

Web-based control of the Rice SPENDULAP*

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The Rice Spherical PENDULum Laboratory Apparatus (SPENDULAP) is a laboratory educational system well-suited for illustrating a variety of important topics in kinematics, dynamics, and control. The SPENDULAP has been used successfully for several years in the classroom so as to enhance students' understanding of three-dimensional kinematics and dynamics including Newtonian and Lagrangian dynamics. The device has also proven useful to illustrate key topics in nonlinear systems analysis such as linearization and the state portrait. Additionally, the SPENDULAP presents an excellent example for illustrating key concepts in nonlinear control and dynamic simulation. This paper describes the adaptation of the SPENDULAP to produce an autonomous web-based laboratory apparatus. The paper presents both the mechanical modifications required to permit unattended operation and the layered, distributed software architecture.

INTRODUCTION

MANY IMPORTANT TOPICS in kinematics, dynamics, nonlinear systems analysis, and control initially appear to students to be abstract mathematical concepts with little physical meaning. Laboratory application of these concepts provides motivation to the students and provides physical meaning to the mathematical theory. The Rice Spherical PENDULum Laboratory Apparatus (SPENDULAP) [1, 2, 15] has proven to be an excellent example of a device suitable to this purpose in a course entitled Dynamics and Systems Analysis offered in the Rice University Department of Mechanical Engineering by the authors. The SPENDULAP is attractive for several reasons. First, it is easy for students to visualize the motion of the pendulum, but somewhat challenging to model kinematically. Second, the nonlinearities and coupling between rotation and swinging give it interesting motion. The SPENDULAP equations of motion can be linearized about an equilibrium position with a modest amount of effort. The construction of a state portrait using software such as MATLAB is straightforward and compliments the linearization results. The equations of motion can easily be programmed using either an algorithmic language such as MATLAB or a block diagram language such as Simulink. The SPENDULAP is an excellent example of an under-actuated nonlinear system, and is therefore also quite useful as a case study for various nonlinear feedback control techniques.

Despite the fact that the SPENDULAP has

proven to be an effective teaching tool, its use was limited to a few laboratory sessions each semester. In order to expand the availability of the SPENDULAP to Rice students, and to share this valuable resource with students and researchers at other universities, the SPENDULAP was modified extensively to permit totally autonomous operation via the Internet.

There have been a number of web-based mechatronics applications developed in the last several years [4] that have proven the viability of web-based teleoperation and controls laboratory experiments. Among these are web-operated laboratory robots [5–7], web-operated rovers [8–12], and mechatronics laboratory experiments [13, 14]. The SPENDULAP modifications and web interface were intended to extend the previous work, in particular the inverted pendulum at EPFL [13], by controlling a more complex device with an extensive initialization sequence, data validation, and increased ability of the user to configure the controller. To achieve these goals, a typical web-based client-server architecture was integrated with a graphical programming system (LabVIEW) such that software modifications (and ultimately user-developed control algorithms) can be rapidly developed and integrated into the system.

SYSTEM DESCRIPTION

The layout of the Rice SPENDULAP is shown in Fig. 1. The pendulum is mounted in a rotating frame that is supported at the top and bottom by bearings mounted in a cylindrical housing. The pendulum consists of an aluminum tube that is

* Accepted 20 February 2003.

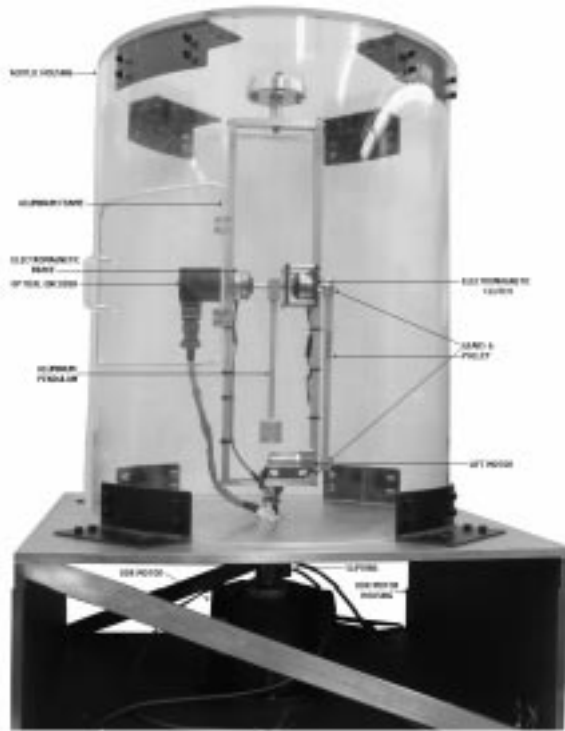


Fig. 1. Rice SPENDULAP layout

threaded on both ends and attached to a cylindrical aluminum bob at the bottom. At the top, the pendulum is attached to a tee that swings on a stainless steel swivel pin. The swivel pin is mounted in bearings to the rotating frame.

The housing consists of an acrylic cylinder. The acrylic cylinder also serves as a safety shield. The top of the acrylic cylinder is an acrylic disk to which the top frame bearing is attached. The frame is supported at the bottom by an aluminum base that encloses the motor and drive mechanism.

The rotating frame is constructed of rectangular cross-section aluminum bar. There is a bearing shaft mounted to the top of the frame and a drive shaft mounted to the bottom of the frame. The drive shaft is mounted directly on the drive motor shaft.

An optical encoder driven by the swivel pin is mounted outside the frame. The encoder has an accuracy of 5000 cts/rev. Inside the frame, adjacent to the encoder, is an electromagnetic brake. When

the brake is energized, it prevents the pendulum from swinging. The braking torque is sufficient to prevent the pendulum from swinging even when the frame is rotating.

An electromagnetic clutch is mounted inside the frame opposite the brake via a custom housing. The clutch, when activated, connects the swivel pin to a shaft which is fitted with a sprocket. Figure 2 shows the relation of the encoder, brake, and clutch on the swivel pin.

At the bottom of the rotating frame, a small geared DC motor (the lift motor) is fitted with another sprocket which in turn drives the upper sprocket via a cogged belt. The subsystem consisting of the lift motor, the cogged belt and sprockets, the clutch, and the brake form the autonomous initial positioning mechanism. This mechanism allows the pendulum to be locked in any desired angular orientation while the frame is stationary, and to remain in that orientation once frame rotation begins, until the brake is released. With both the clutch and brake released, the pendulum swings freely. Figure 3 shows the relation of the belt, gears, lift motor and clutch.

The electrical components mounted on the frame are connected to an 18-channel slip ring mounted directly on the motor shaft. The frame is driven by a direct-drive brushless DC motor (BLDCM). The motor is encased and bolted to an aluminum frame and is powered by a programmable motor controller. The angular rotation is measured by an internal encoder connected to the motor controller. The motor encoder signal is also available as an output from the motor controller. A detailed photograph of the motor section is shown in Fig. 4. A real-time video camera is mounted on a tripod and is connected to the host PC via a Universal Serial Bus interface.

Figure 5 illustrates the overall SPENDULAP hardware configuration. The SPENDULAP interface box conditions signals from the swivel pin encoder and drives the initial positioning mechanism motor, brake, and clutch. The host PC contains a real-time (RT) *PXI-6030E* LabVIEW data acquisition board that accepts inputs from the encoders and produces control signals for the motors, brake, and clutch. The *PXI-6030E* board is a 16-bit board that communicates at a maximum rate of 100 kHz.

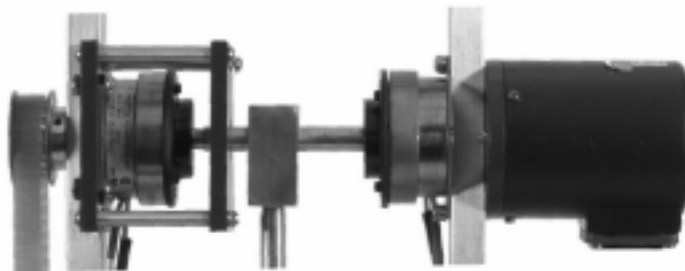


Fig. 2. Encoder, clutch, and brake mounted on the pendulum swivel pin.



Fig. 3. SPENDULAP initial positioning mechanism, consisting of lift motors, gears, pulley, clutch, and brake (brake not shown).

OPERATIONAL SCENARIOS

This section describes typical operational scenarios—the sequence of steps that the software causes the system to perform. There are two classes of experiments—constant frame angular velocity and feedback control.

For the constant frame angular velocity case, the user specifies a frame angular velocity, initial pendulum angular deflection, and experiment duration. For the feedback control case, the user chooses from a set of control algorithms, specifies the initial pendulum deflection angle and setpoint deflection angle, and a set of gains corresponding to the control algorithm. (At present, only setpoint control is implemented.)

For both operational scenarios, the initialization sequence is as follows:

- Release clutch and brake.
- Verify that the pendulum is not swinging.
- Initialize encoder.
- Engage clutch.
- Raise pendulum to specified deflection angle.
- Lock brake.
- Release clutch.

At this point in the sequence, the frame angular velocity is zero and the pendulum is locked at the user-specified initial deflection angle.

Constant frame angular velocity experiments

The simplest SPENDULAP experiment entails rotating the frame at a constant angular velocity and observing the pendulum deflection trajectory. The SPENDULAP equations of motion can be written [15] with swivel pin friction ignored:

$$\begin{bmatrix} I_x & 0 \\ 0 & I_{Fz} \end{bmatrix} \begin{bmatrix} \ddot{\theta} \\ \ddot{\phi} \end{bmatrix} + \begin{bmatrix} \left(\frac{l_r m_r}{2} + l_b m_b \right) g \sin \theta - I_x \dot{\phi}^2 \sin \theta \cos \theta \\ 2 I_x \dot{\theta} \dot{\phi} \sin \theta \cos \theta \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tau$$

where θ is the pendulum swing angle,

ϕ is the drive motor angular displacement, and the dot indicates the derivative with respect to time, I_{Fz} is the frame moment of inertia about its axis of rotation,

I_x is the pendulum moment of inertia about the swing axis,

l_r is the pendulum rod length,

m_r is the pendulum rod mass,

l_b is the length from the swing axis to the centroid of the bob,

m_b is the bob mass,

g is acceleration due to gravity,

τ is the frame drive motor torque.



Fig. 4. Brushless direct-drive DC motor and slipping.

From Equations (1), it can be seen that an equilibrium θ_{eq} exists where:

$$\theta_{eq} = \pm \cos^{-1} \left(\frac{((l_r m_r / 2) + l_b m_b) g}{\Omega^2 I_x} \right) \quad (2)$$

where Ω is the constant angular velocity of the frame.

Thus, there is a constant frame angular velocity associated with any θ_{eq} between -90° and 90° . If, while the frame is rotating at a constant angular velocity Ω , the pendulum is released from an initial deflection of θ_{eq} , the pendulum will remain deflected at θ_{eq} . If the initial pendulum angular deflection is different from θ_{eq} , the pendulum will oscillate in various interesting patterns depending on the frame angular velocity and initial pendulum deflection.

The constant frame angular velocity case provides an excellent opportunity for students to apply a number of nonlinear analysis and modeling tools, including linearization, state portrait, and bifurcation analysis. A typical student assignment is to develop equations of motion and analytically predict the pendulum behavior for a specific frame angular velocity and initial pendulum deflection. Next, the student models the dynamics numerically. Finally, they perform the lab experiment and compare analytical and numerical results to experimental results.

The operational sequence for the constant angular velocity experiment is as follows:

- Execute the initialization sequence.
- Initiate frame rotation at the specified angular velocity. (At present, the motor controller uses a PID control law to maintain constant frame angular velocity. Due to the use of a high-torque direct-drive motor, angular velocity fluctuations are extremely small.)
- Release brake.
- The pendulum will oscillate in a pattern determined by the frame angular velocity and initial pendulum deflection angle. The oscillations slowly decay due to the small amount of friction in the swivel pin bearings.
- Terminate frame rotation at the expiration of the experiment time.

Feedback control experiments

The SPENDULAP is also an ideal apparatus for feedback control experiments. The setpoint control experiments implemented in the web user interface allow students to use both linear (state feedback) and nonlinear (input-state linearization) control laws. In the setpoint control experiments, the goal is to adjust frame drive motor torque so as to cause the pendulum to rapidly stabilize at a pre-selected θ_{eq} . Typically, the experiment begins with the system at rest and the pendulum deflected at some angle different from θ_{eq} . Then, the pendulum brake is released and simultaneously feedback control of drive motor torque is initiated. The

experiment ends after a user-specified time interval.

For the linear controller [16], the system dynamics are linearized about the setpoint θ_{eq} and the drive motor commanded torque is computed from:

$$\tau = -Kq$$

where K is the user defined gain vector and q is the state vector $[\theta - \theta_{eq}, \dot{\theta}, \dot{\phi} - \Omega]^T$ which has as its origin the specified equilibrium. The feedback gain vector can be designed using standard linear systems techniques such as pole placement. Detailed development of linear control of the SPENDULAP can be found in [1, 2, 15].

For nonlinear control, the user can select input-state linearization [17]. Briefly, in this implementation of input-state linearization [1, 2, 15], the motor torque is computed as follows:

$$\tau = \ddot{\phi}_{desired} [I_{Fz} + I_x \sin^2(q_1 + \theta_{desired})] + 2I_x q_2 q_3 \sin(q_1 + \theta_{desired}) \cos(q_1 + \theta_{desired})$$

where $q_1 = \theta$, $q_2 = \dot{\theta}$, and $q_3 = \dot{\phi}$

$$\ddot{\phi}_{desired} = K_\phi (\dot{\phi}_{desired} - \dot{\phi})$$

$$\dot{\phi}_{desired} = \sqrt{u}$$

$$u = \frac{\left(\frac{l_r m_r}{2} + l_b m_b \right) g \sin q_1 / I_x + \nu}{\sin q_1 \cos q_1}$$

$$\nu = K_p (\theta_{desired} - q_1) + K_d q_2$$

where K_p and K_d are PD gains and K_ϕ is a proportional cascade gain. ν is defined as the auxiliary control.

The operational sequence for the feedback control experiments is as follows:

- Execute the initialization sequence.
- Release brake.
- Activate the feedback control law. The controller will compute motor torque according to the selected control law, causing the pendulum to stabilize at the specified θ_{eq} .
- Terminate frame rotation at the expiration of the experiment time.

WEB-BASED CONTROL

This section describes the web-based control software architecture and operational scenarios.

System architecture

The software architecture consists of four main elements: a Java client running on the user's web browser, a Java host program running on the lab computer, a LabVIEW host interfacing with the Java host, and a LabVIEW control program running on the LabVIEW RT Board. The Java

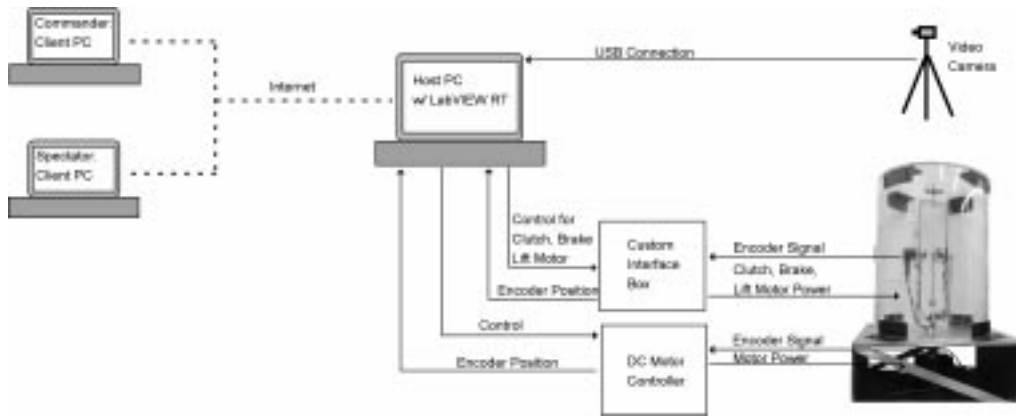


Fig. 5. System communication physical architecture.

client applet contains a real-time video window, a user input window to select from a variety of control laws and set controller parameters, and an output window that displays experiment results. The host application manages the user session and serves as a trusted intermediary between the client and the LabVIEW application. The LabVIEW host converts the Java input via TCP/IP protocol into a compatible form and sends the data to the RT program. The selected control law is implemented, the experiment is performed, and the results are sent back in reverse order to the user.

The data and control flow and software architecture are depicted in Fig. 7. Referring to Fig. 5 there are two types of users: commander and

spectator. We will discuss the communication and control process for each type of user next.

Web-based commander scenario

The Java host computer program allows one user at a time to serve as commander. Commander rights are allocated to individual users via a control file maintained by the system administrator. The commander communication scenario is as follows:

1. Commander logs on to the website and presses the Connect button. Commander enters an assigned user name and password and is connected to Java server running on the SPENDULAP computer. The commander

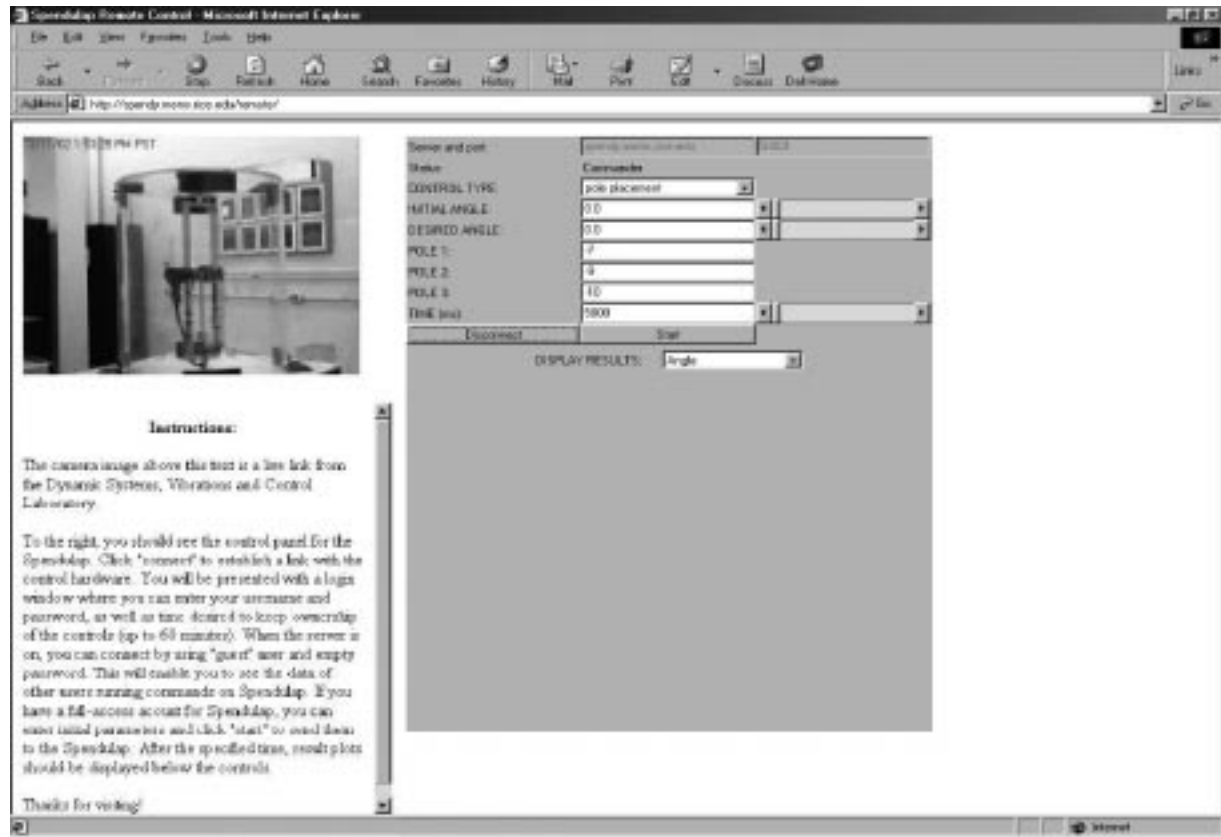


Fig. 6. Commander's user interface display.

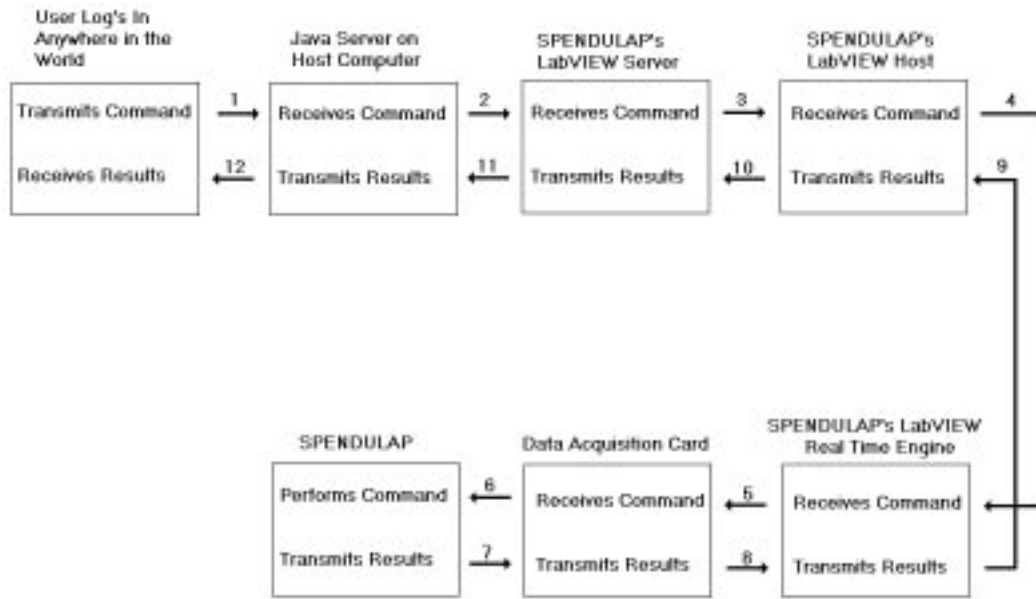


Fig. 7. Data and control flow software architecture.

window (Fig. 6) is displayed on the commander's PC. Commander chooses experiment from menu and sets parameter values. Commander presses Start button to activate the experiment. The Experiment Information (EI) is transmitted across the web to the Java server running on the SPENDULAP Host Computer (SHC).

2. SHC Java server communicates with the LabVIEW server Visual Instrument (VI) via TCP/IP protocol and translates the EI into suitable LabVIEW form.
3. EI is passed from the LabVIEW server to a Host VI. The Host VI validates the data, and if no errors are found, transmits the data to the LabVIEW RT Program (LRTP).

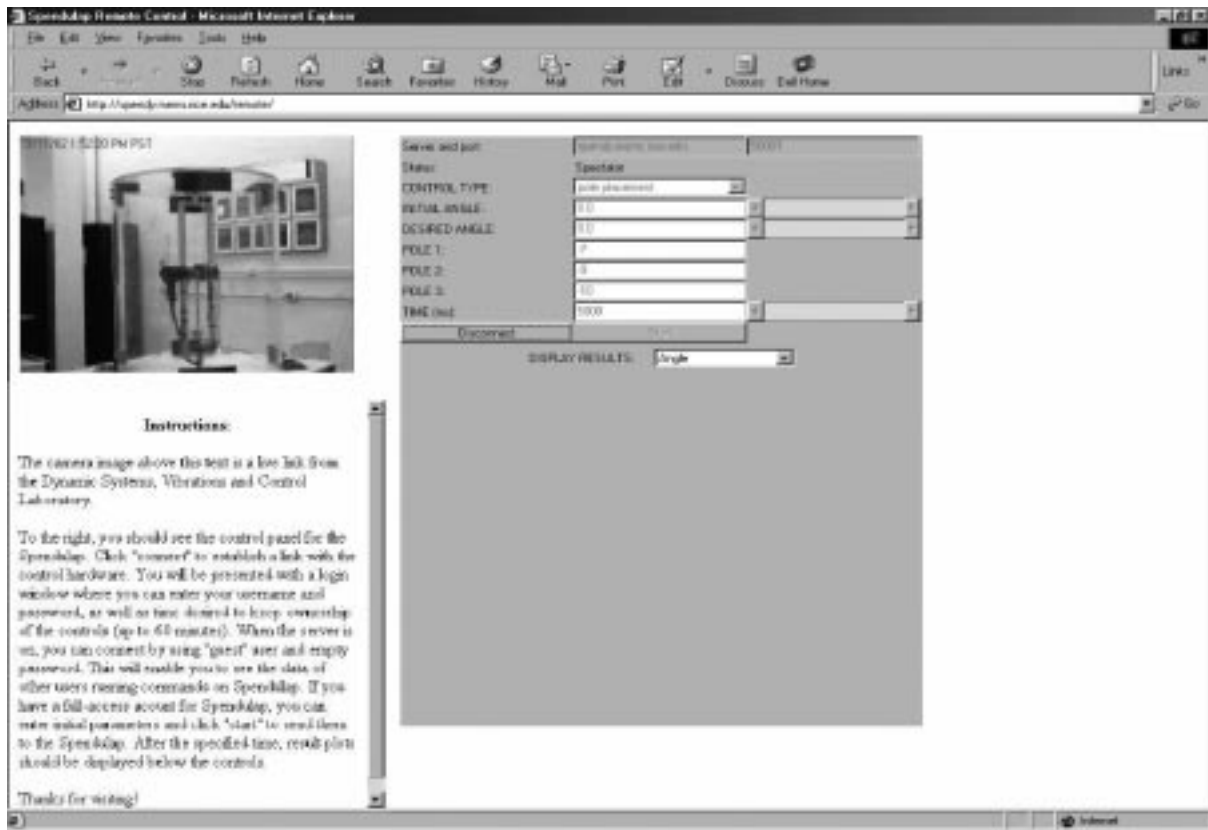


Fig. 8. Spectator user interface display.

Table 1. Experiment data

| Control Type | Input State Linearization |
|---------------|---------------------------|
| Initial Angle | 85° |
| Desired Angle | 30° |
| K_p | 100 |
| K_d | 20 |
| K_ϕ | 25 |
| Time (ms) | 5000 |

4. LRTP receives the data from the Host in a sequential manner and does not activate until all of the EI has been received. This process is ensured by running two nested control loops. (a) The outer loop receives data from and sends data to the Host VI. Once the experiment is complete, the outer loop takes the data from the inner loop and transmits it back to the Host VI. (b) The inner loop is activated on receipt of all parameters. Upon activation, the inner loop executes the experiment sequence and then resets to an inactive state.
5. Data from the inner loop is physically output by the LabVIEW Data Acquisition Card (DAC) that sends the desired voltages into separate control circuits for each electrical device. (The LabVIEW DAC is connected directly to the LabVIEW RT Board.) The control circuits translate the voltages into the necessary values (e.g., on/off, currents, etc.) to perform the experiment.

6. SPENDULAP begins experiment.
7. Data from the SPENDULAP encoders is passed back to the LabVIEW RT Engine through the DAC. The LabVIEW RT Board samples the data at ≈ 100 Hz. (The LabVIEW RT Board can sample data up to 100 kHz, but due to the complex algorithms involved for SPENDULAP, sampling occurs at 100 Hz.)
8. Data from the experiment is stored in the inner loop. Once the experiment has finished the inner loop passes this information to the outer loop and the outer loop transmits the data to the Host VI.
9. The host VI receives the results data and translates into a form suitable for the Java server. The LabVIEW server then transmits the data via TCP/IP protocol to the Java server.
10. Results data is transmitted to the Java server running on the SHC.
11. SHC Java server sends the result data across the web to the commander's browser.
12. The commander's browser receives the data and the results are plotted.

Web-based spectator scenario

While there can be only one commander at any time, the SPENDULAP system allows for an unlimited number of spectators. The spectator communication scenario is as follows:

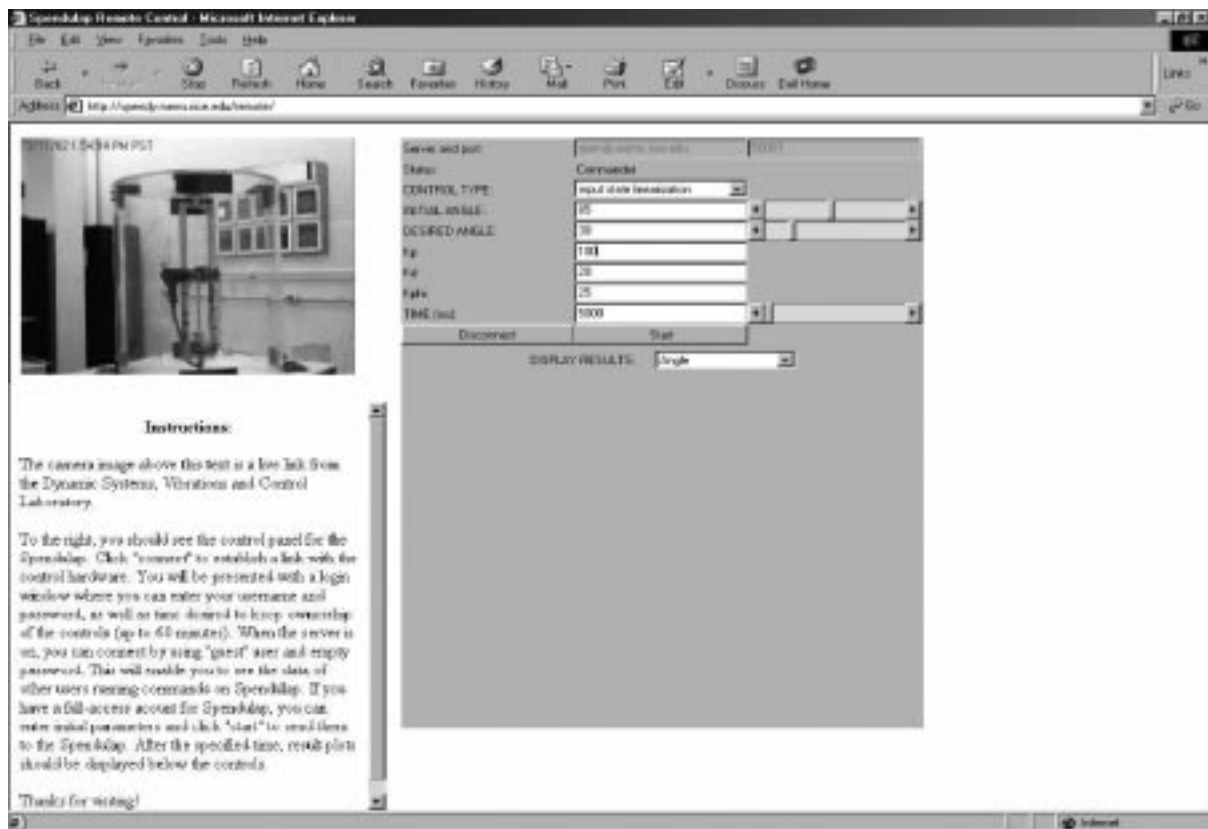


Fig. 9. Commander display after data entry.

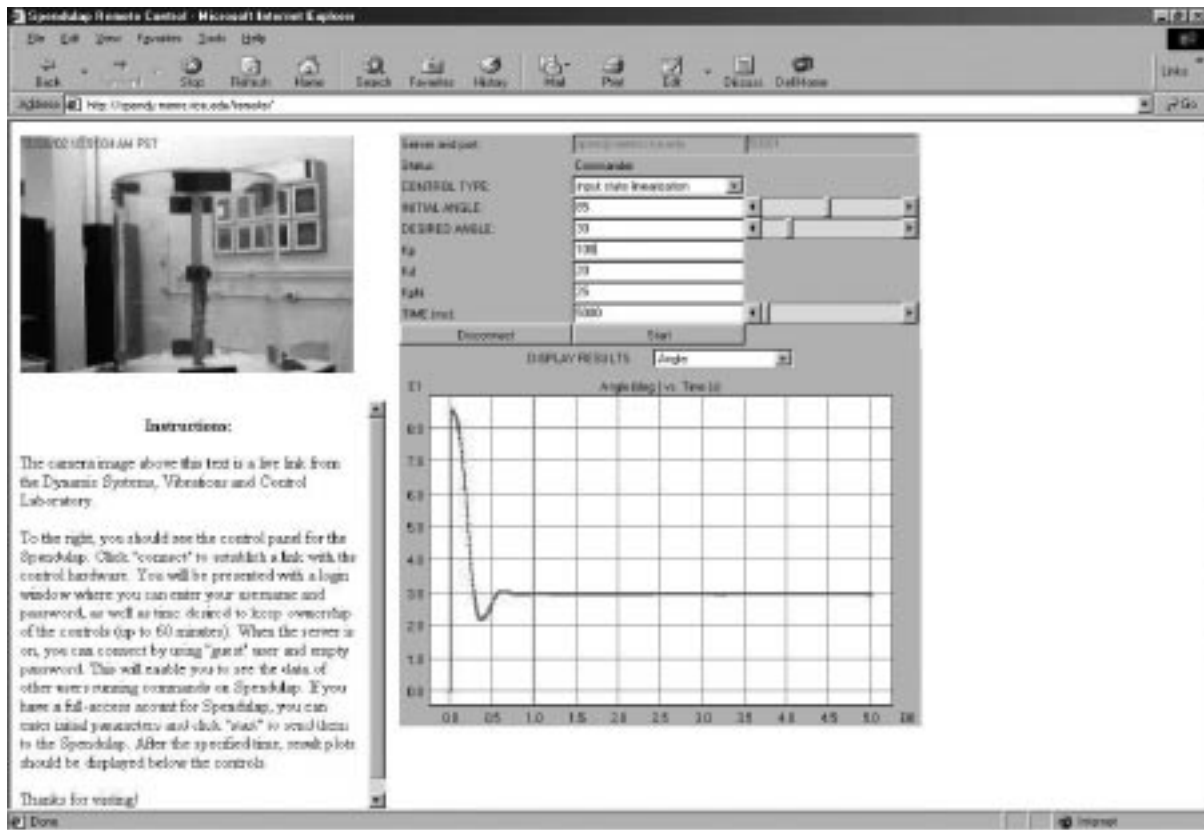


Fig. 10. Commander display after experiment.

1. Spectator logs on to web site and presses the Connect button. Spectator signs on as a guest. The spectator window (Fig. 8) is displayed on the user's PC. (a) The experiment is initiated by the commander.
2. Internal communication process among Java server and LabVIEW components is the same as in the commander's situation.
3. Results are plotted on spectator's browser. Spectator has control over viewing their own plots.

EXAMPLE

This section presents details of a typical feedback control experiment using input-state linearization. Table 1 lists the user inputs. Figure 9 shows the commander's browser display after all input data is entered. After entering the data, the commander clicks the Start button, and the experimental sequence executes automatically. The video window shows the experiment window in real time. Once the experiment terminates, trajectory parameters ($\theta, \dot{\theta}, \phi, \tau$) are transmitted to the commander, and also to any spectators currently logged-on. The browser display, post-experiment, is shown in Fig. 10. The commander

(and spectators) can also save trajectory data on their local storage for subsequent processing and analysis.

CONCLUSIONS AND FUTURE WORK

Modifications to SPENDULAP have extended its availability to remote users via the Internet. The hardware modifications permit unattended operation of the device. The web-based software environment manages user interaction and permits safe, controlled experiments. Future enhancements will include a larger variety of feedback control experiments including tracking control and will permit remote users to develop and upload their own control algorithms.

Acknowledgements—This research was partially supported by NSF Grant CMS-9900194, the Rice University Dean of Engineering and Vice-President of Information Technology, and donations of equipment and software by National Instruments, Inc. The authors would like to express their appreciation for the contributions of many Rice University students who have participated in the development and testing of the SPENDULAP. Additionally two visiting students, Yann Amhoy and Eric Olivet, performed detailed design and implementation of the initial positioning mechanism.

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