Master–Slave Control of a Teleoperated Anthropomorphic Robotic Arm With Gripping Force Sensing

Gourab Sen Gupta, *Senior Member, IEEE*, Subhas Chandra Mukhopadhyay, *Senior Member, IEEE*, Christopher H. Messom, *Member, IEEE*, and Serge N. Demidenko, *Fellow, IEEE*

***Abstract*—This paper details the design and development of a low-cost control rig to intuitively manipulate an anthropomorphic robotic arm using a bilateral master–slave control methodology. Special emphasis has been given to the ease of operation and some form of force sensation. The control rig is fitted to the user's arm, and the forces exerted by the robotic arm's various joints are fed back to the user. Of special significance is the force feedback from the slave when its gripper is in contact with a real object. Several methods of force sensing have been explored and detailed. The effectiveness of the proposed method is confirmed by experiments on a commercially available robotic arm, which is controlled by a prototype three-axis master unit. The robotic arm mimics the dexterity of the human hand, wrist, and fingers. The proposed master control unit is cost effective and will have wide-ranging applications in the fields of medicine, manufacturing, security, extreme environment, entertainment, and remotely operated vehicle teleoperation in undersea recovery or extraterrestrial exploration vehicle.**

***Index Terms*—Anthropomorphic robotic arm, bilateral master–slave control, force feedback, force sensing and measurement, teleoperation.**

I. Introduction

TELEOPERATION has an important role in manipulating remote objects interactively using robotic manipulators, especially in hostile environments [1]. Robotic arms with prehensile functions are now extensively used in telemedicine, such as in endoscopic teleoperation [2] and echographic diagnosis in obstetrics and gynecology [3]. It has been shown that a dedicated robotic arm, holding a real ultrasonic probe, can be remotely controlled from an expert site with fictive probe, and it reproduces on the real probe all the movements of the expert hand [4]. The Da Vinci surgical system from intuitive surgical [5] is an example of a commercially available sophisticated robotic manipulator which translates the surgeon's hand, wrist, and finger movements into precise real-time movements of the surgical instruments inside the patient. ATOM is an industrial six degree of freedom (DOF) force reflecting/controlled hydraulic robotic manipulator designed and built for hazardous waste remediation and is available as a teleoperated or fully autonomous system [6].

In teleoperated systems, significant research attention has been paid to the sense of presence of the object being manipulated. Despite the many advantages of having robotic arms while operating, many surgeons have noted the lack of haptic (force and tactile) feedback as a significant limitation. Although cardiac surgeons have successfully performed robot-assisted procedures, they have found them to be generally more time consuming than conventional operations. Training for basic laparoscopic tasks has proven to be significantly slower with robotic assistance [7]. These can be attributed to the lack of force feedback in the system which interfaces the human to the world in which the object is manipulated. It has been shown that the haptic feedback is critical to the precision and accuracy of force applied during suture ties [8]. Thus, for any dexterous manipulation, some sort of force sensing must be incorporated in a robotic manipulator. The force feedback mechanism has attracted the attention of many researchers in diverse fields ranging from development of simulators for training to telemonitoring [9]–[16]. Most research into force feedback has concentrated on virtual-reality applications in the past. However, research into force feedback for manipulation of objects in the real world is rather in its infancy.

Teleoperated robotic systems employ various forms of master–slave controls [17], [18]. The methodology proposed in [17] is based on the judgment of contact/noncontact condition of the slave unit followed by the switching of unilateral feedback control between position and force. The force feedback to the operator is applied mechanically as a force of the elastic elements instead of electrical feedback control. The bilateral master–slave system for telerobotics, as proposed in [18], is composed of electrohydraulic servo systems with force sensors attached to the actuator. Unfortunately, the designs of master units proposed in [17] and [18] are complex and expensive. The typical operator control hardware on a master unit comprises joysticks, levers, wheels, and pushbuttons. However, when considering the control of a slave anthropomorphic robotic arm, such control devices are the most nonintuitive.

Manuscript received June 15, 2005; revised August 25, 2006.

G. S. Gupta is with the IIS&T, Massey University, Palmerston North PB11222, New Zealand, and also with the School of Electrical and Electronics Engineering, Singapore Polytechnic, Singapore S139651 (e-mail: G.SenGupta@massey.ac.nz).

S. C. Mukhopadhyay is with the IIS&T, Massey University, Palmerston North PB11222, New Zealand (e-mail: s.c.mukhopadhyay@massey.ac.nz).

C. H. Messom is with the II&MS, Massey University, Albany PB102904, New Zealand (e-mail: c.h.messom@massey.ac.nz).

S. N. Demidenko is with the IIS&T, Massey University, Palmerston North PB11222, New Zealand, and also with the School of Engineering, Monash University, Kuala Lumpur KL46150, Malaysia (e-mail: Serge.Demidenko@eng.monash.edu.my).

Color version of Figs. 2–8, 11–13, and 16–21 are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIM.2006.884393

The presented research is primarily concerned with developing a low-cost easy-to-use intuitive interface for the control of a slave anthropomorphic robotic arm (teleoperator). It implements some form of haptic sensing for manipulating an object in the real world and for measuring the rotational forces on the servomotors of the teleoperator. Use of a "wearable" jig in a bilateral master–slave control setup has been proposed to simplify the man–machine interface. The proposed sensing mechanism is cost effective, accurate, and can be easily implemented. The system was developed in two phases. In phase 1, a simple prototype of the master unit was developed to control three basic joints of the slave, namely the wrist, elbow, and the gripper, and the various hardware blocks were hardwired. In phase 2, two major improvements were made. First, the master unit was extended to control the wrist rotation, shoulder rotation, and shoulder back-and-forth motion. Second, the command and data transfer between the slave and master units was using a radio-frequency wireless mechanism.

A short introduction to teleoperation is given in Section II. Section III explains the master–slave control concepts. The wired basic system that has been implemented in phase 1 is detailed in Section IV. Various ways of force feedback are discussed in Section V, while the actually implemented force sensor for the gripper and its characteristics are described in Section VI. In Section VII, we describe in detail the architecture of the wireless embedded system and the improved master unit. Section VIII presents the test results. The concluding discussions are given in Section IX.

II. TELEOPERATION

The idea of teleoperation [19] has been around since the 1970s, a time when it was totally unfeasible to program adaptive robots; instead, it was easier to allow human beings to control the robots from afar [20]. The main advantage of this is that human beings are adaptive and are better able to deal with unstructured environments. However, such systems are difficult to use if the interface is not designed properly. Consider a scenario where a robot is controlled via a wireless link from a computer that accepts numerical input from the user's keyboard that represents the spatial coordinates of the desired position of the robot. A large amount of training would be necessary to get a human operator to the stage where he/she could fluently and effectively manipulate the robot's environment.

Robots are perfect for doing work that human beings either cannot or will not do, such as working in a harmful or aggressive environment (e.g., nuclear waste site or repeatedly performing pick and place operations in a factory). Robots do, however, have one significant problem: They require a highly structured environment to be able to operate, and they will malfunction if that structure of the environment is modified. Most autonomous robots are not adaptive. They are unable to overcome either the evolutionary situation of a task being performed or meet the demands in skillfulness of such a task. With the current state of technology, it is a very challenging problem to make reliable adaptive robots. To do so would require a complex programming to empower the robot to make decisions based on the environmental conditions. However, in situations where it is possible to structure the environment, the use of a nonadaptive robot is often easier and a more cost-effective solution.

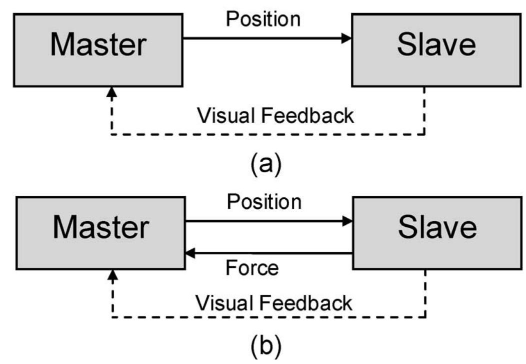


Fig. 1. Master–slave control system. (a) Unilateral system. (b) Bilateral system.

One of the solutions aiming to overcome this lack of adaptability is to have human beings operate the robot remotely (teleoperation), but this causes new problems. The first is that the ease of operation of a teleoperated robotic arm depends greatly on the interface presented to the user, and the second is that it can be difficult for the user to manipulate the robot's environment without any kind of feedback about how much force the arm is exerting.

III. MASTER–SLAVE CONTROL

In the master–slave control methodology, which has been used in this paper, the slave robot (teleoperator) exactly replicates the movements of the master. Methods for controlling master–slave robot systems may be divided into two categories—unilateral control system and a bilateral control system [16]. In a unilateral control system, shown in Fig. 1(a), no force feedback is available from the slave unit. The only form of feedback to the master unit operator is in the form of vision data. Such a system has the merit of having a simple controller and mechanism; however, dexterous manipulation is difficult. Fig. 1(b) shows a bilateral control system in which a force-feedback signal, usually electrical, is available from the slave to the master control unit. Although the controller and other mechanisms become more complex, a dexterous manipulation is possible using such a bilateral system.

The bilateral control systems may be configured in four different ways—symmetric position servo type, force reflection type, force reflection servo type, and parallel control type [17].

Most people find it incredibly easy to use their arms as they have had so much practice. This natural ability of most human beings can be exploited to give a human operator an easy to use tool to control a robot.

The reported system allows the user to move his hand in a natural way, and the robot moves in the same way. In this manner, the user is able to effectively and precisely manipulate the robot with very little training.

IV. SYSTEM CONSTITUTION

The complete system was designed and developed in two stages. In phase 1, the master–slave system was implemented

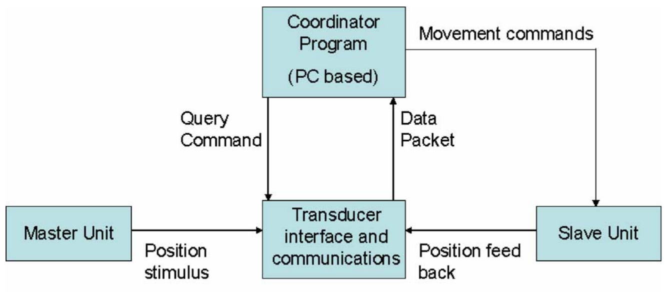


Fig. 2. Functional block diagram of the wired system.

Fig. 3. Lynxmotion Lynx six robot arm.

as a wired connection. The block diagram of the implemented system is shown in Fig. 2.

A more detailed description of each of the functional blocks in Fig. 2 is given in the following sections.

A. Slave Unit

This block represents the robot that is being teleoperated to manipulate objects, which is often called the teleoperator. Specifically, this unit is an anthropomorphic robot arm with six DOF. It is very similar to a human arm with respect to the number and position of the joints. The unit is small, light, and easy to transport. It is usable in any orientation and is inexpensive. The robotic arm used in this paper is shown in Fig. 3. It is the model "Lynx 6" from Lynxmotion [21]. The slave unit may be mounted upside down, as shown in Fig. 4, so that the movements of the joints resemble that of a dangling human arm.

The robotic arm has only revolute joints and no prismatic joints. Of the six DOF, four are for positioning (including the gripper) and two for orientation. If the joints are compared to their human equivalent, then the robotic arm can be said to have the following joints: shoulder rotation, shoulder back and forth, elbow, wrist up and down, wrist rotation, and gripper. The actuators for all of these joints are servomotors. The gripper is a two-finger construction, where each finger has two parallel links.

Three potentiometers are placed on the slave robot: one each at the axis of the gripper, wrist, and elbow joints. The servomotor movements rotate the potentiometer (relative to robot links),

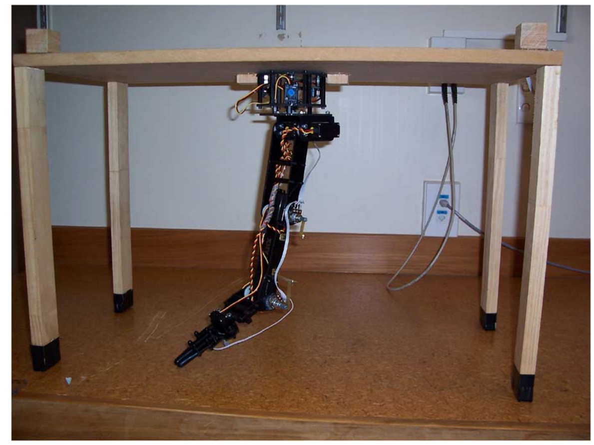


Fig. 4. Slave unit mounted upside down to resemble a dangling human hand.

which in turn generate a variable analog voltage. The voltage signals from the potentiometers are fed to the transducer unit, where their values are sampled and measured by an analog-to-digital (ADC) converter. The voltage is thus a measure of the angular position of the robot joint. This arrangement is used to measure the positional error. A joint is commanded to move to a certain angle, and the voltage from the corresponding potentiometer is read. If the value read does not tally with what it should have been for the desired angle, it is inferred that the joint has positional error.

There is also an option of using a similar robotic arm equipped with stepper motor actuators. However, it appeared that the servomotors offer a better solution due to absolute positioning inherent to them. In contrast, stepper motors only have incremental positioning and thus require additional encoders for position feedback. This leads to higher complexity of the hardware and the controller. Moreover, if the load on the servomotors is increased beyond their maximum, they will not lose their position. At the same time, if the same is done to a stepper motor, it will slip, and as a result, it will provide incorrect data about its position.

B. Command Structure for the Movement of Slave Unit

The commands to the robot arm are transmitted from the personal computer (PC) through COM1 RS-232 serial communication port at 9600 Baud rate. Each command is of 3-B long. The first byte must be the numerical value 255 for synchronization of the servo controller board (an SSC-II, supplied with the robotic arm and mounted on the base of the arm). The second byte provides the identification of the joint to be moved. Its exact value depends onto which output of the servo controller board the servomotor is connected. The value of the third byte represents the angular position that the specified joint is being commanded to move to (0–255). With 256 steps possible on each servo and a 180° range of movement, this means that each joint has an angular movement resolution of 0.7°/step (except for the gripper which has 0.35°/step due to the mechanics of the "fingers"). The measurement of the actual position of the joints is monitored by the transducer interface program running on the microcontroller.

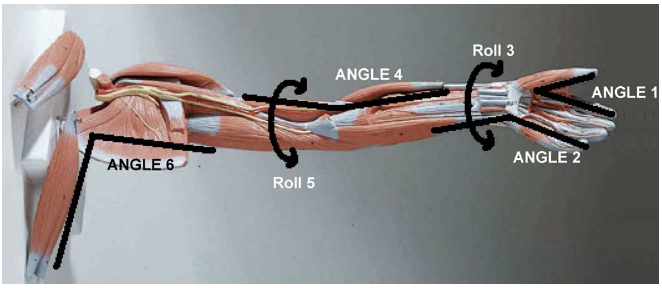


Fig. 5. Mapping the joints of a human hand to the master unit.

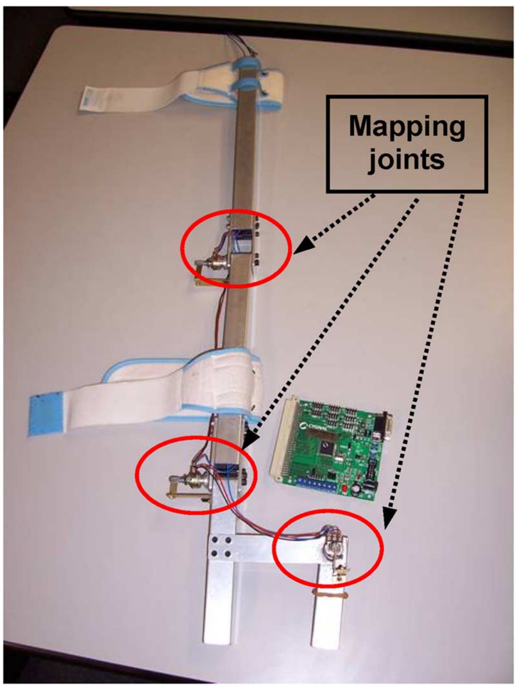


Fig. 6. Master unit with the transducer interface board.

C. Master Unit

This block represents the tool and the mechanism that are used by the operator to provide the slave with position commands. Fig. 5 shows a three-dimensional model of a human arm and the various attributes which are mapped to the master unit.

The prototype of the master unit, shown in Fig. 6, is an aluminum frame which the user straps on to his arm. In phase 1, the master unit had only three "mapping" joints (elbow, wrist, and gripper). That was deliberately done to reduce the complexity of the construction of the frame as well as the complexity of the control software. Three joints were considered suitable for testing and evaluation of the adopted control and feedback methods. The position of each joint was measured (absolutely) by the rotary potentiometers mounted at the axis of rotation of each joint. The output voltages of the potentiometers depend on the angular position of the joints. The voltages were measured by the transducer interface unit and were used to construct the command for the movement of the slave joints.

Fig. 7 shows the master unit strapped on the arm of a user. The purpose of this master unit is to measure the angular position of the joints of the user's arm. These angular positions are transmitted as voltages to the transducer interface.

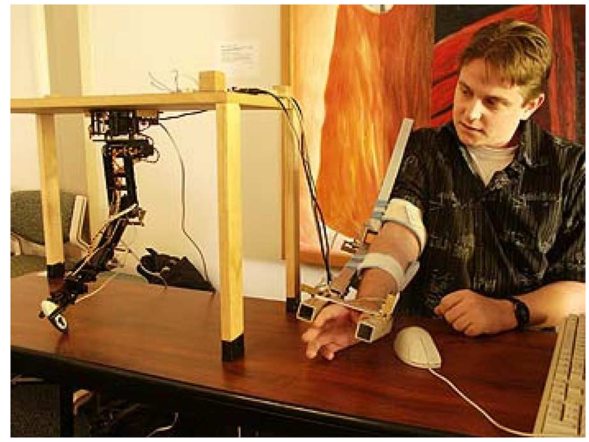


Fig. 7. Master unit strapped on a user's arm.

D. Transducer Interface

This block is built around a Silicon Laboratories microcontroller C8051F020 [22]. The purpose of this block is to convert the input voltages from the master and slave potentiometers from ADC values using on-chip ADC converters. It communicates the digital values to the coordinator program when a request is received.

A microcontroller is necessary here because the PC platform (that the coordinator program is running on) does not have the hardware capability to perform the ADC conversions. The proposed solution is to use a controller working independently from the coordinator program. The coordinator has to have the capability to handle multiple channels, and it has to be readily available. The Silicon Labs microcontroller has been chosen because it satisfies all of the above criteria.

The communication between the coordinator program and the transducer interface is in the form of data packet transmission using COM2 RS-232 serial communication port operating at 28800 Baud rate. The coordinator transmits a 3-B packet requesting angular positions, and the transducer interface replies with a 10-B packet containing a header (55H), RobotID (33H), and the angular positions of all the servomotors. Provision has been made in the packet to accommodate up to eight channels of ADC data, though in our present implementation, not all of them are required.

E. Coordinator Program

This block represents the software that monitors the positions of the joints on the master unit and commands the slave to move. The application runs on a PC under Windows XP operating system. The Microsoft Visual C++ 6.0 programming language was used to design the controls and the user interface. Fig. 7 shows the graphical user interface (GUI).

The GUI allows for easy development of control and testing facilities for the system. The top half of Fig. 8 shows six scroll bars that allow the user to test the movements of the slave independent of the master. The user can move these scroll bars using the mouse, and the joints of the slave unit will be moved. This can help to identify any problem in the slave unit or the coordinator program. Once the slave and the coordinator are

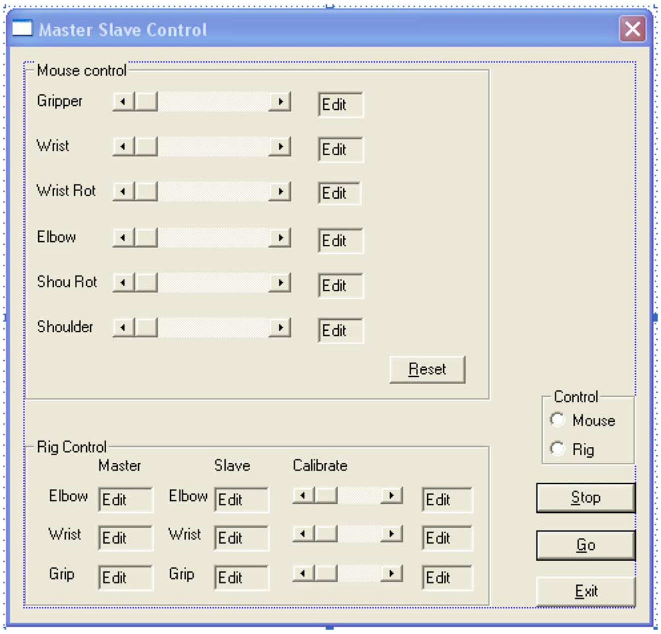


Fig. 8. Design view of the GUI of the coordinator program.

shown to be working, the user can switch to using the master unit (rig) for control, and the GUI will present the user with a series of boxes that shows the positions of each of the joints on the master and slave units. There are also calibration controls that allow the user to correct for errors in the positioning of the potentiometers on the master and slave units.

Essentially, a PC-based coordinator program has been used only because of the GUI that it provided. All of the operations that the coordinator performs could be scaled down and ported to a microcontroller.

V. Force-Feedback Mechanisms

As mentioned earlier, a unilateral master–slave control system is not suitable for dexterous control of the slave. The movements of the robot joints are easy to control. However, the user would have to be very careful not to exert too much force on the objects that the arm is manipulating, as this could damage either the object or the arm. A good example of this would be if the user is required to lift and move an egg using the arm. If the user exerted too much force on the egg, then it would crack, and if he/she used too little force, then the arm would not be able to grip the egg, and the arm would drop it.

Therefore, a question follows: How do the users know how much force they are commanding the arm to apply to an object? Possibly, the best solution would be to give the user a physical sense of the amount of force the arm is exerting. This can be done by applying to the joints of the master unit a force that is proportional to that being exerted by the slave. This process has been called "force feedback," and it is currently used in video games to give the player a better sensation of what is going on in the game.

There are three main ways of measuring the force that the slave unit is exerting: current sensing, force sensing, and positional error measurement. Each of these techniques is briefly described in the following sections.

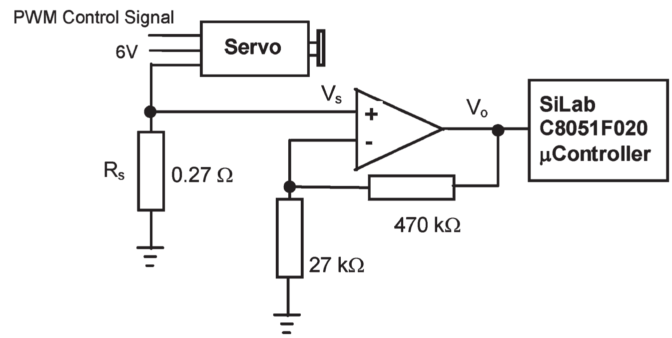


Fig. 9. Circuit for monitoring current through a servomotor.

A. Current Sensing

In this method, the force fed back to the user is made proportional to the current that is being drawn by each of the joint motors. It is known that the current drawn by a dc motor is proportional to the torque that it is exerting [23]. Therefore, it can be used as a measure of force since torque is simply the force of rotation. An example of the use of current-sensing technique was reported in [24]. However, the technique was employed there to prevent motor damage by limiting current and not for force measurement.

The current-sensing method is very suitable for teleoperated robotics, as it is based on actual force measurement and does not require extra force sensors to be added to the manipulator arm. In the implemented system, current sensing has been achieved by placing a resistor in series with the motor control signal, as shown in Fig. 9. A minor disadvantage of this method is the increased complexity of the controller caused by the need to monitor the current drawn by each of the servomotors.

The control input for the servomotor is a 49.5-Hz pulse-width-modulated (PWM) signal. The duty cycle of the PWM control signal varies in proportion to the motor torque. A very small resistor (R_s) has been place in the path of the motor current, and the voltage (V_s) across it is amplified (V_o) by a high-precision op-amp. Using 12-bit counter/timers, the microcontroller measures the duty cycle, thus effectively measuring the motor torque. Fig. 10 shows V_s and V_o for different servo loadings, resulting in PWM duty cycle of 9.7% [Fig. 10(a)] and 67.7% [Fig. 10(b)].

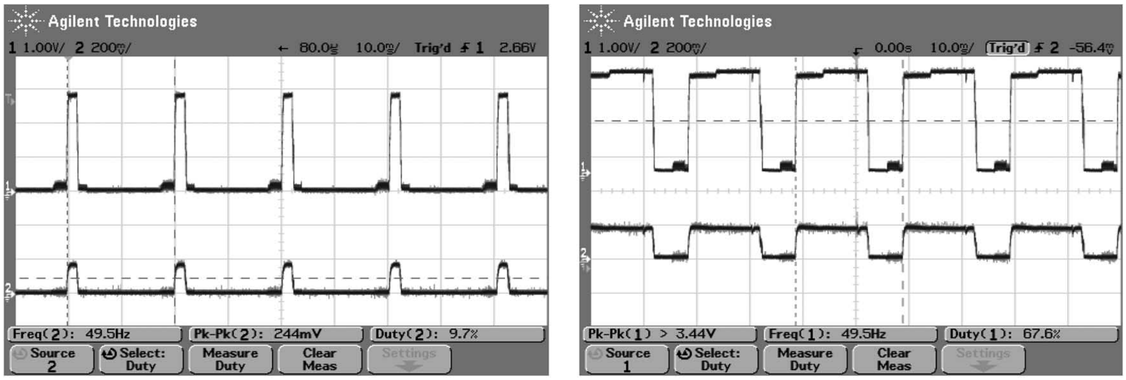
B. Force Sensing

In this method, the force sensors are mounted between the joints of the manipulator. These sensors measure the amount of strain placed on each of these joints: The higher the strain, the greater the amount of force the joint is exerting.

The main advantages of this system are that, it measures the actual forces and that the measurement does not interfere with the operation of the joints themselves. The disadvantage of this approach is the difficulties of mounting the force sensors on the manipulator with no preload them. The force sensor is most suitable for the gripper and is detailed in Section VI.

C. Positional Error Measurement

In this method, the force that is fed back to the user is made proportional to the difference in positions of the master and the



(a) (b)

Fig. 10. PWM control signal for varying torque. (a) Duty cycle of 9.7%. (b) Duty cycle of 67.7%.

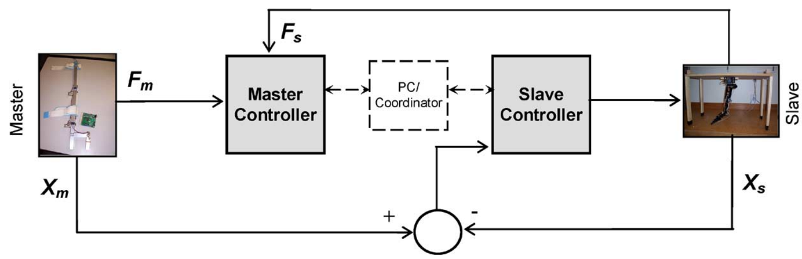


Fig. 11. Force reflective bilateral master–slave control.

slave units. If the positions are very different, it is assumed that the arm is under strain and unable to reach the master's position; therefore, a reflective force should be applied to the master unit to restrain it. This method has the advantage that it does not require any extra sensors to be added to the slave unit. All the calculations can be done by the coordinator program. Whereas the use of potentiometers for angular measurements is simple and effective, it is somewhat less accurate. Over time, a drift evolves on the master unit's position and introduces errors in the measurement of displacement (X_{m}). This is the main disadvantage of this method.

Fig. 11 shows the block diagram of the reflective type of bilateral master–slave controller. The displacements X_{m} and X_{s} are measured by the potentiometers mounted on the master and slave units, respectively.

The force-sensor method has been found to be the most appropriate for feedback from the gripper while current-sensing method has been chosen for the remaining joints.

VI. Gripper Force Sensing

It is appropriate for the gripper joint to use a force sensor to measure the amount of force the slave is exerting on an object in its grip. To measure the force, a sensor is attached to the inside of one of the gripper prongs. When the gripper closes around the object, the sensor is compressed between the object and the gripper prong. From this, the force can be measured. The sensor that has been used is a Tekscan FlexiForce [25] force sensor, which is shown in Fig. 12.

These sensors are mounted on a flexible circuit board and have a small circular dot of force-sensitive ink. The resistance of this ink increases as the force applied increases. By using a simple operational amplifier-based circuit, this force can be converted into an analog voltage that can be fed into one of the ADC inputs of the transducer interface.

Fig. 12. Tekscan FlexiForce force sensor.

Once the force data are accessible by the coordinator program, it could be displayed to the user through the GUI of the coordinator program, or it could be employed to drive a motor attached to the gripper joint of the master unit, thereby giving the user a sense of how much force is applied to an object.

Several sensors having a different sensitivity to force and catering to different maximum loading were tried. For the reported system, the 1-lb sensor has been the most appropriate. The sensor characteristics are shown in Fig. 13.

Fig. 14 shows the transient response of the sensor when subjected to a step load of 300 g (from 100 to 400 g). The settling time is approximately 500 ms, which is acceptable for the intended applications of the system.

The force sensor, which is essentially a variable resistor, is used to change the gain of an inverting high-gain operational amplifier, as shown in Fig. 15. When using another sensor

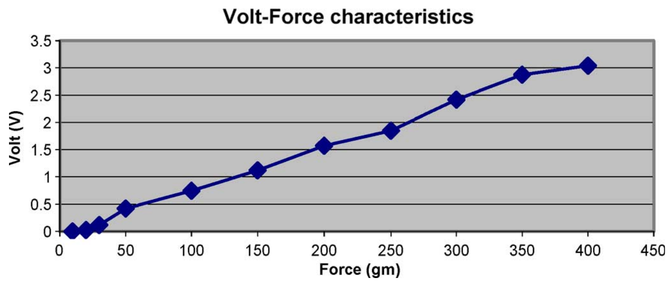


Fig. 13. Force-sensor transfer characteristics.

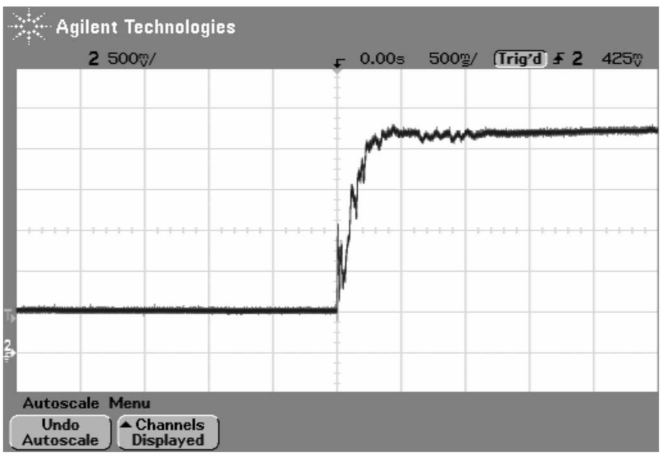


Fig. 14. Transient response of the force sensor.

with a different sensitivity, the amplifier gain may need to be changed. This is achieved by varying the potentiometer R_2 (1).

$$V_{\text{out}} = -V_{\text{o}} * \left(\frac{R_{\text{F}}}{R_{\text{S}}}\right)$$
$$R_{\text{F}} = R_1 + R_2. \tag{1}$$

VII. Wireless Embedded Controller

Many applications of teleoperated robotics arm system would require having the user at a distance from the slave unit (e.g., when the system is used to diffuse a bomb). All the blocks of the system, implemented in phase 1, are hard wired. This limits the maximum feasible distance between the master and the slave units. A wireless or an Internet link block could be incorporated into the system as shown in Fig. 16. In this way, it would be possible to effectively increase the operating range of the system.

In phase 2, a new master unit (control rig) was designed and a wireless master–slave control was implemented using embedded controllers. The new master unit is shown in Fig. 17. The provision to control the three basic joints of the teleoperator, namely the elbow, wrist, and gripper, are still there. Additional controls were implemented for wrist rotation, shoulder rotation, and shoulder back-and-forth motion. As in the phase 1 design, the elbow, wrist, and gripper movements were measured using rotary potentiometers, while the two rotational joints utilize linear potentiometers to map the user's wrist and shoulder rotation into electrical voltages. This is accomplished by having a slip ring rotate around a main inner tube. The linear potentiometer is fixed to the inner tube while its slider is positioned in a helical grove that has been machined into the slip ring. As the slip ring rotates, the helix converts the rotational motion into a translational movement of the slider.

The shoulder back-and-forth motion is measured using an accelerometer which is also capable of measuring inclination.

Fig. 18 shows the block diagram of the wireless system. The analog voltages from the control rig are measured by the master controller and transmitted over the wireless link to the slave controller. The slave controller generates the position commands for the slave unit servomotors and sends these commands over a serial communication wired link to the servo control board. Current sensing and amplification for force measurement are done on the control board, and the PWM signals (one for each servomotor) are sent to the digital I/O ports of the slave controller. The slave controller measures the duty cycle of the PWM signals (effectively the motor torque) and transmits them to the master controller using the wireless link. The diagnostic PC, which is connected to the master controller using a wired serial link, depicts the force on each joint, as shown in Fig. 19.

VIII. System Test Results

The system was rigorously tested for its speed and accuracy of force measurement. The servomotor controller board, together with the current-sensing circuit for force measurement, is shown in Fig. 20.

Using the diagnostic program, the forces from all six joints were measured and updated every 10 ms. The refresh frequency of 500 Hz was very fast for most practical applications of the master–slave control of an anthropomorphic robotic manipulator. The motor torque was measured with a resolution of 0.1% while having an error of less than 0.25%, as shown in Fig. 21.

Since an important goal of this design was to build a master unit, which should be intuitive and easy to use, some subjective and qualitative tests were also performed on the system. They have involved trying the system with different users to gauge how fast they can become proficient in using it to accurately and quickly pick up, move, and release an object placed in the robot's workspace. The results were very positive: The majority of the users became proficient in using the system within approximately 2 min, and they could perform operations of various trajectories. However, there were some acute positions in the robot's workspace which were difficult to achieve (primarily due to the awkward twists of the elbow and shoulder joint).

To gauge the comfort level of the operator, the users were asked to repeat a task of "pick, move, and place" many times with no break. It was observed that the system was rather demanding, and as a result, tiredness set in relatively quickly on average after 30 operations. It is inferred that such a system is not useful for repetitive operations, such as those on the production floor. However, in situations with nonrepetitive operations such as defusing of bombs, medical surgery, etc., where dexterous manipulations are required for a shorter interval of time, it could be very effective.

Another observation made during the tests was the fact that users were not as precise as a programmed robot in positioning

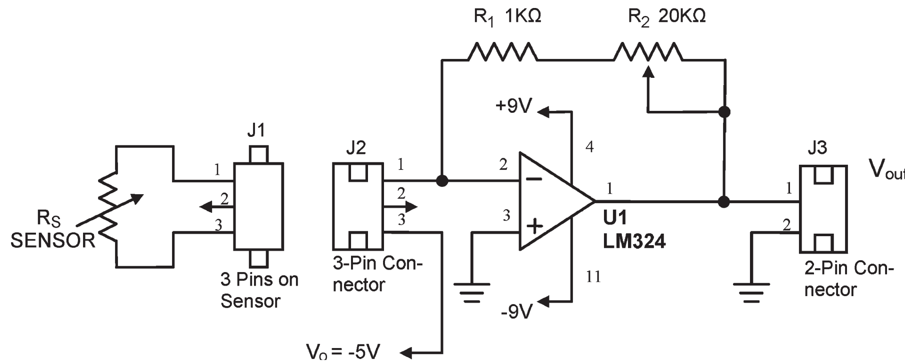


Fig. 15. Amplifier circuit for force-sensor output.

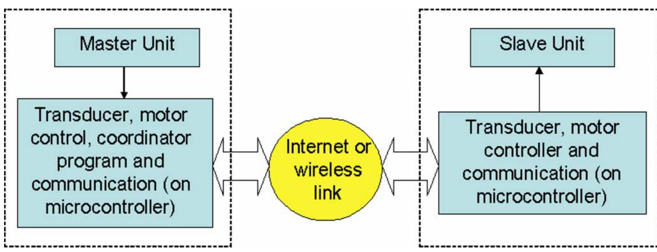


Fig. 16. Block diagram of the teleoperated system using Internet or wireless link.

Fig. 17. Six-axis master unit.

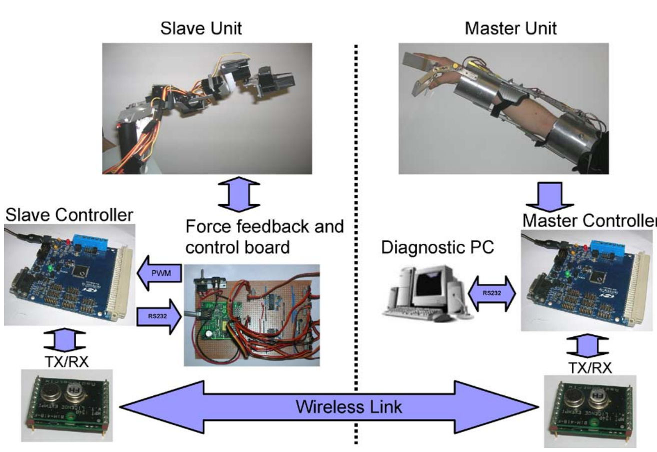


Fig. 18. Wireless master–slave controller block diagram.

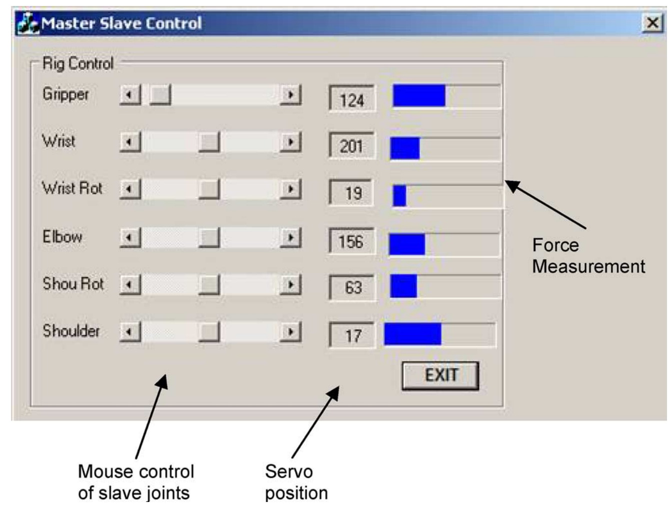


Fig. 19. GUI of the diagnostic program showing a force feedback.

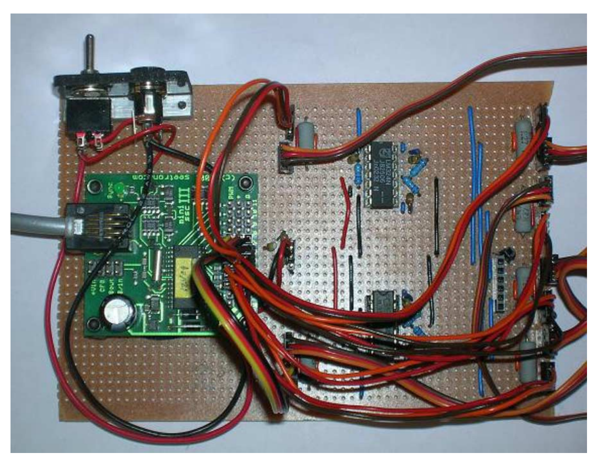


Fig. 20. Servomotor controller board with current-sensing elements for force-feedback measurements.

the gripper at a point. A programmed robot can move to the exact position specified by the program, whereas the users of this system often overshot their mark and had to backtrack. Repeatability of operations is thus an issue, and the drift could be attributed to the lack of training that the users of the system received. It would be valid to say that, with practice, users would be able to command the slave more precisely.

The system offers the user a real-time control interface to move several joints simultaneously. This presented a huge advantage when users attempted to manipulate an object. In comparison, when using a mouse control, which offered only one joint movement at a time, manipulating objects was very cumbersome.

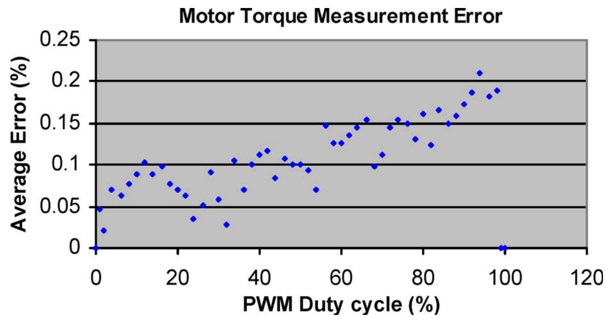


Fig. 21. Torque measurement error at various duty cycles of the PWM current signal.

IX. Discussions

In this paper, we report results of the research that explored the various methods of incorporating force feedback into a force reflective bilateral master–slave control system for teleoperation of objects in the real world. Force sensing using current measurement was extensively tested and implemented. It is proven to be an effective and inexpensive method for providing force feedback, requiring very little modification to the controller hardware. In addition, it allows safety features to be built into the software so that when a motor experiences prolonged stall currents such as when the robotic arm gets trapped underneath a table, it can be switched OFF, thereby preventing the motor windings from burning off. A commercial force sensor was also evaluated for measuring the force exerted on an object grasped by the gripper prongs. The system prototype was successfully designed and implemented while meeting the specifications. The master unit was easy to use to control the slave unit, and it took very little time for a user to learn how to use it.

One of the big challenges faced was incorporating a mechanism on the master unit to control the back-and-forth motion of the slave shoulder joint. Unlike the other joints such as the wrist and the elbow, it was difficult to use a linear or rotary potentiometer for the master unit's shoulder joint. This was solved using a single-chip $\pm$10-g dual-axis accelerometer ADXL210E from analog devices. This chip has a variable duty-cycle output, which was measured by the transducer interface unit.

An issue that will need close scrutiny is the compensation of the master unit's own weight such that the force felt by the operator would be purely that of the slave. A compensation scheme needs to be developed. To alleviate this problem, the master unit was constructed using a light-weight aluminium so that its overall weight was small. The weight of the master unit presented in this paper was 1800 g.

The designed and implemented system is inexpensive and effective, and it can be very useful for operations in hostile environments where it is dangerous for human beings to work. While most research reported in the literature on using force feedback was aimed at manipulation of objects in the virtual world, our system was designed for real-world applications. It can find numerous applications in areas such as medical surgery, security, operations in extreme environments, entertainment, as well as teleoperation in undersea and space exploration. It is proven that the concept of master–slave control of robots is useful when the robot is in an unstructured and unpredictable environment, since the human beings operating them are far more adaptable than behavioral programming could be at this stage of technological development.

References

[1] J. Batlle, P. Ridao, and J. Salvi, "Integration of a teleoperated robotic arm with vision systems using CORBA compatible software," in *Proc. 30th Int. Symp. Automot. Technol. and Autom.*, Florence, Italy, Jun. 1997, pp. 371–378.

[2] O. Ben-Porat, M. Shoham, and J. Meyer, "Control design and task performance in endoscopic teleoperation," *Presence*, vol. 9, no. 3, pp. 256–267, Jun. 2000.

[3] P. Arbeille, J. Ruiz, M. Chevillot, F. Perrotin, P. H. Herve, P. Vieyres, and G. Poisson, "Teleoperated robotic arm for echographic diagnosis in obstetrics and gynecology," *Ultrasound Obstet. Gynecol.*, vol. 24, no. 3, p. 242, Aug. 2004.

[4] P. Arbeille, G. Poisson, P. Vieyres, J. Ayoub, M. Porcher, and J. L. Boulay, "Echographic examination in isolated sites controlled from an expert center using a 2-D echograph guided by a teleoperated robotic arm," *Ultrasound Med. Biol.*, vol. 29, no. 7, pp. 993–1000, Jul. 2003.

[5] Intuitive Surgical, *Da Vinci Surgical System*. [Online]. Available: http://www.intusurg.com/products/da_vinci.html [7/10/05]

[6] International Submarine Engineering Ltd., *ATOM—Autonomous/Teleoperated Operations Manipulator*. [Online]. Available: http://www.ise.bc.ca/robotics.html#atom [7/10/05]

[7] S. M. Prasad, H. S. Maniar, N. J. Soper, R. J. Damiano, and M. E. Klingensmith, "The effect of robotic assistance on learning curves for basic Laparoscopic skills," *Amer. J. Surg.*, vol. 183, no. 6, pp. 702–707, 2002.

[8] M. Kitagawa, A. M. Okamura, B. T. Bethea, V. L. Gott, and W. A. Baumgartner, "Analysis of suture manipulation forces for teleoperation with force feedback," in *Proc. 5th Int. Conf. MICCAI,* T. Dohi and R. Kikinis, Eds., 2002, vol. 2488, pp. 155–162.

[9] C. Pasca, P. Payeur, E. M. Petriu, and A.-M. Cretu, "Intelligent haptic sensor system for robotic manipulation," in *Proc. IEEE IMTC*, Como, Italy, May 2004, pp. 279–284.

[10] S. Lee and H. S. Lee, "Teleoperator control system design with human in control loop and telemonitoring force feedback," in *Proc. 31st IEEE Conf. Decision and Control*, Tucson, AZ, Dec. 16–18, 1992, vol. 3, pp. 2674–2679.

[11] N. Cauche, A. Delchambre, P. Rouiller, P. Helmer, C. Baur, and R. Clavel, "Rotational force-feedback wrist," in *Proc. 5th IEEE Int. Symp. Assem. and Task Planning*, Besançon, France, Jul. 10–11, 2003, pp. 210–215.

[12] M. Bouzit, G. Burdea, G. Popescu, and R. Boian, "The rutgers master II-new design force-feedback glove," *IEEE/ASME Trans. Mechatronics*, vol. 7, no. 2, pp. 256–263, Jun. 2002.

[13] N. Suzuki, A. Hattori, A. Takatsu, A. Uchiyama, T. Kumano, A. Ikemoto, and Y. Adachi, "Virtual surgery simulator with force feedback function," in *Proc. 20th Annu. Int. Conf. IEEE Eng. Med. and Biol. Soc.*, Oct. 29–Nov. 1, 1998, vol. 3, pp. 1260–1262.

[14] A. J. Johansson and J. Linde, "Using simple force feedback mechanisms as haptic visualization tools," in *Proc. 16th IEEE IMTC*, May 24–26, 1999, vol. 2, pp. 820–824.

[15] M. A. F. Rodrigues, R. R. C. Chaves, and W. B. Silva, "Collaborative virtual training using force feedback devices," in *Proc. 17th Brazilian Symp. Comput. Graph. and Image Process.*, Oct. 17–20, 2004, pp. 332–339.

[16] W. Semere, M. Kitagawa, and A. M. Okamura, "Teleoperation with sensor/actuator asymmetry: Task performance with partial force feedback," in *Proc. 12th Int. Symp. Haptic Interfaces Virtual Environ. and Teleoperator Syst., HAPTICS*, Mar. 27–28, 2004, pp. 121–127.

[17] I. Yamano, K. Takemura, K. Endo, and T. Maeno, "Method for controlling master-slave robots using switching and elastic elements," in *Proc. IEEE Int. Conf. Robot. and Autom.*, Washington, DC, May 2002, pp. 1717–1722.

[18] S. Kudomi, H. Yamada, and T. Muto, "Development of a hydraulic master-slave system for telerobotics," in *Proc. 1st FPNI-PhD Symp.*, Hamburg, Germany, 2000, pp. 467–474.

[19] W. Uttal, "Teleoperators," *Sci. Amer.*, vol. 261, pp. 74–79, Dec. 1989.

[20] Helenski Institute of Technology, *From Teleoperators to Robots: Development of Machines and Interfaces*, May 2004. [Online]. Available: www.automation.hut.fi/edu/as84147/Teleoperation-history.ppt (07/10/04)

[21] Lynxmotion, Inc., *Lynx 6 Series of Robots*. [Online]. Available: http://www.lynxmotion.com/Category.aspx?CategoryID=25 [7/10/04]

[22] M. T. Chew and G. S. Gupta, *Embedded Programming With Field-Programmable Mixed-Signal μ Controllers*. Austin, TX: Silicon Laboratories, 2005.

[23] J. N. Nash, "Direct torque control, induction motor vector control without an encoder," in *Proc. Pulp and Paper Ind. Tech. Conf.*, Jun. 1996, pp. 86–93.

[24] A. Edsinger-Gonzales and J. Weber, "Domo: A force sensing humanoid robot for manipulation research," in *Proc. 4th IEEE/RAS Int. Conf. Humanoid Robots*, Nov. 2004, pp. 273–291.

[25] Tekscan, *FlexiForce Force Sensors*. [Online]. Available: http://www.tekscan.com/flexiforce/flexiforce.html [08/10/04]

Gourab Sen Gupta (M'89–SM'05) received the B.E. degree in electronics from the University of Indore, Indore, India, in 1982 and the M.E.E. degree from Philips International Institute, Eindhoven, The Netherlands, in 1984. He is currently working toward the Ph.D. degree in advanced control of robots in a dynamic collaborative system environment at Massey University, Palmerston North, New Zealand.

After working for five years as a Software Engineer with Philips India, Pune, India, in the Consumer Electronics Division, he joined Singapore Polytechnic, Singapore, in 1989, where he is currently a Senior Lecturer with the School of Electrical and Electronic Engineering. He is also a Visiting Senior Lecturer with the Institute of Information Sciences and Technology, Massey University. He has over 40 publications in various journals and conference proceedings. He has authored two books and edited three conference proceedings. His current research interests are in the area of embedded systems, robotics, real-time vision processing, behavior programming for multiagent collaboration, and automated testing and measurement systems.

Subhas Chandra Mukhopadhyay (A'97–SM'99) was born in Calcutta, India, in 1965. He received the degree (gold medal) from the Department of Electrical Engineering, Jadavpur University, Calcutta, in 1987, the Master of Electrical Engineering degree from Indian Institute of Science, Bangalore, India, in 1989, the Ph.D. (Eng.) degree from Jadavpur University, in 1994, and the Dr.Eng. degree from Kanazawa University, Kanazawa, Japan, in 2000.

During 1989–1990, he worked almost two years with the Research and Development Department, Crompton Greaves, Ltd., India. In 1990, he joined with the Electrical Engineering Department, Jadavpur University, as a Lecturer and was promoted to a Senior Lecturer with the same department in 1995. Obtaining a Monbusho fellowship, he went to Japan in 1995. He was with Kanazawa University, as a Researcher and Assistant Professor until September 2000. In September 2000, he was a Senior Lecturer with the Institute of Information Sciences and Technology, Massey University, Palmerston North, New Zealand, where he is currently working as an Associate Professor. His fields of interest include electromagnetics, control, electrical machines and numerical field calculation, etc. He has published 148 papers in different international journals and conferences, written a book and a book chapter, and edited five conference proceedings.

Dr. Mukhopadhyay is a fellow of the Institute of Electrical Engineers and an Associate Editor of IEEE SENSORS JOURNAL.

Christopher H. Messom (M'96) received the M.Sc. and Ph.D. degrees in computer science from Loughborough University, Loughborough, U.K., in 1989 and 1992, respectively.

He was a Lecturer with Singapore Polytechnic from 1993 to 1997, a Senior Lecturer with Dubai University College from 1998 to 1999, and currently, a Senior Lecturer and Director with the Centre for Parallel Computing at Massey University, Auckland, New Zealand. His research includes intelligent robotics and control systems, particularly automatic learning of control systems. The computational complexity of intelligent robotics and automatic learning has led to his interest in parallel implementations of machine learning algorithms as well as distributed processing in robot simulation and control.

Serge N. Demidenko (M'92–SM'95–F'04) received the M.E. degree from Belarusian State University of Informatics and Radio Electronics, Minsk, Belarus, in 1977 and the Ph.D. degree from the Belarusian Academy of Sciences, Minsk, in 1984.

During his career in Belarus, he progressed from an Engineer to a Head with the Joint (Industry–Academy) Test Laboratory of a large electronic manufacturing company and Head of Department posts by working for academia and industry. From 1990, he was an academic staff with institutions of higher learning in several countries. His research areas include electronic design and test and fault-tolerance and signal processing. He has authored of four books and more than 80 papers and holds 25 patents.

Dr. Demidenko is a fellow of the Institute of Electrical Engineers and a U.K. Chartered Engineer. He is a Chair of Electronic Engineering and Associate Head of the Institute of Information Sciences and Technology, Wellington Campus, Massey University, Palmerston North, New Zealand. He is an Associate Editor of five international journals including *JETTA: Journal of Electronic Testing: Theory* and *Applications* and the IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT. He is a Cochair of TC-32 of the IEEE I&M Society, a member of the Board of Directors of IMTC, and a Chair of the IEEE I&M Malaysia Chapter.