
AC 2012-4866: SMART BOX FOR SECURE DELIVERY OF CONTROLLED SUBSTANCES IN MEDICAL CENTERS

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SMART BOX FOR SECURE DELIVERY OF CONTROLLED SUBSTANCES IN MEDICAL CENTERS

Introduction

The aim of capstone senior design project is to culminate the undergraduate experience, where knowledge gained in the classroom is applied to a major design project. A meaningful project would be one that is developed in collaboration with the industry and also tailored to meet the ABET educational goals.

This paper presents the technical and educational outcomes of a one semester capstone senior design project. The project goal was to develop a portable electronically monitored system to transport controlled medical supplies (e.g. medical narcotics) in a medical center under strict surveillance and security. A team of four senior electronics engineering technology students was tasked with the design effort. They had to utilize their knowledge and demonstrate their ability to analyze and design a working prototype within one semester. This required quick formulation of feasible innovative ideas in electronics, communication systems, computer systems and the ability to apply project management techniques. During the design and development of the project industrial like technical and economic constraints were imposed. Such constraints required a thorough resource and literature survey, followed by brain storming sessions to decide on the appropriate design approach during each stage of the project development. A close supervision and guidance by the advisor was warranted for the students to successfully achieve their goals.

Learning Objectives

The specific objectives were for the students to:

1. Engage in a creative electronics engineering system design to develop and implement a working product.
2. Demonstrate the ability to extend their learning beyond the class room knowledge specifically in state of art technology.
3. Demonstrate the ability to think critically, reason and judge on the best solutions to design problems under strict technical and time constraints
4. Demonstrate an effective team effort and the importance of team leadership in completing a complex electronics engineering project within the one semester time constraint
5. Demonstrate their ability in oral and written communication skills.

The team proposed the development of a SMART BOX for secure delivery of controlled drugs (narcotics) in hospitals. The idea was originated by two members of the team during their co-op training at a large medical center. While performing a system-wide logistics study the current drug delivery operation caught their attention, specifically the controlled substances delivery to acute patient care units. At present the pharmacy technicians are required to manually deliver these controlled drugs to multiple units throughout the hospital 2-3 times per day. This process is

a wasteful task since it interrupts their primary drug preparation tasks. A robotic delivery system utilizing three Aethon automated TUG robots ¹ have taken over some of the responsibility of delivering these drugs. However, as with many robotic-technologies, there are some inherent constraints associated with this delivery method. The TUGs are fairly large which means they struggle to navigate through the small hallways, crowded units, and elevators. They also have limited capacity because only the top drawer is RFID-enabled for narcotics delivery. These robots are very expensive and utilized only for ad-hoc or one-off deliveries (usually one drug going to one unit) so they are not optimized for a full-takeover of medication delivery.

The drug delivery process has its dilemma; the “Chain of Custody” requirement imposes many safety and security measures that need to be followed. In short, each controlled substance (narcotic) needs to be fully tracked and traced as it travels downstream from the pharmacy area to the point-of-use area (patient in unit). This log requires the “WHEN, WHERE, & WHO” for each transaction in the delivery process. If these three questions are answered and the drugs are placed in a secure lockable container then any logistics staff could potentially take over control of the medication delivery process which would add value and eliminate waste in the pharmacy department. This innovative SMART BOX idea offers a cheaper and more efficient solution for drug delivery with the chain of custody in mind. A visual representation of the proposed SMART BOX-enabled medication delivery concept is shown in Figure 1.

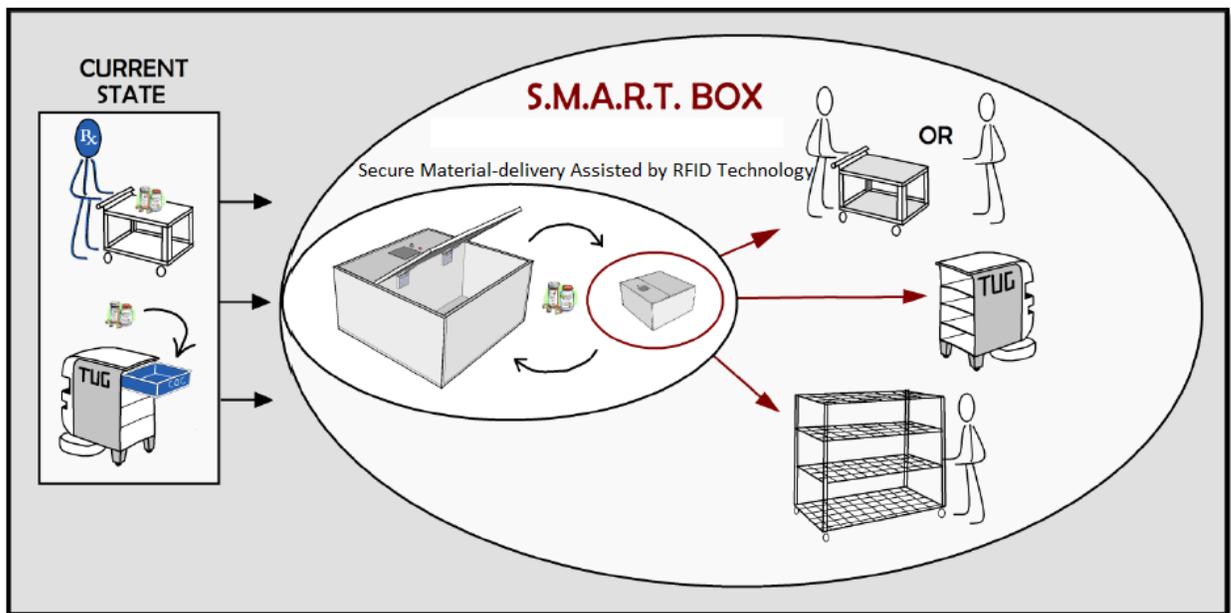


Figure 1. Smart Box delivery concept

This paper introduces the project development stages starting with the initiation phase, system hardware and software development and their integration, the technical results, and finally the lessons learned and the educational outcomes.

Project Initiation

Prior to project initiation the rules of the senior design project were clearly explained. The students must design and develop a “working” prototype during a one semester 4 hour/week

senior design project course with a limited budget. To ensure the successful completion of the project under the constrained conditions they were required to:

- submit bi-weekly progress reports,
- Confer with supply chain director at the medical center to ensure the conformance of the design with the chain of custody requirements
- Undergo industry like project review where they had to submit two interim detailed design reports and formally present them to be discussed with the course instructor (advisor) and a faculty member acting as the project consultant:
 - A preliminary design review (PDR) and,
 - A critical design review (CDR);
- Submit a final design report (FDR) followed by a formal presentation. The final presentation will be open to all department faculty members for evaluation, as well as to the industrial advisory board (IAB), one of whom will be the supply chain director at the medical center.

To initiate the project the first step was for the advisor to assess and approve the feasibility of completing the project within the allocated time frame. The students formulated the design concept following multiple brain-storming sessions. They decided on a universal solution for a box that is fully-capable of tracking the WHO, WHAT and WHEN for every item transported or transacted whether it be narcotics, jewelry, precious metals, money, or important documents. The SMART BOX, whose basic concept is shown in figure 2, must ensure that a packaged item will arrive safe and secure at its destination.

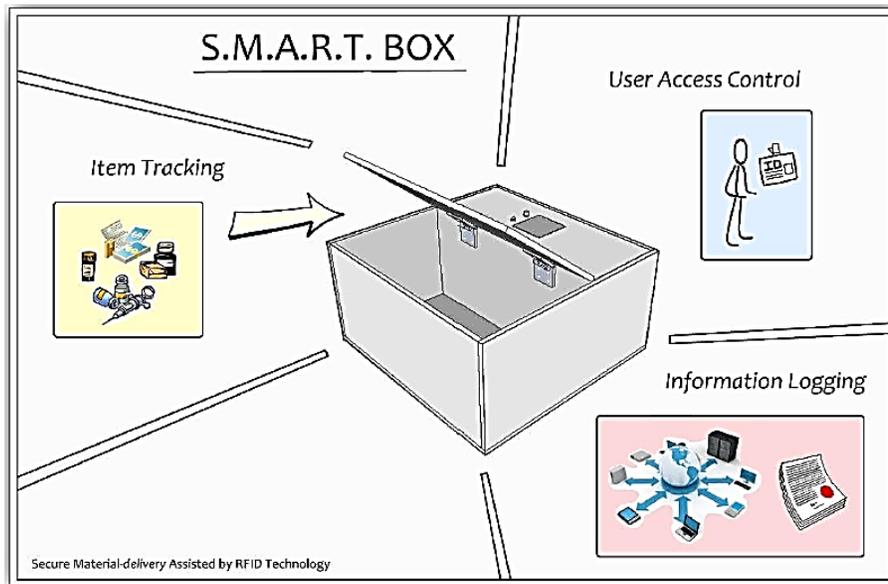


Figure 2. Basic design concept

Project Design Goals

The functionality of the box must comply with the medical center drug delivery logistics. After meetings and discussions with the hospital supply management director, the following requirements were defined:

- The box must be portable, secure and can only be transported by pre-authorized medical staff.
- When the box is delivered to an assigned location, the authorized staff identity must be verified and approved prior to accessing the box content.
- Any addition/removal of tagged items must be monitored and time logged at a central monitoring computer, preferably in the pharmacy.

Following a thorough discussion the team reached a consensus on the main box functions:

- User access control
- Item tracking
- Information logging and monitoring
- A microcontroller to coordinate and manage the above three functions
- A small rigid box with an electronically activated locking mechanism.

For user access and item tracking, radio frequency identification (RFID) was the system of choice. Wireless 802.11 Wi-Fi technology was chosen as the means for information logging through the university wireless network to the university server. The Arduino microcontroller² was chosen to manage and coordinate the functionality of the box. Consequently, the RFID as well as the wireless devices must be compatible with and controlled by the Arduino.

Team Tasks Assignment

Responsibilities were shared between the team members; two students tasked with the mechanical structure of the box and the development and integration of the RFID systems, one student was assigned the task of developing the microcontroller control and monitoring program, and one student was tasked with wireless connectivity and information logging. Team leadership was assigned to the project idea originator whose task was supervising the hardware and software integration to ensure a working prototype.

User Access Control

User tracking and verification is accomplished using a simple low-frequency (125 KHz) RFID system consisting of a small size reader with a built-in antenna. The system (Innovations ID-12)³ reader controls and monitors user-access to the box. It is located inside the box facing up for easy access; its signal power provides a range of 2-3 inches when used with compatible passive tags. The passive tags, when within range, are activated by the reader radio frequency (RF) signal power and responds by transmitting its unique identification (ID) code to the reader⁴. When the code is identified by the ID-12 reader it outputs a string to be processed by the microcontroller which executes the appropriate action (Unlock box or keep locked). A typical ID-12 system is shown in figure 3, and its specifications are shown in table 1.

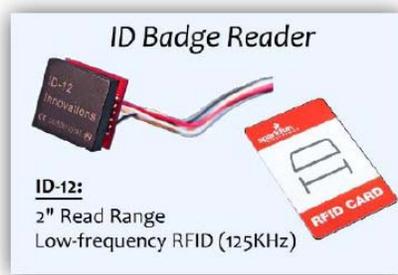


Figure 3. Basic ID-12 RFID system

Table 1. Reader and tag specifications

ID-12 Reader & Tag Specifications:	
Module Features:	Tag features:
Dimensions: 25 x 26mm	Dimensions: 54 x 85.5 x 0.8mm
5V supply	EM4001 ISO based RFID IC
125kHz read frequency	125kHz Carrier
EM4001 64-bit RFID tag compatible	2kbps ASK
9600bps TTL and RS232 output	Manchester encoding
Magnetic stripe emulation output	32-bit unique ID
100 mm read range	64-bit data stream [Header+ID+Data+Parity]

ID-12 Reader Effective Range

To determine the reader effective detection range the reader’s radiation pattern was plotted using compatible ID tags, shown in figure 3. The ID-12 reader circuit was built and positioned at a fixed location, see figure 4. The tag was placed such that to insure maximum detection range which occurs when the reader and tag maximum radiation patterns peak levels are coincident. The tag was then rotated 360° around the reader at 10° intervals. At each location the maximum detection distance was recorded and plotted vs. the angle of rotation. The radiation pattern is plotted in figure 5.

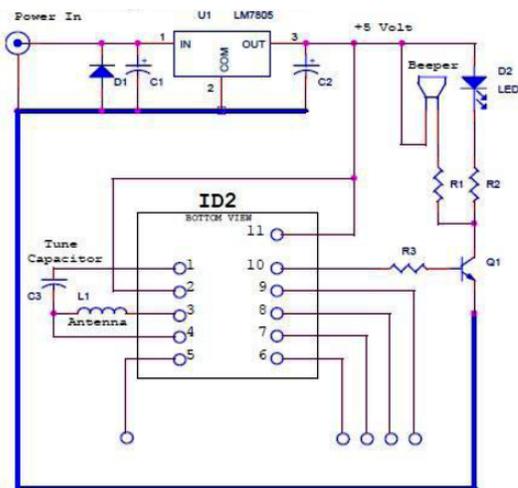


Figure 4. ID-12 reader circuit diagram

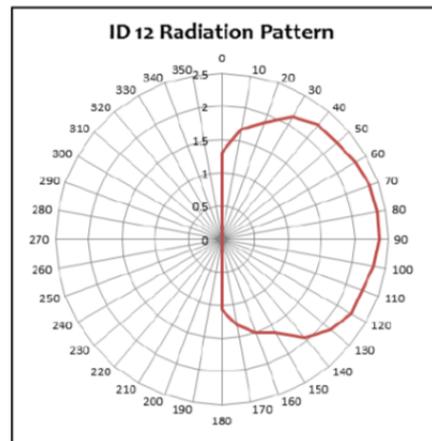


Figure 5. ID-12 RFID system detection pattern

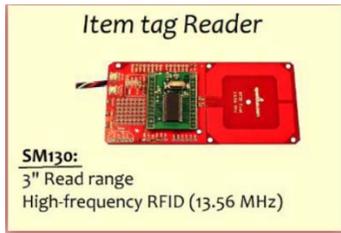
Item Tracking:

An essential design requirement is the ability to securely deliver multiple uniquely identified items to different locations; therefore RFID reader specifications must satisfy the following:

- Support anti-collision technology and identify multiple items simultaneously
- Can be interfaced and controlled by with Arduino microcontroller.

In addition the RFID tags must be usable on all types of items, including liquid or metal, and be of low cost and small size. With diligence the students researched different RFID systems that satisfy the requirements; the SonMicro SM130⁵, 13.56 MHz RFID system, was deemed to be the most suitable choice. The system is shown in figure 6, and its specifications are outlined in table 2.

Table 2. Item tracking RFID system specification



SM130 Reader & Tag Specifications:	
Module Features:	Tag features:
5V supply	Dimensions: 54 x 85.5 x 0.8mm
Supports ISO14443A	Mifare Classic 1K, Mifare Classic 4K, Mifare Ultralight
UART interface up to 115200bps	Communication speed up to 106 KHz
I2C interface up to 400 KHz	
2 general purpose I/O's	
Supports Anti-Collision	
120 mm read range	

Figure 6. Item tracking RFID reader

The SonMicro SM130 is a compact 13.56MHz RFID Read / Write reader module designed for the ISO14443A standard. It supports various Mifare tags⁶ and can be controlled by external devices over UART and/or I2C bus using simple protocols. The system supports Anti-collision technology, i.e. it can simultaneously read multiple tags' information. Its frequency of operation is a good compromise for tagging liquid or metal items⁷. The reader control and the tag data access were implemented using the Arduino microcontroller UART interface.

For effective detection, the determination of the reader orientation and placement with respect to the tagged items in the box was necessary. Consequently, the reader's radiation pattern was plotted, using compatible ID tags (figure 7), giving an effective detection range of 2 to 3 inches.

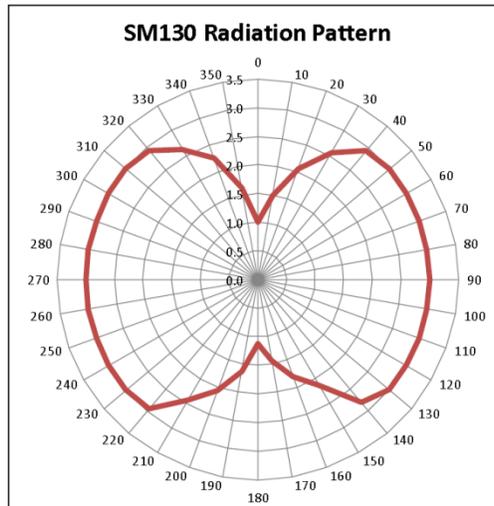


Figure 7. Item tracking reader detection pattern

Wi-Fi Connectivity & Information Logging

The SMART box must communicate vital information back and forth through the wireless network to a data hosting site e.g. a central computer or secure website so that:

- It can be tracked in-building,
- Its contents can be monitored,
- Authorization for unlocking the box can be issued remotely.

For compatible system integration the Arduino compatible clone “Diamondback” microcontroller⁴ was chosen since it provides the required 802.11b wireless connectivity as well as the ability to communicate with RFID systems. It provides the user the ability for sending and receiving information via HTML POST and GET requests using the open-source microcontroller programs, hereby referred to as “sketches”, provided by Asynclabs⁸. Sketches were uploaded to instruct the Arduino to provide or request information on an internet connection.

The university’s wireless network was utilized to access the internet, which was initially problematic for two reasons. The first stemmed from network security issues. The university wireless access points (WAPs) were secured using WPA (Wi-Fi Protected Area) Enterprise data encryption protocol. This required a user name and a password to be authenticated and validated by the host machine. However, the Arduino sketch files supports only the PSK (Pre-Shared Key) type of WPA encryption which allows users to log onto a WAPs using a single pass-phrase. Determining the exact syntax required for transmitting these pieces of information and re-writing the Arduino code was futile. A more fruitful practical solution presented itself after consulting with the university network administrators, who provided the team with a separate WAP using PSK type of WPA. The Arduino code was then configured for use with this router achieving a full wireless access connection.

The second issue: the university network generally uses Dynamic Host Configuration Protocol, or DHCP, which assigns a *different* IP address to a client machine each time that client connects

to the network. For a simple client like the Arduino there seems to be no way to check the IP address assigned by the network, it can only respond to the IP address pre-assigned in its code. To resolve this problem, the team met again with the campus network administrators who thankfully agreed to allocating a static IP address to the Arduino's Wi-Fi card.

Wi-Fi Connectivity Sequence Chart

The student tasked with wireless connectivity and information logging had no prior knowledge of wireless networking or experience with the Arduino. However, he enthusiastically took the challenge of developing a program for Arduino microcontroller to implement the wireless connectivity sequence based on the following algorithm:

1. Initial program upload. The wireless network connectivity program is written using Arduino source program and the following information uploaded and stored into Arduino's memory, including: MAC address (unique identifier for the Arduino), Arduino network pre-assigned IP address, SSID (name of wireless router), Gateway IP address (network address of router), Passkey (password required to gain access to router), and subnet mask (determines which range of addresses is valid for client machines on a particular router).
2. Arduino gets wireless router's attention by calling its SSID name and gateway address. Then, it transmits single passkey to gain access to wireless router.
3. Wireless router checks with server to validate access?"
4. Server authenticates client for access; using the client reserved IP address on the network.
5. Wireless router receives go-ahead to grant network access to Arduino
6. Arduino gets information about the box opening or closing and transmits the data to the internet using an HTML POST request to the specified URL (in this case, Pachube.com)
7. POST request sent from router to server
8. POST request sent from server to internet. Data now successfully uploaded to "Pachube.com" the data hosting website

Data-Logging

Students investigated the means by which they can log and retrieve the SMART BOX information. The website Pachube (pronounced "patch-bay") is a free-to-use data-hosting website intended for any type of electronic measurements to be uploaded to the internet on Pachube's servers. The uploaded information can be viewed in a web browser as a live data feed; downloaded to a personal computer for further analysis or interpretation, or even downloaded to a different machine so that two devices can send data back and forth using Pachube as a go-between. The Arduino was programmed to communicate with Pachube using the wireless network by sending specially formatted HTML requests; POST requests to upload new data to the Pachube, while GET requests to retrieve data. A visual basic program was written to retrieve the box information and display the date and time log of SMART BOX status and contents.

System Integration

A final SMART BOX prototype required both hardware and software integration and testing to determine its conformity with the specifications:

Hardware Integration

The hardware, including the electronic components, boards, and power supplies, are housed in a portable box and wired according to the circuit diagram shown in figure 8.

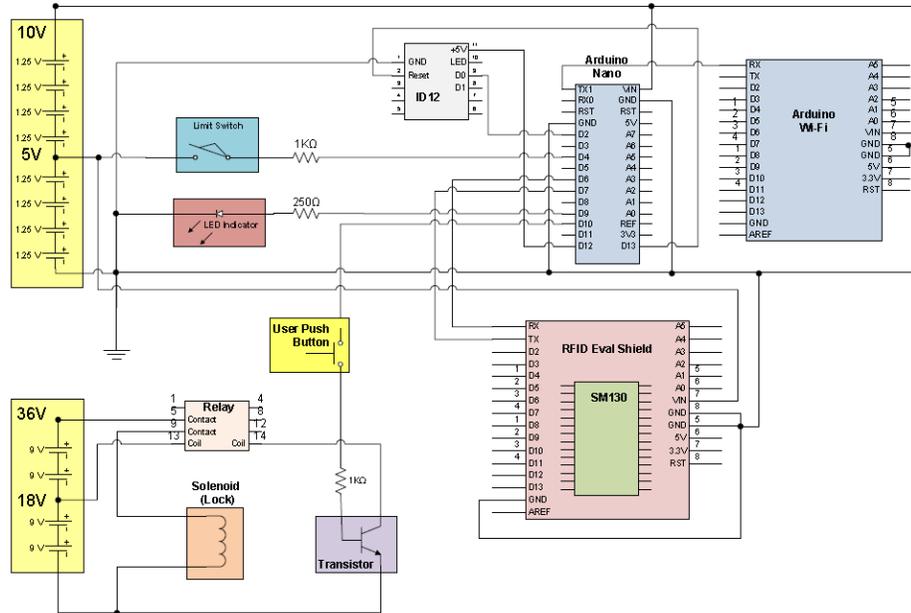
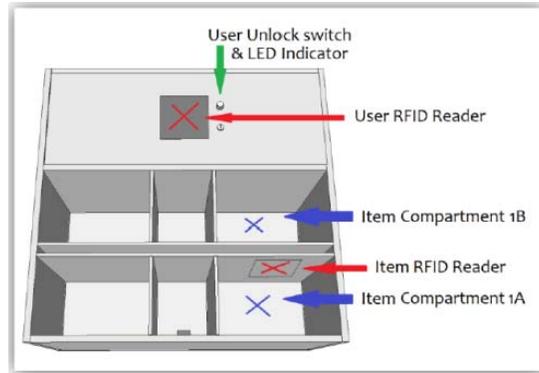


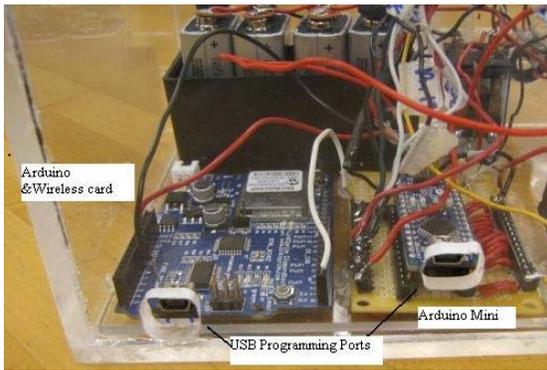
Figure 8. System hardware circuit diagram

The box was constructed, as shown in figure 9, using plexi-glass and according to the following design specifications:

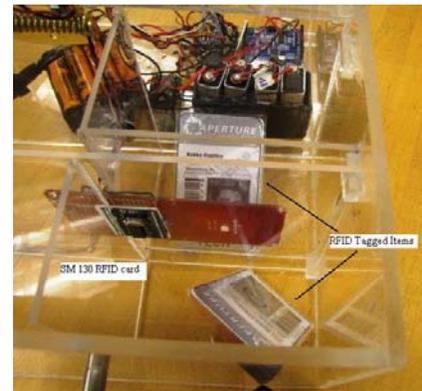
- Compact, portable, and low cost
- Must have compartments to accommodate all the electronic components, and the delivered tagged items
- Must have a controlled lock mechanism which can only be opened by an authorized person at a pre-specified location.
- Made of strong material to ensure safe delivery
- Transparent so that all the internal components are visible for the final demonstration



(a)



(b)



(c)

Figure 9. Box layout and construction

The item compartments sizes were based on the predetermined radiation pattern and detection range of the RFID SM130 system to ensure reliable item identification, and each compartment can house multiple items, see figure 9c. The locking mechanism was designed using a small pull-type solenoid. When the lid is fully closed the solenoid is de-energized and latches keeping the box secured. When a user is authorized by the ID-12 reader, only then he activate the electronic circuit that energizes the solenoid to open the lid.

System Software Integration

The system level operation is outlined by the flow chart shown in figure 10. The various functions are integrated and controlled by the Arduino microcontroller.

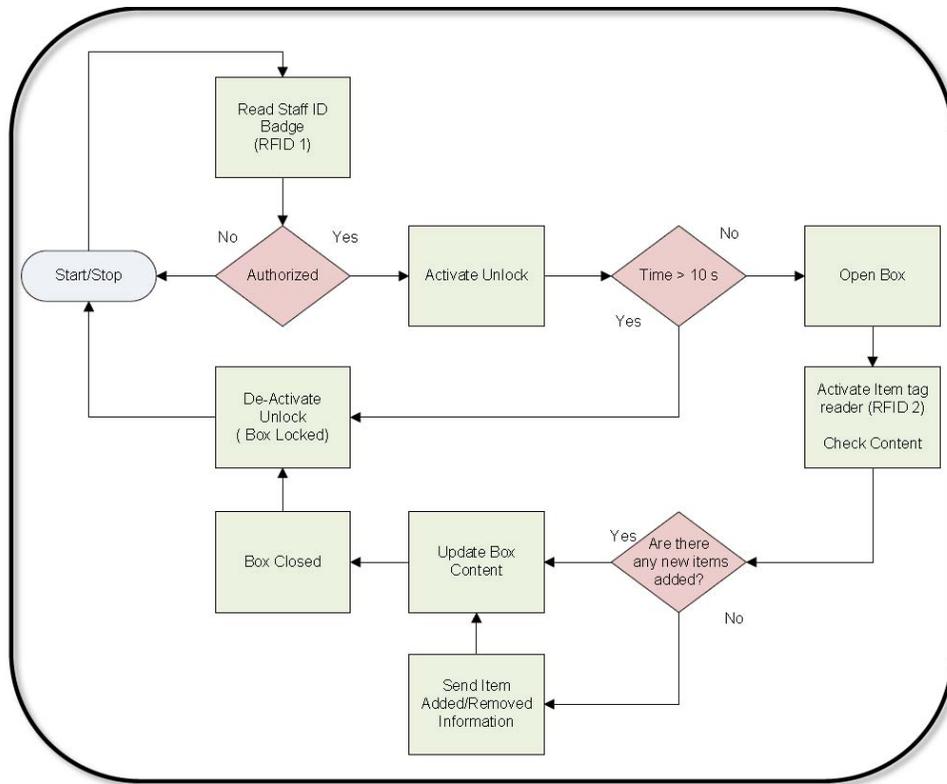


Figure 10. System level operation flow chart

Arduino Microcontroller

The Arduino microcontroller was programmed using the Arduino IDE (integrated development environment), an open-source programming tool based on the C programming language. It can be programmed to retrieve data from its various attached devices, interpret this data, and relay significant information to other devices or users.

While the box is closed, the Arduino’s microcontroller “listens” for incoming data from the ID12 RFID reader user badge scanner using the “NewSoftSerial” sub-program to emulate the action of a serial port. When the ID badge has been scanned, the Arduino compares the badge’s data to data stored in its memory to see if the tag is one of the valid users on its “approved-for-access” list. If the badge has authorization, the ID12 shuts off, and a command is sent to the second RFID reader, the SM130, in anticipation of contents being added or removed.

Once a response comes from the SM130 telling the Arduino that the device is prepared to scan objects, an LED is lit to indicate to the user that they may now attempt to open the box. Simultaneously, power is delivered from the Arduino to a pushbutton to drive a switching transistor to activate the solenoid that unlocks the box. Without proper authentication, the Arduino will not output a voltage to activate the solenoid.

Once the box is unlocked, a contact switch detects that the box has been opened, and the SM130 remains *on* in order to monitor items entering or leaving the box. Once the box has been closed (which again is determined by the state of the contact switch), the SM130 is powered down, the solenoid in the box returns to the re-lock position, and the box’s contents are reported.

All of these events are continuously monitored and sent by a second Arduino (the Nano) to the “diamondback” Arduino with Wi-Fi connectivity. Once the diamondback detects a new message from the nano on its serial input, it passes this information in a specially-formatted HTTP POST request to Pachube’s servers. The POST request includes authentication credentials needed to grant data access to Pachube, as well as the data value, the time it occurred, and the data stream to send the data to.

A visual basic program was configured such that the users can simply enter a date range and click “start,” and the visual basic program will automatically form an HTTP GET request. Again, this request uses the Pachube data stream information, as well as the start and end dates. The process control flowchart is shown in figure 11.

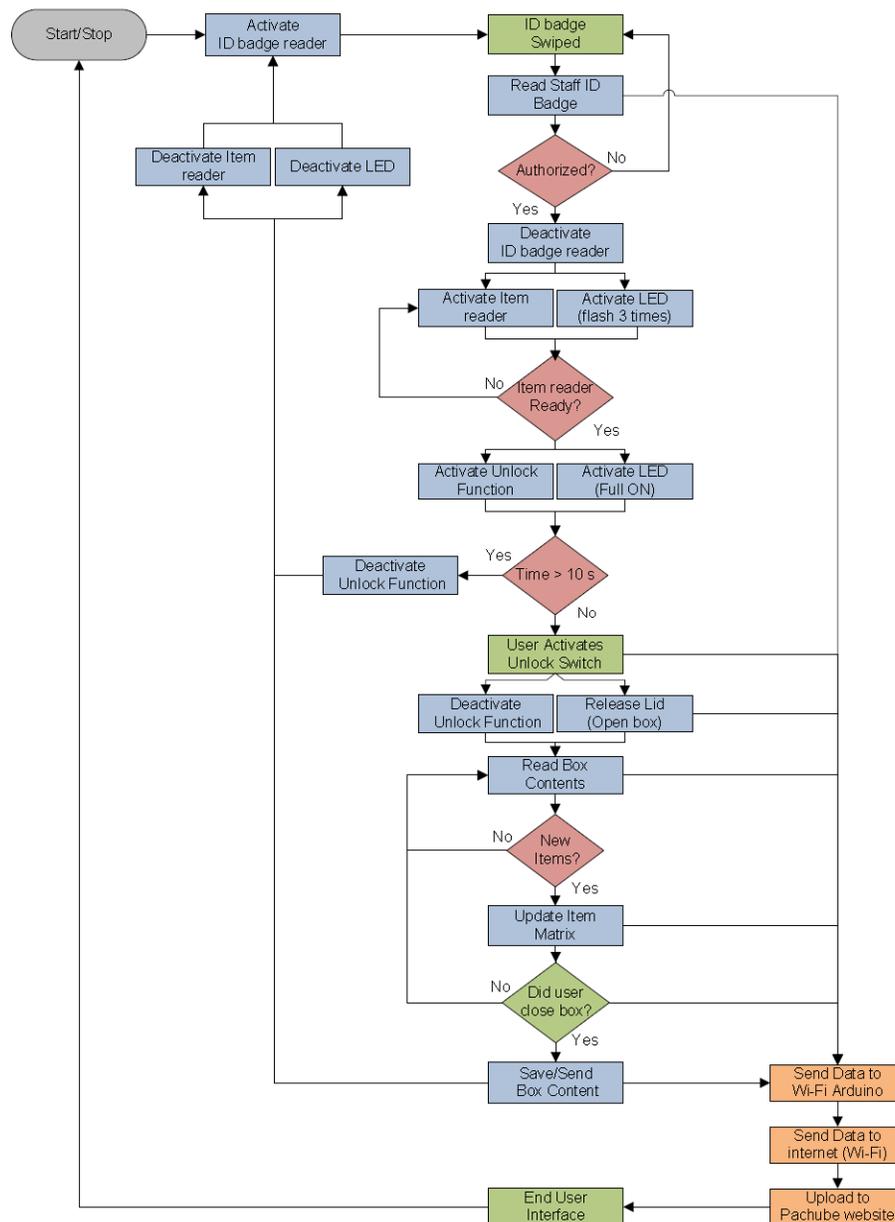


Figure 11. Process flow chart

Technical Discussion

The SMART BOX functions were successfully integrated. The Arduino communicated all the information to and from the online data-logging website (Pachube). The most challenging part of the project was combining the Wi-Fi & Pachube code with the RFID reader code which required extensive programming changes (using C++ Libraries) in the Arduino software. Once this was finalized, the SMART BOX was able to send in real-time the user and item details (Who, What & When) directly to the Pachube website. Each individual part of the code insured successful communication with the ID12 and the SM130, and acknowledged changes in contact switch states, communicating between Arduinos, and uploading to Pachube, therefore the prototype formed a working proof-of-concept

Students' Response and evaluation

At the end of the course, a student survey was conducted to evaluate the educational outcomes of the project. The survey included the following questions:

1. How did the senior design project (SDP) reflect on your learning process?
2. How did the SDP reflect on you ability to reason and make quick intelligent decisions considering the time constraint imposed?
3. Did the SDP provide a venue to expand your learning and apply the knowledge gained in the program to solve real world problems?
4. Was the short time constraint imposed a motivating challenging experience
5. Did the PDR and CDR report writing and presentation has added value to the SDP learning outcome
6. How well are you prepared to write a professional technical report and give a presentation if you're asked to do so by your employer, after you graduate?

The team's response was highly positive regarding the experience and knowledge gained, as well as their ability to think and be creative in their approach to solving practical real world problems. Following is a summary of their responses:

- The project introduced us to new concepts such as: effective use of C++ in a practical engineering applications, RFID, wireless network protocols, and Arduino.
- The senior design project allowed the team members to exchange ideas, think of alternative solutions and reach a consensus on the most practical ones.
- The project provided a good venue to apply the knowledge gained in the class room. It involved everything from design, re-engineering, implementation and testing of a real world practical problem.
- Going from theoretical applications to real world challenges was very rewarding and meaningful.
- The project helped me learn new technology by teaching myself.
- Writing the PDR, CDR, and the final reports taught us to be more professional in presenting our design ideas, we feel more confident and prepared to write a professional technical report.

- Writing PDR and CDR reports transformed our thoughts and outcomes into a structured document which kept the whole team on the correct track to achieve the final working product.
- The project was very challenging , it tested the team members’ creativity, cooperation, and time management skills

The comments indicate that the project has achieved its educational objectives despite the time and budget constraints.

Student Assessment

The students were confronted with a challenging task of developing and implementing a complex electronic system under strict time constraint. Assessing their performance required objective, quantitative and qualitative assessment procedures to ensure compliance with the project and ABET goals. They were informed at the beginning of the semester of the assessment breakdown which included:

- Biweekly report with Gantt chart clearly indicating the assigned tasks and the project progress
- PDR and CDR reports and presentations
- Final Report, to be evaluated by the advisor and the faculty consultant. Assessment rubrics were developed, see table 3.

Table 3. Project report assessment rubrics

	10	8	6	4	
Professionalism (30%)	Professionally presented with correct references and Excellent English/grammar	Well presented with correct references and Reasonable English/grammar	Just beyond minimum, some references cited.	Student did not demonstrate basic college level English skills, no references cited.	
Depth of Coverage (30%)	Well thought out, high level analysis of all project goals	All project goals investigated acceptably	Most project goals investigated.	Some project goals investigated.	
Justification of Conclusions (40%)	Well thought out, carefully considered solutions to the Project goals, schedule met and documented	Reasonable solutions to the project goals with some regard to project management techniques	Adequate solutions to the project goals with minimal display of project management techniques	Solutions show minimal justification or project scope drastically reduced due to time constraints.	
TOTAL					

- Final presentation to be evaluated by :
 - The Advisor and faculty consultant. Assessment rubrics were developed as shown in table 4.

Table 4. Final presentation assessment rubrics

	10	8	6	4	
Delivery (40%)	Superior Delivery, detailed and accurate answers.	Effective Delivery, answered all questions satisfactorily	Adequate delivery and answered most of the questions satisfactorily	Poor delivery, difficulty with several questions	
Organization (30%)	Outstanding organization Made effective use of time	Well organized presentation Stayed within allotted time	Adequately organized presentation Stayed within allotted time	Poorly organized presentation Did not utilize time allocation effectively	
Appearance and Legibility (30%)	Appealing Display, Effective use of graphics and text	Attractive and Legible presentation	acceptable appearance, Adequate eligibility	unacceptable appearance, Difficult to see or read	
TOTAL					

- o Attending department faculty members and IAB members.

The PDR and CDR reports were presented and discussed during meetings with the course instructor (advisor) and a faculty member acting as the project consultant. Following each design review, the advisor and the consultant submitted written comments on their reports and presentation suggesting improvements to the design process, the report write-up and presentation. The prelude PDR and CDR were extremely important to develop the students' skills and handling of an industry like project and to keep it on track.

For the final report and presentation the advisor and consultant assessment grade was 92%, the attending faculty members' assessment grade was 85%. The IAB members' assessment was qualitative. Their comments were "Very high level project, the team was able to integrate the microcontroller, the wireless Wi-Fi, the RFID and the internet to implement a working system, a very good effort in a very short time". The director of supply chain management at the medical center commented "an excellent understanding and solution of the current requirements. Need to identify and solve the limitation in mobility and accessibility at different locations".

Educational Outcome

The educational outcomes were gratifying, the team's achievement exceeded expectation, especially when they were under a short time constraint and a limited \$300 budget. Team work and leadership were the determining factors. The design tasks were divided between the students, each student was assigned a well-defined task to complete. All the design tasks were finally integrated into a working prototype. The students utilized their co-op experience to materialize a project proposal which has a potential real world application. They ventured into the field of radio frequency and wireless communication with only basic knowledge gained while concurrently attending an RF communication course. They utilized the web efficiently to extend their knowledge in search for the state of art technology to develop their system. Through dedication, creative thinking and well organized team work, they managed to analyze the system requirements and think of best solutions. They learned with patience from the advisor and the consultant's comments during the PDR and CDR meetings. The team also learned how to

discuss important design issues scientifically, come up with creative practical solutions and learn how to write professional reports. The students asked many insightful questions during project development stages, questioned their own design several times, accepted feedback in the most appropriate manner and acted as professionals during the final project presentation. The advisor never felt the need to micromanage the team because they consistently kept him up to date on their progress.

Conclusion

In the final presentation, the students successfully demonstrated a working SMART BOX prototype, explained its security features, how the box status was monitored and accessed using information and data logging capabilities. They identified a number of possible improvements, more specifically, the power supplies and box electronic lock designs. Given what has been accomplished, the project concept has a potential application in the Healthcare Supply Chain world.

Based on the experience gained from supervising this project, the implementation of a well-defined project with clear goals and thoughtful project management is possible in one semester. Team leadership and division of tasks between team members according to their individual capabilities are essential to project success. Following an industry like project evaluation process is necessary; it prepares the students for the real world. Training the students to be thinkers and problem solvers can be achieved by encouraging them to persevere in achieving solutions to seemingly tedious problems within a constrained time frame and limited budget.

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