

CANADIAN VIRTUAL LABORATORY FOR TELE-EDUCATION IN AEROSPACE AND MECHATRONICS

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Abstract: Virtual laboratories and remote access to experimental hardware have become feasible with the advent of high-level web-based languages and communication protocols. In this paper, we introduce an international co-operation, the principal objective of which is to develop a Virtual Laboratory for tele-education and research in aerospace and mechatronics. The project involves several universities in Canada and Europe, each offering a test facility for the laboratory. The paper describes in detail the hardware, system architecture and experiments developed at one of the nodes of the Virtual Laboratory, the Planar Robotics facility at the University of Victoria. *Copyright © 2002 IFAC*

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1. INTRODUCTION

1.1 Motivation for Virtual Laboratories

Recent developments in the information and telecommunication technologies, and particularly the rapid expansion of Internet users, have enabled new opportunities for research and education (Shor, 2000). Of interest to this paper is the development of *virtual laboratories*, where equipment and hardware from universities around the world is linked via Internet, thereby allowing their remote use by students and researchers. Many users can thus share costly laboratory experiments, while limiting their investment to one of several available pieces of hardware. In this manner, a wide spectrum of educational tools is made accessible at a lower cost. Remote access to the same facilities can also benefit researchers working in a team spread over different continents.

A virtual laboratory can offer several advantages to *local* university users. It could allow them the opportunity to advance in the course material at their own pace, knowing that the laboratory equipment is available at any time, day or night. Completely computerised interface with the facility could also provide the user opportunities for viewing the experiment not available otherwise.

The *TEAM* project, *Tele-Education in Aerospace and Mechatronics*, sponsored by the Human Resources Development Canada and the European Union, was launched to develop such a virtual laboratory for use in tele-education and tele-research.

1.2 TEAM project

The objective of the *TEAM* project is to provide teams of international students and faculty staff with the opportunity to:

- develop an international virtual laboratory, specialised in aerospace control and mechatronics, with facilities spread over Canada and Europe;
- use this laboratory for tele-education in aerospace control and mechatronics;
- expand the laboratory to other fields of mechatronics and to other universities;
- foster, in the process, student mobility and cultural exchanges between Canada and Europe.

The three-year project is currently in its second year, in which the development of the Virtual Laboratory is to be completed and prototype demonstration of the experiments by partner universities is to take place.

1.3 TEAM partners

The current *TEAM* participants in Europe are the University of Bologna, the University of Siegen, the FH Ravensburg-Weingarten and Aalborg University. Experiments and facilities offered by these institutions include 'The GPS Navigation Laboratory', 'Control of Mobile Robots' and 'Satellite Attitude Control'.

The Canadian ensemble involves the University of Victoria, in British Columbia, the University of Toronto in Ontario and the Université de Sherbrooke

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in Québec. The Université de Sherbrooke's contribution to the Virtual Laboratory addresses the design, development and implementation of dynamic models, algorithms and software for the control of *mechatronic* systems. The educational objectives cover the full spectrum of control theory, from classical and modern optimal techniques to robust and neuro-fuzzy control. Research objectives include autonomous guidance, navigation and control, as well as failure detection and identification. Three experimental setups are currently at different stages of development at the Université de Sherbrooke: (1) a servo DC motor for classical control, (2) a three-dimensional, 10-state crane for state-space control and (3) a three-axis laboratory minisatellite for more advanced controller design and for research on space autonomy.

The group at the University of Toronto Institute for Aerospace Studies has developed an experimental facility for *network robotics*, which forms this university's node of the Virtual Laboratory. The global research objective is to develop network-robotics technology for space exploration. The facility consists of six mobile robots (Barfoot, *et al.*, 2001), shown in Figure 1, which communicate with each other and a desktop computer via radio modems. The research focus is on the autonomous control of such a network. A number of experiments have been demonstrated locally using the network of robots. For example, one experimental test is the task of *formation* (Earon, *et al.*, 2001), where the robots are to organise themselves in a given pattern, without being directed to any particular place in the pattern. Pattern formation would be needed in a space-exploration context when, for example, deploying a large antenna array consisting of dipole units.



Fig. 1: The fleet of rovers at the University of Toronto

1.4 Objective of the paper

This paper will describe in detail the robotics facility at the University of Victoria (UVic), the educational objectives for that test-bed and the tele-education experiments that are currently provided at the UVic node as part of the TEAM international laboratory.

2. ROBOTICS LABORATORY AT UVIC NODE

2.1 Overview and Objectives

The University of Victoria's node of the Virtual Laboratory is centered around the Planar Robotics Test-bed. This facility is used to support research in dynamics, motion planning, control and parameter identification for space robotics manipulators. The test-bed, in existence since 1994, has been recently upgraded to allow completely electronic operation in order to enable Internet-based access to the experiments as part of the TEAM Virtual Laboratory. At present, the facility houses a three-degree-of-freedom robotic manipulator driven by Harmonic Drive (HD) actuators and supported on a large glass-covered table. Two other arms are also available, one serving as a dual to the HD arm, but actuated with Direct Drive motors (Nahon, *et al.*, 1995). The third manipulator, a Small Articulated Robotic Arm, was designed for experimentation with macro-micro manipulators (Van Vliet and Sharf, 1998).

As part of TEAM, the facility will continue to be used as an experimental tool for research in dynamics and control of robotic systems for space applications. In the short-term, the test-bed will support ongoing investigations in robot control and parameter identification for constrained robotic operations. As an educational tool, the robotic arm can be employed to demonstrate performance of impedance and force control strategies for contact operations. The data collected from the experiments can be post-processed with a variety of signal processing techniques to identify environmental stiffness and damping. Long-term objectives include:

1. Usage of multimedia and Internet technologies to enhance education in dynamics, control and parameter identification for robotic systems.
2. Expansion of laboratory capabilities to allow users to experiment with own control strategies and maneuvers.
3. Expansion of the virtual laboratory to include experiments with free-floating systems, cooperating robots, and macro-micro manipulators.

2.2 Description of the Test-bed

Manipulator: Figure 2 shows the present configuration of the test-bed with the three-degree-of-freedom Harmonic Drive (HD) arm and a special-purpose fixture. During operation, the elbow and wrist joints float on air-pads over the table while the base joint is vacuumed down to the table. The arm is equipped with a custom-designed end-effector featuring a remote centre of compliance device, a force sensor and a peg (see Figure 3). The former was developed for peg insertion tests conducted in a previous project (Van Vliet, *et al.*, 2000). For the contact parameter identification experiments, a bearing was mounted at the tip of the peg to minimise frictional effects during contact. The force sensor located at the base of the peg (Figure 3) contains three identical load cells, supported in a frame, with a range of ± 333 N.

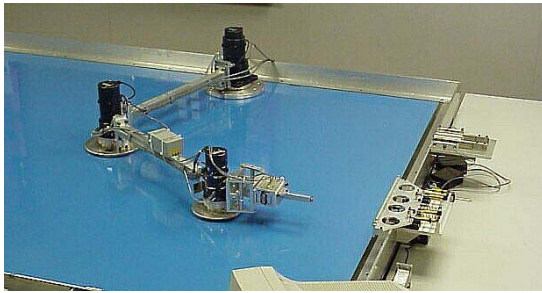


Fig. 2: Photograph of the test-bed

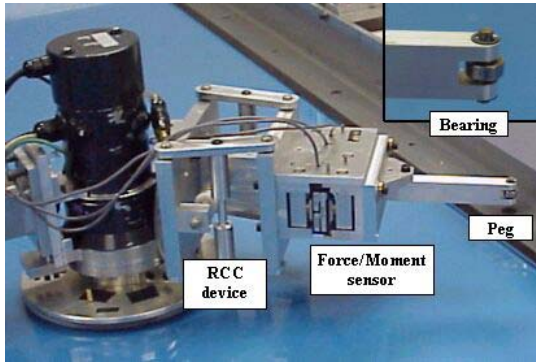


Fig. 3: Photograph of the end-effector

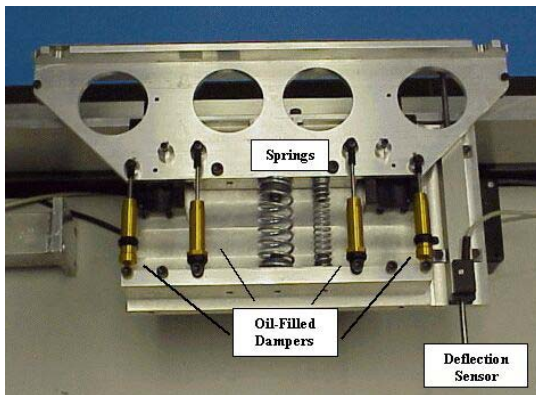


Fig. 4: Photograph of the wall fixture

Wall fixture: A flexible wall (Figure 4) is used in the experiments to produce linear mechanical impedance resulting from its mass, stiffness and damping. The wall, mounted on the edge of the table, moves on linear bearings, and includes two modular springs and oil-filled dampers. By changing the springs and dampers, it is possible to alter the values of the impedance. The wall fixture also includes a linear potentiometer, which measures the deflection of the wall in a range of 10 mm with resolution of 0.1mm.

Control Hardware: The arm is controlled by a PC computer via a series of motion control and interface boards. QNX operating system is used to execute the control/interface software written in C/C++. A block diagram of the manipulator, the control system and the sensors is shown in Figure 5. The interface boards include:

- two motion-control boards (MFIO3-A) to provide full control of the motors. They contain three channels of 16-bit D/A, three quadrature encoders(A/D), interval and watchdog timer.

- the digital/analog converter, CIO-DAS6402/16, to measure the forces on the peg and deflection of the wall.
- one digital I/O board, CIO-DIO48, to regulate air/vacuum generation.

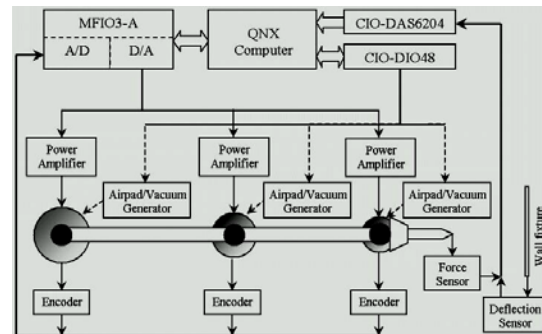


Fig. 5: Block diagram of the HD Robotic Arm

System architecture for remote access: The architecture shown in Figure 6 presents an overview of the setup of the virtual laboratory. Two workstations, communicating via a socket server are used in our facility. The QNX Workstation runs the real time control software of the robotic manipulator and is used exclusively for this task. To provide the remote user with a visual feedback of the experiment, a video camera, QuickCam Pro from Logitech, was installed on the test-bed. The second workstation executes the video- and Web- servers to communicate with the remote user.

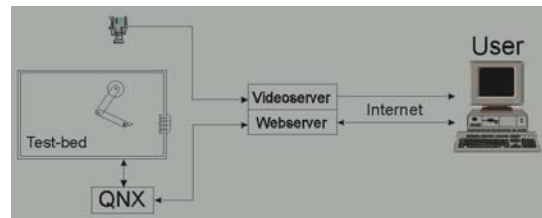


Fig. 6: System architecture

The videosever receives the video data stream recorded by the video camera, and distributes the signal to appropriate users. The Webservice contains Web pages of the Virtual Laboratory which present the information about the test bed and the experiments. The Webservice also handles the communication between the user and the QNX station via a Java servlet. This overall architecture allows the user to gain remote access to the experiments by using a standard Web browser with enabled Java Virtual Machine.

3. CURRENT EXPERIMENTS

3.1 Control and Parameter Identification for Constrained Robotic Tasks

3.1.1 Objectives

The experiments offered for the TEAM Virtual Laboratory demonstrate a simple constrained robotic task. The tests involve bringing the arm in contact with a special-purpose fixture, acting as a flexible

wall. During the experiment, data is collected from joint encoders, the force sensor on the arm and the linear potentiometer on the wall. The main objectives of the experiments are:

- to demonstrate a constrained robotic maneuver where the manipulator comes in contact with a 'generic' environment;
- to demonstrate the performance of two controllers typical of those employed in constrained robotic operations: pure position (impedance) control and force tracking impedance control;
- to use the data collected during the experiments to identify environmental stiffness and damping;
- to illustrate the effect of persistent excitation on the quality of parameter identification.

3.1.2 Theoretical Background

Environment Model: For the present experiments, the following linear model of the environment is assumed:

$$F_e = K_e(x_e - x) + B_e(\dot{x}_e - \dot{x})$$

where F_e is the contact (normal) force, K_e and B_e are the environmental (contact) stiffness and damping, x_e and x are the location of environment and manipulator, respectively. More sophisticated, nonlinear models of the contact force are available in literature (Marhefka and Orin, 1999), but not used here in order to simplify the identification task.

Control Strategies: Two control strategies are available for running the experiment: position-tracking (Love and Book, 1995) and *force-tracking impedance* controller (Seraji and Colbaugh, 1997). Conventional *impedance* control (Hogan, 1985)---a popular strategy for constrained robotic operations---suffers from its inability to directly control the contact force. Instead, the contact force results from the target impedance dynamics reference trajectory and environmental properties. At the same time, a *force* control strategy is beneficial to ensuring stable contact with the environment. Accordingly, *force-tracking impedance* controllers command the robot to exert a specified contact force on the environment.

The block diagram for the position-tracking controller is shown in Figure 7. The reference trajectory used in the impedance filter for both strategies commands the peg to penetrate the wall fixture resulting in robot-environment contact. During the contact phase, a desired force $F_d=50N$ was specified for the force-tracking controller. The target impedance coefficients used in the force tracking and position tracking algorithms are set to: $M_t = 5$ kg, $B_t = 100$ kg/s, $K_t = 500$ N/m, for mass, damping and stiffness respectively.

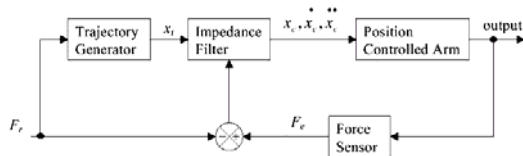


Fig. 7: Block diagram of the position-tracking algorithm

Persistent Excitation: In specifying the experiment, the user can also choose whether to run the experiment with or without persistent excitation. It has been established that accurate damping estimation can be guaranteed only with a persistently exciting reference signal. A common approach to create such a signal is by adding several sinusoidal signals with distinct frequencies. In the present case, we wish to identify two unknown parameters (contact stiffness and damping), and hence only one non-zero frequency is required.

Two types of persistent excitation are employed in our experiments: sinusoidal and white noise. The latter is simulated by using a pseudo-random binary sequence (PRBS). For the sinusoidal excitation, a persistently exciting input to the force-tracking controller was defined by adding a small amplitude sinusoid to F_d to give $F_r = F_d + 8 \sin(20t)$. For the position-tracking scheme, the persistent excitation is added directly to the desired trajectory, giving $x_r = x_d + 0.02 \sin(20t)$.

3.1.3 Description of the Experiment

Remote access to the facility is gained through the Control Window, implemented with Java applets (see Figure 8). The window is password protected and can be accessed by one user at a time. The control interface includes a Java applet which displays the live video of the testbed (upper left corner) and another Java applet to give the user remote access to the manipulator. The latter offers a choice of several experiments with different types of constrained manoeuvres. In particular, one can choose among two control strategies (trajectories) and types of persistent excitation, as described in Section 3.1.2. The user can specify a sample frequency for the experiment and a cut-off frequency used to filter the experimental data. After selecting appropriate parameters, the user would execute the experiment by activating the 'run' button.

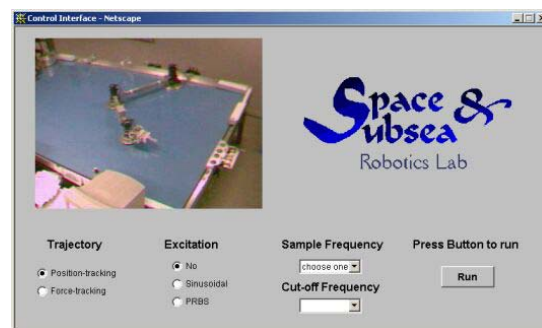


Fig. 8: Control window for remote access

A typical maneuver demonstrated in the Virtual Laboratory involves the following stages. First the arm is 'homed' by moving it against the far railing of the table. Subsequently, the arm is moved to its initial position with the peg touching the wall fixture. This is followed by a brief withdrawal of the arm from the wall, then an approach when the arm touches the wall, stays in contact with the wall and withdraws from the wall again.

3.1.4 Results

The measurements collected during experiment are saved in binary format in a file available for download. The variables saved at a sampling rate specified by the user include joint angles, commanded joint torques, axial and lateral components of the contact force, the displacement of the wall, reference trajectory and reference force (if applicable). The data collected during the experiment can be downloaded after its completion and processed by the user to meet his/her educational or research objectives. For example, the user may analyse the data with a variety of estimation techniques, such as Kalman filter or Recursive Least Squares procedure. Matlab code to read the data is provided on the laboratory web pages. A sample of joint angles, velocities, torques and contact force during a position-tracking experiment is shown in Figure 9.

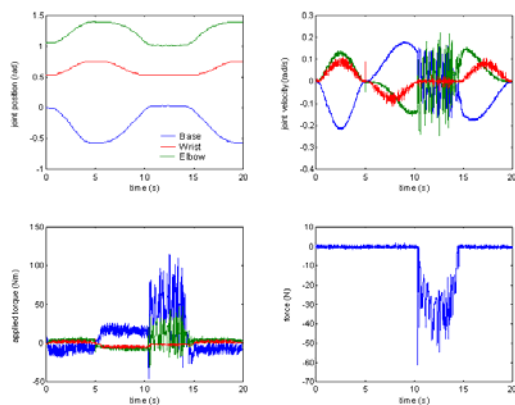


Fig. 9: Example of experimental joint positions, velocities, torques and contact force

4. FUTURE GOALS AND DEVELOPMENTS

The UVic node of the virtual laboratory described in this paper is presently operational and available for remote access. A number of enhancements, however, are envisioned to improve the quality and functionality of the remote access, the feedback to the user, as well as the number and variety of experiments offered in the laboratory. These are briefly described below.

Experiments with the robotics test-bed are presently not available around the clock because of the mechanical limitations of the air-flow system used to float the air pads of the manipulator. Since round the clock access is required, the air system will have to be modified to remove these limitations.

Several additions are planned to augment the feedback to the remote user. These include sound feedback, real-time data transfer and plotting, and advanced visual feedback. The latter would be accomplished by implementing interactive communication between the user and a dedicated

camera-pointing device and possibly the use of multiple cameras.

One essential feature for the *researcher* using the robotics test-bed is to have autonomy to develop and implement his/her control algorithms. Thus, functionality will be added to the laboratory interface to allow the users to download their controllers and test them on the facility. Needless to say, additional security measures will have to be implemented to prevent damage to the facility.

Finally, several new experiments can be integrated into the virtual laboratory from the repertoire of experiments conducted with the facility previously or developed afresh. Some of the possibilities are: peg in hole insertion tests, experiments in flexible-link manipulator dynamics and control, active damping experiments with macro-micro manipulators and control of cooperating robots.

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