RoombaCreate® for Remote Laboratories

http://dx.doi.org/10.3991/ijoe.v10i4.3776

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***Abstract*—Internet has advanced significantly with the aid of electronics and communication technologies. This allows us to undertake ambitious activities over the Internet, which are unthinkable even few years back. With this new scenario, performing experiments that involve real hardware remotely over the web is now a reality. Controlling hardware experiments remotely is labeled as remote laboratory. Considering the complexities of technologies involved with remote laboratories, hardware experimental systems need to be customized before they can be integrated within a remote laboratory system. One such system is a mobile robot that can be used for various student learning laboratory activities. This paper reports the customizing of a commercial mobile robot known as RoombaCreate® so that it can be integrated within a remote laboratory facility. The process involves automated movement with obstacles avoidance, wireless control, real-time video, and control over the web.**

***Index Terms*—Remote lab, Mobile robot, Embedded system, and Learning management.**

I. INTRODUCTION

Robots are having application within the society where industry was their only work place in the past. This becomes possible with the aid of innovative technology, exponentially increasing computing power, and emerging control algorithms. Robots now have mobility and have started to roam around us in different shapes and forms. These robots can walk, run, and climb and are commonly known as mobile robots. Most of these developments are demand-driven and are developed through the realization of scientists' imaginations [1, 2, 3]. The areas benefiting from mobile robots are medicine and surgery, care for the elderly and disabled, office assistance, emergency rescue, defense, and household assistance.

In medicine, daVinci developed a surgical system for robotically assisted surgery. The daVinci system provides minimally invasive surgery, even for complex surgical procedures, and its acceptability and use is increasing rapidly [4, 5, 6]. With a growing elderly population, mobile robots have found use for elder care as mobile servants as well as for personal assistance and rehabilitation. Mobile robots are extensively used in emergency services after a natural disaster like earthquakes, building collapse, fire rescues, and homeland security (dealing with terrorists and bomb diffusing). One of the areas of mobile robotics that is developing very fast but without much notice is their use in defense, mainly to assist soldiers in carrying out logistical reconnaissance around the front line [7, 8, 9, 10]. To promote these developments, the CLAWAR Association is taking a lead on the advancement of education and science for the public benefit in the field of robotics and associated technologies. Recently, ISO has published their first standard for personal care robots **[11]**.

Controlling these mobile robots remotely provides additional potential in accommodating these within our work environment. Remote manipulation of a real hardware, in this case a mobile robot, is a remote laboratory exercise. Including mobile robots within the academic activities will provide our students with capability and insight into the new generation of robots. In general, remote laboratories are gaining popularity among researchers and educators, and there are a number of reported initiatives in terms of system design, technology use, and pedagogical issues. The remote laboratories entail physical (real) laboratory equipment being controlled remotely over the Internet [12, 13]. These laboratories have great potential and can bring a new dimension for teaching the STEM (Science, Technology, Engineering, and Mathematics) disciplines [14, 15].

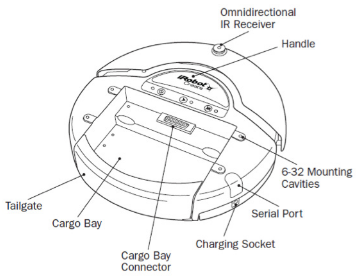
In an academic setting regular laboratory classes are only scheduled for a limited time period. Considering the mixed ability level of the students, sometimes students want or feel a need to perform additional experiments beyond their assigned tasks [16]. It is usually difficult to accommodate any extra time due to the lack of resources to keep the laboratories open, and ironically, too much experiment equipment lies idle during most of its usable lifetime. Remote experimentation facilities can provide cost effective and unlimited access to experiments and maximize utilization of available resources [17]. Additionally, this will allow inter-experiment collaboration among universities and research centers by providing research and student groups with access to a wide collection of expensive experimental resources at geographically distant locations.

Considering all these, the lead author took an initiative to integrate a household mobile robot within a remote laboratory platform so that students would be able to study the mobile robot systems as a part of their academic study. The goal of the initiative is to provide a platform for the students to manipulate and control the robot's performance on specific tasks via the Internet. This paper will provide a description of the mobile robot, its customization for a remote laboratory, the integration with a remote laboratory facility, and an illustration of a remote laboratory learning management system. The second section describes the Roomba Create that has been used as the mobile robot for this development. The third section shows the hardware modification of the Roomba Create for its customization with a remote laboratory facility. The fourth section describes the software development and controller designs using LabVIEW. The fifth section illustrates the integration of a customized mobile robot with an existing remote laboratory facility.

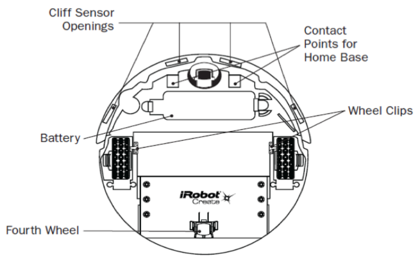
II. ROOMBA CREATE- THE MOBILE ROBOT SYSTEM

The project deals with a commercially available open architecture mobile robot system that is known as Roomba

Create (RoCr). This is designed and developed by the iRobot [18]. This is a complete robot development system that allows one to program new robot behaviors without thinking much about mechanical assembly and low-level control. iRobot's RoCr's Open Interface (OI) provides a set of commands, such as drive commands, demo commands, song commands, and sensor commands [19]. These can be used to develop new behaviors and add third party electronics and write Open Interface-based programs to control iRobot RoCr using a serial communication. One can also attach and control other hardware and electronic devices to iRobot RoCr, such as a robotic arm, light display, or ranging sensor. A top and bottom view of a RoCr showing all the main components is provided in Figure 1. In addition to the inbuilt sensors, one can attach additional



(a) Top View.



(b) Top View.

Figure 1: Top view of a Roomba Create.

hardware electronics (sensors and actuators) such as a robotic arm or light sensor to RoCr via the cargo bay connector. The connector is located around the upper middle part of RoCr and can provide four digital inputs, an analog input, three digital outputs, three low-side driver outputs (useful for driving motors), a charging indicator, a power toggle, a serial Tx and Rx, a 5V reference, a battery ground, and a battery voltage.

A. Open Interface (OI)

The RoCr OI consists of an electronic interface and a software interface for controlling the RoCr's behavior and reading its sensors [19]. The hardware interface includes a 7 pin Mini-DIN connector for connecting RoCr with a PC and a DB-25 connector in the cargo bay area. The software interface allows a user to read its sensor and manipulate the RoCr's behavior through a series of built in commands. The commands include mode, drive motors, song, demo, and sensor status request. The RoCr serial port setting consists of 8-data bits and 1-stop bit without any parity or flow control. The baud rates that are supported by RoCr are 57600 and 19200, with a default rate of 57600. One can change the baud rate on the Roomba Create itself or through a computer connected to it, using a hyper terminal programs like 'tera term.

Open Interface Modes: The RoCr OI has four operating modes: Off, Passive, Safe, and Full. The RoCr can switch between operating modes at any time by sending an appropriate command to the OI [19]. Upon sending the Start command or any one of the demo commands, the OI enters into Passive mode (default mode). When in Safe mode, the user has the control of RoCr, with the exception of few safety-related conditions, such as detection of a cliff while moving forward, backward, or turning; detection of a wheel drop (on any wheel); and when a charger is plugged in and powered on. When in Full mode, the user has complete control over all of its actuators and all of the safety-related conditions that are restricted when the OI is in Safe mode. When in Full mode, the RoCr shuts off the cliff, wheel-drop and internal charger safety features. To put the OI back into Safe mode, one must send the Safe command.

Open Interface Commands: The RoCr has a number of OI commands. Each command starts with a one-byte opcode, and few commands have additional data byte. As an example, the Start command has an opcode of 128 without any data byte following it, while the Baud command has an opcode of 129 along with a one data byte. The opcodes control the motion and various other activities of the RoCr. The data bytes that succeed the opcodes are specifications of various parameters in a control operation like distance, velocity, and music notes. The commands are of six types: Mode commands, Demo commands, Actuator commands, Input commands, Script commands, and Wait commands. A complete list of OI commands, including their required data bytes, can be obtained from a reference [19].

Sensor Data Packets: Depending on the requested packet ID, the RoCr sends back one or all 43 different sensor data in the form of packets. Each packet can be 1 or 2 bytes in size. It is also possible to request all of the sensors data in the form of a group packet. Within a group packet, packet subsets are assembled to accommodate all of the sensors' data. The sensing items are bumps and wheel drops, wall, cliff left, cliff front left, cliff front right, cliff right, virtual wall, over-currents, IR byte, buttons, distance, angle, charging state, voltage, current, battery temperature, battery charge, battery capacity, wall signal, cliff left signal, cliff front right signal, cliff right signal, user digital input, user analog input, charging sources available, OI mode, song number, song playing, number of stream packets, velocity, radius, right velocity, and left velocity [19].

B. Bluetooth Interface

To create wireless personal area networks (PANs) Bluetooth technology is being used. PANs were designed to be used by a single user where Wi-Fi networks can have hundreds of users. A BlueSMiRF was used for Bluetooth implementation, which is a relatively inexpensive Bluetooth modem that implements the Bluetooth Serial Port Profile (SPP) and presents a normal 5V logic set of serial lines [20, 21, 22]. The BlueSMiRF is connected directly to the RoCr via the serial 7-pin DIN connector. When the BlueSMiRF is paired with the host computer, the serial lines are virtually connected to the computer as a normal serial port.

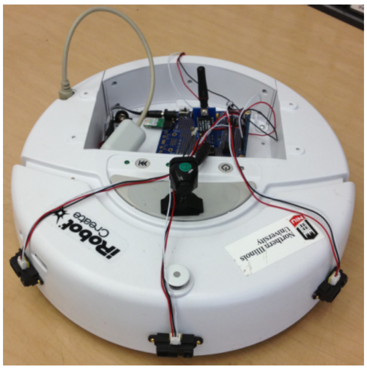


Figure 2: Top view of a Roomba Create.

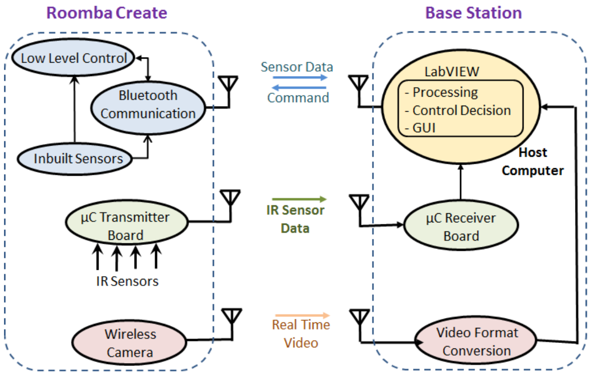


Figure 3: System block diagram of modified Roomba Create.

III. MODIFIED ROOMBA CREATE

The RoCr has been modified both for hardware and software. In terms of hardware, Bluetooth communication capability, four infrared (IR) sensors for obstacle detection, and onboard real time video camera have been added to the system. For the software part, LabVIEW is used to develop a controller based on the various sensor data as well as for designing a graphical user interface for user manipulation. An image of the modified RoCr is show in Figure 2.

The first item of modification is the Bluetooth capability of the RoCr wirelessly connecting the system with a host computer. This allows a user to have all the sensors' data on the computer and send command output to the system using various control strategies. In its original form, the RoCr uses three micro-switches to sense an obstacle. The switches are mounted behind a spring-loaded bumper located at the front and sides of the RoCr. The newly added IR sensors allow the RoCr to detect an obstacle ahead of time and to avoid any contact with an obstacle. Three of the sensors are in the front, with two on the sides and one on the back. The IR sensor data are passed to the host computer using a RF link. The sensor outputs are connected to a microcontroller system via A/D converters. The microcontroller prepares the digitized sensor outputs in a serial format before passing these via a RF transmitter. A receiver unit is placed around the host computer where the data are collected by another microcontroller system and pass the collected data directly to the host computer for further processing by LabVIEW for controller operation. In addition, a small wireless camera is mounted on the RoCr to have a real time video when it moves around. The camera has its own inbuilt transmitter along with a receiver system that is connected to the host computer via an analog to digital converter.

A block diagram showing the modified RoCr system with the base station is shown in Figure 3. The base station is composed of the host computer connected to three entities. The first one is a Bluetooth transceiver to receive the RoCr's inbuilt sensor data and send command signals to the RoCr. The second is the microcontroller receiver board for the IR data. The third is the real-time video from an onboard camera. The RoCr sends its inbuilt sensor outputs to the base station and receives commands for its maneuvers, both via the Bluetooth connection. The microcontroller transmitter board is on the RoCr and transmits the IR data after the initial processing. The RoCr also holds the wireless camera and passes a real time video to the base station using a separate RF communication channel.

A. *Obstacle Avoidance*

An obstacle avoidance system is needed so that RoCr can roam around without any collision. A number of Infrared sensors (IR) are used for obstacle avoidance along with a microcontroller. The system was developed for managing the collected obstacle detection data and transmitting to the base station. Considering various factors, propeller microcontrollers were used for both the transmitter and receiver sides. The transmitter part is located on the RoCr and is connected to the IR sensors via A/D converters, while the receiver is connected to the base station and passes the received IR sensor data to the computer. The hardware system for IR obstacle detection consists of two microcontrollers, four IR sensors, the two A/D converters, and two transceivers.

Propeller Microcontroller: The Propeller chip is designed to provide high-speed processing for embedded systems while maintaining low current consumption and a small physical footprint [23]. In addition, it has eight processors (called cogs) that can perform simultaneous independent or cooperative tasks, all while maintaining a relatively simple architecture. The propeller uses 'spin' language that is a high-level object-based language designed by Parallax specifically for the Propeller chip [23]. Spin provides control of the Propeller's multi core hardware and encourages the principles of the Propeller's real-time application design in ways that were not represented by existing languages. Spin was inspired by portions of C, Delphi, and Python, and a host of problem/solution scenarios explored by its designers. This language allows users to utilize the eight cogs of the processor effectively. The spin or the propeller assembly language can execute up to 160 MIPS (million instructions per second), i.e. 20 MIPS per cog.

The microcontroller boards used for the transmitter and receiver have 32kb of EEPROM for program storage and can hold a program after a power reset. The transmitter board has been programmed to run the IR sensors, extract the sensor signal from them, send them to the A/D converters, set the A/D converter in the right mode of operation, store the obtained 12-bit digital data from A/D converter and transmit it to the base station through a RF transceiver. All these tasks are performed in parallel by taking advantage of propeller's multi-core architecture.

Infrared Sensors: IR sensors are used as proximity sensors for obstacle detection. The idea behind using IR sensors is to minimize the use of bumpers in the RoCr. In terms of its operation, IR sensors send out IR signals and receive return signals if there is any obstacle to bounce the signal. The strength of the received IR signal corresponds to the distance between the sensor and the obstacle. The received signal can be used to determine the distance between the RoCr and an obstacle. The IR sensors used for this project are from Sharp and are a distance measuring sensor unit with a combination of PSD (position sensitive detector), IRED (infrared emitting diode) and a signal processing circuit [24]. The variety of the reflectivity of objects, ambient temperature and duration of operation does not influence the accuracy of detection as it uses triangulation method of calculation. The sensor provides analog voltage output corresponding to the detection distance. It is important to note that if an object is too close to the sensor (8cm or less), the output voltage decreases and does not provide any meaningful measure of distance.

Analog to Digital Converter: To digitize the IR sensors' outputs, MCP3202 analog to digital (A/D) converters are used [25]. The MCP3202 is a successive approximation 12-bit A/D converter with on-board sample and hold circuitry. The MCP3202 is programmable to provide a single pseudo-differential input pair or dual single-ended inputs. Differential nonlinearity (DNL) is specified at ±1 LSB, and Integral Nonlinearity (INL) is offered in ±1 LSB (MCP3202-B) and ±2 LSB (MCP3202-C). The MCP3202 A/D converter employs a conventional SAR architecture. With this architecture, a sample is acquired on an internal sample/hold capacitor for 1.5 clock cycles starting on the second rising edge of the serial clock after the start bit has been received. Following this sample time, the input switch of the converter opens and the device uses the collected charge on the internal sample and hold capacitor to produce a serial 12-bit digital output code. The MCP3202 device offers the choice of using the analog input channels configured as two single-ended inputs or a single pseudo-differential input.

The digital output communicates with the propeller microcontroller via a simple serial interface compatible using the Serial Peripheral Interface (SPI) protocol. The SPI bus is a synchronous serial data link standard, named by Motorola that operates in full duplex mode. Devices communicate in master/slave mode, where the master device initiates the data frame. Multiple slave devices are allowed with individual slave select (chip select) lines. Sometimes SPI is called a four-wire serial bus, contrasting with three-, two-, and one-wire serial buses. SPI is often referred to as SSI (Synchronous Serial Interface).

RF Transceiver: The Parallax 433 MHz RF transceiver is used to pass the sensor data from the transmitter board to the receiver board and utilizes a frequency of 433 MHz; this works out to be a wavelength of approximately 0.69 meters [26]. On the receiver board, an RF transceiver receives a signal sent from the transmitter board and then sends the signal to host computer via the prop plug. The 433 MHz RF transceivers do not have a built-in error handling protocol and therefore are not immune to noise and errors in the signal. To ensure the validity of a data packet, the microcontroller initiates an error-checking scheme.

Transmitter and Receiver: The transmitter part includes two A/D converters, a propeller microcontroller, and a RF transmitter. The A/D used in this project can process two analog inputs simultaneously; so two A/Ds are used for converting four IR analog outputs. The processor receives the digitized IR distance sensing data from the A/D converter and processes them to form a serial chain of data along with some markers. One cog of the microcontroller is required to control each A/D, so two cogs are used to monitor and receive the converted signal. A third cog is used for collecting data from the two cogs (that are used for collecting data) and includes some markers to form a serial stream of data called a packet. Between each sensor signal within the packet, the processor introduces a 'Right Tab' (RT) character and a 'Carriage Return' (RT) at the end of a packet. Each packet is 18 bytes in size, 8 bytes for the sensor data, 4 bytes of Right Tab, 1 byte of Carriage Return and 5 bytes for additional information required to transmit the packet (Figure 4). This packet is then passed to the RF transmitter for transmission. A schematic diagram for the transmitter board is shown in Figure 5.

B. *Video Streaming*

One of the features of the modified RoCr is to have an onboard camera so that it can provide a real-time video of its surroundings. A miniature wireless camera mounted on top of the RoCr to provide a front view from the robot operates at 2.4GHz [27]. A block diagram shows the implementation of wireless camera (Figure 6). The Radio AV receiver receives the transmitted signal and sends it through composite cables. The video is then converted to digital format and passed to the computer using a Video Xpress [28].

C. *Control Strategies*

The main goal of controlling the modified RoCr is to avoid any obstacle in its way and to develop an alternative path when necessary. Based on the data from the RoCr's inbuilt sensors and additional IR sensors, LabVIEW implements control strategies and the host computer sends commands to the RoCr via Bluetooth channel. Three steps

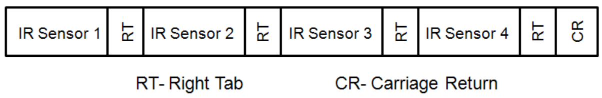


Figure 4: Serial data format formed by transmitter microcontroller.

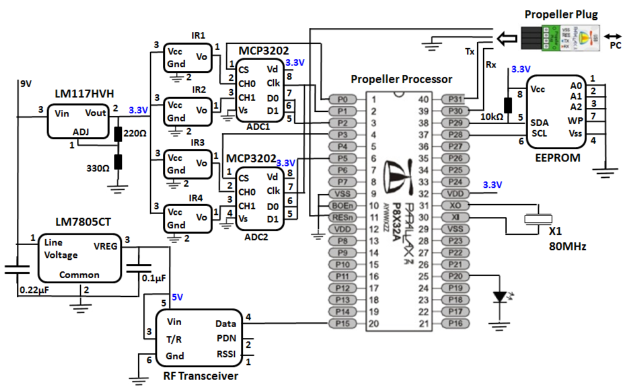


Figure 5: Schematic of the transmitter board.

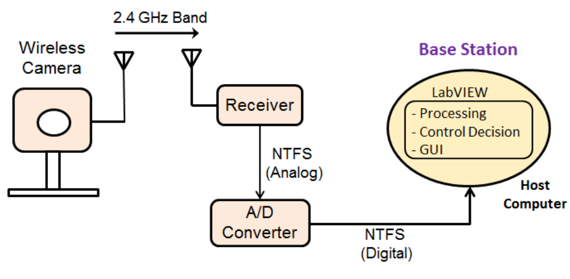


Figure 6: Block diagram for wireless camera system.

are involved to obtain a closed loop control of the RoCr: a) determine the sensor status of the RoCr, b) determine the commands to be sent in case of any obstacle detected by the RoCr, and c) issue a control command. Initially the controller drives the RoCr in a straight-line path and keeps checking the IR obstacle sensors as well as the inbuilt bounce sensors. Upon receiving any obstacle signal, the controller will automatically redirect the RoCr in a revised course. Three anticipated scenarios and different control strategies are implemented for each scenario. In addition to the automatic control, the RoCr can also be controlled manually via a GUI. The manual control has a higher priority than the automatic control.

Within the automatic control approach, there are three control strategies for handling three different obstacle scenarios. The scenarios are obstacle on the right, obstacle on the left, and obstacle on the front. One of the scenarios is explained here. When the RoCr senses an obstacle on its right side, the controller will direct the RoCr to turn left with a constant turn radius for some time and drive forward after it. Figure 7 shows a diagram depicting the movements for this scenario. Similar to this, a lef side obstacle will turn the RoCr to the right and a front obstacle will drive it backwards and then to the right.

IV. LABVIEW IMPLEMENTATION

The LabVIEW software is the main driving force for controller design and Graphical User Interface (GUI) development. This is also used for displaying the real time video from the RoCr. The LabVIEW is a powerful tool for controller designs as well as for user friendly GUI. The LabVIEW design involves the connection with the Bluetooth, collecting data from the microcontroller receiver unit and collecting the digitized video as transmitted from the RoCr. Once the data are collected, the task is to process them to implement control strategies as well as display of the real time video through a GUI.

GUI Development: This section describes the development of a GUI using LabVIEW. The Figure 8 shows a screen shot of the developed GUI that controls the RoCr. As shown, the GUI includes all the desired control functionalities as well as notifications and video. The rest of this subsection provides a description of the different parts of the GUI. A programming flowchart used for the GUI development is shown in Figure 9.

The top part of the GUI provides the initialization and port setup process. The left bottom part of the GUI shows the speed and turning radius adjustment markers. The remaining area is divided for the RoCr command and control buttons, displaying the Video, and showing the RoCr sensor status. The available commands within the GUI are move forward, move backward, turn right, turn left, stop, load and play tunes, and change speed and turning radius. The sensor data used for making decisions (in the back end of GUI) are the right bump sensor, left bump sensor, override current sensor, and IR sensors. Apart from the last one, others are inbuilt sensors of the RoCr. In addition, the GUI displays a few other sensor statuses: home detect sensor, wheel drop sensors, battery temperature sensor, and battery charge sensor.

V. WEB HOSTING

A web server is hosting the web site for the facility, including all the applications and interfacing hardware and

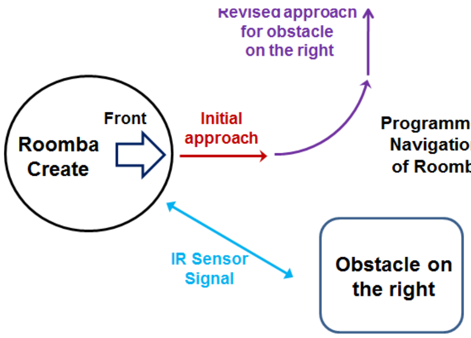


Figure 7: Controlled motion after detecting right side obstacle.

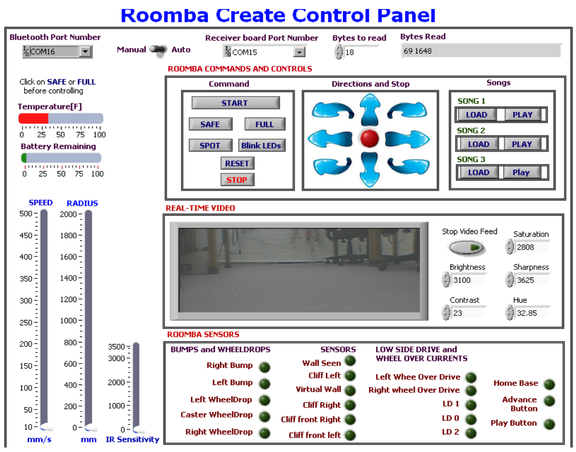


Figure 8: Image of the GUI for RoCr control.

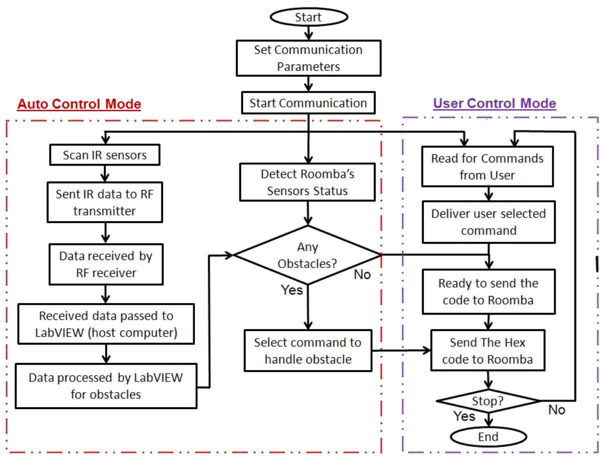


Figure 9: Flowchart for controlling Roomba Create.

software. In terms of hardware, the web server is having a *Intel Xeon* X3370 (12M Cache, 3GHz, 1333 MHz FSB), and National Instrument's I/O card. For the software part, it has Windows 2003 Server (OS), LabVIEW, Internet information services (IIS) server, .NET, XML (EXtensible Markup Language), XSLT (EXtensible Stylesheet Language Transformations), and SQL server 2008. A block diagram showing an overall software interaction is provided in Figure 10.

LabVIEW is also used for data collection and visualization. The IIS provides the services to the http requests coming through the Internet. This is a component provided within Windows 2003 server. The IIS makes it easier to share documents and information over the Internet. Web-publishing, security, administration, and applications can work together to increase performance and reliability—

while lowering the cost of ownership and also improving the web application environment. Only an authorized client with a valid password can access the system. This requires password protection and a dynamic web page. This has been implemented using ASP.NET.

The .NET Framework is the infrastructure for the new Microsoft .NET platform and is a common environment for building, deploying, and running Web Services and Web Applications. The .NET Framework contains common class libraries like ADO.NET, ASP.NET, and Windows Forms. This is to provide advanced standard services that can be integrated into a variety of computer systems. This is a language neutral framework and supports C++, C#, Visual Basic, JScript (The Microsoft version of JavaScript), and COBOL. The new Visual Studio.NET is a common development environment for the new .NET Framework and provides a feature-rich application execution environment, simplified developments, and easy integration between a number of different development languages. ASP.NET along with ADO.NET is used to build this web application and has used C# as the programming language for its simplicity and completeness [29, 30, 31].

VI. LEARNING MANAGEMENT

In terms of learning management system, there is an application developed for student and administrative activities. Students' activities involve using the facility for performing experiments and interacting with other students; while the administrative activities deal with access control, facility usage monitoring, and supporting assessment activities.

The remote laboratory offered with a custom developed learning management system (LMS) [32]. This LMS have administrator and student levels of access. With administrator level of access one can perform a number of activities- laboratory management, experience sampling method (ESM) data management, facility usage monitoring, weekly survey management, and data download. An image of the administrator access page is provided in Figure 11.

The laboratory management feature allows an administrator to manage laboratory groups, group time slots and laboratory experiments. Experience Sampling Method, briefly known as ESM, is a method of measuring students' engagement on Likert scales indicating enjoyment, concentration, and interest in a given activity. This measurement has been shown to have strong psychometric properties and is positively related to achievement [33]. The ESM is used to gather data on the subjective experience of individuals while they are engaged in particular activities [34]. Within the software facility provision has been made so that students were prompted with pop-up windows (while using the environment) to respond to a number of scaled items in which they would report on their concentration, enjoyment, and interest in the activity they are doing at that moment as well as their perceptions of the challenges involved in the activity. The facility usage feature allows an administrator to monitor the usage of the developed facility. This enables an administrator to get a statistics in terms of facility usage by students for a given period of time. Using the weekly survey management feature an administrator can update the weekly survey questions and analyze the data gathered.

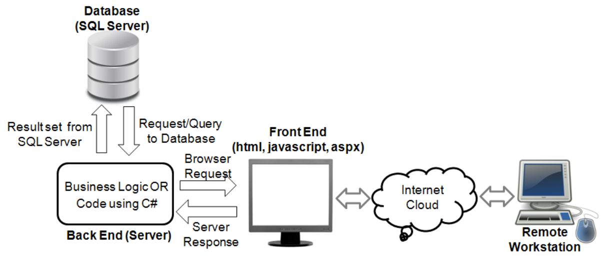


Figure 10: Software interaction scheme.

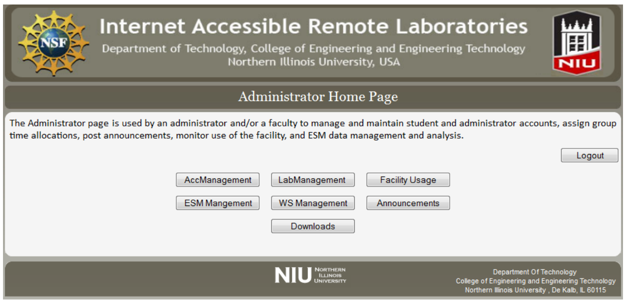


Figure 11: Image of the administrator page.

VII. CONCLUSIONS

The paper provides an account of modifying a Roomba Create mobile robot so that it can be integrated with a remote laboratory facility for remote access. The process involves understanding the RoCr, design and development of new functionalities. The functionalities involves a microcontroller based system (hardware and software) for obstacle avoidance, remote communication with the base station, GUI design for user interaction for remote operation. In addition, provision has been made to provide a real time video of its surroundings while in operation. Finally, the developed system is integrated with an existing remote laboratory facility along with a LMS. The LMS is used as a portal for offering remote laboratory courses as well as for overall management of the facility.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of the National Science Foundation (NSF) for this project. The NSF is a federal funding agency in US. Most of the design and development work reported in this paper are funded through two NSF awards (Numbers DUE-0442374 and DUE-0837138).

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Submitted 20 April 2014. Published as re-submitted by the authors 08 June 2014.