

Omni-directional Robotic Wheel - A Mobile Real-Time Control Systems Laboratory

Bharath Ramaswamy, YangQuan Chen and Kevin Moore

Abstract—A mobile laboratory was developed for students of the ECE5320 Mechatronics and ECE7750 Distributed Control Systems courses at Utah State University. A serial server was connected to the embedded controller of a stand-alone 3-axes robotic wheel assembly. This enabled communication between the wheel and any internet-enabled computer. A telepresence control system and a prototype networked control system (NCS) were developed and tested. This system was suitably modified to accommodate the needs of the course laboratories, thereby enabling students to design, debug and test their laboratory projects in real-time at their chosen time and locations. A fully-functional demonstration of this remote laboratory is available from: <http://www.csois.usu.edu/people/smartwheel/CompleteInfoPage.htm>

I. INTRODUCTION

RAPID strides in the use of telepresence systems for distance learning and remote experimentation purposes have resulted through proliferation of the Internet, advances in mobile communications technology and availability of high-speed computers. These developments have also greatly benefited the field of Control Systems education and proprietary platforms like National Instruments' LabVIEW [1] and Quanser's Wincon have been used in teaching laboratories.

The Department of Electrical & Computer Engineering at Utah State University offers a graduate-level course in Distributed Control Systems [2]. This course deals with the design, implementation and stability issues in networked control systems, wireless sensor networks, and distributed parameter systems.

The department also offers a course in Mechatronics [3], which deals with the principles, interfacing, and signal-conditioning of motion sensors and actuators, the modeling, analysis, and identification of discrete-time systems, and

Manuscript received September 14, 2005.

YangQuan Chen is Acting Director, Center for Self-Organizing and Intelligent Systems, and Assistant Professor, Department of Electrical and Computer Engineering, Utah State University, Logan, UT 84322 USA (phone: 435-797-0148; fax: 435-797-3054; e-mail: yqchen@ece.usu.edu).

Bharath Ramaswamy was Graduate Research Assistant at Center for Self-Organizing and Intelligent Systems, Department of Electrical and Computer Engineering, Utah State University, Logan, UT 84322 USA. He is now Engineer at Qualcomm Incorporated, San Diego, CA 92121 USA (e-mail: bharath.ramaswamy@qualcomm.com).

Kevin Moore was Director, Center for Self-Organizing and Intelligent Systems, Utah State University, Logan, UT 84322 USA. He is now the G.A.Dobelman Distinguished Chair and Professor of Engineering, Division of Engineering, Colorado School of Mines, Golden CO 80401 USA (e-mail: kmoore@mines.edu).

digital controller design methods.

This paper describes a low-cost remote laboratory solution developed at Utah State University for the Mechatronics and Distributed Control Systems courses. The paper is organized into eight sections. Section-II addresses the need for a remote laboratory from a pedagogical perspective. Section-III gives background information on the "Smart Wheel" system which is the plant to be controlled during the laboratory sessions. Section-IV provides the objectives and overall structure of the course laboratory. Section-V describes the hardware and software architecture of the system. Section-VI provides details on how a student of the course can perform the laboratory "on-the-go". Finally, Section-VII and Section-VIII summarize the results and outlines future project goals.

II. PEDAGOGICAL MOTIVATION

It is imperative that engineering courses especially those in the area of control systems include a hands-on laboratory component to extend the classroom experience. However, the setup, operation and maintenance of laboratory equipment become resource-intensive, time-consuming and expensive. Virtual laboratories offer a cost-effective alternative; however they often fail to model the practical effects, and cannot substitute for experience with the real system.

Remote laboratories offer distinct advantages over conventional and virtual laboratories. Apart from cost-reduction, more efficient usage of laboratory equipment, reduced maintenance, flexible and self-paced learning, there is the ability to give students the same kind of experience they would ordinarily obtain in a traditional laboratory setting with use of versatile, real-world equipment.

A remote learning application called "Second Best to Being There" (SBBT) was developed at Oregon State University [4]. This solution incorporates several features such as data-collection facility, live video and audio streaming, safety and stability measures, regulation of access, and collaboration support all of which make the remote laboratory a pleasant and immersive experience for the student.

III. PLANT BACKGROUND INFORMATION

The Center for Self-Organizing and Intelligent Systems



Fig. 1. Smart Wheel Assembly on a Mobile Rig.

(CSOIS) at Utah State University has designed and developed several prototype robotic vehicles based on a key enabling concept called the “Smart Wheel.” It is a self-contained robotic wheel module with 3 independent axes namely the steering axis, the drive axis, and the z-axis. When multiple smart wheels are attached to a chassis, the resulting vehicle is called an omni-directional vehicle [5].

CSOIS has a stand-alone smart wheel assembly (shown in fig. 1) equipped with steering and drive motors, a linear actuator for z-axis movement, drive circuitry for the motors and actuator, encoders for drive and steering feedback, a microcontroller, and a power distribution unit.

The smart wheel assembly was modified and augmented for use in the two courses mentioned. The intended outcomes were to enable students to design and test their own controllers for the steering and drive axes of the wheel. The assembly also doubles up as a demonstration system [6] to showcase the capabilities of the smart wheel to visitors, *in situ* and visitors to the CSOIS website.

IV. SYSTEM OVERVIEW

A. Introduction to the Laboratory

Since both courses mentioned earlier include a study of networked control systems (at varying levels), it was necessary to develop a laboratory component in order to augment the classroom theory.

A networked control system is a feedback control system in which the control loop is closed through a communication network [7]. It is imperative that remote experimentation be used for this laboratory. In this case, the plant and feedback-sensor is situated inside the university’s research center, the controller is located on the remote student’s computer, and the communication network is the IP network between the plant/sensor and the controller.

However, dedicated equipment for such a specialized laboratory is expensive and planning and installation is time-consuming. A low-cost solution, in which a serial server was used to make the smart-wheel assembly teleoperable, was conceived and implemented.

B. Distributed Control Systems Design Laboratory

In this course, the student is expected to design and test a networked control system for the steering axis of the smart wheel.

The serial port (RS232) on the smart wheel’s embedded controller was connected to an Ethernet Hub via a Serial Server, which translates messages between Ethernet and RS232 formats. The microcontroller on the wheel was programmed to poll the position encoder and transmit these values through its serial port. It also accepts velocity values via the serial port and converts it into pulse width modulated (PWM) signals to drive the motor.

The student with the Internet-enabled computer at any remote location will install a virtual COM driver, in order to communicate with the smart wheel’s serial server. He can develop his controller program on the computer, which will transmit velocity values to the smart wheel, calculated based on the encoder readings received from the smart wheel. The Internet introduces random time delays and perturbations. These network-induced effects need to be taken into consideration while designing the controller, through the use of suitable techniques such as network prediction and delay-compensation. The performance of the control system can be examined, by parsing and plotting the encoder data on the remote computer. Any windows-based environment may be used for development.

Fig. 2 shows the user-interface for a prototype networked control system implemented for the steering axis of the smart wheel developed in Visual Basic. The set-point (steering angle) and controller gains (PID controller) are user-selectable and the user can view the system performance by observing the angular position plot that appears in real-time on the graphical display. An Internet camera streaming live video and audio enables the student to view and hear the wheel motion in real-time on the control panel.

C. Mechatronics Design Project Laboratory

Since this is a course at the undergraduate-level, the students can design and test simple PID networked controllers for the steering and drive axes on their internet-enabled computers, but without considering network-induced effects into their design. It is proposed to extend the use of the smart wheel assembly for the Mechatronics course in the year 2006.

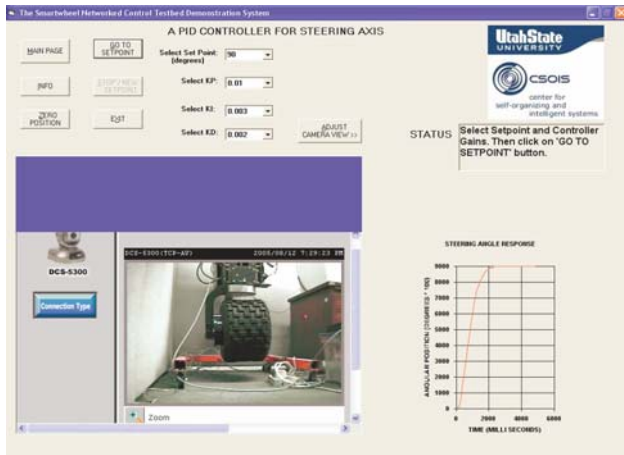


Fig. 2. Screen-shot of the Prototype Networked Control System Application.

D. Demonstration System

The microcontroller on the smart wheel also has its own set of control algorithms for the steering, drive and z-axes. In this case, the microcontroller accepts set-points from a pair of joysticks or the remote computer for each of the three axes and controls the wheel according to its on-board control program. This feature enables the capabilities of the wheel to be showcased to visitors *in situ* and visitors to the CSOIS website when the wheel is not being used for the course laboratories. Fig. 3 shows the user-interface for the smart wheel’s telepresence control system.

Suitable handshaking, control and arbitration protocols coordinate between joystick, telepresence and networked control modes, and also ensure predictable behavior when multiple users attempt to access the system.

analog converter (DAC) and the feedback from the linear potentiometer.



Fig. 3. Screen-shot of the Telepresence Control System Application.

V. SYSTEM DESCRIPTION

A. Architecture

The architecture of the stand-alone smart-wheel demonstration system [6] is shown in fig. 4.

The steering motor, drive motor, and linear actuator control the steering axis, drive axis, and z-axis of the smart wheel, respectively. The steering and drive motors are controlled by PWM and direction signals from their respective motor drivers. The steering motor is coupled to an absolute encoder, which measures the absolute angular position of the wheel. The drive motor is attached to a quadrature encoder that measures the relative motion of the wheel. The linear actuator moves the entire steering column up or down along the linear slide. The linear potentiometer provides feedback about the z-position of the steering column. The z-axis control box commands the linear actuator based on the voltage value from the digital-to-

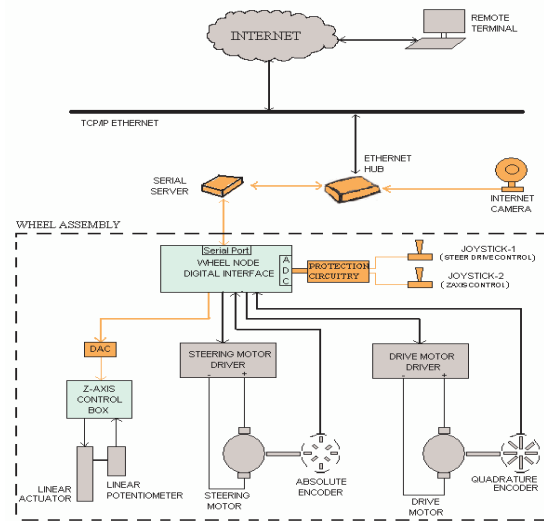


Fig. 4. Smart Wheel System Overview.

The wheel node digital interface board consists of the Tattletale Model 8 (TT8), a microcontroller by Onset Computer Corporation [8] based on Motorola’s MC68332 microprocessor. It also provides interfaces for serial communication, motor drivers, DAC, absolute and quadrature encoders, circuits for power supply and regulation, level-shifting, and optical isolation, and the hardware watchdog unit.

The steering and drive motors are each driven by a 50A8DD Series PWM servo amplifier (or motor driver) from Advanced Motion Controls. The duty cycle of the pulse width modulated (PWM) signals determines the speed of the motor and logic level of the direction signal determines the direction of rotation.

Two joysticks have been provided in order to enable visitors to control the 3-axes of the wheel *in situ*. During this time, the system is said to be in *Joystick mode*. One of them (Joystick-1) is a 3-axis joystick wherein the x-axis is used to set the drive speed and the twist axis is used to set the steering speed. Another single-axis joystick (Joystick-2) is used to set the z-axis position.

The remote operator communicates with the smart wheel through a device known as the serial server, which converts messages from RS232 format into Ethernet format and vice-versa. The DE-311 serial server from Moxa Technologies was selected for use in the system [9] on account of its low-cost, easy-to-install software drivers, and throughput (50 bps to 230.4 Kbps).

A DLink DCS5300 Internet camera [10] located near the smart-wheel assembly directly sends streaming video (up to 30 fps at 640*480 resolution) and audio of the smart wheel motion to the remote operator. It allows up to 20 users to view the lab activity while only one of them is interacting with the plant.

The remote operator can communicate with the system either in *Telepresence mode*, during which the on-board control algorithm on the wheel controls the 3-axes of the wheel based on set-points received from the remote computer; or in *Networked Control System Laboratory mode*, during which the control algorithm on the remote computer commands the wheel's axes based on sampled encode-feedback readings received from the microcontroller on the wheel.

B. Mechanical Hardware Description

A cross-sectional view of the smart-wheel assembly (without z-axis actuator features) is shown in fig. 5.

The steering suspension supports the entire steering mechanism and wheel electronic systems. The steering spindle is directly coupled to the steering motor. The yoke fastens the drive assembly to the steering spindle. The yoke also houses the power and communications cables, which go down to the wheel. A custom slip ring allows infinite rotation of the wheel about the steering axis. The entire drive assembly including the drive spindle, motor, failsafe brake, and encoder is enclosed inside the wheel shell. The drive motor is a Kollmorgen model QT-6407 frameless torquer motor and the steering motor is a MicroMo series GNM 5440 PM DC motor. A CP-560 quadrature encoder from Computer Optical Products is used to measure relative wheel position. The absolute encoder used to measure absolute angular position of the steering motor in body-fixed coordinates is a Model 40H from Sequential Electronic Systems.

Z-axis actuation capability was added by mounting the assembly shown in fig. 5 on an Electrak linear actuator from Warner Electric. A linear potentiometer is mounted adjacent to the linear actuator near the top. The power

distribution units are enclosed behind the damper. A control box for the z-axis movement is mounted on one side of the power distribution unit housing. The wheel electronics and motor drivers are mounted on either side of the steering column. The entire assembly is mounted on a wheeled stand. Refer to fig. 1 again to see a complete picture of the system.

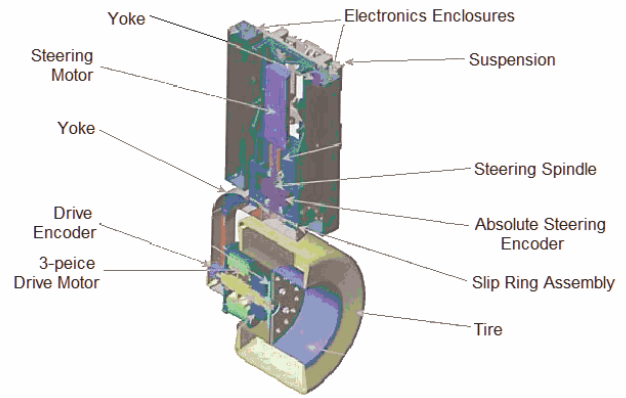


Fig. 5. Smart Wheel Mechanical Assembly.

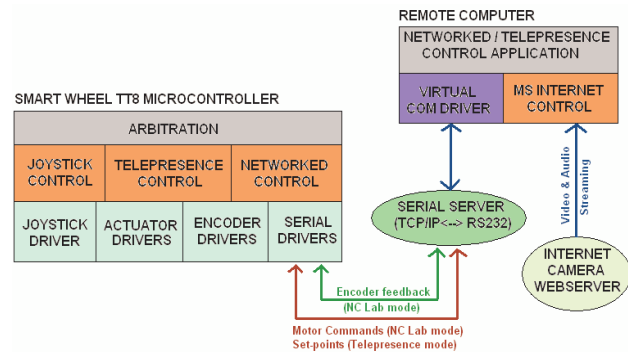


Fig. 6. Smart Wheel Software Architecture.

C. Software Description

Software for the stand-alone smart-wheel demonstration system comprises the following:

- Embedded software on the TT8 microcontroller board.
- Video and audio buffering and streaming software on the Internet camera's web server.
- Embedded software on the serial server to perform conversion of messages between Ethernet and RS232 formats.
- Virtual COM driver that allows communication between the student's remote computer and the serial server.
- Application software for Networked Control of the smart wheel's axes on the student's computer.

The software architecture of the system is depicted in fig. 6. Of these, the Virtual COM driver (Moxa tech.), the serial

server software (Moxa tech.), and the Internet camera webserver software (DLink corp.), have been provided by their respective manufacturers. The embedded software on the smart wheel's TT8 microcontroller board includes control algorithms for controlling the 3-axes of the wheel based on inputs from the joysticks (joystick mode), or based on inputs from the remote computer (telepresence mode). In the networked control laboratory mode, the microcontroller software merely samples and transmits encoder readings via the serial server to the remote computer and drives the motors based on the commands sent to it by the control software on the remote computer. It also arbitrates suitably between the three modes based and responds with appropriate messages when multiple users attempt to access the system simultaneously [6]. For purposes of preventing idling and increasing resource utilization, the acquisition of the system on a first-come first-served (FCFS) basis is done when resolving multiple requests to access the plant.

VI. NETWORKED CONTROL SYSTEMS LABORATORY

Fig. 7 depicts the laboratory setup for the networked control system design for the steering axis of the smart wheel as implemented during the Spring 2005 offering of the ECE7750 Distributed Control System course at Utah State University. The student is required to install the virtual COM driver on his/her computer. This makes the smart wheel's serial server appear to the computer as just another serial port. Using a simple protocol and packet structure [11, 12], the students can open a session, receive encoder-feedback values and transmit motor velocities to the wheel's microcontroller. The microcontroller converts motor velocity values received from the student's computer via the serial server and converts it into PWM signals for the motor driver hardware. The microcontroller also samples the encoder and sends the readings along with the time-stamp (using its on-board timer peripheral) via the serial server. The system response can be plotted on the student's computer for performance-evaluation purposes.

The Internet camera located near the smart wheel assembly directly sends streaming video and audio of the smart wheel motion to the student's computer. This enables the motion of the wheel axis to be seen and heard in real-time during development and testing.

A safety mechanism enables the student to stop the wheel (through the use of a special command) if he/she notices any abnormal behavior through the live video. To ensure stability of the control loop and in-case of power outage, network failure, etc the system enforces a time-out if there is no communication for a specified period of time.

This setup will also be used in the ECE5320 Mechatronics course in the year 2006 [12]. The students can use the same system to design and test simple

networked controllers, but they will not be expected to consider network-induced effects in their design.

VII. LABORATORY BENEFITS

At the time of preparing this paper, the system was used in the Spring 2005 offering of the Distributed Control

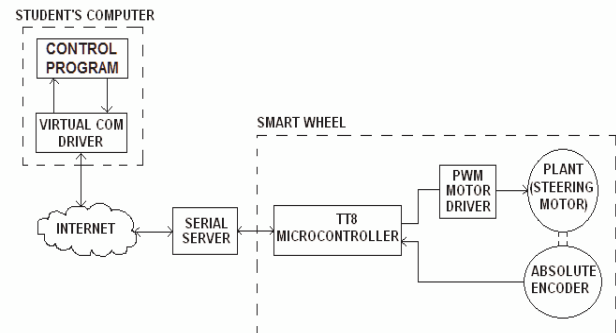


Fig. 7. Networked Control System Laboratory.

Systems course at Utah State University. The students were able to successfully develop and test their networked control system designs from any wireless or wired internet-enabled computer and gain a better understanding of networked control related design issues.

Much of modeling, analysis, design and programming work could be done "off-line". The system could then be used for testing their design and iteratively moving towards better closed-loop performance. Since all of this could be done at the time and place of their convenience and the system was available for access round-the-clock, resource conflicts were minimal. Issues with providing students access to the research center that houses the equipment and possible contention with the center's other activities do not arise here.

With only one laboratory station, every student was able to experience the system. This helped the department control the cost of developing a laboratory for such a specialized topic while maintaining the quality of the course, which is a key objective of internet-based education [13].

VIII. CONCLUSION AND FUTURE WORK

The stand-alone robotic wheel assembly can now be used for both demonstration purposes as well as control systems education. The use of the serial server invalidates the need for a local computer to interact with the plant, thus making for a cost-effective and self-contained embedded remote learning solution.

It is proposed to extend the NCS laboratory to include velocity control of the drive axis of the smart wheel. This will enable the students to implement and experience different scheduling approaches for the steering and drive

axis control threads, and deal with issues concerning the polling and commanding of multiple sensors and actuators (multirate control).

REFERENCES

- [1] D.Gillet, C.Salzmann, R.Longchamp, D.Bonvin, “*Telepresence: An Opportunity to Develop Practical Experimentation in Automatic Control Education*”, European Control Conference, 1997.
- [2] YangQuan Chen (January 2005). ECE 7750 Distributed Control Systems, Utah State University, Course website [Online]. Available: <http://mechatronics.ece.usu.edu/ece7750/>
- [3] YangQuan Chen (January 2005). ECE 5320 Mechatronics, Utah State University, Course website [Online]: <http://mechatronics.ece.usu.edu/>
- [4] Burcin Aktan, Carisa A. Bohus, Lawrence A. Crowl, Molly H. Shor, “*Distance Learning Applied to Control Engineering Laboratories*”, IEEE Transactions on Education, 1996.
- [5] Nicholas Flann, Kevin Moore, “*A Six-wheeled Omnidirectional Autonomous Mobile Robot*,” IEEE Control Systems magazine, 2000.
- [6] Bharath Ramaswamy, “*Embedded and Telepresence Control of a 3-Axis Smart Wheel Assembly*,” M.S. thesis, Dept. Electrical and Computer. Eng., Utah State Univ., Logan, Utah USA, 2004.
- [7] Octavian Beldiman, “*Networked Control Systems*,” Ph.D. Dissertation, Dept. Electrical and Computer. Eng., Duke Univ., Durham, NC USA, 2001.
- [8] Onset Computer Corporation, *Tattletale Model 8 Installation and Operation Manual*, 1999.
- [9] *NPort DE-311 Serial Device Server Solutions Datasheet*, Moxa Technologies Co. Ltd., Taipei Taiwan.
- [10] *DLink Securicam DCS 5300 Internet Camera Datasheet*, DLink Systems Inc., Fountain Valley, CA USA, 2003.
- [11] *Networked Control Systems Design Laboratory, Project-1 for ECE7750 Distributed Control Systems*, Course Laboratory Handout, Dept. Elect. Comp. Eng., Utah State Univ., Logan USA, 2005.
- [12] *Networked Control Systems Design Laboratory, Project for ECE5320 Mechatronics*, Course Laboratory Handout, Dept. Elect. Comp. Eng., Utah State Univ., Logan USA, 2006.
- [13] Sandra E. Poindexter, Bonnie S. Heck, “*Using the Web in Your Courses: What Can You Do? What Should You Do?*”, IEEE Control Systems magazine, 1999.