Exploring TeleRobotics: A Radio-Controlled Robot

Walter F. Deal, III and Steve C. Hsiung

This article introduces the concept of telerobotics—that is to control a robotic system remotely using low-cost, off-the-shelf radio transmitter and receiver electronics.

Introduction

It has been about ten years since the launch of the NASA Pathfinder Mission. The Pathfinder mission began December 4, 1996 and took about seven months to travel to Mars and place a "lander" on the Martian surface. The landing took place on July 4, 1997. Pathfinder's small rover, Sojourner, transmitted data for seven weeks. Sojourner is one of the most popular and well-known robot rovers that have been developed through NASA's Mars exploration projects.

Pathfinder's Sojourner missions demonstrated how low-cost technologies could be used for space exploration. The mission was directed toward technology, science, and mission objectives. The technology focused on a small micro-rover design, morphology and geological sampling, navigation, imaging, sensors, spectrometry, UHF communication link, and other experiments. A key part of the mission and technology was the communication in collecting and transmitting data back to the lander and subsequently back to earth (NASA).

In April of 2004, two mobile rovers named Spirit (Mars Exploration Rover A) and Opportunity (Mars Exploration Rover B) successfully completed their primary three-month missions on opposite sides of Mars. The primary mission's scientific goals were to search for and characterize a wide range of rocks and soils that hold clues about past water activity on Mars. Initially, the Mars Exploration Rover
mission was to last about 90 days and, as of this writing three years later, Spirit and Opportunity are still collecting data and transmitting it back to earth. Unlike the Sojourner rover, Spirit and Opportunity have enhanced communications systems that enable them to communicate with earth stations directly and with spacecraft orbiting Mars. However, Spirit and Opportunity communicated with the orbiter Odyssey to transmit scientific and image data back to earth stations as opposed to a relay link from the rovers to the lander. (MER). As a result of the media coverage of the Mars missions of the Sojourner, Spirit, and Opportunity rovers, there has been a significant increase in interest in robotics and control technology.

Today there are a number of entertaining, educational, and consumer robotic products and devices available. For example, there are robotic lawn mowers, such as the Lawnbot Evolution that will cut up to three-fourths of an acre, robotic vacuum cleaners (Roomba), action robots such as Robosapien and Roboraptor (Figure 2), and the familiar LEGO Mindstorms and LEGO NXT and VEX robot construction sets. While these devices may serve some useful purposes, offer learning experiences, or provide entertainment, they all share some common elements with industry and scientific robots.

Most robots used in industry and manufacturing, space exploration and research, and entertainment share many common elements. Robotic devices and systems typically have a mechanical system that provides the form and structure, a motion and drive system, electronics that include sensors and output devices, and programmable control systems. While robots will vary significantly in size, complexity, and intelligence, they all share these common elements. Some robotic devices have very complex instruction sets to provide very precise repetitive control of a robot, and some may even learn new processes and responses to external stimuli using artificial intelligence techniques, while others may be programmed to perform simple operations.

We generally think of robots as being autonomous and self-contained, where they have their own energy source, motion or transport system, instructions, etc. However, we will find that robots may be tethered to a control console via a multiwire cable, like the deep Sea Explorer robots, where one or more persons may operate and control the robot. We also see wireless links that use infrared light energy as a communication channel or radio frequency (RF) waves to control robotic systems and transmit data from sensor devices.

Robotics is a rich and exciting multidisciplinary area to study and learn about electronics and control technology. The interest in robotic devices and systems provides the technology teacher with an excellent opportunity to make many concrete connections between electronics, control technology, and computers and science, engineering, and technology. This article introduces the concept of telerobotics—that is to control a robotic system remotely using low-cost, off-the-shelf radio transmitter and receiver electronics.

Telerobotics and teleoperation, two terms that we commonly see regarding the operation of robotic systems, may be defined as the control and operation of robots at a distance (NASA). We see these kinds of control technologies used in fast-action robot games on television (Battlebots), surgical procedures (telemedicine) both local and remote, and in space exploration. Additionally, there are many competitive robotic contests and events, such as FIRST Robotics Competitions (FRC), that combine problem solving, team skills, and insights into engineering and technology at all educational levels.

Our objective is to build a mobile robot platform that can be teleoperated at a distance using radio waves (RF) to navigate an obstacle course. The robot platform includes a motor drive system and electronic motor controller, and incorporates a miniature UHF transmitter and receiver pair to serve
as a communication link. The robot platform is designed around two 8-1/2" diameter PVC disks that are cut from 1/8" PVC sheet, with appropriate spacers, and a dual DC motor gear box (shown in Figure 3.) The PVC material is easily shaped and fabricated into a design of the builder's choice.

**Constructing the Teleoperated Robot**

The robot chassis is constructed of 1/8" low-density sheet PVC, which is available in small quantities from educational and hobby suppliers or plastics suppliers in 4' X 8' sheets. Since it is a low-density material, it is easily cut, drilled with hand tools, or machined as necessary. A scroll saw may be used to make all external and internal cuts on the base material. Holes are easily drilled with a cordless drill. *Be sure to observe all appropriate safety precautions when performing cutting and drilling operations.* Layout lines should be used for accurate placement of holes and cutouts. Pencil layout lines are easily removed with a damp cloth. Rough edges left from the cutting operations can be removed with abrasive paper. Our telerobot uses a Tamiya dual motor drive gear box and two-inch diameter "off-road" wheels that are easily mounted to the platform base. However, if other types of gear motors are used, then appropriate motor mounting techniques must be addressed. The battery holders and solderless breadboards are attached with double-sided tape. Platform spacers may be made from PVC structural shapes or just plain wood dowels. Small machine screws and self-tapping screws are used as fasteners.

Direct current (DC) motors can be controlled by several different methods. They can be controlled with switches, relays, transistors, and silicon-controlled rectifiers, and special integrated circuits called H-Bridges. It is a common practice to use a special circuit design called an H-bridge to control a DC motor's current in order to determine speed and direction of rotation. The two Tamiya motors mounted on a robot platform are controlled by an L293D integrated circuit H-bridge. A 74HC04 hex inverter is added to manipulate the motor's start, stop, and direction remotely and allow only two legs of the bridge to be used at any time.

A radio link is established by using a pair of low-cost transmitter and receiver modules manufactured by Laipac Tech Incorporated. The TLP434A transmitter and RLP434A receiver communicate with each other on a 432.9 MHz frequency. The modules are easy to use because they can be used directly, with no software or microcontroller required in applications such as described here. A pair of Holtek encoder and decoder integrated circuits (HT12E and HT12D) are used to manage the address encoding and decoding and checking of the validity of the transmitted and received data.

Figures 4 and 5 show the schematic of transmitter and receiver used in this activity. The technical data sheets for the transmitter and receiver are available at Laipak Tech's website (www.laipak.com) and provide sample circuit applications. The HT12E encoder and the HT12D encoder (U1 & U2) are used to encode and decode the recognized addresses in the RF communications. The 8-Bit DIP switches on both the transmitter and receiver are used to set the address of the RF signals in order to set up proper recognition of the controlled pair. All the address lines are pulled up high to eliminate any possible noise signal using the “resistor packs.” However, individual resistors can be used.

The control data is selectable through four push-button switches (D0, D1, D2, and D3) to control the robot's two wheels: start, stop, forward, and reverse. Figure 6 (pg. 18) shows the transmitter with the push-button switches. The Transmission Trigger switch has to be pressed to start the RF transmission. The operation procedure is to first select/press the switch of D0, D1, D2, and/or D3 for the control function you desire, then press the Transmission Trigger switch to send the signal through the RF transmitter and receiver. A "truth table" is shown in Table 1 that describes the state and action of each of the drive motors. An "X" means "does not care," and the pressing of any of these switches will send a high signal out.
Circuit Operation and Explanation

The encoder is used to send an address (set by user on an 8-Bit DIP switch) along with 4-bits of data, which is done by the user pressing the push buttons D0, D1, D2, and D3. The TLP434A transmitter module transmits an RF signal continuously as long as the transmission trigger push button is pressed. The HT12D decoder will receive address bits and data bits via the RLP434A receiver module. It will compare its received address along with its own address setup three times continuously and check for any error or unmatched bit. If there is no discrepancy, then the 4 data bits received will be transferred to its output pins that are connected to the push buttons to control the motors' functions. Using off-the-shelf components, such as these encoder and decoder integrated circuits and the Laipak Tech transmitter-receiver pair, simplifies the design of the wireless communication electronics, software, and integrity of the radio signal.

From an engineering and design point of view, there are a number of advantages in using off-the-shelf modules like the transmitter and receiver pair. Two major advantages are the cost and the simplicity of prototyping and production of a product design based on the transmitter and receiver modules rather than in-house design and discrete part construction. These kinds of component modules can satisfy a variety of basic needs in RF wireless communication applications, such as garage-door openers and other remote-control applications, and in recognizing that wireless communication is an open-ended media signal that anyone can gain access to. Additionally, such signals are prone to noise interference. Where these issues are of a concern, they must be addressed carefully. The addition of a microcontroller with customized software and appropriate communication protocols can reduce security and interference concerns. Integrating a microcontroller to handle the address recognition and validity of the data checking will

<table>
<thead>
<tr>
<th>ENABLE_M1 D0</th>
<th>ENABLE_M2 D1</th>
<th>DIR_M1 D2</th>
<th>DIR_M2 D3</th>
<th>Motor Action</th>
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<tbody>
<tr>
<td>Lo</td>
<td>Lo</td>
<td>X</td>
<td>X</td>
<td>Motor 1 &amp; 2 Stopped</td>
</tr>
<tr>
<td>Hi</td>
<td>Lo</td>
<td>Lo</td>
<td>X</td>
<td>Motor 1 Going Forward</td>
</tr>
<tr>
<td>Hi</td>
<td>Lo</td>
<td>Hi</td>
<td>X</td>
<td>Motor 1 Going Backward</td>
</tr>
<tr>
<td>Lo</td>
<td>Hi</td>
<td>X</td>
<td>Lo</td>
<td>Motor 2 Going Forward</td>
</tr>
<tr>
<td>Lo</td>
<td>Hi</td>
<td>X</td>
<td>Hi</td>
<td>Motor 2 Going Backward</td>
</tr>
<tr>
<td>Hi</td>
<td>Hi</td>
<td>Lo</td>
<td>Lo</td>
<td>Motor 1 &amp; 2 Going Forward</td>
</tr>
<tr>
<td>Hi</td>
<td>Hi</td>
<td>Hi</td>
<td>Hi</td>
<td>Motor 1 &amp; 2 Going Backward</td>
</tr>
</tbody>
</table>
make the RF communication more secure. A comprehensive protocol design in the microcontroller software can make the RF signal difficult to decode and less prone to noise problems.

**Making Classroom Connections**

As we look at the goals of the Mars Exploration Rover missions, we can see the emphasis on science and technology. The challenges that the scientists, researchers, and engineers faced required knowledge and skills from a variety of disciplines and focused on critical thinking, problem solving, and team skills. These same kinds of skills are an integral part of our programs in classrooms and technology laboratories. Interdisciplinary learning activities that make connections between real-world jobs and careers in science, mathematics, and technology can provide a meaningful context for learning that can build interest and enthusiasm.

There are a number of mathematical skills that relate to the theory and operation of the telerobot. As we look at the motor-control system, we can see that a combination of buttons must be pressed to enable the robot to travel forward, backward, or make turns. The button sequence is based on Boolean logic that can be expressed in a “truth table” such as the one described earlier. Also included in the motor-control circuit is a Hex Inverter. This logic circuit has its own truth table where it basically inverts any signal input on its output. What would an inverter truth table look like? Understanding the purpose and value of truth tables reinforces knowledge and skills gained in math classes and adds to a greater understanding of why the sequence of buttons pressed causes certain robot actions to occur. What determines the speed or velocity of the robot? What factors affect the robot speed? Here we can apply ratios, time, force,

<table>
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<tr>
<th>#</th>
<th>Part Name</th>
<th>Quantity</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>TLP434A</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>RLP434A</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>HT12E-18DIP</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>HT12D-18DIP</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>8 Bit DIP Switch</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>Push Button Switch</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>10K Resistor</td>
<td>23</td>
</tr>
<tr>
<td>8</td>
<td>1K Resistor</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>33K Resistor</td>
<td>1</td>
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<tr>
<td>10</td>
<td>730K Resistor</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>74HC04 Hex Inverter</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>L293DNE H-Bridge</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>Tamiya 70097 DC Dual Motor &amp; Gear Box</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>Tamiya 70096 Wheel set</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>3-cell Battery Holder</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>Experimenter Socket 3.3&quot; X 2.125&quot; Jameco</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>Experimenter Socket 6.5&quot; X 2.125&quot; Jameco</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>9-Volt Battery Snap</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 6. A solderless breadboard is used to construct a prototype of the transmitter unit. The address DIP switches and the push buttons can be seen on the left side of the board. The Laipak transmitter module can be seen on the right side of the board and is about the size of a postage stamp.

weight, and distance calculations to apply and expand on basic math skills.

The radio transmitter and receiver modules have range limitations. How can the range limitations be determined? What relationships can be developed in comparison to the radio capabilities of Sojourner, Spirit, and Opportunity? The transmitter and receiver modules have antennas to radiate the radio signals. How long should these antennas be? How long does it take for a radio signal to travel to Mars? Would the time it took a radio signal command to travel from Earth to Mars be a critical factor in controlling a rover? Why?

Team Challenge Activity
The team challenge is to construct a teleoperated robot, such as the one described here, that can be controlled using a radio communication system. The robot must be capable of moving forward, backward, turning left or right, and stopping on command. Individual teams will compete against each other in navigating a predetermined course as established by the teacher. It is recommended that a 4-foot by 8-foot platform be constructed and include obstacles and dead-end paths. Teams will control their telerobots via a closed-circuit television link from a remote location. The competition evaluation criteria should be based on navigating a prescribed path with the fewest navigation errors in a defined period of time, and the design and construction of the team’s telerobot. Each team should maintain an engineer’s log that reflects the planning, design, construction, and testing of the team’s telerobot. The teams should make a technical presentation to the class based on their engineer’s log.

Similar to the Pathfinder mission with the Sojourner rover, our telerobot uses some off-the-shelf components and modules. The key modules are the receiver and transmitter that can be purchased at very low cost, providing minimal time constraints to build the control transmitter and robot radio receiver. NASA engineers faced similar challenges in planning and designing a communication system for the Sojourner rover in 1993. The same decision options face our technology team when the motor and gear box selection is made. Should the telerobot team use a commercial dual-motor gear box or build one using individual components? Some of the highlights of the radio design and planning issues that the (JPL-NASA) engineers faced were:

- Should NASA engineers design and make the communication electronics and antenna at the Jet Propulsion Laboratory? Alternatively should JPL purchase them from an outside vendor according to their requirements?
- If off-the-shelf communication equipment is available, should JPL purchase commercial- or military-grade equipment? If we buy the commercial grade, can we reliably fly them to Mars?
- If we buy a military grade, can we carry the heavier weight and provide the larger power-supply needs?
- What kinds of modifications and tests do we need to perform on the hardware to prove their reliability?
- If we make the communication equipment, will we have enough time and enough money?
- What communication frequency should we choose?

As students plan and design their telerobots, they will be faced with issues and concerns similar to the ones that NASA engineers and technologists faced in designing rovers for the Mars Explorations. Problem solving and critical thinking are important dimensions in technological literacy as well as careers as engineers, technologists, and technicians.

Summary
It has been about ten years since the Sojourner rover and Pathfinder lander landed on Mars. Since that time, additional rovers and robot explorers (Spirit and Opportunity) have been sent to Mars for scientific explorations. Increasingly we are seeing many applications of robotic devices used in industrial, consumer, entertainment, and research applications. Today there are literally hundreds of robot-like toys that have surprising capabilities, such as the Roboraptor mentioned above.

The telerobotics rover described here incorporates many of the basic systems that we would expect a robot to include. Robots typically have mechanical systems, the chassis that forms the structure, a motion-and-drive system, sensors
and output devices such as a manipulator or arm, and a control system that may be programmable or remotely operated. In addition to these basic systems, telerobotic devices have some means to enable remote operation either by a tethered cable or radio-frequency technologies.

The telerobot uses off-the-shelf components as part of a radio-controlled robot system. The radio transmitter and receiver pair uses encoder and decoder integrated circuits to manage an addressing-and-control scheme that allows the user to simply press control buttons to remotely control driver motors that can be used to navigate the robot.

There are opportunities for problem solving, critical thinking, and the application of logic and math in the design and construction of the telerobot.

Resources

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