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Abstract

This paper reports on a hands-on project aimed at learning and experiencing the system-of-systems concept. The motivation behind this project is to provide an example for the creation of a mentor-based educational experience for engineering students learning design, analysis, and synthesis of multi-level systems.

The goal of this project is to challenge the engineering students to develop an RF-based system capable of sensing, monitoring, communicating, and controlling a multi-vehicle system that is connected via a wireless network. It must be a fully integrated and complete system in which the vehicles that belong to a network can become aware of their location, communicate with nearby vehicles (sometimes with no visible line of sight), and be notified of the presence of different objects located in their immediate vicinity (obstacles, such as abundant vehicles). In addition, all the vehicles will be constantly monitored and communicated with a central location.

Students have been working on multi-system development and understanding, including a hierarchical system (system of systems) integration. They have been learning how to deal with all system level components from a very low level (vehicle communication and control) to a very high level (vehicles location). They have been experiencing real-life implementation problems and dealing with multiple sampling rates, signal processing, communication protocols, as well as overcoming security issues. They have learned how to analyze and synthesize multi-level systems, make appropriate measurements at different system levels, understand the limitation of different components and sub-systems, as well as deal with interactions between software and hardware components.

The projects final result is the demonstration of a complex, functional, and robust system built and tested for other projects to use and learn from. By implementing and integrating RFID,WIFI, and ZigBee communication protocol, it is expected that the system created will have four sub-systems that can identify the location of other vehicles, create awareness of its environment for every vehicle, transfer the location data from the local vehicle to the remote user, and finally generate a two dimensional representation of the vehicles' location.

Introduction

System of systems (SoS) engineering is an emerging field focused on studying the integration of multiple interdependent systems into a more adaptive and complex system that delivers unique capabilities, sometimes referred to as metasystem or super system [2][3][5]. The integration of these systems sets aims to generate a dynamic system with the capability to evolve over time in order to respond to the dynamic issues and problems in both their present and future stages. As in natural systems, human made systems reflect the functioning of multiple components that are enhanced together to accomplish the same goal. A great example of a natural SoS is the human 'machine'. The human machine is composed of multiple single systems that operate together to give multiple capabilities to the human body, such as cognition, communication, movement, and evolution. In engineering, single or traditional systems that form part of an SoS are made to be a piece of a solution to solve a multilevel necessity. These single systems are designed and developed based on a well-structured problem with fixed boundaries [3]; therefore, they emerge with a clear, capable, implicit, and limited set of goals. In addition, their design is based on the integration of tangible and intangible components (software and hardware) that are interconnected following a hierarchical structure. This hierarchical structure allows all the components to operate and interact in unison, from the lowest level element to the highest component level, to carry out a process in an efficient and desired manner.

In general, the primary function of these systems is to process and act upon external data. They start by sensing the information, continue onto data analysis and classification for the next stage of decision making, which in turn allows the system to produce or generate an action that solves a specific problem. Therefore, as the problem increases in complexity, the system structure increases giving rise to complex systems. The introduction of SoS concepts provides the possibility for the development of robust systems that do not have limited operational boundaries, while being capable of evolving further more over time to solve new complex problems.

In this paper we discuss the process of teaching SoS concept to the students, first by introducing them to the essential concepts of an SoS. Then we address the challenges in the generation of systems thinking in the students. Finally, we address the application of the systems concepts in a specific RF-based project that can control, monitor, and communicate with vehicles in a multivehicle network.

System of systems background

The concept behind the design of an SoS is the enhancement of a process by the integration of a set of single systems that all belong to the same network. The success of the integration and the functioning of this kind of system are based on: the autonomy level of each one of its subsystems to carry out their corresponding task, the effectiveness to communicate between subsystems to transmit and receive data, while simultaneously assuring the security of the system as a whole. In short, interoperability, scalability and security are the key concepts that characterize the design and development of a multi-level complex system.

Interoperability is given when all the subsystems communicate and work as one regardless the of their hardware and software configuration [1]. Every standalone subsystem requires input information to carry out its corresponding task. Consequently, every subsystem must be autonomous to process the data from the low sensor component level to the high data control level, and generate an output data that can be used for the next subsystem as its input information. This data is processed and analyzed by every single subsystem in its own unique language, and then translated to a universal language that is understood by all the subsequent subsystems. The connection between the constituents of an SoS is architected in a scalable way making the subsystems interdependent from other subsystems; even though, its information is a necessity for the functionality of other subsystems. Thus, the failure of a subsystem can compromise the capability and results of the entire SoS. [2]

The second concept in the design of an SoS is scalability. SoS is said to be scalable if its performance, and fault tolerance remains the same or improves as the number of its subsystems increases.[2] The performance of an SoS is measured according to the output of every single one of its subsystems. The output of every single subsystem must be achieved within an expected period of time and with a minimum amount of error. Scalability is also measured based on its capability to operate regardless of the geographical location of its subsystems or users. It also depends on the architecture of the system; if the system architecture increases, the complexity of the subsystems interconnection increases as well. There are two types of interconnections between subsystems: centralized and decentralized [1]. In the centralized system there is a central controller /coordinator through which all information must pass before arriving at its destination, while in the decentralized system, the coordinator does not have control over all the information that is transferred throughout all the subsystems. In the latter case, the information shared between subsystems can be transferred directly without the need for a main coordinator. Finally, the fault tolerance is measured in accordance to a system's ability to perform with the presence of faults. The SoS structure must be able to identify a fault and isolate it to continue with its task.

The third main concept in an SoS's design is the security of the system. In order to provide a robust, reliable and efficient system, an SoS must not only have a well-designed structure that is fully interoperable, its topology must also follow a security protocol. The main purpose of a security protocol is to protect the system from cascaded failures. [2] Security complexity is directly proportional to the number of subsystems. As the number of elements increases the number of security factors increases. Therefore, the connection for all these elements must be fixed and limited in order to avoid the loss of data and interference with elements of other systems found in the same environment. For example, in network based systems where the amount of connected elements fluctuates according to their activity state, the connection for every single element goes through an identity check each time the element becomes active. This process also allows the security protocols to define the accessibility level to information among the system elements.

Teaching System of Systems

As the complexity of the engineering systems that solve the ever evolving natural and man-made problems increases, the interest and need of engineers to be educated and trained to develop such complex systems also increases. The current engineering education program in the United States follows the criteria of the Accreditation Board for Engineering and Technology (ABET), which establishes the minimum requirements for engineering programs at the colleges and universities that form the future high-qualified engineers capable of solving problems by the means of technology in a constantly evolving society. Students who choose engineering careers take a variety of courses that teach them how to apply the fundamental principles of science and math in the learning and understanding of engineering theorems, which are the building blocks of processes and systems. Some of these courses are Control Theory, Digital Signal Processing, and Linear Systems which provide students with information on retrieving, analyzing, and processing data for the new generation of specific systems and processes. Students learn all the information related to the understanding of the functioning, structure, operability, and controllability of every single component of a system or process; however, there is a breach in the learning how to think systematically and how to apply all this knowledge in the integration of complex systems. Therefore, a primary challenge in the learning and teaching of SoS concepts is the lack of engineering classes teaching students the ability to integrate the collective technical theory acquired in the separate classes, causing a deficiency in generative thinking at the system level in students.

The lack of courses where students are challenged to integrate all the knowledge they have acquired during their undergraduate engineering career, and the high volume of demand of engineers with system integration knowledge has led some engineering schools to develop graduate programs that educate engineers on how to incorporate all their engineering background knowledge, and experience in the practical development of engineering systems. For example, the Massachusetts Institute of Technology offers a graduate system engineering program that emphasizes the importance of design system modeling, analysis and visualization theory, which together assist students in the generation of more reliable systems. [15]. They have introduced an approach within an interdisciplinary program that combines engineering knowledge with organizational and socio-economical disciplines, which in turn leads students to take into account customer needs, system validation, system performance, manufacturing costs, and scheduling. On the other hand, other schools, such as Pennsylvania State University, have designed programs that teach students how to manage complex systems by the integration of science, technology, business, and human interaction [11]. A few schools, such as Georgia Institute of Technology, have implemented a graduate systems engineering program that expands on the system knowledge of professional engineers by providing a curriculum that offers a hands-on approach to system engineering by focusing in areas such as modeling, simulation, integration, system engineering processes among others[16]. However, there is still a lack of a clear methodology for teaching students to think systematically.

In the process of teaching SoS concepts, one of the fundamental skills that students need to acquire is systems thinking. According to professor Moti Frank, at Holon Academic Institute of Technology, Holon Israel, systems thinking is the ability to visualize the inner and outer functioning of a system; meaning that the engineer/student need to have a complete understanding of the system components, processes, issues and capabilities [10]. There are four main constituents in the process of generating system thinking in students:

- Conceptualization of a system
- Analysis of system requirements
- Generation of alternative solutions
- Optimization of a solution

Conceptualization is referred to the ability to see the big picture, referring to visualizing the whole system structure, functioning, and response. In other words, it is the visualization of how the end result can be achieved by the integration of different components. The analysis of the system requirements emphasizes that the student/ engineer must have the capability to fully understand the problem requirements, including the conditions of the environment where the system will operate. In this case, the student must know how to interpret the problem requirement and start translating it into a possible system structure. Then, the generation of alternative solutions takes place as the student designs a possible solution that meets the different requirements based in the feasibility and capability for the design, taking into account the time and resources available for the system development. Finally, the last constituent in teaching SoS design is the optimization of systems. Student must be able to maximize system process by analyzing each level of components in the system, and calculate the tradeoff in case one of the components is changed when targeting towards a more reliable and robust system design.

There are some systems thinking principles that are used in the generation of system thinking: closed loop thinking, generic thinking, dynamic thinking, structural thinking, operational thinking, and scientific thinking [8]. Closed loop thinking gives the capability to analyze any problem and visualize a solution (or SoS) by the integration of the interdependent processes; while the generic thinking, gives the capability of integration of ideas, knowledge and concepts. The operational thinking principle refers to the understanding of how components, elements, and subsystems interoperate. Structural thinking refers to the ability to generate the scalability of the process that would meet the problem requirements. Scientific thinking refers to the ability to analyze the feasibility of a process by analyzing and testing possible solutions. Finally, dynamic thinking gives the ability to understand and analyze the behavior of the system aiming to optimize its response according to the system environment, as well as, the possible evolution of the problem over time. Thus, systems thinking plays a fundamental role in the process of teaching the SoS concept since it gives the student the ability to see the big picture, conceptualize an idea, analyze the idea requirements, test the possible solutions, and optimize the chosen one, thereby allowing the generation of a robust and reliable system that is fully interoperable, scalable, and secure.

RF-based SoS Project

In our process of teaching the concept of SoS, we challenged our students to develop a solution for indoor location, monitoring of, and communicating between, vehicles and a higher level system. Indoor location issue is an area of engineering that has gained interest in the last years due to the interest of government, industry, and schools in designing a platform that can overcome the signal attenuation constraints to monitor the different agents located in a specific indoor location [12][13][14]. Indoor location system idea rules under the same ideas as Global Positioning Systems (GPS). A local receptor calculates its location using the data received from a controller. This location is time-space based, meaning that data received from the controller is time measured and calculated according to the distance traveled by the signal. In the case of GPS, a local receptor device calculates its location by measuring the time-difference of the received electromagnetic wave that travels from referenced orbiting satellites. These electromagnetic waves operate in the range of 1.5 GHz, which makes them able to travel through the line of sight from an altitude of 20,000 Km from the sky to the earth's surface [12],[13]; however, when this signal reaches the receptor, its power level is very low as a consequence of free space loss. Therefore, this technology is not a suitable approach for the indoor location issue since the signals would have to go through an additional loss due to the building structures, decreasing its power to an even lower level for the receivers. Thus, the system is limited to having its location component inside the same area in order to assure that the waves can reach their destination.

The main idea behind the project was to challenge the students to incorporate system engineering concepts of interoperability, scalability, and security, in addition to applying the system thinking principles, to design an SoS that would give a solution for indoor location. The students were asked to generate an indoor location system capable of reporting accurately the location of local vehicles to a remote subject, which we termed the 'big brother'. In addition, the SoS needs to be able to provide awareness to the local vehicle of obstacles found in its immediate environment; establish a two way communication between the local vehicles and the 'big brother'; and finally, show the local users' location to the 'big brother' in a two dimensional display, regardless of the big brother's geographical location.

The students' approach started by analyzing the problem requirements, followed by visualizing the big picture of the intended system, identifying the system requirements, searching for possible application, and selecting the best technology that would allow the development of a reliable indoor location system.

The first step of the indoor location SoS design was the conceptualization of the functioning and the expected output of the system. Figure 1 gives the pictorial representation of the system's bigger picture. The system will have two types of users: the local user who navigates through unknown space, and the remote user, the 'big brother', which has the ability to observe the local users' location, as well as control and communicate with the vehicle. Therefore, the system must be able to first identify the location data of the local user, then analyze it and transfer it to the remote user for further analysis, and lastly, display the local users' location. Once the 'big brother' is able to observe the local users' location, it would be capable of making decisions and returning a feedback to local users.

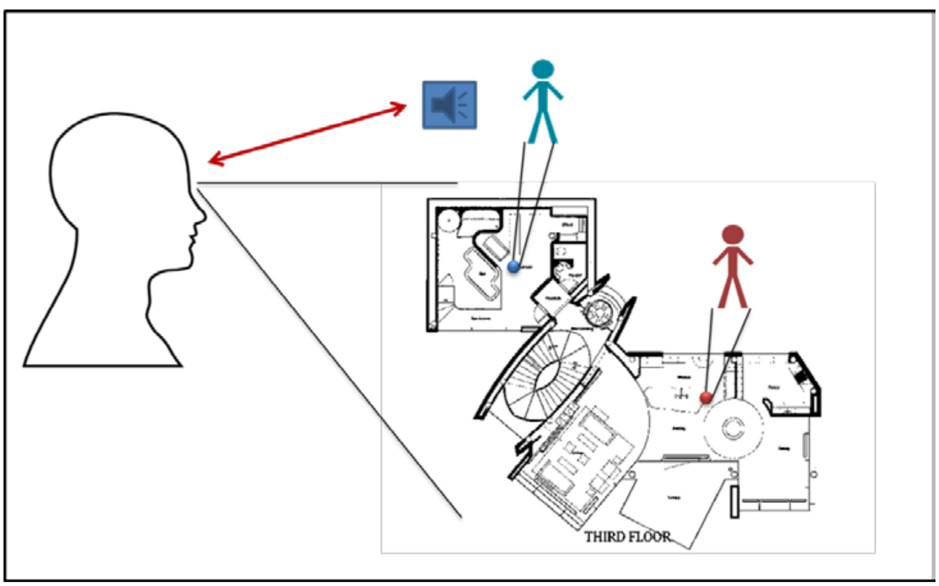

Figure 1: Conceptualization of the indoor location system

The second step was the analysis of system requirements. Once the system's main functions were conceptualized, the students identified the different system requirements and considered them in order to accomplish the end task; the complete process to provide indoor location must be divided into different subsystems defined with their respective subtasks. The first main requirement of the system is the accurate identification of the local users' location and detection of nearby obstacles. Therefore, the first subsystem would be in charge of detecting the local vehicle's location and its surroundings by processing the collected data and producing two different outputs: environment awareness and location coordinates. The first, environment awareness, is the audio output to alert the local users of their location and the obstacles found in their surroundings. The second output is the users' location data which would be transferred wirelessly to a remote user for further analysis. To transmit this last output, the data needs to travel to a local station from the local users where it would be stored. The remote user will access the local station to retrieve this data in order to generate a two dimensional visual display. This data needs to be able to travel in an environment where signal attenuation is a major constraint due to building structure. As a consequence this controller must be located inside the same building in order to successfully receive, transfer, and store any data that is collected. Moreover, this local station must be accessible by the 'big brother' system regardless of its geographical location. The next requirement is another subsystem that carries out the retrieval and implementation of the information into the generation of a two dimensional display. In addition, the indoor location awareness of the local user must be independent of the other subsystems. Thus, if the remote user subsystem fails, the local user subsystem that gives location and awareness will continue to operate. The final requirement will be that using the same structure and method that is used to transfer the data from the local user to the 'big brother' and vice versa, the system must be able to transmit back any feedback from the remote user.

After analyzing the problem, conceptualizing the system functionality, and identifying its requirements, an investigation to explore the different practical approaches utilizing different technologies was carried out. The main focus of this research was based on the four main constraint factors for indoor RF communications technologies: reduction of the power contained of the transmitted signal, sensitivity of the receiving equipment, the environment through which the wave travels, and the presence of interference [17]. These constraints are well explained in regards to the relationship between power and distance. RF communications system structure is comprised of a transmitter and receiver. As the signal propagates away from the transmitter's antenna, the signal strength deteriorates, due to its power being affected by the different obstacles found in its traveling environment. In addition to the attenuation due to material properties, the transmitting signal has to face interference with the reflected waves.

Among the solutions found, there are two methods that have been identified as most promising for solving the issue of indoor location: the network based system and the proximity system [14][15]. The network based system uses the structure of its network and the strength of the signals to locate an agent. The distance is calculated by subtracting the known distance of the receiver from the actively-changing location of the transmitter, and measuring the time it takes the signal to arrive from the transmitter to the receiver node. The advantage of this method is its use of wireless infrastructures that are found in some buildings such as a Wi-Fi network. However, multiple paths of signal reception and signal obstacles, limit the accuracy of the calculation of the local user location. The second method considered is the use of proximity sensors. In this case the system is based on multiple sensors distributed along the structure of a specific area. The location of the local user is detected when the user moves within the range of the sensor area. This method is considered to be the most accurate since the location of the local user is the same as the known location of the sensor.

Figure 2 summarizes the two methods for indoor location and their respective technologies. In the case of the network based system, Zigbee is used to generate a communication network structure in which the signal strength of its nodes are used to calculate the local's user location. Its operational method is based on a topology structure comprised of three components: controller, router, and end devices. The controller stablishes the network to which the router and the end devices connect to communicate and transfer data, while the router replicates this network channel to give a larger coverage area as well as serving as a bridge for the communication between the end devices and the controller. Lastly, end devices are in charge of collecting and transmitting the data to the controller. In indoor location, the end devices transmit their signal strength information (RSSI) to the controller, which is then used to calculate the distance of the end device with respect to the controller. The effectiveness and accuracy of Zigbee for indoor location was calculated to be less than 3m [14].

In the method of sensor based systems, Bluetooth Low Energy (BLE) along with Radio Frequency Identification (RFID) are among the technologies that can be utilized for this method to approach the problem of indoor location. The operational principle of BLE is based on the topology of its communication network in which there are two roles that a device can play, that of master or slave. The slave announces its location to the master which is then used by the master to calculate and identify its own location. The trade off in the use of this technology lies in the limited connection between slave and master, since the slave can only connect to one master device, therefore limiting the number of local users to one[18].

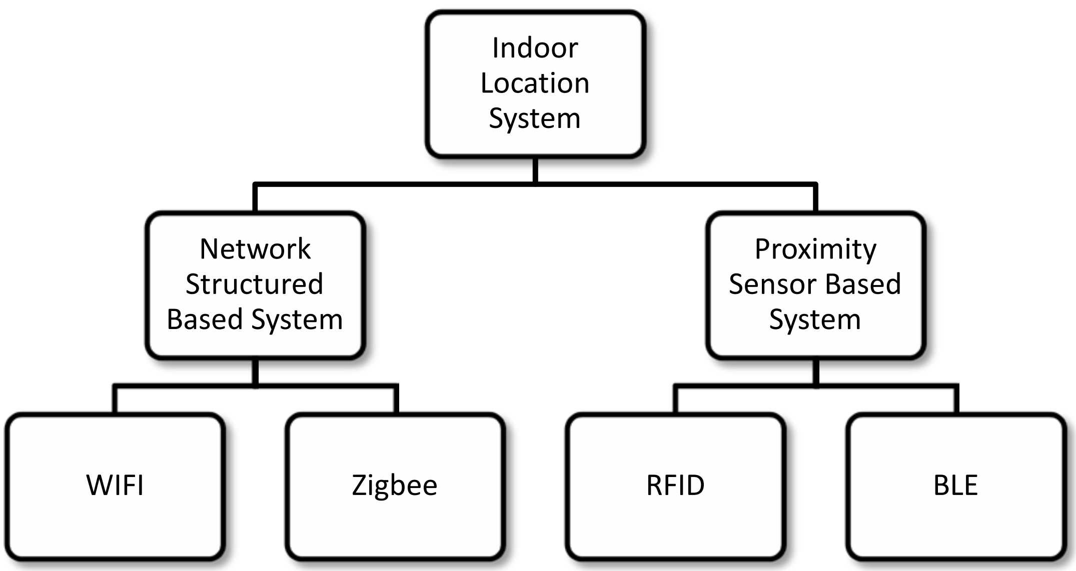

Figure 2: Methods and technologies for indoor location.

Finally, RFID communication which operates in frequencies of 125KHz, 13.56MHz, 915MHz, 2.4GHz, and 5.8GHZ, has the capacity to overcome indoor RF indoor communication constraints as well as maintain an unlimited connection between its components. RFID communication systems have two main components: a RFID tag comprised of an antenna attached to an embedded memory chip that hosts a unique identifying code, and a RFID transponder that reads and writes data on to the tag. The operation principle of this system is simple: the RFID reader transmits a magnetic wave that activates the embedded memory chip when it is within range of the RF-tag. Once the RF-Tag's memory chip is activated, it sends back a magnetic wave that contains its unique identifying code, and then the reader decodes the data which is then transmitted to a processing unit. The RFID 125 K-Hz frequency is the ideal technology to be used in places where attenuation and reflection are a major constraint. At this low frequency level the attenuation is very little, which gives the magnetic waves the capability to penetrate through a large variety of materials, including metal [17].

RF project structure

Having RFID as the main technology used to identify the location of the local user, the SoS designed to give indoor location and awareness is described in figure 3.

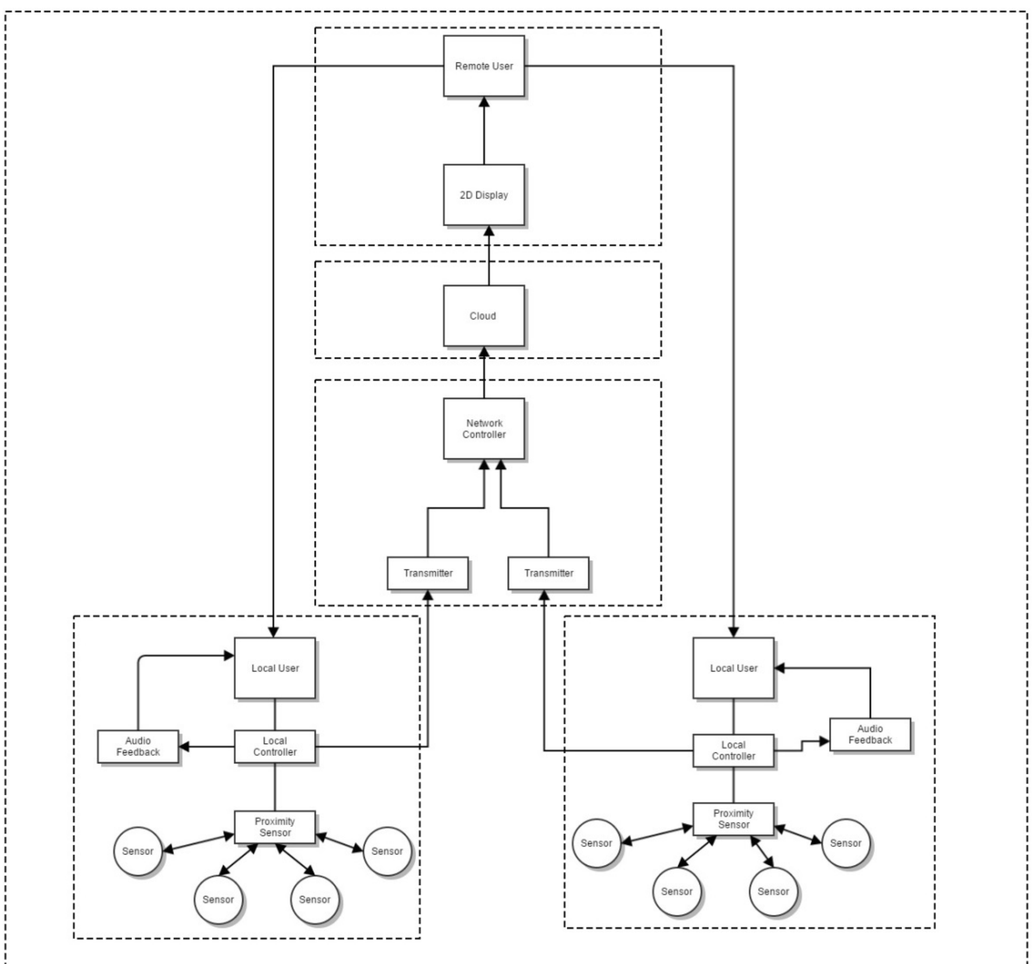

Figure 3: Design structure for indoor location SoS

As it can be seen here, there are four subsystems:

- Local user location identifier system
- Network controller system
- Server/cloud system
- Remote user display system

The first subsystem, the local user's location identifier, is in charge of determining and transmitting the local user location, in addition to alerting the local user of obstacles found in its immediate environment. This subsystem, which operates with RF principles, is comprised of six different interconnected components: Passive RFID tags, RFID reader, central microcontroller, Xbee, Bluetooth microcontroller, and a cellphone app. The operating sequence of this subsystem is fully scalable. As the local user navigates, the RFID reader senses the strategically placed RFID tags which are located on the floor and on obstacles. When the reader approximates to passive labels, its 125KHz emitting electromagnetic waves energizes the tag activating its internal chip. Once the chip becomes active, it becomes a transmitter that sends its corresponding unique identifier code to the RFID reader. The code is then decoded by the RFID reader and is transmitted to the central microcontroller where it is matched with two specific types of data: environment awareness and location coordinates. The first data, environment awareness, contains a specific predetermined sentence corresponding to the detected tag, which is then transmitted through the Bluetooth shield to the cellphone app. In the phone, the app receives this data and converts it into a vocalized announcement to aware the local user of its location or obstacles found in its immediate environment. The second type of data, location coordinates, contains the longitude and latitude coordinates coded into a global data package that can be read by the second subsystem, the network controller. The interconnection between the first and second subsystem is achieved by the functioning of ZigBees.

The structure of the second subsystem is a centralized wireless adhoc network comprised of a main controller and several end devices. The main controller, through which all the data must travel, is also connected to a Wi-Fi shield that serves as a bridge for the interconnection and intercommunication between both the network controller and the cloud. The main function of the second subsystem is to give mobility to the local users and serve as the medium for transferring the data acquired by the first subsystem. The end devices of the network are composed of the transponders that every local user has in its structure in order to send and receive data wirelessly. These ZigBees are set to communicate through a specific channel, to transmit its node destination address, and to authenticate its identity by exchanging the specific personal area network ID (PANID), in order to assure the correct operation of subsystem two, and the integrity of the whole system. After the data is collected by the first subsystem and transferred wirelessly by the second subsystem, the main network controller processes it and translates it to a global package sent through Wi-Fi network to the third subsystem: the cloud.

The cloud's task is to archive, process, and classify the data. The structure of this subsystem consists of a server which hosts a database containing with the location of each of the different local users. The server uses an algorithm that classifies the received data from the second subsystem, and reproduces a report of the location of each and every local user. This report is then accessed by the fourth subsystem to generate the two dimensional display.

The fourth and last subsystem is structured by a Lab View algorithm. This algorithm accesses the database in the third subsystem and retrieves the last known location of every single local user to then overlap it with a floor plan of the building or area which the local users are navigating. Once the 'big brother' is aware of the location of every single local user, 'it' can send a message to the local users using the same structure that it used to transmit the local user location. In this case the 'big brother' types the message which is sent from LabView to the server. In the server it is archived in another database which is then accessed by the main controller of the wireless adhoc network. This message must contain the local users' id and the message. In the wireless adhoc network the main controller identifies the correct corresponding local user to which it sends the message. In the local user subsystem, the data is received by the local controller, and then sent to the phone app to be finally sent to the user through a vocal announcement.

SoS Experiment Results

In our experiment to test the operability and the effectiveness of this system's design, we deployed two local users on the same floor inside a building on school campus. The local users were represented by RC cars that navigated through a floor containing a vast combination of rooms and obstacles, such as tables and sofas. Every RC car was equipped with all of the components of subsystem one seen in figure 4. The RFID tags were located on the floor in front of each room opening and adjacent to all obstacles. The central controller was placed into another room with its location in respect to the other rooms was designated the center of the building's floor. The server was placed inside a random room on the same floor, while the remote user was located in a different building. The two main focuses of the systems' tests were to check the accuracy of the system's ability to identify the vehicles location correctly as well as determine the independence ability of subsystem one to operate in case of failure of the subsequent subsystems.

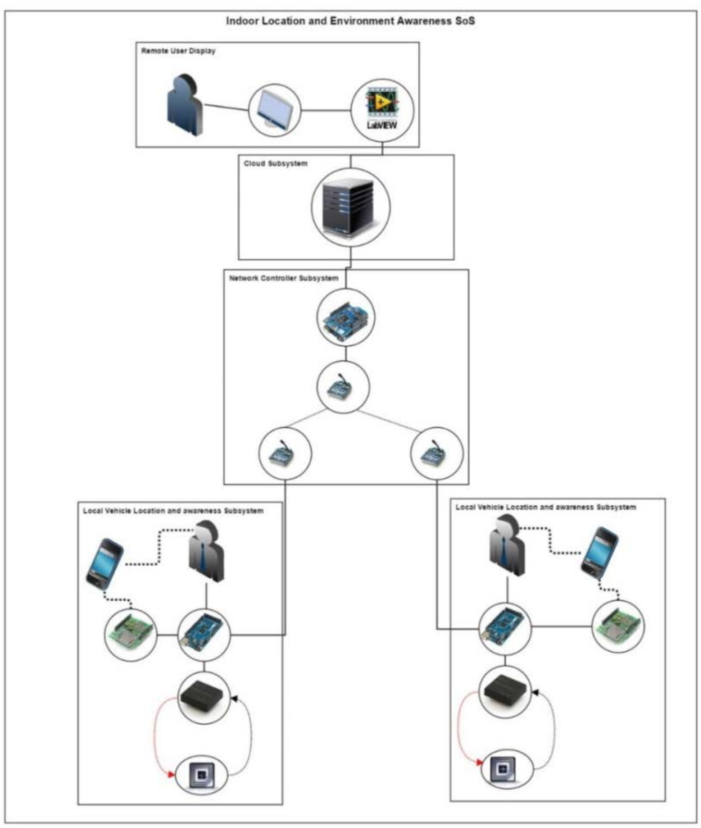

Figure 4: Indoor Location SoS structure

The response of the whole system showed that the accuracy to identify the vehicles' location was 100% but with a time delay of 15 seconds. This delay was measured from the instant that subsystem one read the RFID tag to the instant that the vehicles' location were displayed by subsystem four. It was observed that large part of this delay occurred in the interaction between subsystem three, and four, since the time response of subsystem one to alert the user of its location and the presence of nearby obstacles was less than a second, and the time response of subsystem two to deliver the location data to subsystem three was maximum 3 seconds. In addition, it was also observed that the detection range for the RFID reader and the tag was limited to 10cm due to the reader's low frequency operation. Finally, we manually deactivated subsystem two (the network controller) for intervals of 3 to 4 minutes to simulate a failure in the system. This last experiment showed subsystem one's function of environment awareness was not affected by the inoperability of the rest of the SoS,

Reflection on the Process

Beyond the positive results of the system design implementation, this hands-on project has had an invaluable impact on the students' learning experience by enhancing their cognitive and technical skills. There are some important observations that should be highlighted about their experience:

- The project enhanced the students' ability to observe, analyze and synthetize a multi-level system.

- Throughout the different stages of this project, students were challenged to utilize their existing knowledge acquired during their four year educational engineering studies, as well as to seek new concepts and methodologies related to hierarchical SoS design.

- The project provided hands-on experience in the integration of software and hardware at different system levels. Students were required to apply concepts learned in RF, Microcontroller programing, and software implementation classes, while simultaneously exploring new knowledge given in embedded systems, RFID, Wi-Fi, and ZigBee communication protocols and principles, as well as PHP and MySQL language programing and LabVIEW. As a result, students not only were able to learn and understand system engineering thinking, but also they obtained more tools to solve complex problems.

Conclusion

System thinking plays an important role in the development of complex systems. By the introduction of SoS' concepts and principles, students can learn the design process with an emphasis in multi-level system thinking that will help them to generate systems that are interconnected as one can evolve to generate a process that can give a solution to natural or people-made problems. In this current project, there is still space for further development in regards to the testing and optimization of the overall system design due to the limitation of a roughly 10 cm range in the detecting of the RFID tags due to the low frequency of operation of the RFID reader.

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