CRCO: Low-Power Wireless Communications for Virtual Environments - Design Document

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1. Introduction

An NSF Combined Research Curriculum Development (CRCO) project at Iowa State University integrates research from areas of wireless communications, low-power embedded systems, virtual environments, and human factors in an interdisciplinary program. The project involves both research and education activities.

The research goal is to design and implement low-power wireless communications systems for wearable sensor networks in virtual environments. The new communication systems expect to provide a unified and extensible communication mechanism between heterogeneous sensing devices (e.g., accelerometer, data glove, and wand) and virtual reality applications. The C6, which is a three-dimensional, full-immersion, synthetic environment at Iowa State University, serves as our testbed to demonstrate our systems.

The education goal is to develop an integrated educational program in which faculty members in different disciplines work closely together to mentor students to solve a complex interdisciplinary problem that combines real-time systems, wearable computers, human factors, Virtual Reality (VR), and wireless devices. For a better understanding of such an interdisciplinary problem, let us consider the development of a virtual kickboxing application. This application requires several different disciplines from its design to implementation stages. For example, students should know how hard a user punches his/her virtual opponent (human factor), how to measure the position, direction, and acceleration of arms (sensors), how to interface between sensors and the C6 (wireless communication), how to implement a virtual opponent in the C6 (VR application), and so on. Figure 1 shows communications and devices for a user in the C6 Cave.

One challenging issue in teaching is how to present such an interdisciplinary problem to students having different disciplinary training. To address this, we introduced a design document to define and present the problem in a way that supports students with different backgrounds so as to have the necessary discipline-specific information and understand the multidisciplinary aspects of the problem². A central design document describes the larger system, and ancillary documents describe specific subsystems. Through a design document, a student should be able to

understand what knowledge and skills are relevant to each subsystem and how a particular subsystem will affect the larger system.

Figure 1. Communications and devices for a user in the C6 Cave

We have identified several important qualities of the design document¹. Based on these qualities, we are developing a web-based design document by coordinating with an existing Content Management System (CMS) groupware. The web-based design document aims at providing faculty members with systematic methods to integrate, organize, and present information consistently. It also provides students with tools to share their understanding of the problem.

In the following sections, we will present the design document and its web-based version, focusing on how we make use of the existing CMS groupware for the design document and a case study showing how the design document helps to improve the learning of interdisciplinary subject.

2. Design Document

The design of virtual reality systems is difficult due to the cross disciplinary nature of the task. This is exacerbated by a lack of understanding between different disciplines. To address this, we introduced a design document. The goal of the design document is to present the problem in a way that supports students in diverse disciplines so as to have the necessary discipline-specific information and understand the multidisciplinary aspects of the problem.

Several important qualities of the design document are as follows¹:

- hierarchical information model (e.g., different levels of content)
- navigation aids (relationships, drilldown)
- terminology glossary and cross-references
- high-level diagrams of system structure and behavior

- interface descriptions (interfaces between subsystems)
- information flows
- multiple views
- user scenarios
- constraints (quantitative and qualitative specification)

Based on these qualities, we are developing a central design document and sub-design documents. A central design document describes the larger system, and sub-design documents describe specific subsystems. When the individual parts are created independently, the system as a whole becomes very difficult to integrate. However, if students have an understanding of the problem as a whole and at least a rudimentary understanding of the issues of the other parts of the development, integration can be eased. Through a design document, a student should be able to understand what knowledge and skills are relevant to each subsystem and how a particular subsystem will affect the larger system.

A full central design document was presented in our previous work². The first part of the central design document introduces the C6 virtual environment and the problems with the existing system. Next, common C6 usage scenarios were described to explain how to students how their work fits into the larger problem. Appendices to the document gave the specific requirements for different parts of the system such as the wireless subsystem and the software engineering.

2.1 Subsystems – Sub-Design Documents

As shown in Figure 1, there are a number of wireless devices being used in a confined area. Although most of them are operating in different frequency ranges, they still have a tendency to interfere with each another. This problem motivates the new wireless VR system. Focusing on data flow, Figure 2 depicts a new design of wireless VR system. The diagram focuses on how the data (e.g., position, direction, acceleration) measured by sensors propagates through the system. The data measured by the sensors is delivered to a personal area network (i.e. Data acquisition and control subsystem) via one of several communication protocols. The system supports analog data transfer, Serial Peripheral Interface (SPI), and the Inter Integrated Circuits bus (I²C). The personal area network is formed using FM (frequency modulated) wireless communication. The data is then accessed via a serial port from a wearable computer running VRJuggler⁷. VRJuggler then transmits the data over on IP (Internet Protocol) network to the graphics computer. VRJuggler defines an Application Programming Interface (API) that the application developers use to access the data. The graphics computer delivers the audio and visual (AV) rendering of the virtual world to the C6 virtual reality system. The goal of the proposed system is to consolidate all wireless communications from an array of low-powered transmitters into a single high-bandwidth connection. External sensors attached to these low-powered transmitters gather data. The data is then sent to a receiver that is attached to a wearable computer. The wearable computer packs and sends the data over wireless Ethernet to the graphics computer which renders scenes with the data.

Figure 2. Data flow diagram of the new wireless system

Each subsystem in this design is elaborated in the form of a sub-design document. These sub-design documents describe discipline specific information which is necessary for designing and developing the subsystem. A sub-design document consists of several sections:

- **Description + Goal:** describes an overview. e.g., what is it for?, why do we need it?, when do we need it?
- **Input/Output:** describes information necessary for interfacing with other subsystem(s). e.g., what data should be given?, what data will be generated?
- **Operations:** describes functionalities of the subsystem.
- **Requirements:** describes required capabilities.
- **Constraints:** describes any assumptions. e.g., frequency range should be within the ISM band, ideally 915 MHz, for the Data Acquisition and Control subsystem.
- **Resources:** describes necessary resources for designing and developing the subsystem. e.g., necessary H/W, S/W, references
- **User scenarios:** e.g., how it works, how it interacts with other subsystem(s).

Based on this format, two examples of sub-design document (Data acquisition and control subsystem, Wireless communications subsystem) are given below.

Data Acquisition and Control Subsystem

- **Description + Goal:** Data Acquisition and Control subsystem: Collect data from the on-body sensors and reliably send the data to a wearable computer. To successfully monitor, control and transmit the desired data from each sensor node, one has to designate the network topology of the subsystem. The wireless sensor network platforms designed by Crossbow¹⁹ called Motes are used to develop an unified, wireless automated data acquisition and control subsystem. The Motes have a microprocessor and a radio transmitter that operate at 915 MHz and employ frequency modulation to encode the transmitted sensor data. There are two types of Motes that differ in size and number of inputs. The Mica2Dots are the smallest and will mostly be placed around the body. The Mica2 is larger and heavier, but has more inputs, so it would only be used for measurements if the extra inputs are needed. The Motes utilize TinyOS²⁰, an operating system originally designed by UC Berkeley, which allows programmers to effectively customize a designate the network topology of the two-way mesh radio network.
- **Input/Output :** The Motes can collect data from several analog or digital inputs. There are 6 analog inputs, which are converted to 10 bit digital data, and 6 digital I/O pins on the Mica2Dot. They have serial communication abilities. In addition, the Mica2 has I2C and SPI interfaces, plus additional analog and digital inputs.
- **Operations:** The Motes collect the sensor input data. The Motes must also perform some simple filtering because the size of data they receive from the sensors could be too big for the limited bandwidth on their wireless connections. The sensor data will be packaged and sent to another Mote connected to the wearable computer. The format of the data sent will need to agree with the format expected by the wearable computer. The data sent will include from which Mote the data was collected. The Mote connected to the wearable computer receives data through the wireless communication channel and then sends the same data over the serial port to the wearable computer. The Motes support two-way communication. The wearable computer can control the Motes and devices attached to them.
- **Requirements:** Transmit data wirelessly more than 5 feet and less than 10. (a personal area network) Network a minimum of 5 Motes on the body. (One on each hand and foot. One connected to the wearable PC)
- **Constraints:** The radio communication channel is limited to 38.4kbps. The analog inputs of the Motes are limited from 0-3V.
- **Resources:**
 - XBow Mic2Dot and Mica 2 Hardware
http://www.xbow.com/Support/Support_pdf_files/Motetraining/Hardware.pdf
 - TinyOS, <http://webs.cs.berkeley.edu/tos/>

- **User scenarios:** The sensors is attached to the Motes. A selection of sensors is dependent on their usages in the application. The user attaches the Motes to their body. This is most likely be the Mica2Dots since they are the smallest and lightest. They are attached to the hands and feet by using wrist bands or Velcro straps. Another Mote is then connected to the wearable computer's serial port.

Wireless Communications Subsystem

- **Description + Goal:** Wireless Communication subsystem: To receive input data and make it accessible to the application developer.
- **Input/Output:** The wireless communication subsystem can use an array of different inputs. It supports various ports, such as Serial, USB, and Ethernet. In this particular case, the input will be serial since that is the interface that the Motes provide. The output of the VRJuggler sub-system is the data that was captured from the Motes. The application developer will have access to this data as either a boolean value for the discreet digital input pins or a normalized (between 0.0 and 1.0) floating point value for the continuous input (for example a reading from the analog to digital converter).
- **Operations:** A wearable computer is used by the wireless communication subsystem. It will be running VRJuggler. VRJuggler on the wearable machine is responsible for gathering the data via a serial connection with the Motes. VRJuggler's remote input manager will then relaying this information to the graphics machines so that it can be used for interaction in the virtual world.
- **Requirements:** Collect, process, and send data to the graphics computer in realtime..
- **Constraints:** The data arriving from the Motes will be in a predefined format. The wireless network will have enough bandwidth to support all data being transmitted from the wearable computer
- **Resources:**
 - VRJuggler, <http://www.vrjuggler.org>
 - Gadgeter Web Site, <http://www.vrjuggler.org/gadgeteer/index.php>
- **User scenarios:** The wireless communication subsystem serves as the main link between the sensors and the graphics computer. The wearable computer is connected to the Motes with a serial cable. It accesses the data packaged by the Mote. The application developers use the API provided by VRJuggler to access this information. The data transmitted over a wireless network is completely hidden from the application developers. They write their code as if the device were attached to the machine they are running the graphics on.

3. Web-based Design Document

The issue that is central to this paper is how to organize and present a design document effectively and consistently. A central design document and sub-design documents should be organized in a way that helps students understand a problem easily and find information as quickly as possible. Their presentation should be consistent to avoid any confusion in understanding the problem. In addition, a design document should be dynamic. Developing a design document is an iterative process between faculty members and students, and among students. Faculty members should be able to update the document dynamically on request. Also, students should be able to share their understanding/knowledge/experience among themselves, which leads to active learning.

Figure 3. Tikiwiki-based Web-based Design Document

To meet these requirements, we use an existing Content Management System (CMS) groupware. The CMS is software that enables users to add and/or manipulate content on a web site¹⁸. The CMS allows content managers to manage the creation, modification, and removal of content without in-depth knowledge of web authoring. The most common features of CMS are web-based publishing, revision control, search, and format management. PostNuke¹³, Callisto¹⁴, Jcms¹⁵, Cascade¹⁶, and Tikiwiki¹² are good examples of CMS. For our design document, we use Tikiwiki. Tikiwiki is a php & SQL-based CMS groupware which is an open source package. Figure 3 shows an overview of the Tikiwiki-based web site.

(a) Editing history

(b) Differences between two versions

(c) A part of the central design document

(d) A sample sub-design document

Figure 4. Use of Tikiwiki for the design document

Tikiwiki supports Wiki¹⁷ which is software that enables document editing using any web browser. Wiki is a collaboration environment where the users can edit the pages they read. It uses a special editing syntax to ensure a consistent formatting. An editing history is kept for each page so document editors can view differences or rollback a page to a previous version. Figure 4(a) shows an editing history of a particular Wiki document and Figure 4(b) shows an automatically generated log showing differences between two versions of the document. Figure 4 (c) & (d) show the snapshots of a part of the central design document and sub-design document generated with Wiki.

In addition, Tikiwiki provides several useful built-in tools that support qualities deemed important for a design document:

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- Terminology glossary and cross-references:** The “Hotword” feature of Tikiwiki makes it easy to implement a terminology glossary and cross-referencing. This feature allows faculty members to register important terms needed to be explained. Then, all the instances of the registered terms in Wiki documents automatically appear as a hyper-link which leads to their definitions in the term glossary. The combination of terminology glossary and automatic cross-referencing is very useful for clear and consistent understanding of technical terms.

Figure 5. Terminology glossary and automatic cross-referencing

- Forum and comments:** Forums are an essential feature for dynamic interaction. A forum is a place where students and teachers can share understanding, knowledge, and experiences. A forum is organized as a collection of topics and each topic is a collection of user messages about that topic. Using forums, students can post or retrieve questions & answers ranging from a general problem understanding to specific technical issues. Tikiwiki allows content managers to set permissions to determine who can create/administer forums and topics, and who can post messages. Individual permissions can be set for forums so that private forums, only visible to some user groups, can be created. Figure 6 (a) shows sample topics created for the design document. A comment feature is useful to provide instant user feedback. Comments can be displayed or hidden using simple controls and the user can control how to sort votes, the number of votes to see by page, and the minimum threshold (score) for a vote to be displayed. Figure 6 (b) shows sample comments.

(a) User forum

(b) User comments

Figure 6. Forum and comments

- **Integrated search:** An integrated search engine helps students quickly find necessary information in all types of documents. For instance, given a keyword, 'circuit design', a search engine finds all documents, forum topics, and forum messages, which relate to 'circuit design'. Search results are sorted by relevance and category. Figure 7 shows sample search results.

Results found in Documents

Results found in Forums

Figure 7. Integrated search results

4. Case Study

The following case study shows how students in various disciplines benefit from a design document in solving an interdisciplinary problem. In this case study, groups of students in VR (CprE 577) and wireless communication (EE 423) courses work together on developing a new type of VR application in the C6. The following sections describe, in chronological order, tasks performed by each group and interactions between the groups.

A group of students taking a virtual reality course has decided that for their semester project they would like to develop a virtual kickboxing application. After evaluating the current interaction methods available in the C6 (position tracking and button press information), they realize these methods are not adequate for their application. They would like to know how hard a user is punching or kicking the virtual opponent. Since the opponent is virtual, no pressure or force can be measured (the user is punching thin air). Instead, they decide to measure the user's arms and

legs' acceleration for the interaction method. The design and implementation of interfacing an accelerometer to the C6 is beyond the scope of the virtual reality course. On the other hand, the construction of the sensor board and the communication of the sensor to the C6 are covered in a wireless communications course. The groups in both of these classes agree to participate in the project.

Figure 8. Snapshot of subsystem and system components of virtual kickboxing application

The groups develop the overall system design including subsystems and system components (Figure 8). The students in the wireless communication course are responsible for data acquisition from the sensor and interface between sensors (accelerometers) and the Mica2Dot wireless nodes. Finally, the virtual reality team will use this data in implementing the interaction methods for the kickboxing application. The activities of each of these teams are presented in detail in the following sections.

The groups need to figure out what types of sensors will be most suitable for detecting punching and kicking (Figure 9). They would like to know how hard a user is punching or kicking the virtual opponent. Since the opponent is virtual, no pressure or force can be measured (the user is punching thin air). The students in the wireless course have a better understanding about what sensors are available and what they measure while the students in the VR course have a better understanding of actually interfacing with the human. The two groups put their knowledge together and decide to measure the user's arms and legs' acceleration for the interaction method.

Once the measurement type is decided, the VR group can start programming the interaction. The wireless group tries to find an appropriate accelerometer.

(a) Student discussion for selecting a sensor

(b) Sensor information

Figure 9. Snapshots of student discussion for selecting a sensor and a part of design document describing sensor information

Since interfaces are well defined in the design document, the team in the VR course does not need to wait for the teams in the other class to implement their project. The design document tells them what sort of data they will be receiving. More specifically, the system will be providing three normalized floating-point values representing the acceleration along the X, Y, and Z axes. The design document also suggests the use of a scaling factor for each acceleration value so that the normalized value can be transformed into something that correlates to the physical world. Following the guidelines in the design document, the team can implement the entire application without having access to the device. VRJuggler's modular design enables the team to test the interaction using either a simulated input device (sliders on a screen) or a readily available physical device (such as USB game pad).

The team in the wireless communication course must select an appropriate accelerometer and provide the necessary circuitry so that it can function and talk to the wireless subsystem. The students create a forum thread where they can discuss the selection of the accelerometer. By accessing the application developers' portion, they discover the possible ranges of motion of the human body. Specifically they find the maximum acceleration a human can produce. The selected accelerometer should meet the sensitivity, acceleration range and orientation measurement needs required by the application developers. Anything beyond that becomes superfluous. The team also accesses the data acquisition and control portion of the design document. There they discover that Motes have an onboard analog to digital converter (Figure 10). This adds to the requirements, which implies that the accelerometer must provide an analog

output. Finally, the students turn to the portion of the design document associated with their area and find further requirements. The requirements specify the method of designing the final product such as on a printed circuit board. Most importantly, they are given limitations on the amount of power the circuit is allowed to draw. If they are unable to meet the output power requirements, they have to utilize their knowledge of designing voltage regulators to satisfy the preset constraints. Armed with all this information the students are now ready to select an accelerometer and to build the appropriate circuit board.

(a) Student discussion for wireless node

(b) Wireless node information

Figure 10. Snapshots of student discussion for selecting a wireless node and a part of design document describing wireless node information

The VR team continues working on the application using simulated input. The wireless team starts building the circuit for the accelerometer to interface with the Mica2Dots. The students are given a test VRJuggler application that they use to verify that the sensor data is accessible to application developers. When the teams complete their work, another forum is started for discussion a final integration. The VR team needs to know what the normalized value they will be accessing in their code corresponds to in the real world. Finally the hardware is hooked up, both teams see how the components work together. By changing the configuration files, the application will be able to interface with the desired sensors. Of course, it is always necessary to test and fine-tune the whole system and the design document instructs the students to do just that after system integration. Thus, by using the design document and well-defined interfaces, students can concentrate on the components that fit the class they are attending but still have a means to access the information that they may need from other disciplines. An additional benefit is that in most cases the components do not depend upon implementation choices and thus the work can be performed simultaneously.

5. Summary

Presenting an interdisciplinary problem to students having different disciplinary training is a challenging task. To address this, we introduced a web-based design document. The web-based design document aims at providing faculty members with systematic methods to integrate, organize, and present information consistently. It also provides students with tools to share their understanding of the problem. In this paper, we present our prototype of the web-based design document using the Tikiwiki CMS groupware. The Tikiwiki groupware provides several useful built-in tools which support systematic creation and management of the web-based design document. Our case study has shown the potential benefits of a web-based design document. We plan to continue to develop it and investigate what will make it an effective learning tool.

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