Remote laboratories on motion control systems

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ABSTRACT: Remote and virtual laboratories are gaining prominence as an effective access tool in engineering and technology education, often with unique and expensive equipment being available 24/7 from any location on the globe with Internet access. Those remote facilities are increasingly shared between educational, research and industrial institutions. This article discusses one of the specific areas of remote laboratories that involve not only a simulated user environment, but also real electromotion/electrical machines and drive setups that are accessed remotely to enable experiments on the real hardware, performed over a thousand kilometres away from the physical location of the equipment. Several remote control laboratory solutions of motion control systems are reviewed. They are contrasted with the system originally developed at the University of South Australia (UniSA), Adelaide, Australia, that offers a versatile reconfigurable remote experiment environment to conduct control experiments including the sophisticated H-infinity control used among others in the space exploration, and never before used in the classical remote laboratories.

INTRODUCTION

The Internet has provided tertiary and secondary education with the opportunity to develop innovative learning environments. The teaching and learning of practical skills has gained a new dimension with the emergence of remote laboratories. Remote laboratories allow students to perform experiments on real equipment remotely via the Internet. The rapidly growing number of remote laboratories (RLs) worldwide is the evidence that the educational community has recognised their potential to develop into a creative, flexible, engaging and student-centred learning environment. Even a brief review of the existing RLs shows the wide diversity in their structure, design and implementation. However, their real potential is yet to be discovered.

Recently, there has been a strong tendency among universities to share their RLs on the global computer network. This creates an opportunity for students to access a range of equipment and experiments giving them previously unprecedented flexibility and learning opportunities. Furthermore, RLs offer students an opportunity to collaborate with students from other countries and enrich their cultural experience and on-line collaboration skills. As a computer supported learning environment RLs can be integrated with virtual learning tools.

TECHNICAL SOLUTIONS IN CONTROL LABORATORIES

In this section, the focus is on the most representative hardware and software solutions used in remote motion control systems laboratories. The laboratories are usually quite complex and require sophisticated hardware and software solutions.

Rapid Control Prototyping System (RCP) DSP-2 [1] uses TI TMS320C32 floating point processor, Xilinx FPGA (Field Programmable Gate Arrays), motor control set-up, including pulse width modulation (PWM)) generator, A/D and D/A converters, controller area network (CAN) bus. In terms of software, it applies MATLAB/Simulink for the development of control algorithms and simulations, as well as LabVIEW VIs and a server. A variety of control experiments can be conducted.

Rapid Development System PACM [2] uses dSPACE real-time simulated and hardware environment. MATLAB/Simulink platform for modelling allows conducting a variety of on-line tests and analysis of control algorithms (PID, fuzzy logic and neural network) for a brushless DC BLDC motor.

Remote Laboratory for Multilevel Power Converters [3] employs a line-side converter with a direct vector and synchronous current control. Sinusoidal, space-vector or third harmonic PWM are used. Process integration (PI) parameters for adjustment of the DC-bus and current controllers, phase-locked loop (PLL). Conducted experiments include: control without passive load, reactive power compensation and control with passive load.

The Power Electronics Laboratory [4] applies mobile power electronics test beds; electronic devices and sensors, needed to study motion control circuit design and control strategies; range of instrumentation devices, NI DAQ. Data analysis, waveform generation, signal observation and formula calculations with LabVIEW VIs. MATLAB software tools for simulation and analysis, are also used.

The tele-operated BLDC Controller [5] has symmetrical PWM with Synchronous Sampling SPSS; full four-quadrant control and phase switching of the Insulated-Gate Bipolar Transistor IGBT bridge. It allows for control of a tele-operated robot for manual driving of a nuclear fuel handling machine.

Web-accessible control of permanent magnet synchronous motor (PMSM) [6] is demonstrated by direct torque field programmable gate arrays (FPGA) controller with soft power supply unit (PSU); PMSM motor. Java applets for the control panel and for remote control are on the software side.

Remote Laboratory for Teaching PWM Techniques [7] uses practical experiments with the three-phase IGBT inverter. It features multimedia presentations and simulations of carrier-based PWM and space-vector modulation for two-level converters.

Virtual Laboratory for Low Power Electrical Drives [8] has three test benches for control of DC, BLDC and stepper servomotors; feedback devices: incremental optical encoder, absolute encoder, DC tacho-generator and rotor position device. NI PCI-7534. LabVIEW environment is implemented to a motion control system using the FlexMotion library with proportional-integral-derivative controller PID and PIV (proportional position loop integral and proportional velocity) servo control topologies.

Distant Laboratory for Teaching Industrial Electronics is the working principle of the resolver as a rotor position measuring device and the phase relationship between excitation input signal and Sin/Cos output signals [9][10].

Power Engineering and Motion Control Web Laboratory [9] is using identification, modelling and analysing a mechatronic control system. MATLAB/Simulink is used for simulating dynamic models. Experiments are represented with LabVIEW VIs. PD and computed torque controller designs are applied in an experiment of mechanism with spring.

PEDAGOGICAL APPLICATIONS OF LABORATORIES FOR MOTION CONTROL SYSTEMS

The pedagogical applications of the remote control systems laboratories mentioned in the preceding section are reported here. It is obvious that there is a continuing investment into the remote laboratory facilities nationally, regionally and world-wide, seen as a new vehicle in the engineering and technology education at any location.

The conceptual approach allows rapid prototyping of new engineering systems. Rapid development architectures are introduced by Hercog et al [1] and Yang et al [2]. Power electronics experimentations are presented by Rodriguez et al [3] and Williams et al [4]. A tele-operated BLDC and PMSM motor controllers are introduced by Chang-Hwan et al [5] and Hoshi et al [6]. The theory and practice of Pulse-Width Modulation (PWM) principles, as part of the Electrical Drives and Power Electronics course, are discussed by Kaminski et al [7]. A comprehensive platform with particular attention to a DC motor servo system with controlled motor load, is demonstrated by Baluta et al [8]. A work introducing experiments with feedback devices for motion control is described by Wolbank et al [10][11]. A mechatronics motion control and hardware-in-the-loop simulations laboratory is presented by Rojko et al [9].

UNISA MOTION CONTROL LABORATORY

The remote laboratory for motion control developed at the University of South Australia is a complex mixture of hardware, software and control solutions [13-15]. The hardware is essentially the laboratory workbench consisting of various moving mechanical parts, sensed and controlled by electronic devices. The controller is the mathematically synthesised feedback control algorithm, adapting several H-infinity control techniques and utilising a precise model of the plant. The software is the interface connecting the end users remotely and providing the means of interaction with the mechatronic device. However, its main and most complex function is the hard real-time implementation of the controller (the control algorithms) into the embedded computer.

Hardware Solution for the Workbench

Uniqueness has been one of the main challenges during the development of the remote laboratory. A hardware solution was found (a combination of mechanical and electronic devices), which has not been applied in a remote laboratory beforehand. The workbench, shown in Figure 1, replicates a motorised axis, which is widely used in industrial systems, CNC machines and robots. It is flexible and allows easy changes in its configuration and, hence, different control experiments can be implemented in a convenient manner. Therefore, the proposed experimental structure is a sound and effective way for practicing of control systems engineering and electromotion.

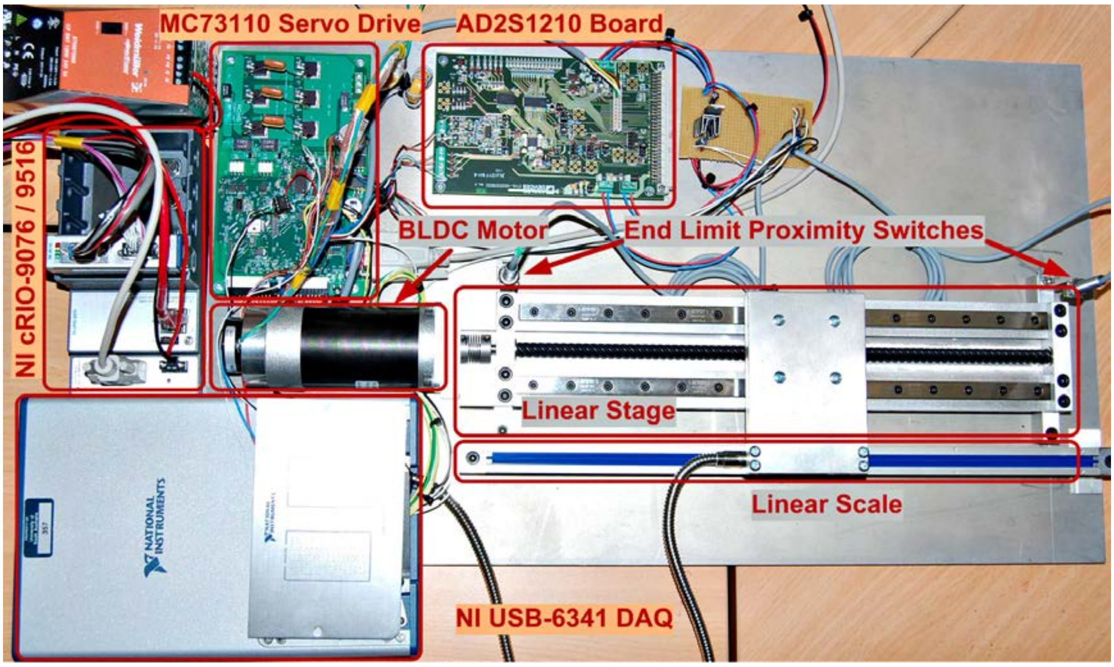

Figure 1: Hardware utilisation of the remote laboratory.

The following hardware components were used to utilise the functionality of the workbench:

- A 12-inch linear stage with helical coupling and anti-backlash lead-screw assembly;
- A brushless DC four-pole motor with sinusoidal BEMF;
- An FPGA-based high performance stand-alone motion controller PMD MC73110 [12]. The high performance motion controller MC73110 was chosen as the best option, since it incorporates all the needed internal blocks to work as a stand-alone servo controller. It can utilise either trapezoidal or sinusoidal type of control, depending on the chosen motor, and has inputs for velocity, position and commutation feedback signals. Further, the operational modes are complimented by field-oriented control. A diagnostic and setup interface was created in NI LabVIEW environment, which shows/initialises over 120 profile commands/parameters needed for the normal operation of the servo controller. Thus, users/students can benefit from the extended flexibility and functionality of the interface and learn servo-motion practices in depth;
- A full-bridge low-voltage inverter;
- An integral real-time controller with industrial processor and robust real-time operating system for control, data logging and analysis - National Instruments cRIO 9076 [13]. It utilises a stand-alone flexible embedded architecture with real-time operating system capable of execution of deterministic LabVIEW applications. Its main advantage is the integrated reconfigurable FPGA core;
- A precise motion control servo drive dual-encoder interface, supporting position and velocity control loops;
- A high speed, multichannel, multifunctional USB data acquisition board with advanced timing and triggering. It played an important role for high speed signal acquisition and monitoring, system identification of the dynamic system and model validation, and experimental control of the workbench. However, it proved not to be applicable for real-time advanced H-infinity control;
- A precision optical linear scale, providing a position feedback from the linear stage via incremental encoder interface, and a rotor-excited resolver for rotary position feedback;
- A complete 10-bit to 16-bit resolution tracking resolver-to-digital converter providing all interface signals;
- A contactless magnetic rotary encoder for accurate angular measurement for additional devices/axes.

System Identification

For the purposes of system identification and control experimentations, there are a number of excitation signals which are easily applicable on the motorised linear stage. They have to allow the moving table to be kept around a certain start point (usually the middle of the linear stage) and protect the mechanics from destruction. Namely, they are:

- *Square pulse signal* - it initiates a rapid wide range motion into a pre-defined range in positive and negative direction, finishing at the start position, and allows excellent signal to noise results to be achieved;
- *Pseudo-Random Binary Sequence (PRBS)* - a deterministic periodic sequence varying between two levels at multiples of an internal clock period, also exhibiting a good S/N ratio while exciting wide frequency range;

- *Swept-sine (periodic chirp) signal* - it allows the amplitude and frequency response of the system to be examined for a wide range of frequencies while at the same time the power is spread equally in the range.

For a proper filtration and smoothing of the signals of interest (e.g. the instantaneous current and quadruple encoder signals), a finite impulse response (FIR) Savitzky-Golay low-pass filter was employed [14]. It showed excellent waveform shape replication with zero phase-shifting, preserving the shape and height of the waveform peaks. Failing to do so may result in high model orders and inappropriate description of the dynamic system.

Furthermore, in order to avoid unnecessary high model orders and to achieve the closest possible model description, a methodology of a model prediction was favoured and a Box-Jenkins parametric model prediction was successfully applied. The adequacy of the results was reaffirmed with rigorous application of several model-validation techniques: residual analysis (auto-correlation and cross-correlation analysis) and one step predictive (model forecasting) analysis. That proved the applicability of the model for the next stage - controller synthesis.

H-infinity Controller Synthesis

The main goal of this project has been to attest the applicability of the H-infinity control methods in a remote laboratory for motion control. The application of these control methods requires a complex applied mathematics and their practical implementation in real-time hardware systems has not been always successful. Therefore, the main question was which control strategies, while conforming to the actual physical system, are most suitable for practical hardware and software employment. Getting into consideration a number of arguments implied from the necessity of a decent control design approach and its pertinent utilisation in the already predominant FPGA hardware environment, the following H-infinity control strategies were chosen and successfully applied [15-17]:

- S/KS mixed sensitivity approach;
- Glover-McFarlane loop shaping procedure;
- 2DOF design based on Glover-McFarlane loop shaping procedure;
- A reference PID controller, based on the linear-quadratic cost-function optimisation method was also synthesised, since as an industrial standard it provides a base of comparison to the H-infinity controllers.

The practical implementation of the synthesised controllers was another major milestone. A two-transfer-function model proved to be feasible for adoption of all the control algorithms. A successful application of NI LabVIEW FPGA programming module contributed significantly to the accomplishment of the project objectives and obtaining valuable experimental results. These results illustrated how different trade-offs in the controller design reflect on its performance, stability and robustness. It is clear that an *ideal* controller is very hard to design, synthesise and implement in the real word, and the design should be carefully selected according to the requirements for every particular case.

The majority of the synthesised controllers behaved in the way they have been designed for, and the 2DOF controller appeared to be superior in terms of stability and robustness. However, if performance is not the most important design goal, the Glover-McFarlane loop shaping controller showed very good stability and robustness while requiring easier, quicker and effortless design.

User Interface of the Remote Laboratory

Remote laboratories for motion control are an important tool for teaching the students in mechatronics courses of control systems engineering and experimentation with a wide range of feedback devices. The GUI is the interface, which connects the sometimes geographically displaced students to the experimental workbench and delivers the means of interaction with the software layer controlling the equipment. On the one hand, the interface is supposed to be flexible enough to provide a variety of choices for setting up and performing the control experiment. On the other hand, it must deliver valuable experimental results in terms of graphical plots and measurement data files, and create a sense of reality for the distant user. Further enhancements (such as Web-cameras, chat-rooms, various forms of on-line presentation of the theoretical material, etc), extend the sense of reality and *hands-on* experience in the user.

For example, the *Experiment Execution* GUI (depicted in Figure 2) allows distant users to execute the already arranged control experiment and to collect the experimental data from several selectable sources. Consequently, the data are plotted on the screen by means of LabVIEW Waveform Graph Window and saved for further analysis with LabVIEW post-processing virtual instruments in the form of measurement data. In addition, the amount of control energy output for the control experiment is calculated and shown on the screen.

A virtual moving linear stage compliments the graphical interface and creates a feeling of reality of the remote experiment to the end user. In real-time, it recreates the movements of the moving table and shows its current position. The positions of the proximity/software end limit switches are also visualised.

The *Waveform Graph Window* displays the selected graphical data (signals) from the current experiment and provides functionality for a number of manipulations of the visualised graph, such as the areas of interest to be shown in a convenient way. Signals, which can be selected and plotted on the graph are: excitation, torque, rotary encoder position, linear encoder position, controller input error, etc.

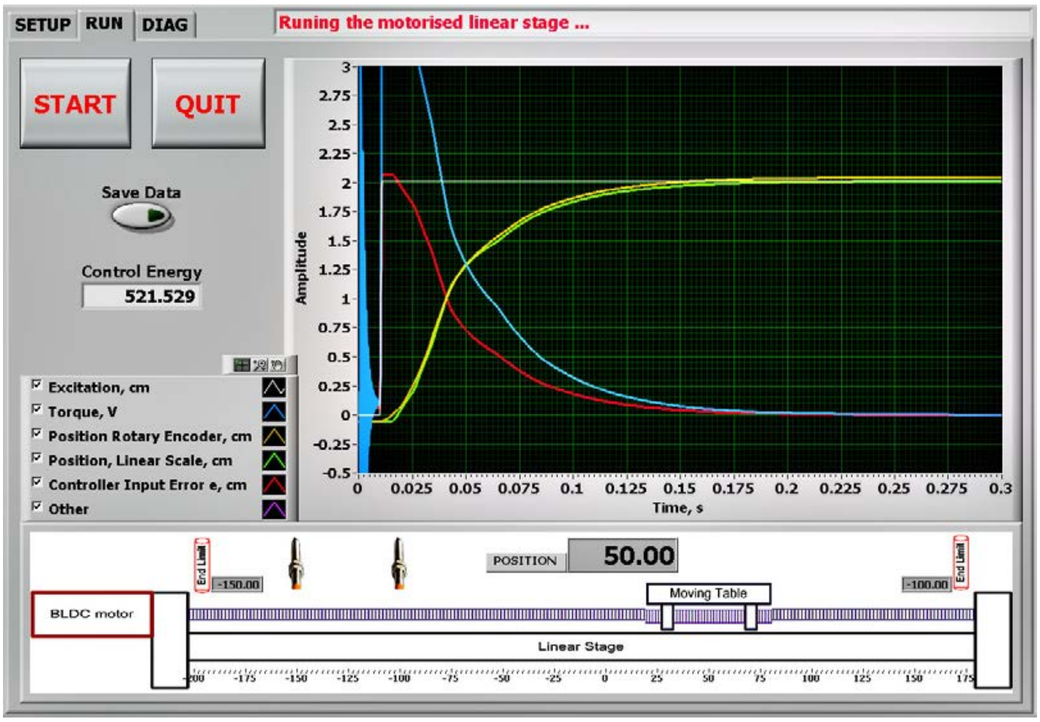

Figure 2: User interface and virtual reality representation.

CONCLUSIONS

This article presented the achievements of remote laboratories for motion control in technical (hardware and software) and educational aspects. It is well known that the modern Web-based education necessitates the application of *Good Practices in Undergraduate Education* [20]. In order to achieve two critical educational values for the development of engineering students: *learning complex theory* and *learning practical skills,* the following directions in the development of the remote laboratory were well considered:

- Theoretical introduction to the control experiment, including modelling of the dynamic system, simulations and analysis of the results;
- Execution of the control experiments where different algorithms (H-infinity/PID), conditions, control parameters and signals of interest could be required;
- Analysis of the results, including comparison between the simulations and actual experimentation results, and writing reports (and other tools of assessment);
- Feedback and recommendations for improvements from the facilitator of the laboratory, as well as the students;
- Other tools for effective management of the remote laboratory.

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