AC 2008-1272: MEDICAL ROBOTICS LABORATORY FOR BIOMEDICAL ENGINEERS

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Medical Robotics Laboratory for Biomedical Engineers

Abstract

The increasing role of technology in the delivery of healthcare services has necessitated the training of engineers with complimentary background in engineering and health sciences. In response to this demand, universities and educational institutions around the globe are beginning to create undergraduate programs in biomedical engineering and developing new curriculums to support such programs. Medical Robotics is a Level 4 compulsory course in McMaster University's new established Electrical and Biomedical Engineering program. This paper provides an overview of a laboratory component which has been co-developed by McMaster University and Quanser Consulting Inc. for this course. First, the motivations for introducing a Medical Robotics course into the Biomedical Engineering curriculum and the desired learning outcomes pursued by the proposed laboratory experiments are discussed. These are followed by a brief introduction of the hardware/software system used in the lab as well as detailed descriptions of four experiments developed to achieve the learning objectives.

1. Background and Motivation

In recent years, interest in applications of robotics technology in medical interventional procedures has grown enormously. Although the number of existing robotic-based clinical procedures is still limited, there is ample evidence that market for such technologies is rapidly expanding [1]. Robotic devices are emerging as essential components of state-of-the-art of computer-integrated surgical platforms. Whether in orthopedic surgery, percutaneous therapy, or minimally-invasive surgery/telesurgery, robotics technology has enabled new and improved methods of healthcare delivery resulting in less patient trauma, improved operation outcome, and shorter hospital stays [2-4]. For example, robotic-assisted minimally invasive surgery has significantly improved upon conventional laparoscopic surgery by allowing direct control of the surgical instrument inside the patient's body, by removing surgeon's hand tremor, and by providing motion scaling capability. Vision-guided robotic systems have increased the accuracy and effectiveness of radioactive seed implantation and tissue biopsy in percutaneous therapy. Robotic-based medical simulators have also the potential to revolutionize the training of medical interventional procedures by allowing student trainees to operate in virtual environments while receiving realistic force and visual feedback from the task. The growing use of robotic-assistive technologies in healthcare delivery is creating an increased demand for biomedical engineers with educational background in robotics and real-time control systems. Conventional courses offered in electrical, computer, and mechanical engineering bachelor's programs each to some extent cover certain aspects of this emerging field. However, in our opinion, it is critical to develop a dedicated course to the subject matter so these multidisciplinary subjects can be taught in a coherent curriculum with an emphasis on biomedical applications.

The Department of Electrical and Computer Engineering at McMaster University has recently launched an innovative undergraduate program leading to the Bachelor of Engineering degree in Electrical and Biomedical Engineering. Due to the growing impact of robotics on the field of biomedical engineering, a new course in Medical Robotics was introduced in 2006 to fill the existing educational gap in this area. The target audience of this course is primarily fourth-year undergraduate students of the biomedical engineering program of the department while the course is also open to graduate students with interest in medical robotics research. The course has no particular prerequisite but the students are encouraged also to enroll in an undergraduate course in control systems. Medical Robotics is a one-semester course and has been thought at McMaster University in the past three (3) years with an average enrolment of 30 students per year.

Medical robotics is a multidisciplinary area building on the established disciplines of robotics, control systems, and medicine. Given the limited scope of an undergraduate course, the diversity of medical robotics applications, and the evolving nature of the field, it was decided to emphasize on common underlying principles of medical robotic systems rather than merely focusing on specific applications. This course introduces basic concepts in the design, analysis and real-time control of robotic systems within the context of medical applications. Traditional topics in robotics including rigid motions, coordinate systems and transformations, kinematics, and motion planning are covered. Basic principles of feedback controls are also reviewed. Applications of image-guided robot control in medical interventions are discussed. Finally principles of haptic interaction and telerobotics systems are introduced and their applications in robot-assisted minimally invasive surgery/telesurgery as well as training of medical procedures are studied.

2. Learning Objectives and Customized Laboratory Experiments

Hands-on experimentation is critical in learning new concepts, particularly in an applied area such as medical robotics. Applications of medical robotics are diverse and as such a number of commercial systems have been developed which are dedicated to specific medical procedures. However, these are largely costly and complex systems which cannot be used for educational purposes. One of the most exciting features of the new medical robotics course is an innovative laboratory curriculum that has been jointly developed by McMaster University and Quanser Consulting Inc., Markham, Ontario. The experimental setup and the lab experiments have been designed to expose the students to commonly used principles in medical robotic systems as opposed to focusing on a particular procedure. These include concepts of robot motion planning and control, contact control, haptic simulation and telerobotics. Using Quanser robotics and real-time control technologies, students can rapidly develop hardware-in-the-loop experiments to thoroughly explore each of these subjects. The open structure of the labs allows students to develop their skills in robotics, control systems, instrumentation and real-time computing using a state-of-the-art technology. The proposed experimental platform can also be used in a traditional robotics or control systems course.

3. Assessment

The students are required to conduct the experiments in groups of two under the supervision of the course teaching assistants. Pre-laboratory assignments are used to familiarize the students with concepts behind each experiment. During the labs, instead of following a set of predefined steps, the students develop their control system from scratch based on the problem requirements and often undergo a few iterations of revisions before reaching a final solution. This approach is very effective in learning enforcement. Each individual member must provide a written report within two weeks of the completion of the experiment. The lab report should include a description of the activities in the lab and should present the resulting experimental data with appropriate analysis. The lab mark is calculated based on a combination of the pre-lab and final reports as well as the student in-lab performance gauged by the teaching assistants. During the past few years, we have observed a great deal of enthusiasm amongst students about the laboratory experiments and its significant impact on learning the concepts taught the course.

The rest of this paper is dedicated to describing the hardware setup and software architecture, as well as the laboratory experiments that have been developed based on this platform.

4. System Description

4.1. Hardware

The experimental setup, shown in Fig. 1., consists of two robot units mounted on a base plate, a hardware-in-the-loop data acquisition board, a linear current amplifier, and a desktop computer.

4.1.1. Quanser 2DOF Pantograph

The 2-DOF Planar Pantograph robot is designed for research and education in haptics as well as robotics. The interface has two degrees of freedom allowing for planar translation. This is achieved by using a Pantograph arrangement, as shown in Fig. 1. Parallel arms in the Pantograph arrangement are capable of applying large force while bearing simple structure and low friction. The 2-DOF Pantograph is driven by a rotary capstan drive mechanism which enables the user to apply high forces without noticeable backlash or friction. Therefore the two motors drive the Pantograph-type mechanisms such that the end-effector can be controlled in a plane. The standard end-effector is a circular knob but can be readily replaced by other types of end-effectors if desired. The 2DOF mechanism is actuated by two DC motors and the motor shaft angular positions are measured by high-resolution optical encoders.

4.1.2. Quanser Linear Force Actuator (LFA)

The LFA (Linear Force Actuator) is a low friction and low mass linear module which is ideal for high-fidelity 1 DOF haptic rendering. LFA is actuated by a linear capstan drive using a DC motor. The linear position of the actuator is measured by a high resolution optical encoder mounted on the motor shaft as can be seen in Fig. 1. The LFA can be controlled independent of the 2DOF Pantograph. Alternatively, it may be attached to the end-effector of the 2 DOF Pantograph resulting in a parallel redundantly actuated manipulator that can only move along one axis.

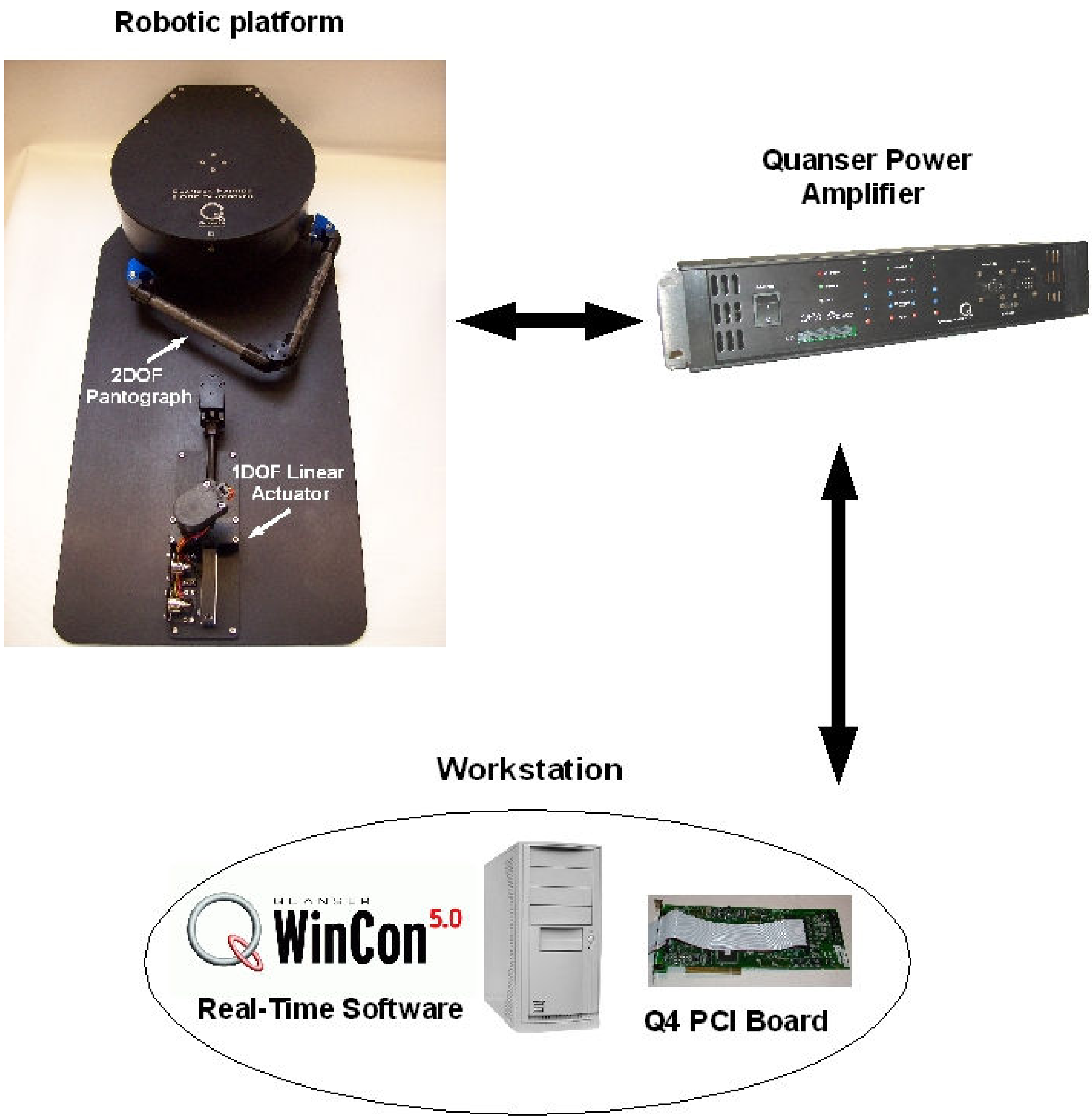

Fig. 1: The laboratory experimental setup.

4.1.3. Quanser Power Amplifier (QPA)

The four-channel QPA series power amplifier, shown in Fig. 1, consists of four linear current amplifiers. This is a two-unit rackmount chassis containing four linear current amplifiers. Signals to and from the robot are channeled via the amplifier to the Q4 data acquisition board. The QPA used for the 2-DOF Pantograph and LFA has two independent internal power supplies.

4.1.4. Quanser Data Acquisition Board (Q4)

Q4 is a high resolution data acquisition and control board with an extensive range of input and output support. It supports simultaneous sampling of A/D and encoder inputs. The I/O is composed of 4 each of A/D, D/A, encoder and 16 DIO. The Q4 is integrated with MATLAB/Simulink/RTW via Quanser WinCon.

4.2. Real-time Control Software

WinCon is a rapid prototyping and hardware-in-the-loop simulation workhorse for control system and signal processing algorithms. It is a real-time Windows application that runs Simulink models in real-time on a PC. WinCon allows for quick and seamless design iterations without the need to write code by hand. It enables the user to create and control a real-time process entirely through Simulink and execute it entirely independent of Simulink. Using Ardence's® RTX real-time kernel, WinCon's architecture ensures the real-time process has the highest CPU priority and is not pre-empted by any competing tasks other than the core OS functions. (see Fig. 2).

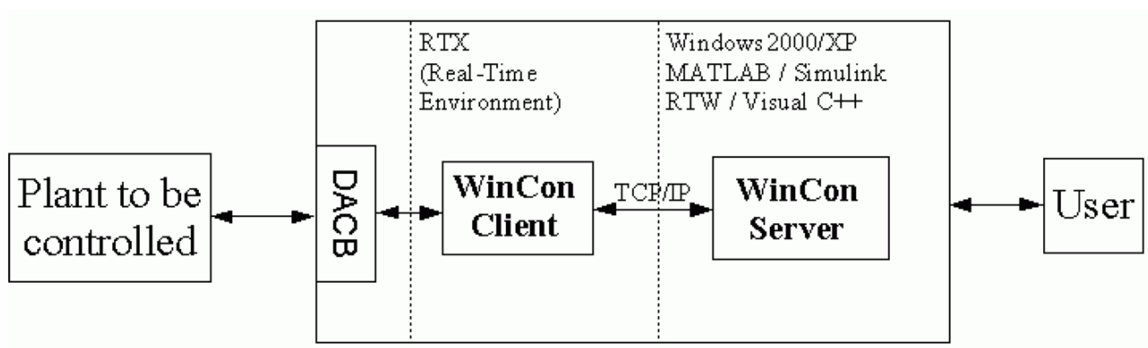

Fig. 2: WinCon, PC and RTX configuration.

Quanser Toolbox provided with WinCon includes data acquisition Simulink block enabling students to interface with the robots and Q4 through an interactive Simulink model. The toolbox also features real-time TCP/IP and UDP network communication blocks allowing for real-time control over an Ethernet-based network. Fig. 3 shows a sample Simulink model that may be used to control LFA and 2DOF.

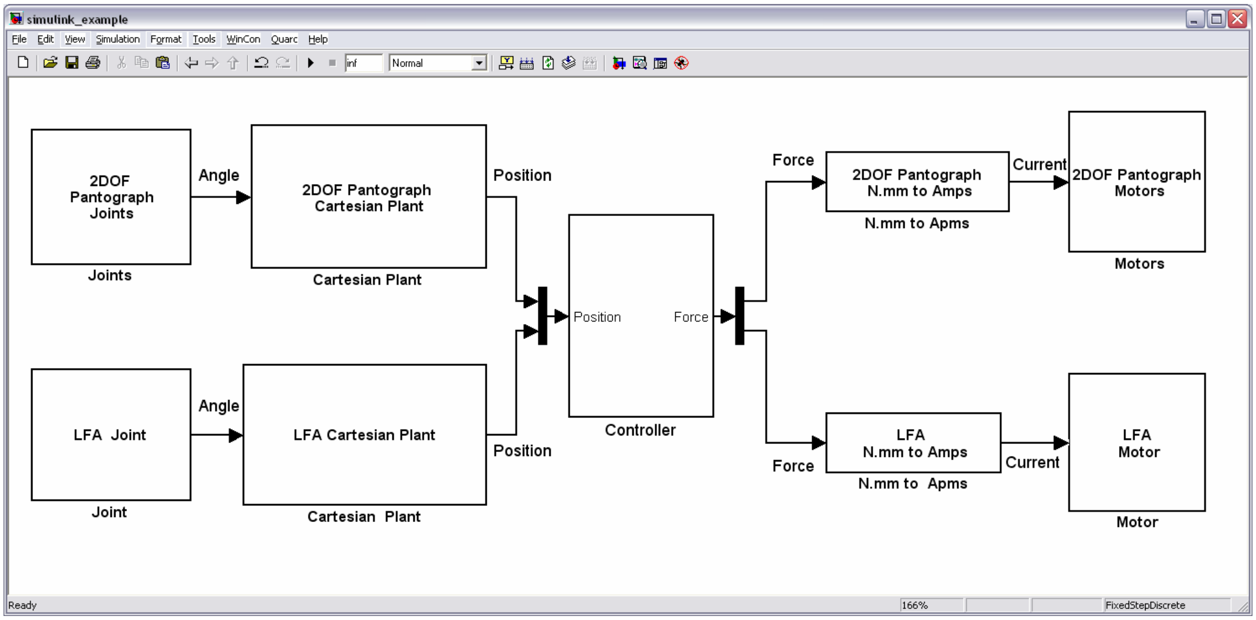

Fig. 3: An example of a Simulink model used for real-time control of robots. WinCon generates and runs the real-time, stand-alone and executable code for Simulink models.

5. LABORATORY EXPERIMENTS

5.1. Experiment I: Motion Planning and Position Control of the 2DOF Planar Parallel Robot

In some medical robotics applications, the robot must follow a desired trajectory in the task-space in order to autonomously or semi-autonomously execute certain predefined tasks such as cutting and milling of bones in orthopedic surgery, implanting radioactive seeds for prostate cancer treatment, or taking tissue biopsies (although the latter two could involve flexible needles as opposed a rigid mechanism used in these experiments). The first laboratory experiment is designed to expose students to some of the basic concepts in motion control. These include: i) planning smooth motion trajectories using polynomial curve fitting; ii) deriving forward kinematics, inverse kinematics, and Jacobian matrix of a robotic manipulator; iii) work-space motion control; iv) joint-space motion control; and v) motion control of redundant robotic systems. Lab preparation involves a take-home assignment in which students would derive the forward kinematics, inverse kinematics, and Jacobian matrix of the 2DOF parallel robot.

5.1.1. Part 1: Trajectory planning and control for a circular path:

The objective of this part of the experiment is to control the 2DOF robot such that it would complete a circular path as shown in Fig. 4 within a given task completion time t_f . Using polynomial curve fitting, smooth point-to-point trajectories are generated both in joint-space and work-space coordinates such that the initial and final velocities of the robot are zero. Proportional-Derivative (PD) feedback controllers are developed and implemented in both coordinates using the robot forward and inverse kinematics, as well as its Jacobian matrix. To investigate the effect of task completion time and the control gains on the system transient response and tracking errors, the experiments are repeated with a few different sets of parameters.

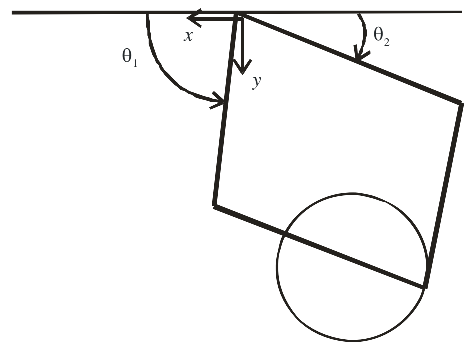

Fig. 4: Robot must follow a circular path in the workspace.

Figures 5 & 6 display block diagram implementations of the controllers in the Matlab/Simulink environment. In Figures 7&8, the results of experiments with the work-space and joint-space PD controllers with one set of parameters are given.

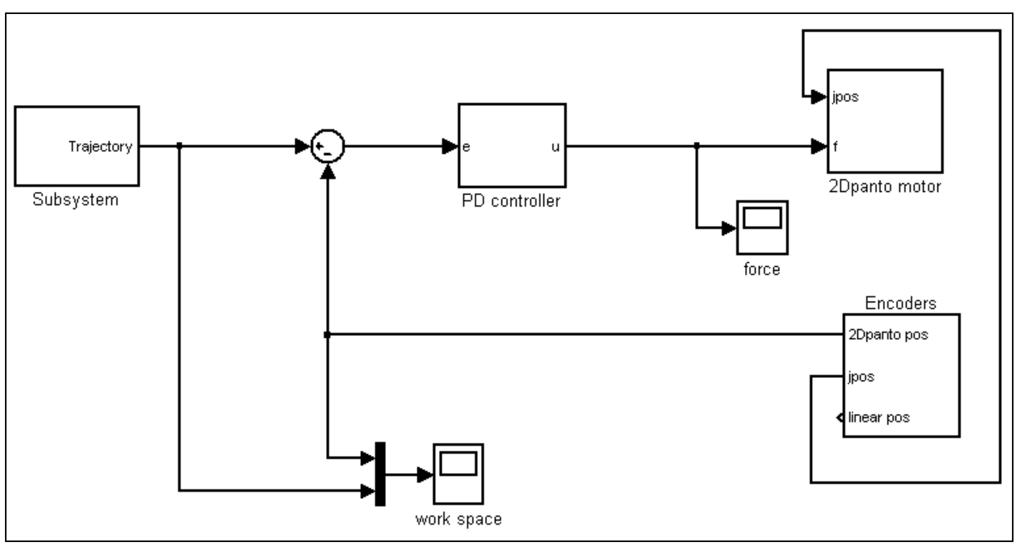

Fig. 5: Work-space motion control of the 2DOF robot.

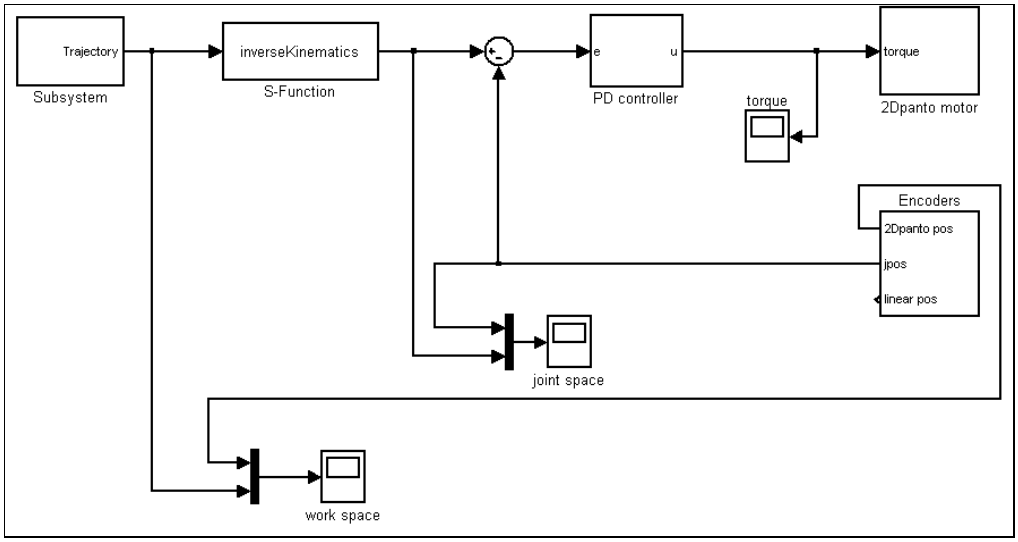

Fig. 6: Joint-space motion control of the 2DOF robot.

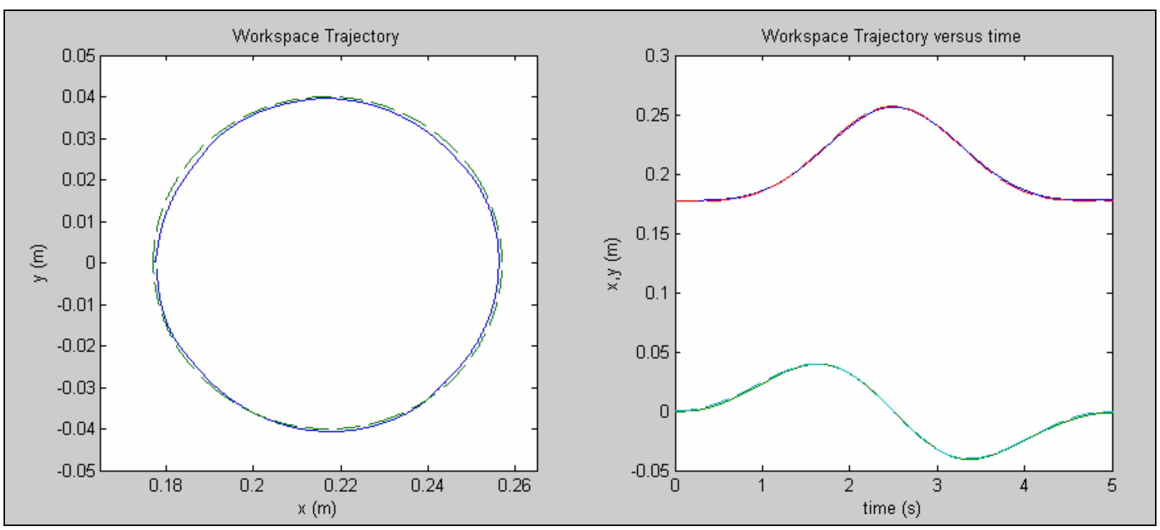

Fig. 7: Experimental results for work-space trajectory control; the dashed lines represent the desired trajectories.

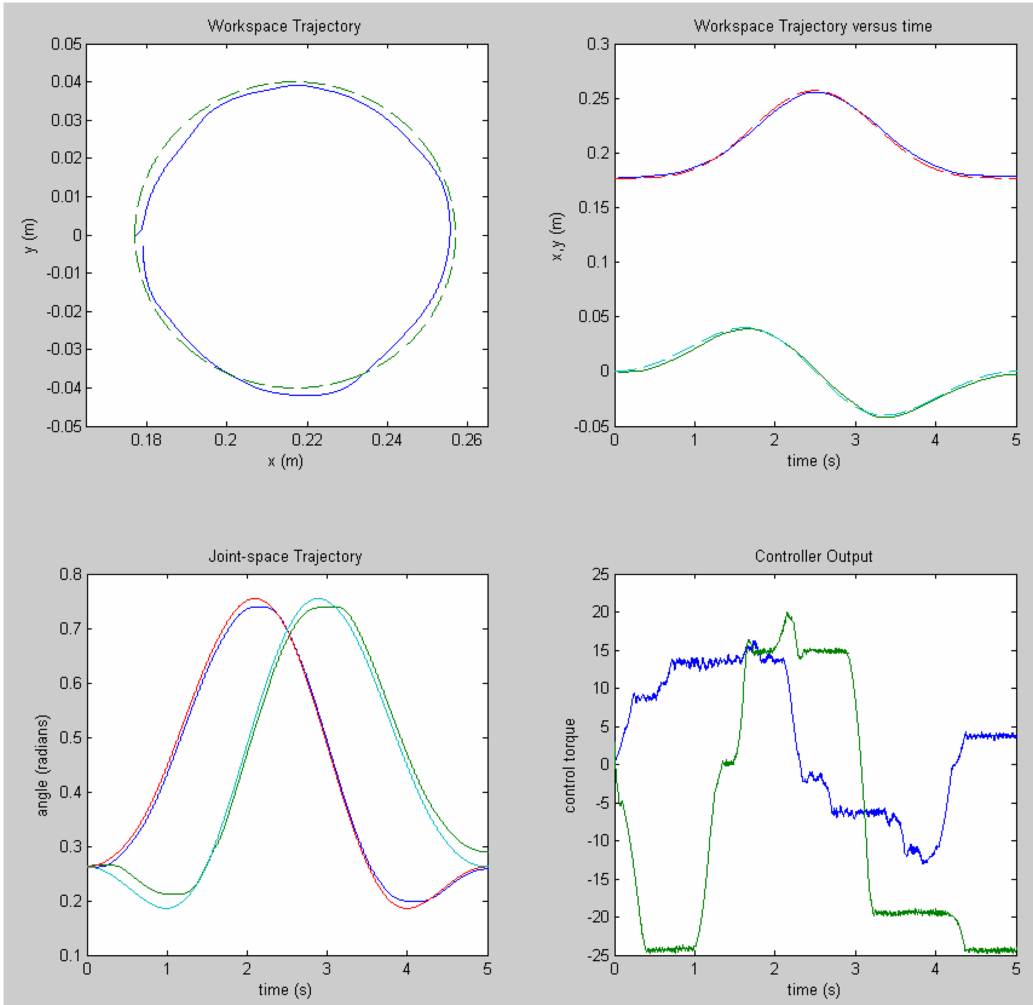

Fig. 8: Experimental results for joint-space trajectory control; the dashed lines represent the desired trajectories.

5.1.2. Part 2: Control of a robot with redundancy in force actuation:

In this part of the lab, the 2DOF parallel robot is attached to a linear 1DOF actuator as shown in Fig. 9. Due to a mechanical constraint, the resulting manipulator which has three actuators can only move along the *y* axis. Such parallel redundant mechanisms can be used in applications where a stiff mechanism with large output force is required, e.g. in orthopedic surgery. First, a relation between the generalized work-space and joint-space force vectors is derived in the form of a Jacobian matrix. Similar to Part 1, a smooth point-to-point trajectory for motion along the *y* axis is generated and a work-space PD controller is developed for following this desired trajectory. The pseudo-inverse of the force Jacobian matrix is used to map the one-dimensional work-space control force to the three-dimensional generalized actuator force/torque vector, resulting in a minimum-norm actuator force/torque solution. The block diagram of the control system and the results of one of the position control experiments are provided in Fig. 10 and Fig. 11, respectively.

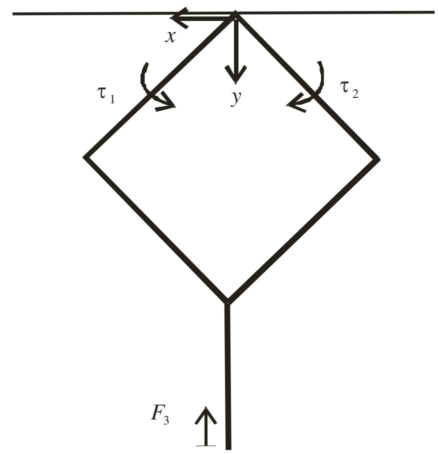

Fig. 9: Redundant parallel mechanism comprised of the 2DOF robot and the 1DOF linear actuator.

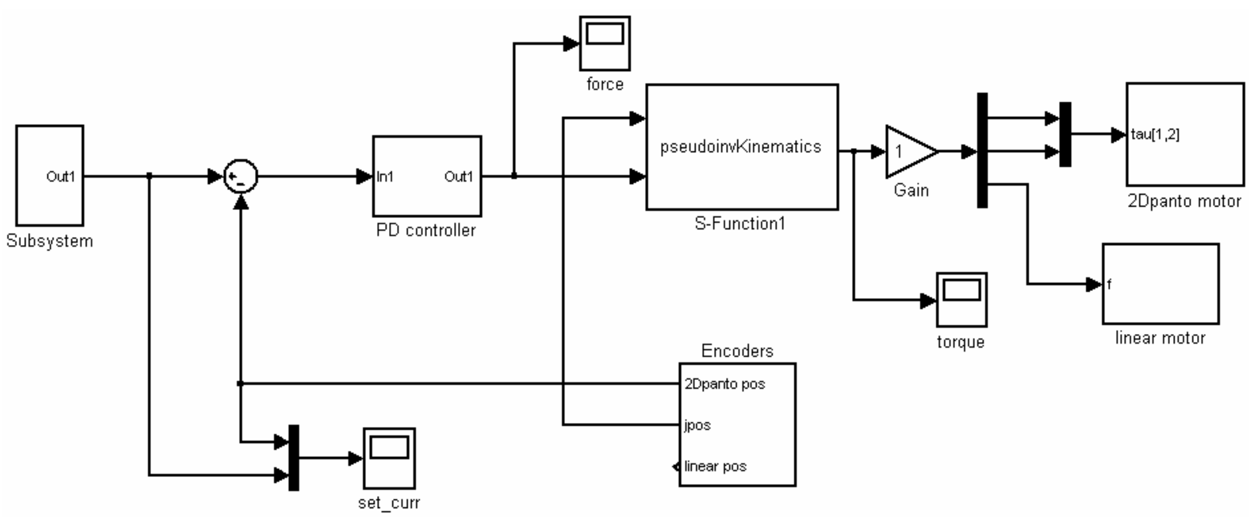

Fig. 10: Simulink block diagram for the control of the redundant parallel mechanism.

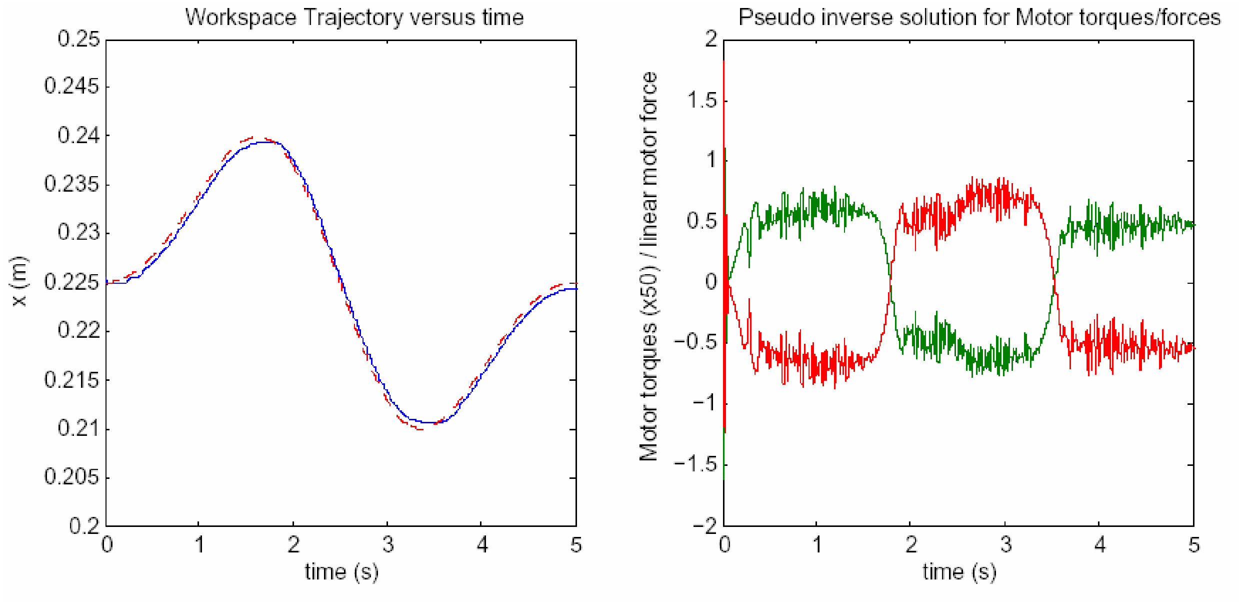

Fig. 11: Experimental results for position control of the redundantly actuated robot.

5.2. Experiment II: Contact Control for the 2DOF Planar Robot

In the first lab, controllers were developed for free motion control of the 2DOF robot. However, there are certain situations in which a medical robot may interact with an external environment. For example in skull milling or orthopedic surgery, a robotic instrument can make contact with the skull and bones. Similarly in robot-assisted ultrasound examination, the robot that holds the ultrasound probe needs to maintain contact with the patient's skin. Using motion controllers in such cases can result in excessive contact force and consequently potential tissue damage. The objective of these experiments is to allow students develop an alternative controller that can regulate the contact force between the robot and an external environment. A schematic of the experimental setup is shown in Fig. 12 in which the linear actuator, using a PD controller, is programmed to act as an environment with a known stiffness K_e and a viscous damping B_e.

In these experiments, the motion of the 2DOF robot is confined to the *x* axis by using a PD controller that regulates the robot position along the *y*-axis to zero. In the first experiment, a PD position controller along the *x*-axis is employed to move the robot from a starting point A outside the environment to a finishing point B inside the environment. This is to demonstrate that using a position control strategy in this case may result in excessive contact force due to contact with the environment. In the second part of the experiment, a contact force controller shown in Fig. 13 is implemented to control the contact force between the robot and the spring-damper environment. Fig. 14 illustrates the results obtained from one of the experiments where the use of the force controller given in Fig. 13 allows for tracking of a desired force profile specified by the user.

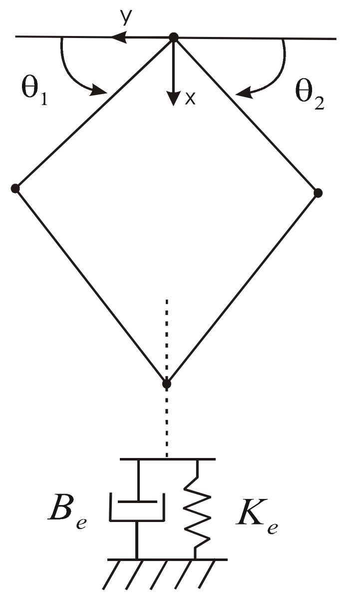

Fig. 12: Schematic of the experimental setup in the contact experiments.

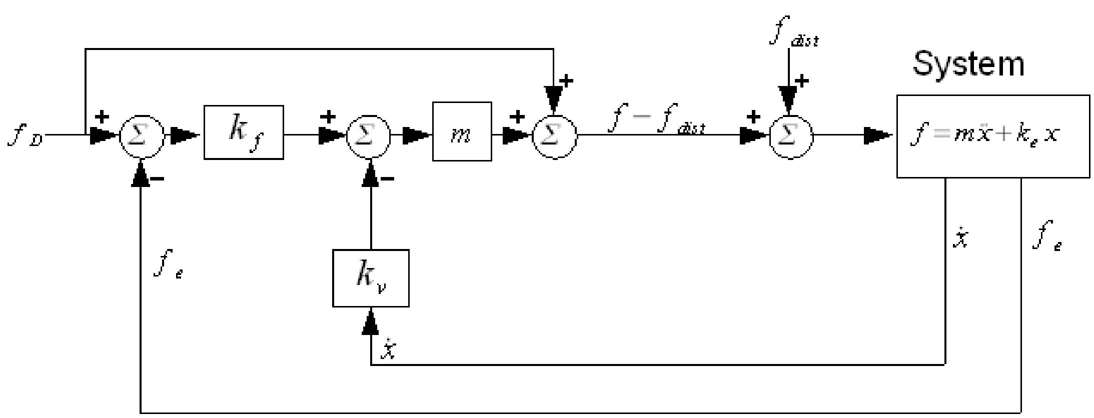

Fig. 13: Block diagram of contact force control system.

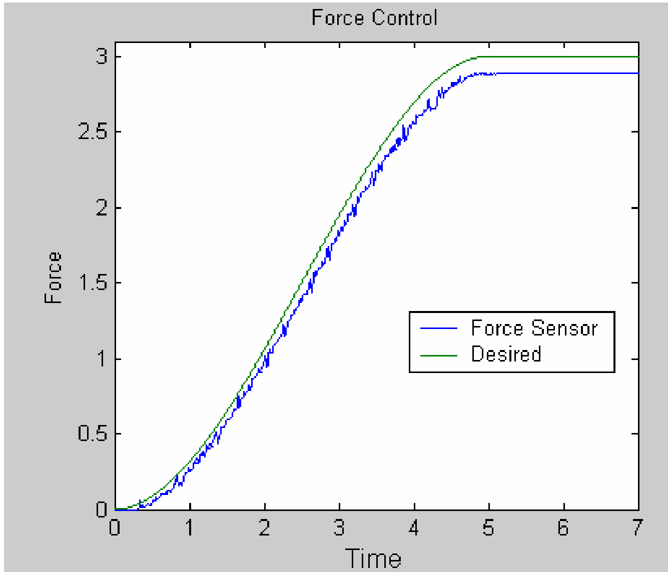

Fig. 14: Result of contact force control experiment. Note that the force measurement is not from a real sensor but rather is computed based on the output of the linear actuator controller.

5.3. Experiment III: Haptic Guidance for Robot-assisted Medical Interventions

Haptic devices are bi-directional human-machine interfaces (HMI) that can simultaneously provide a user with kinesthetic and force feedback while sensing the user's position and/or force inputs. A prominent application of this technology is in robotic and telerobotic assistive surgical tools, as well as in medical/surgical training simulators. In robotic surgery, the surgeon can use a force-feedback joystick to control the robotic arms and perform minimally-invasive or open surgery. In hand-held robotic assistive surgical tools, the force-feedback capability can guide the surgeon during the operation, e.g. by preventing him/her from entering sensitive areas of the body and potentially damaging the tissue during delicate neurosurgical operations. In medical training simulators, medical students and practitioners can enhance their operational skills by practicing on virtual patients while receiving realistic force and visual feedback clues. This experiment introduces the students to some basic concepts in haptic simulation and haptic guidance. The 2DOF Pantograph haptic interface is employed to interact with a virtual organ based on a computer model of the organ implemented in the Matlab/Simulink environment. To avoid entering a hypothetical sensitive region, a virtual barrier based on the concept of potential force fields is created.

5.3.1. Part 1: The virtual organ

The objective of this part is to create a virtual organ consisting of three parts, i.e. a soft outer membrane filled with viscous fluid, and a relatively rigid tumor as shown in Fig. 15.

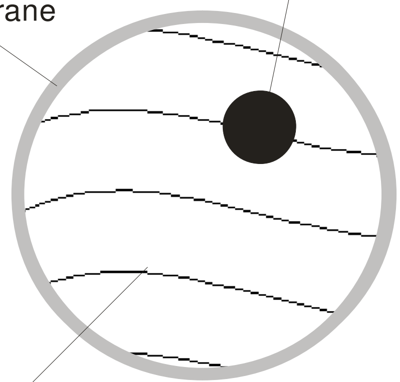

Fig. 15: The virtual organ.

(a) Model of the membrane:
The force of the haptic device upon entering the organ through the membrane is modeled by a simple linear spring based on the penetration depth along the radius (the force direction is also along the radius). If this force passes a predefined threshold, f_{tresh}, the membrane is pierced and the device enters region filled with fluid. Note that the device force is zero when its position is outside the organ.

$$f_{memb} = -k_m \delta r, \quad |f_{memb}| < f_{tresh}$$

(b) Model of viscous fluid:
Inside the organ, the device force is proportional to its velocity. This would create the effect of moving inside a viscous fluid, i.e.

$$f_{fluid} = -k_f v$$

where v is the device velocity vector in its workspace.

(c) Model of a stiff tumor:
A stiff spring-damper can be utilized to model the tumor. Note that similar to the case in (a), the direction of the reaction force from the tumor is normal to its surface at the contact point.

$$f_{tumor} = -k_t \delta r - b_t v .$$

All of the aforementioned models are implemented in the Matlab/Simulink environment using s-function blocks. The students employ the haptic device to explore the virtual organ and locate the tumor.

5.3.2. Part 2: Potential force field for haptic guidance

In this part, a repelling force field is created as a virtual barrier to prevent the operator from entering a critical region and accidentally damaging sensitive tissues as shown in Fig. 16.

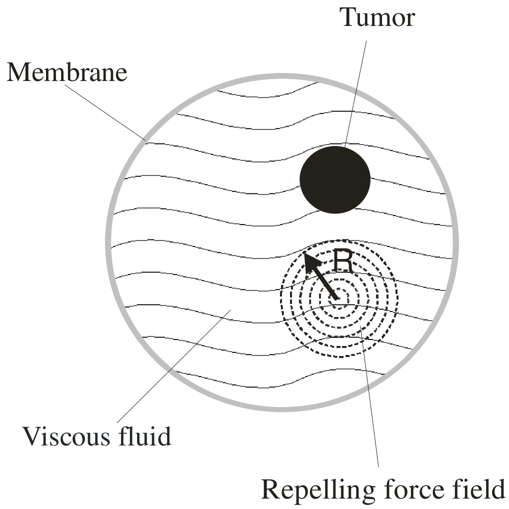

Fig. 16: The virtual organ with repelling force field for haptic guidance.

The force should increase as the haptic device approaches the center of the field. The following force law is used to implement the repulsive force field:

$$f_{repel} = \frac{k}{R^{\alpha}} \qquad \left|f_{repel}\right| \leq f_{\max},$$

where *R* is the distance of haptic point from the center of force field as shown in Fig. 16. An upper bound is placed on the force to prevent the application of large forces that might damage the device. A separate s-function is implemented for the haptic guidance algorithm in Part 2. The haptic exploration experiments in Part 1 are repeated with the repelling force field to assess the effectiveness of haptic guidance for robot-assisted medical interventions.

5.4. Experiment IV: Control Architectures for Teleoperation

In master/slave telerobotic systems, a human operator can remotely control a robotic arm in order to interact with a task environment. In this context, force-feedback haptic interfaces can be employed to reflect the environment force back to the operator, creating a sense of tele-presence. Applications of teleoperation are numerous, ranging from space operation, underwater exploration and mining, to nuclear and toxic material handling. In surgery, telerobotic systems assist surgeons in performing complex minimally-invasive or open surgical procedures while providing position and force scaling capabilities. In telesurgical applications, the surgeon can operate on the patient from a distant location allowing for delivery of critical healthcare services to remote areas with limited access to specialists. The basic elements of a bilateral teleoperation system are shown in Fig. 17 which includes the human operator, master robot, controllers and communication channel, slave robot, and the environment.

Fig. 17: A typical bilateral teleoperation control system.

The main objective of these experiments is to familiarize the students with basic teleoperation control architectures and their relative advantages and shortcomings in terms of performance and stability. Communication time delay is a major cause of concern in teleoperation systems in which the operator and environment are far apart. The effect of time delay on the performance and stability of telerobotic systems is also examined in this lab. The experiments involve a pair of the 2DOF Pantographs connected over a LAN using WinCon's real-time TCP/IP communication blocks. The 1DOF linear actuator is programmed to emulate a mass-spring-damper environment.

5.4.1. Unilateral teleoperation architecture:

In a unilateral teleoperation system, the position and/or force information are transmitted from the master site to the slave site but only visual feedback from the task environment is provided to the operator. Unilateral teleoperation is relatively easy to implement and is robust with respect to communication time delay. However, this approach suffers from the lack of haptic feedback which can be detrimental to the operator's perception of the task, particularly in robotic-assisted surgery/telesurgery. In this experiment, a workspace PD position controller is implemented at the slave side. The set point for this controller is master's workspace position which is transmitted over the network. In this configuration by moving the master robot, the operator can remotely control the slave robot but would not have any feeling of interaction with the task environment except through visual feedback. The master and slave control block diagrams are displayed in Fig. 18 and Fig 19. The results of a unilateral teleoperation control experiment are given in Fig. 20.

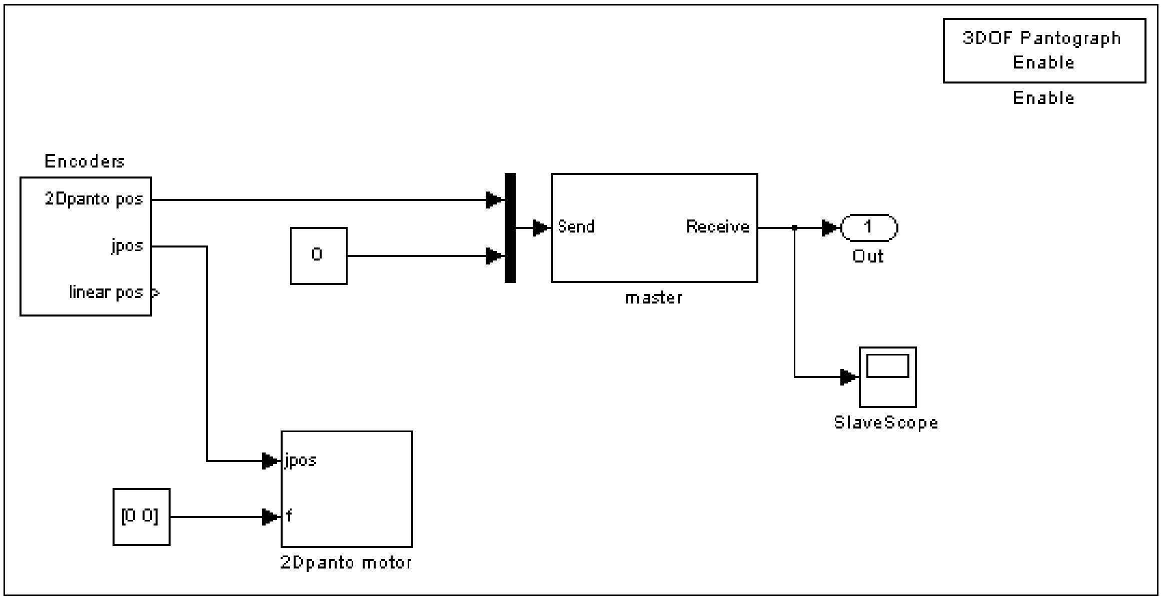

Fig. 18: Unilateral teleoperation controller at master side.

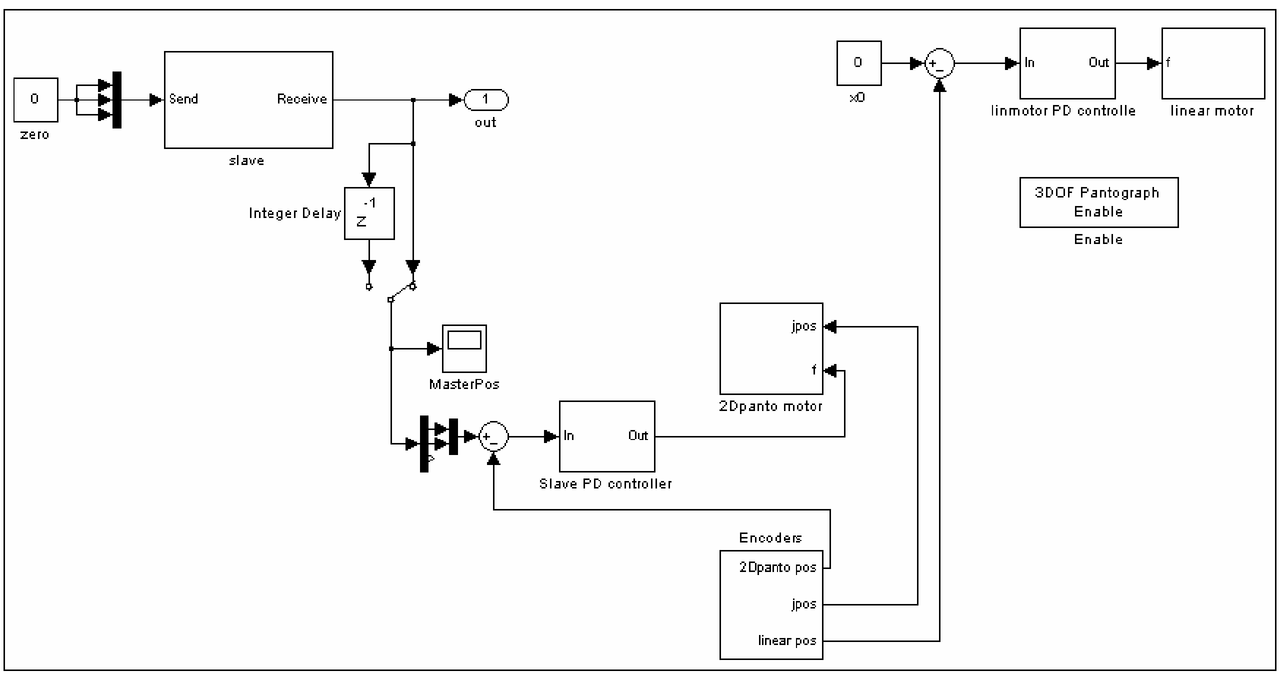

Fig. 19: Unilateral teleoperation controller at slave side.

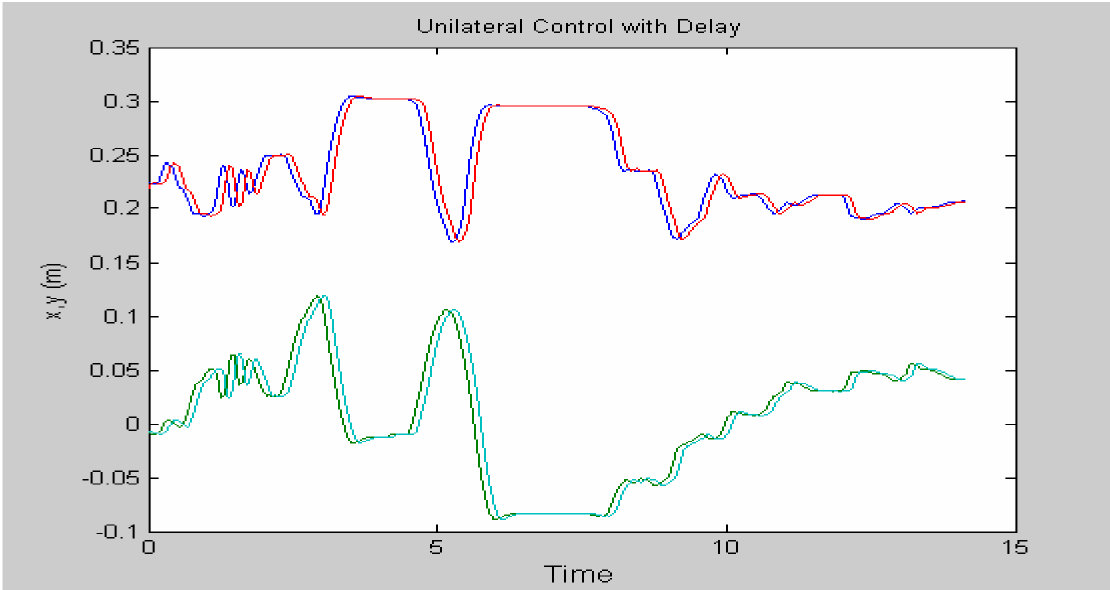

Fig. 20: The results of experiments with a unilateral teleoperation controller with a communication delay of 120ms.

5.4.2. Two-channel position-position bilateral teleoperation

In bilateral teleoperation, position/force data are communicated in both directions, i.e. from the master to slave and vice versa. A position-position teleoperation controller for the two 2DOF robots is implemented using PD position controllers at the master and slave ends. The reference trajectory for the master controller is the slave position (see Fig. 21) and the reference trajectory for the slave controller is the master position. The position signals are communicated over the TCP/IP network using WinCon's real-time communication blocks. The experiments are repeated for different sets of PD gains, i.e. (i) when the gains are the same at both sides (equal control authority) ; (ii) when the control gains are higher at the slave end (master has higher control authority); and (iii) when the control gains are higher at the master end (slave has higher control authority). The effect of communication time delay on the stability and performance of the teleoperation system is also experimentally investigated. The master and slave positions in *x* and *y* directions for delay-free and delayed bilateral teleoperation are plotted in Fig. 22 and Fig. 23, respectively.

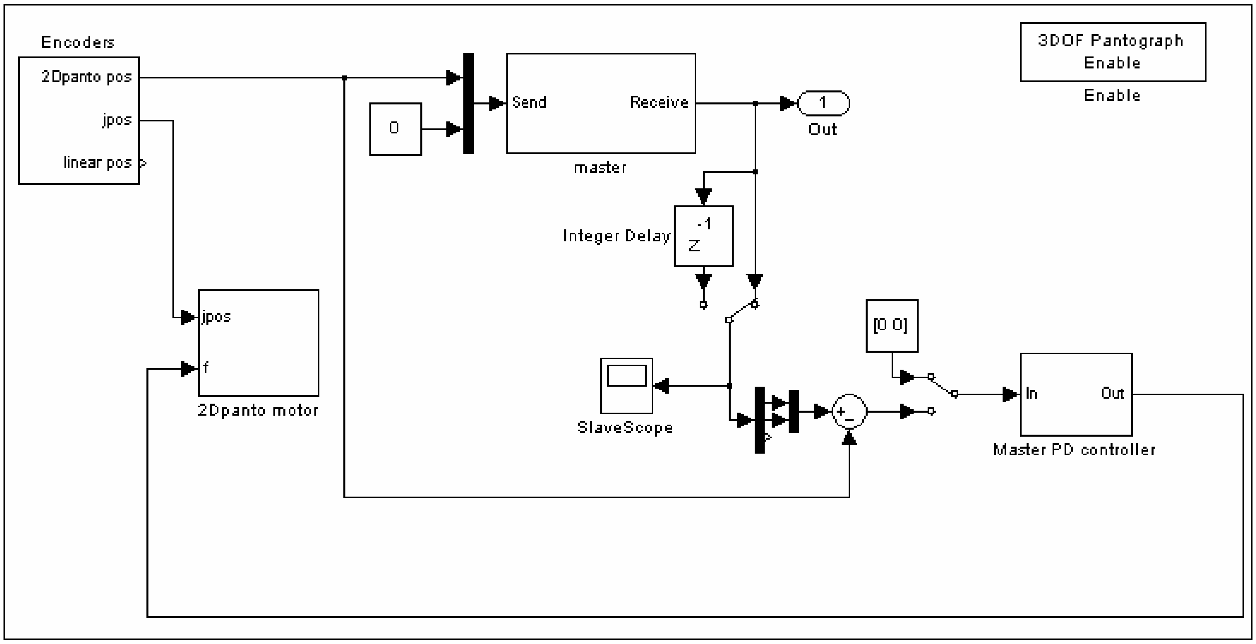

Fig. 21: Bilateral position-position teleoperation controller at master side (the slave side controller is similar to the one given here).

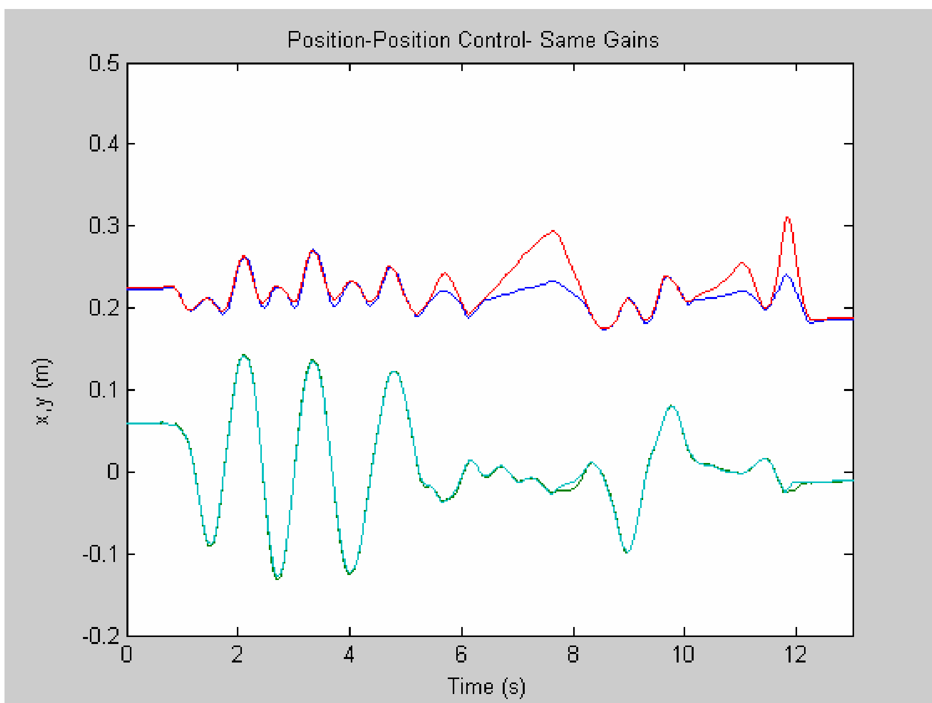

Fig. 22: Master/slave position tracking in delay-free bilateral teleoperation. Note that the position tracking error increases along the y direction as the robot comes to contact with environment.

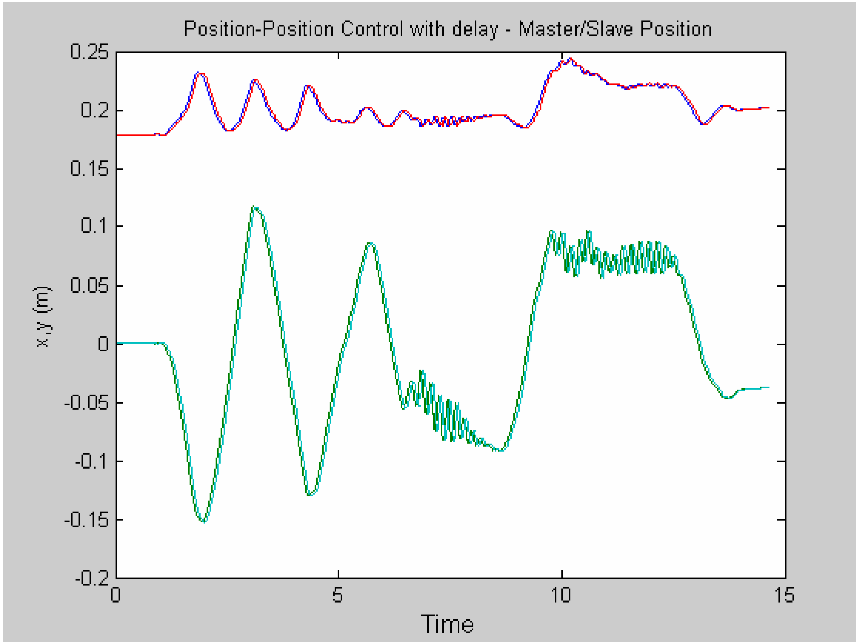

Fig. 23: Master/slave position tracking in time-delay bilateral teleoperation. Highly oscillatory response due to communication time delay can be observed.

6. Conclusions

This paper presented a series of laboratory experiments for biomedical engineering students to learn fundamental concepts in robotics and control theory as they relate to medical applications. These include principles of motion planning and control, force and contact control, haptic simulation, and telerobotic systems. Building on Quanser's robotics hardware and real-time control software technologies, an experimental platform is developed that allows for rapid development and implementation of hardware-in-the-loop experiments for learning basic as well as advanced concepts in medical robotic control systems. Four laboratory experiments developed based on this platform were discussed in the paper. Each lab experiment was motivated by relevant medical applications and contained details of the experimental procedure. The system can be easily configured by the user for other types of experiments than those discussed in the paper, if needed. Currently, a new experiment for real-time image-based robot control is being developed.

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