contact transient between the peg and hole to continuous vibrations indicating that the peg is sliding smoothly into the hole.

The frequencies of interest for this application are not clearly defined. Human tactile sensitivity ranges from DC to well over 1 kHz, with peak sensitivity around 250 Hz (Boff and Lincoln 1988). For many tasks that involve contact between hard surfaces, which probably includes the great majority of offshore oil uses, dominant vibration frequencies range from a few dozen Hz to over 1 kHz. This is also the range of greatest sensitivity of the Pacinian corpuscle or FAII unit, the human mechanoreceptor with greatest vibrotactile sensitivity (Johansson, Landstrom, and Lundstrom, 1982). We have selected this as the target frequency range for the initial prototype system reported here. Tests with this system, however, revealed that low frequency response, down to a few Hz, would provide very useful information about grip and contact force. In the discussion section below we consider the design implications of extending the response to low frequencies.

2.2 Sensor Design

Based on previous research, there are two leading approaches to building a vibrotactile sensor for this type of application. The first uses accelerometers attached to the rear surface of the gripper (Hawkes 1983, Howe and Cutkosky 1989). One advantage of this approach is that accelerometer transducers are a mature technology, and ready-to-use devices with remarkably high dynamic range may be purchased commercially. In addition, because the accelerometer senses the second derivative of position, response to a constant displacement input increases as the frequency squared, which results in very good sensitivity to high frequencies. Unfortunately, this also means that response is poor at low frequencies. Another problem is the strong response to inertial transients generated within the manipulator structure, so that the sensor output includes vibrations generated by joint motion as well as contact with the external environment.

The alternative approach is a force (stress or strain) sensor built into the contact surface of the gripper (Howe and Cutkosky 1993). Piezoelectric transducers are particularly appropriate as they are solid state devices that can be readily designed to withstand the anticipated high loads of this application. High frequency response is excellent, and with appropriate design of the interface circuitry the low frequency response can extend down to near-static level. In addition, because the sensor responds to contact rather than inertial forces, sensitivity to internal vibrations generated by the robot actuators can be minimized (Son and Howe 1997).

Based on the ability to sense low frequencies and the relative immunity to internal vibrations, we have selected the piezoelectric contact sensor approach. The prototype device developed for the tests reported here consists of a layer of compliant material, hard rubber, between two steel plates, the rear one attached to the gripper jaw and the front plate forming the new gripping surface (Figure 2). The 5.1 x 7.6 cm rear plate of the sensor package fits into the V-grove on the TITAN-II gripper, providing a solid mechanical coupling with the gripper body. The rear plate bolts into holes drilled through the gripper jaws. The front plate encloses the rear mounting plate on five sides, providing high shear stiffness and enhancing robustness. The outer side of the front plate is grooved to create the new jaw surface. The front plate is also longer, 5.1 x 8.3 cm, providing protection for the electrical cabling junction at the inner edge of the sensor. Molded between the steel plates is silicone rubber (General Electric RV 630), selected for high tear and tensile strength after several different types of silicone rubber were tested.

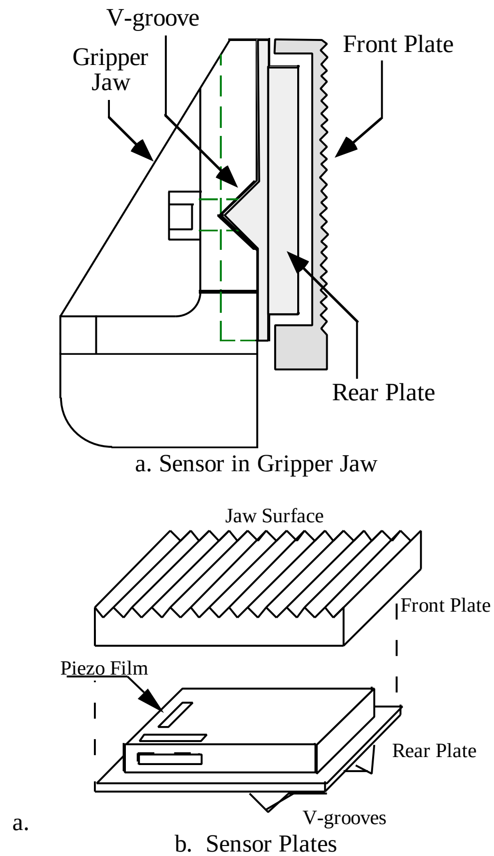

Figure 2. Sensor design. The rear plate of the sensor bolts onto the jaw of the remote manipulator. Between the two plates is a compliant rubber which contains the piezoelectric film.

Embedded in the compliant material are four pieces of piezoelectric polymer film (0.3 x 2.5 cm) near the edges of the front plate (Figure 2). The piezoelectric film material is polled polyvinylidene fluoride film (PVF2, Amp Flexible Film Sensors, Valley Forge, PA), a flexible polymer with good piezoelectric response. Two strips are mounted parallel to the inner surface of the front plate aligned to respond to normal loads. The other two strips are mounted perpendicular to the front plate, parallel with the edges of the gripper jaw and aligned to respond to shear loads.

The piezoelectric film acts as a capacitor which develops charge in proportion to the stress applied to the film. The low frequency response is determined by the electrical impedance which is connected to this capacitance, and charge amplifiers are often employed with piezoelectric sensors to provide low frequency response. Unfortunately, the extremely high input impedance ($<10^{10}$ ohms) of these amplifiers poses severe design challenges for the subsea environment, due to charge leakage through cabling and connectors. Because these initial tests were aimed at relaying vibration frequencies from a few dozen to a few hundred Hz., we used a unity gain noninverting voltage amplifier circuit. A 10 megohm resistor spans the two terminals of the piezo-electric film and sets the effective amplifier input impedance, with a predicted low frequency corner of about 60 Hz. One terminal of the film is electrically grounded while the other connects to the noninverting input of a FET-input operational amplifier configured as a unity gain voltage follower. A current-to-voltage amplifier was also constructed and tested (Howe & Cutkosky 1993); however, the tests described below did not indicate substantial differences between the two circuits. For simplicity, and because the piezoelectric films generate ample signals, we selected the voltage amplifier.

The frequency response of the sensor-amplifier combination was tested by mechanically exciting the sensor with an input containing frequencies of interest, a swept sine wave from 2 to 1200 Hz. A sinusoidal signal, generated with a function generator and current amplifier, excited a linear voice-coil motor. The free end of the motor was attached to the front plate of the sensor using a threaded fastener enabling it to both push and pull. A force sensor located between the shaker and the sensor measured the applied input force. A digital oscilloscope connected to the input (the force transducer) and the output (the sensor) signals computed the fast Fourier transform (FFT). The magnitude of the transfer function were also generally flat, rolling off at approximately 6 dB/octave below 50 Hz and rising only slightly between 50 and 300 cycles per second. Sensitivity in this range was approximately 0.1 v/N, easily sufficient for the 1 to 10,000 N anticipated range.

A series of mechanical tests determined the mechanical durability and natural frequency of the sensor. The first test statically loaded the sensor to 16,000 N in an arbor press. Sensor output saturated at first but returned to baseline after a few time constants. Deflection of the sensor was not visibly noticeable during loading and there was no measurable deformation after the load was removed. Impulse testing by tapping the front plate with the rear plate rigidly mounted confirmed that the fundamental natural frequencies of 1300 and 3000 Hz were beyond the tactile feedback frequency range of interest. Noise levels were low, with peak values ranging between 15 to 20 mV at 60 Hz.

2.3 Display Design

To convey the sensed vibrations to the human operator, a simple vibration display was mounted on the master controller for the TITAN telemanipulator (Figure 3). It consisted of a voice coil motor, removed from a miniature loudspeaker (8 ohm, 2 watt, 7.6 mm coil), mounted on an aluminum base. The display simply clamped onto the distal end of the unmodified master controller. The freely moving coil of the motor actuates a 13 mm strip of spring steel cantilevered from the aluminum base. The steel spring provided stiffness in lateral directions, keeping the coil aligned in the motor and compliance in the other allowing the motor to move vertically. The operator rests a finger on the steel strips transmitting the voice coil vibrations to the human operator. A voltage-to-current converter drives the motor with the amplified sensor output signal. The display differs from the vibrotactile feedback system developed by Kontarinis and Howe (1995) in that the force of the voice coil is directly transmitted to the finger tip. In Kontarinis and Howe (1995) the voice coil force

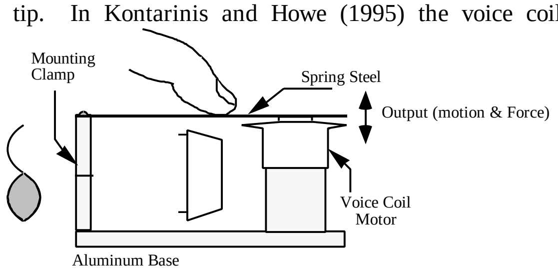

Figure 3. The vibrotactile display. The display mounted on the existing master controller did not require any modifications of the master controller.

accelerated the inertia of the motor mass and the operator felt the resulting inertial force. As with the accelerometer sensor approach described above, the peak response of this inertia-based display scheme increases as the frequency squared, providing good output at high frequencies but little response at low frequencies. The advantage of the direct display is its better low frequency response.

3 PROTOTYPE SYSTEM TESTING

3.1 Test Setup and Tasks

To test the function of the entire system, the sensor and display were mounted on a TITAN-II remote manipulator and master controller. The output of the sensor amplifier was conditioned by a variable-gain low noise amplifier with variable frequency single-pole low and high pass filters (Stanford Research Systems model SR560 Preamplifier). This permitted variation of the frequency content and amplitude of the vibrotactile feedback signal. The final signal conditioning stage converted the voltage of the amplified sensor signal to a current driving the electromagnetic voice coil of the display. The force produced by the linear motor is proportional to the current. An accelerometer (Kistler Instrument Co.) mounted to the back side of the gripper provided an independent measure of the gripper vibration. An additional accelerometer was mounted on the spring steel contact surface of the display to measure the output waveform. A portable computer with data acquisition board sampled the signals from the sensors and accelerometers at 4 kHz for two second intervals.

With the system mounted on the TITAN, operators completed several typical telemanipulation tasks. The operator was seated with the master controller approximately 3 m behind the robot arm with an unobstructed view of the task space. Tasks included grasping a T-bar tool handle, completing a "hot-stab" hydraulic connector mating, and tapping and scraping objects. We also operated each of the manipulator joints without activating the gripper to assess the sensitivity of the sensor to the mechanical noise created by joint motion. A second series of system experiments examined the subjective enhancement when visual feedback of the robot arm was reduced to a closed circuit TV monitor. Each operator filled out a questionnaire after each task examining the operator's perceived difficulty with and without vibration feedback. Tasks included completing a "hot-stab" (N=5 subjects), grasping a hanging cable (N=3), and stacking four wood blocks end-to-end (N=3).

3.2 Results and Discussion

3.2.1 Sensor Performance

To demonstrate sensor and display output in a typical tool grasping task, the output of one of the piezoelectric sensors and the accelerometer on the vibration display is shown in Figure 4. In these cases, the handle's location could be readily ascertained using vision, and the operator was not instructed to minimize forces. The sensor signal often shows large, relatively low frequency peaks as the grasp force first begins to increase, followed by higher frequency peaks as the tool handle reorients and slides within the gripper until the final grasp configuration is attained. During theses tasks the peak magnitude of the sensor output ranged from 0.25 to saturation (±5 volts) and the mean frequency of the power spectra ranged from 180 to 400 Hz. Table 1 lists the output magnitudes and the mean frequencies for the different tasks completed.

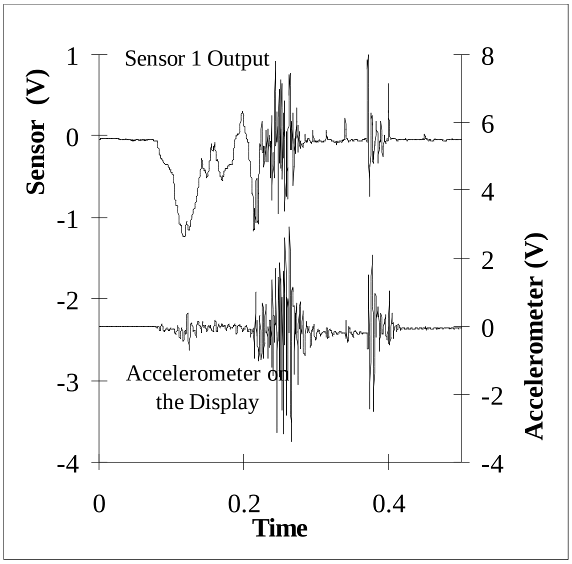

Figure 4. Sensor and display accelerometer output during a grasping task. The sensor contains lower frequency components than the display, but follows the sensor well at higher frequencies

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Tests showed that noise due to the hydraulic joint actuators is relatively small compared to the signals measured during tasks. Table 2 lists the baseline values of the sensor signal during motion of each joint of the robot; noise levels increase with the proximity of the joint to the gripper. Figure 5 illustrates the increase in sensor signal as the wrist roll joint begins to rotate. Comparing the magnitudes of the task signals in Table 1 to the noise level with no joint motion (first row of Table 2), the signal-to-noise ratios range from about 120 to over 1200. With joint motion, the lowest signal-to-noise ratios (due to roll motion at the wrist) decrease to about 14 for the grasping task and 2.5 for the scraping task. These noise levels are adequate for tasks with high signal levels (e.g. grasping, tapping), and operators can minimize noise generation by limiting wrist motion during sensitive tasks. The sensor responds to forces applied between the two plates, which includes inertial forces generated by shaking of the sensor's front plate. Reducing the mass of the sensor's front plate in subsequent designs will reduce the magnitude of the vibration signal generated by joint actuation.

We examined the variation of the vibration signal with contact velocity by placing the arm in a fixed position and closing the gripper on a steel bar at calibrated speeds. Figure 6 summarizes the resulting peak signal amplitudes and mean frequencies for both the piezoelectric and gripper accelerometer signals. As the contact speed increased, the mean frequencies of the piezoelectric and accelerometer signals increased. The magnitude of the piezoelectric signal also increased approximately in proportion to the closing speed, although the peak accelerometer signal showed little variation. As the speed of the gripper closing increases, the resulting impact force should increase. Furthermore, the impact period should decrease and hence the signal frequencies should also increase. The relatively small variation of the accelerometer signal probably reflects its limited low frequency response; since it responds only to the high frequency components of the signal, low closing velocities fail to produce large accelerometer signals. This result further emphasizes the advantage of the piezoelectric sensor for more complete tactile feedback in a broad range of tasks.

Table 1. Task Parameters

Joint Moved	Sensor 1 Vpp (V)	Sensor 1 μF (Hz)	Sensor 2 Vpp (V)	Sensor 2 μF (Hz)
Grasp	3.4 (0.8)	227	5.1 (0.7)	160
Peg-in-hole	1.7 (0.2)	406	4.5 (0.4)	322
Tap	2.7 (0.3)	357	4.9 (0.6)	314
Scrape	0.6 (0.3)	353	0.6 (0.3)	400

μF = mean frequency of the signal power spectrum, mean (standard deviation)

Vpp = maximum peak-to-peak signal, mean (standard deviation)

Table 2: Joint-Induced Noise Assessment

Joint Moved	Sensor 1 Vpp (V)	Sensor 1 μF (Hz)	Sensor 2 Vpp (V)	Sensor 2 μF (Hz)
(Hydraulics on)	0.005 (0.001)	857	0.004 (0.001)	925
Wrist (Roll)	0.241 (0.028)	319	0.103 (0.014)	409
Wrist (Yaw)	0.185 (0.016)	350	0.088 (0.008)	419
Wrist (Pitch)	0.024 (0.003)	562	0.048 (0.002)	571
Elbow	0.023 (0.002)	650	0.008 (0.001)	873
Shoulder	0.029 (0.003)	560	0.015 (0.002)	760
Waist (Base)	0.010 (0.001)	806	0.006 (0.001)	936

μF = mean frequency of the signal power spectrum, mean (standard deviation)

Vpp = maximum peak-to-peak signal, mean (standard deviation)

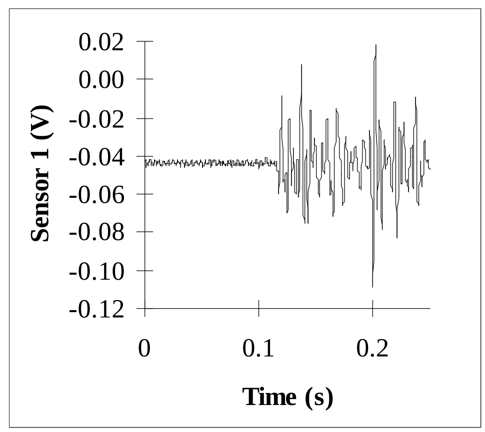
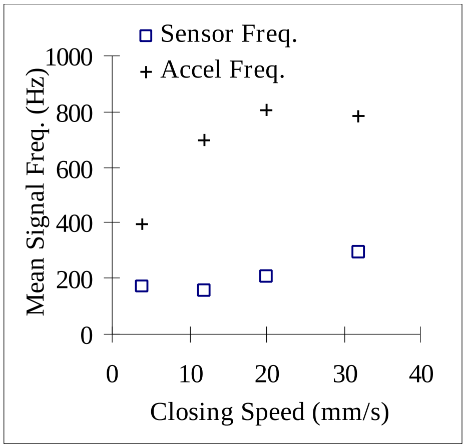


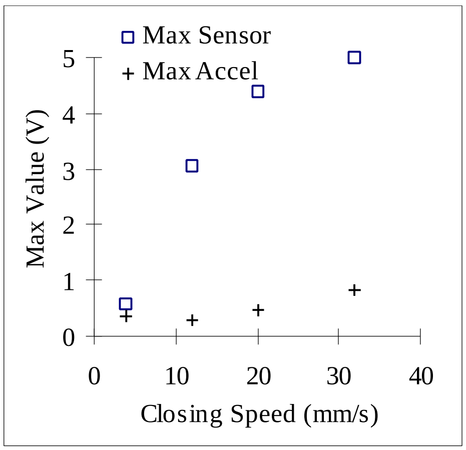
Figure 5. Sensor 1 output during the initiation of a wrist movement. The sensor is sensitive to wrist movements, however, the signal-to-noise ratio remains high and adequate for the tasks performed.

3.2.2 System Integration and Performance

During one set of tasks a miniature accelerometer mounted on the display measured the motion of the display surface, allowing comparison of the input and output of the vibrotactile system. The MATLAB software package (Mathworks, Natick, MA) was used to estimate the magnitude of the sensor-to-display transfer function using data collected during twelve different tasks. Assuming a linear system, the nonparametric estimated transfer function (Ljung 1987) indicates the magnitude increases between 10 to 250 Hz and



(a)



(b)

Figure 6. Varying gripper closing speeds. The mean frequency of the signal spectrum (a) and its maximum (b) of both the sensor and accelerometer signals increased with increasing sensor speed.

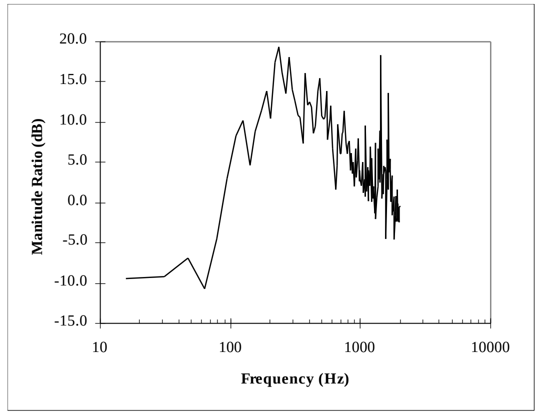


Figure 7: The estimated transfer function of the vibrotactile system. The transfer function input was the sensor signal and the output was the signal of the accelerometer mounted on the display

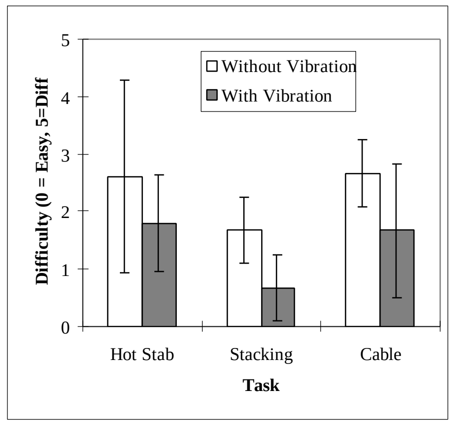


Figure 8: Operator perceived difficulty. All subjects reported the vibrotactile feedback reduced the task difficulty when visual feedback was limited to a video image. The error bars represent one standard deviation.

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then decreases at about 20 dB per decade (rad/sec) above 250 Hz. (Figure 7).

Because the goal of this study was to confirm the viability of the system design in the industrial setting, no systematic measurement of operator performance was conducted at this stage; these tests are planned with the next generation of hardware. However, subjective reports of the experienced operators indicated that the vibration display enhanced operation of the manipulator, particularly in situations with reduced visual feedback. For example, vibrotactile feedback allowed operators to determine the first instant of contact, before large forces were applied. Two experienced operators reported that the vibration feedback reduced the force they applied during a “hot-stab.” For the subjects who viewed the robot through a video monitor the perceived difficulty of the telemanipulation task was less with vibrotactile feedback than without it (Figure 8). It was also possible to detect the vibrations generated as the gripper slid over surfaces in the environment.

One important result from the informal operator testing is the significance of vibrotactile information at relatively low frequencies. Using the high and low pass filters in the preamplifier, operators could alter the frequency content of the feedback signal. For many tasks, low frequency response was subjectively useful, and operators consistently preferred to increase low frequency gain. While vibrotactile feedback cannot reproduce the information present in full kinesthetic force feedback, these preliminary results suggest that displaying frequencies below the usual vibrotactile range of a few dozen Hz might be useful in this modality.

4 CONCLUSIONS AND FUTURE WORK

The design and test results presented here demonstrate that a practical vibrotactile feedback system can be configured for high-capacity industrial telemanipulators. A durable and rugged vibration sensor with large signal-to-noise ratios and good sensitivity has been designed that meets the challenges of the industrial environment. This system conveys contact information at a fraction of the cost and complexity of conventional force feedback. The system can be readily added to existing telemanipulators, and since it is independent of the kinesthetic manipulator control system, it does not compromise system reliability.

The next step in the development effort is the improvement of the hardware system design, followed by extensive user testing. For the sensor, the main issues are reducing sensitivity to joint actuator induced noise and increasing response to low frequency input. The former problem can probably be solved through reduction of the mass of the outer sensor plate, which will reduce the amplitude of inertial vibrations. The problem of improving low frequency response is more complex; response down to a few Hz or even lower frequencies is probably advantageous. The key requirement is increasing the time constant for the piezoelectric transducer, by raising either the piezofilm capacitance or the amplifier input impedance. The use of larger areas of piezofilm can perhaps increase the capacitance by a factor of five to ten, which would provide flat response to about 10 Hz. Raising the amplifier impedance is more difficult; the subsea environment precludes external cable runs at the required high impedance. It may be necessary to place the first amplifier stage within the gripper jaw, a significant challenge given the large mechanical stresses to which the gripper is subjected.

The operator testing will consist of a series of detailed experiments to evaluate performance enhancements due to vibrotactile feedback. Planned tests include measurement of the time and effort required to complete tasks with and without vibrotactile feedback. For the tests with vibrotactile feedback, the frequency range and amplitude of the displayed vibration will be varied to examine the effects of the system bandwidth on task performance. The experiments will simulate the actual operation environment by eliminating auditory feedback and providing visual feedback through video displays, with variable image degradation to simulate subsea viewing conditions. Lighting will also be controlled to simulate the industrial setting.

One area of particular importance in this testing process is development of appropriate user controls. Based on the initial tests, it is clear that useful signals and noise will span a large dynamic range, from faint signals that indicate first contact between a massive grasped object and a surface in the environment, up to large signals that indicate a jammed peg has been freed. Users will require a gain control to set the sensitivity to detect the signal of interest and diminish the background noise generated, for example, by joint motion. Similar considerations suggest that users will benefit from control of the frequency response range of the system. By examining performance in a variety of tasks, we will determine the best configuration for these user controls.

Based on previous laboratory studies and the informal testing described above, we anticipate significant performance improvements in tasks such as contact detection where vibrations indicate a change in the state of the system. It will be interesting to see if extending the low frequency response to a few Hz will improve performance in tasks such as peg-in-hole insertion, where force feedback has been shown to be especially effective and conventional high frequency vibrotactile feedback has not (Kontarinis and Howe 1995). Finally, we look forward to testing the system in the offshore environment, where highly experienced operators will have a chance to use the system while performing a wide range of tasks. It will be particularly interesting to see if these operators find new and completely unanticipated uses of vibrotactile feedback.

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REFERENCES

Boff, K.R., Lincoln, J.E., eds. (1988). *Engineering Data Compendium: Human Perception and Performance*. Ohio: H. G. Anderson Aerospace Medical Research Laboratory.

Crabb, T.M., Richter, R.C. (1996) Initial development of the electromechanical vibro-tactile stimulation system. *Proc. IMAGE Conference*, Scottsdale, AZ, June 23-28.

Hawkes, G. S. (1983). *Apparatus providing tactile feedback to operators of remotely controlled manipulators*. U.S. Patent No. 4,655,673. Filed May 10, 1983.

Howe R. D., Cutkosky, M. R. (1989). Sensing skin acceleration for texture and slip perception. *Proc. IEEE Conf. Robotics and Automation*, Scottsdale, AZ, May 14-16.

Howe, R. D., Cutkosky, M.R. (1993). Dynamic tactile sensing: Perception of fine surface features with stress rate sensing. *IEEE Trans. Robotics and Automation*, **9**(2): 140-151.

Johansson, E.A., Landstrom, U., Lundstrom, R. (1982). Responses of mechanoreceptive afferent units in the glabrous skin of the human hand to sinusoidal skin displacements. *Brain Research*, **244**: 17-25.

Kontarinis, D. A., Howe,R.D. (1995). Tactile display of vibratory information in teleoperation and virtual environments. *Presence*, **4**(4): 387-402.

Ljung, L. (1987). *System identification: Theory for the user*. PTR Prentice Hall, Englewood Cliffs, New Jersey, U.S.A.

M. Minsky, M. Ouh-young, O. Steele, F. P. J. Brooks, & M. Behensky. (1990) Feeling and seeing: issues in force display. *Proceedings of Symp. on Interactive 3D Graphics*, 235-243.

Sheridan, T. B. (1992). *Telerobotics, automation, and human supervisory control*. MIT Press, Cambridge, MA.

Son, J. S., Howe, R. D., (1997). Evaluation of touch sensors for contact detection. Submitted to *IROS '97: IEEE-RSJ International Conf. Intelligent Robots and Systems*, Grenoble, France.