Smart Connect: Developing an SMS-Based Communication System for Health Clinics in Vietnam

Krysta Yousoufian

krystay@cs.washington.edu

Adviser: Richard Anderson

anderson@cs.washington.edu

[illegible]

Honors Senior Thesis

June 7, 2011

Presentation delivered May 12, 2011

Smart Connect: Developing an SMS-Based Communication System for Health Clinics in Vietnam

Krysta Yousoufian

ABSTRACT

Smart Connect is an SMS-based system that enables rapid information transmission to and from rural health clinics in developing countries. It is designed to make communication faster and more direct in countries with geographically isolated health clinics and limited Internet availability. The Smart Connect system consists of a network of custom-built, low-cost devices that communicate with a central server to send and receive data via SMS. Here, we describe the development of a vaccine stock management application to be deployed in Vietnam. In most respects we were successful in building this complex application on a simple device; however, severe memory constraints currently prevent the device from being usable in a full-scale deployment, a problem we are working to mitigate.

1. INTRODUCTION

Rural health facilities in the developing world often have limited communication options. They may be isolated geographically with limited road access [1], and Internet access is typically out of reach either for cost or lack of infrastructure. Communication delays can affect critical health services. In Nicaragua, for example, health workers often do not learn the results of diagnostic tests on patients' blood samples until long after the tests were performed – and often after the health workers begin administering treatment if they suspect the disease [1]. Cellular phone networks are rapidly emerging as an alternative medium for rapid data transmission, as they often extend to considerably more rural areas than Internet coverage.

Smart Connect capitalizes on the availability of cellular phone networks, providing an SMS-based communication system to transmit information to and from rural health facilities. Participating facilities receive a “Smart Connect” device with a screen and keypad. The device accepts user input, displays data, and connects to external sensors. It uses an SMS scheme to communicate with a country-wide central server connected to a web interface, allowing an administrator to view data received from the devices and send out messages. The SMS layer is effectively invisible to users, freeing them to interact with simple menu-based interfaces.

Previous work on Smart Connect has focused on a pilot application in Nicaragua [1]. This application uses a temperature sensor to monitor a vaccine refrigerator and allows health workers to record information about patient visits for surveillance reporting. The proposal of a second pilot application in Vietnam emerged from the Optimize project, an initiative to overhaul the country’s system for tracking the vaccine supply chain led by PATH and the World Health Organization. Vietnam’s widespread cell phone coverage makes an SMS-based application feasible.

Here, we report on the development of the Smart Connect Vietnam application. The application tracks the use and distribution of vaccines throughout the country. The Smart Connect device stores the quantity of each lot currently in stock or in transit for its health facility. Health workers can record changes to current stock, which are reported to the server. The server also notifies the device of incoming shipments containing new lots. Additionally, the device uses an external temperature sensor to monitor a vaccine refrigerator. If the refrigerator becomes too warm or too cold, threatening to damage the vaccines, the device will sound an alarm, alert a storekeeper through SMS, and report the problem to the server. So far the application is in the development stage, but we expect to begin a field deployment in the coming months.

2. THE SYSTEM

2.1 The Smart Connect Device

We partnered with the nonprofit organization Inveneo to develop the hardware for the Smart Connect device (Figure 1). Built to be economical and rugged, the device features a simple 20x4 character, black-and-white LCD display and 3x4 numeric keypad for the user interface. Along the sides are ports for a USB cable, AC adaptor, and temperature sensor. The device runs on the Arduino ATMEGA 1280 microprocessor, which contains 4KB of RAM and 4KB of non-volatile Electrically Erasable Programmable Read-Only Memory (EEPROM). The device also contains an additional 1MB of EEPROM external to the microprocessor board. The firmware is written using the Arduino programming language and integrated development environment.

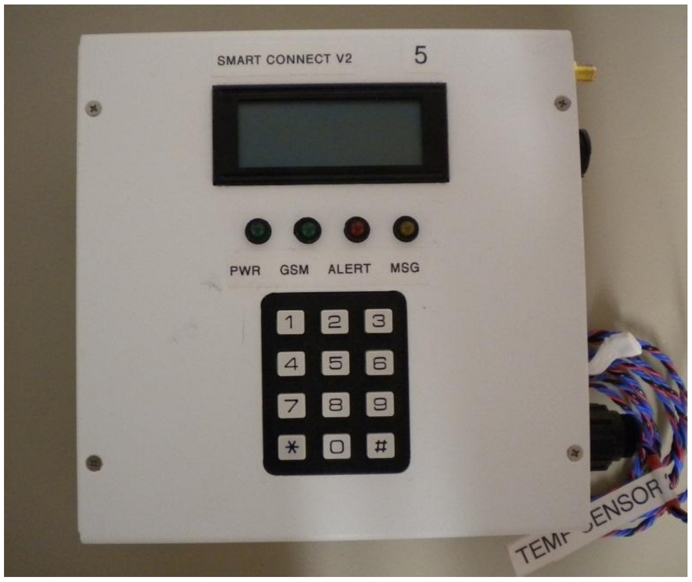


Figure 1. The Smart Connect device with attached temperature sensor.

2.2 The Server

The SMS server with which the devices communicate is built on RapidSMS, a free and open-source framework for SMS-based data reporting applications [2]. It provides high-level functions for processing incoming messages, sending outgoing messages, and creating a web interface to view or update data. It is also highly flexible, allowing developers to build custom applications. This "ensur[es] that the software is built specifically for the project, rather than trying to alter the project to fit the software" [4].

RapidSMS was designed for applications in low-resource environments like Smart Connect [5]. It has a strong reputation, backed by a number of large-scale deployments in developing countries [3], and boasts an active developer community for technical support. It is written in Python and built on the Django web-development framework. It is compatible with a number of database backends for data storage, and here we use MySQL.

The server is connected to a MultiModem GPRS cellular modem produce by MultiTech Systems, model MTCBA-G-U-F4. It is one of the modems most widely tested with RapidSMS and found to be compatible [6].

3. VIETNAM APPLICATION

3.1 Features

On the Smart Connect device, health workers can:

- Manage stock
    - View the quantities, lots, and expiration dates of vaccines currently in stock
    - View the contents (vaccines, lots, and quantities) of incoming shipments and mark shipments as received
    - Update quantities in stock along with a reason for each update: received shipment, sent shipment, used locally, wastage, expired, or other
    - View a log of recent stock updates
- Manage temperature
    - View the current temperature of an attached sensor
    - Receive immediate notification when the temperature becomes unsafe through an on-screen alert, an audible buzzer, and a text message sent to the storekeeper

    - View recent instances where the temperature has become unsafe, including how long it remained in the unsafe range and the most extreme value it took during this period
- Manage settings
    - Change language between Vietnam and English
    - Set phone numbers for the server and the storekeeper
    - Set GSM band for SIM card
    - Change the password for the device
    - View the names of “child” locations, health facilities that receive stock shipments from the current location, and a “parent” location that ships stock to the current location.

3.2 Workflow

The server administrator uses the server’s web interface to add and update general information:

- Full and abbreviated names of all vaccines in the catalog
- Names of all vaccine manufacturers
- Names and device phone numbers of all Smart-Connect-enabled locations, plus their associated locations (the locations they send stock to or receive stock from)
- Levels organizing the above locations – e.g. “regional,” “district,” “province”

The server administrator also initializes the chain of vaccine distribution by entering:

- Existing lots – their lot number, associated vaccine, manufacturer, and expiration date
- Stock shipments sent from the country’s central distribution point to some Smart-Connect-enabled facility, including the quantity of each lot the shipment contains

When the server number is first entered on the device and each time the device is powered on, the device contacts the server to receive and store the following information:

- Names of vaccines
- Names of manufacturers
- Names of locations that send stock to or receive stock from the given location
- Several other configuration values (only when server number is first entered)

Figure 2 shows the complete process of initializing data on the device.

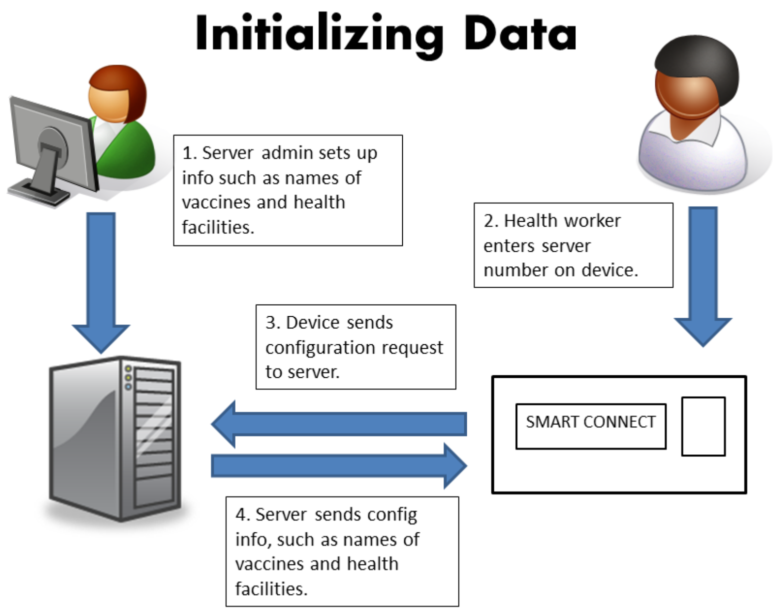

Initializing Data
1. Server admin sets up info such as names of vaccines and health facilities.
2. Health worker enters server number on device.
3. Device sends configuration request to server.
4. Server sends config info, such as names of vaccines and health facilities.
SMART CONNECT

Figure 2. The process by which data is initialized on the device.

The device also receives and stores the following updates from the server over time:

- Notifications of incoming shipments, with the quantity of each lot the shipment contains. The notification includes each lot's number, expiration date, and manufacturer. Shipments notifications are either entered by the server admin or received from another device and forwarded on.
- Additions, deletions, and modifications to vaccines, lots, manufacturers, and locations

The device receives and stores the following information from user or sensor input:

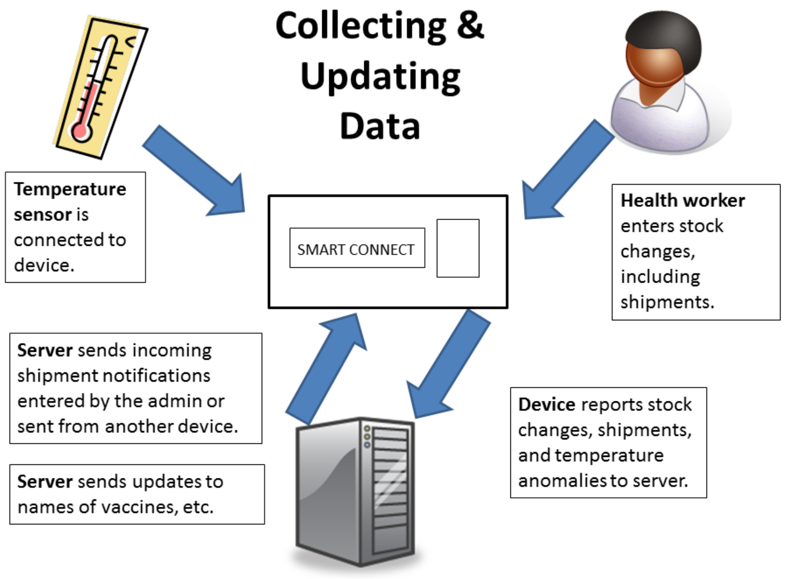
- Server and storekeeper phone numbers
- Changes to vaccine stock: received shipments, sent shipments, local usage, etc.

- Out of range temperatures

The following data is reported from the device to the server and can be viewed by the server administrator:

- Changes to stock
- Recent out-of-range temperatures

Data sent from the device to the server is bundled into a single daily report. The only exception is notifications of outgoing shipments, which are sent immediately to the server so they can be forwarded to the recipient more quickly.



Collecting & Updating Data
Temperature sensor is connected to device.
SMART CONNECT
Health worker enters stock changes, including shipments.
Server sends incoming shipment notifications entered by the admin or sent from another device.
Server sends updates to names of vaccines, etc.
Device reports stock changes, shipments, and temperature anomalies to server.

Figure 3. The process by which data is received and transmitted through the Smart Connect system.

Figure 3 shows how data flows between the user, device, and server over time.

4. DEVELOPMENT PROCESS

4.1 Web Mockups

Because the Smart Connect hardware and software were developed in parallel, the software development began with a virtual prototype built in HTML and JavaScript to explore the UI appearance and data structures to use. The web prototype proved to be much faster and easier to develop than the device firmware, as the latter required us to implement low-level functions for input and display. As a result, the decision to begin with a web prototype had several advantages. First, it enabled us to build and modify the UI more quickly than on the firmware so we could focus on optimizing the appearance without being distracted by implementation details. Second, knowing how the UI would look before the firmware programming began meant we did not waste time rewriting low-level display functions as the UI design changed. And third, our partners in Vietnam were able to review the prototype online and provide feedback earlier.

The first prototype was developed before the appearance of the screen and keypad were known (Figure 4). Later, the prototype was modified considerably to represent the device's 20x4 character screen and 3x4 keypad (Figure 5). Several additional buttons represent two keys pressed simultaneously.

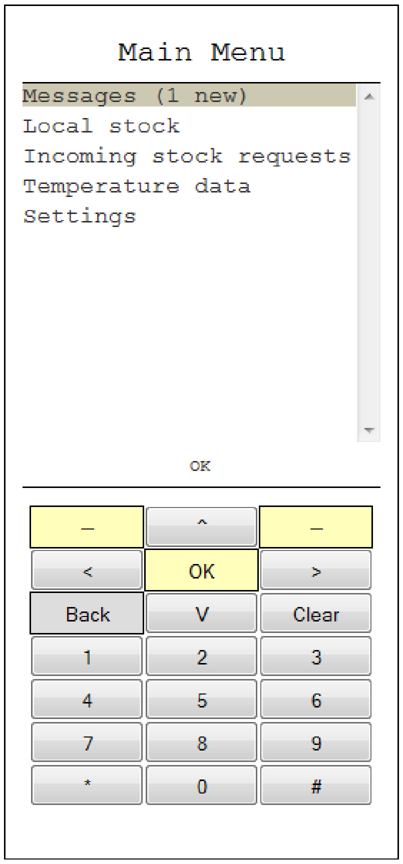


Figure 4. The first HTML and JavaScript prototype was designed with a more advanced screen and keypad than the device would eventually have.

4.2 Static Firmware Code: UI Development

The basic firmware code we received was minimal and designed for a much simpler application. It implemented only the lowest-level behavior, such as responding to user key presses and sending SMS messages. By contrast, the UI for the Vietnam application pushes the simple screen and keypad to their functional limits with scrollable menus and lists, the ability to navigate forward and backward through menus, multi-column forms that accept input on each row, and more. Implementing such functionality was a project in itself. The first stage of firmware development focused on building the

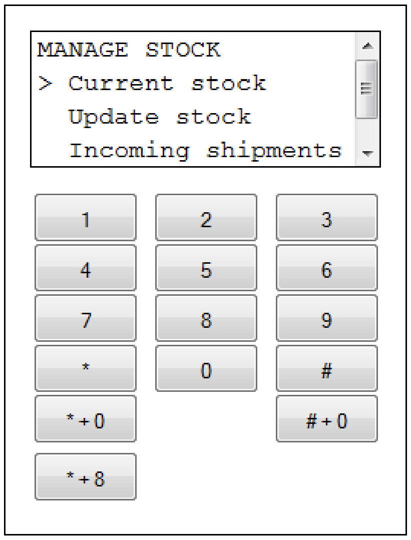


Figure 5. A second version of the web prototype reflects the appearance of the true screen and keyboard. Additional keypad buttons represent pressing two given keys simultaneously.

UI and data structures with hard-coded data, using no SMS communication – that is, porting the behavior of the prototype to the device.

4.3 Dynamic Firmware Code: SMS Communication

After developing the static UI, we integrated support for sending and receiving SMS messages. These capabilities eliminate hard-coded data, with the device dynamically initializing and updating the vaccine catalog and other information from the server. The device also reports data to the server and storekeeper. Because the device firmware was mostly written before the server-side code, we used a Google Voice account as a mock server during development.

The user enters the server number when first setting up the device. Immediately the device sends a configuration request to the server, which replies with a set of configuration variables, such as the upper and lower limits of the safe temperature range. The server also sends a second message with the names of vaccines and manufacturers and a third message with the names of the device's associated locations. Although the server number and configuration variables are stored in non-volatile memory and only needs to be entered once, the vaccines, manufacturers, and locations are stored in RAM and erased when the device loses power. Every time the device regains power it pings the server to resend this data.

A message to or from the server consists of a three-integer header, explained below, followed by the type of message and any data or parameters. Each SMS also begins with '@' and ends with '!' to identify it as a correctly formatted Smart Connect message. Using such a wrapper is a convention in SMS-based reporting applications.

As an example of a message, the server or device might send the following to acknowledge the receipt of message #12:

@35 0 1: ACK 12!

where “35 0 1” is the header, “ACK” identifies the message as an acknowledgment message, and “12” is the ID of the message being acknowledged.

Other messages that involve vaccines, manufacturers, and locations refer to these entities with ID numbers assigned by the server exclusively for device-server communication. Referring to these objects by ID number rather than by name allows for more robust, compact messages.

Creating a robust SMS communication system involves many technical challenges. These include:

Long messages

Transmitting long datasets may require more than the 160 characters each SMS message can contain. For instance, sending the complete vaccine catalog and manufacturer list to the device at initialization takes at least two messages. Both the device and server must be able to split long outgoing messages into several pieces and recombine received messages, and each SMS message contains a three-integer header for this reason. The first number indicates the message ID. The devices and server each maintain their own message ID counter and increment it after sending each message. If a message is split into multiple parts, each part has the same ID. The second number indicates which part of the larger message this particular SMS message contains, with numbering beginning at 0. Finally, the third number in the header indicates the total number of parts for that message.

Each SMS message in a multipart message contains the “@...!” wrapper, a header, and a payload with as many characters from the longer message as will fit. The message can be truncated mid-word or mid-integer. Upon receiving an SMS message, the device or server uses the third number in the header to determine whether it belongs to a multi-part message. If so, the payload is stored until all the last part is received. Then the complete message is reconstructed by concatenating the individual parts.

Dropped messages

Both the server and devices must be able to trust that their messages were received. For most outgoing messages, the sender expects a reply acknowledging receipt. (Clearly recipients do not acknowledge an acknowledgment message, which would start an infinite chain of acknowledgments!) Only one acknowledgment is sent for multi-part messages, after the entire message has been received.

If no acknowledgment is received within ten minutes, the message is resent. If there is still no reply ten minutes later, it is resent again. If there is no reply even after the third attempt, the message is deemed a failure and the message is not resent. If a device sent the message, the device enters an alert state, displaying the message “Unknown Error / No response from svr.” If the server sent the message, it keeps the message in the database and flags it as failed, which could be used to alert the server administrator to a technical problem or unresponsive device.

In the case that the *acknowledgment* message was dropped, rather than the original message, a recipient may receive the same message twice. Messages should therefore be approximately idempotent: receiving the same message twice either has no effect at all (e.g. updating the expiration date of a lot twice to the same value) or a relatively benign effect (e.g. sending a shipment notification twice: the device will think it has two incoming shipments, but the user can mark one of the shipments as received with no lots).

Once a day the device and server also check for any pieces of a multi-part message that have been stored for more than 24 hours while waiting for the rest of the message to come in. Ordinarily no such message should be found, but if so the parts are deleted to free memory and prevent confusion if that message's ID number is later reused for another message.

Spacing messages apart

The GSM module on the device can only handle one incoming or outgoing SMS message at a time. It is prone to crash when two messages are sent or received too rapidly, which is especially a problem for multi-part messages. Outgoing SMS messages from the device are stored in a queue, with each message in the queue only sent after the GSM module has finished processing the previous message. For incoming SMS messages, the server waits ten seconds between sending each message to the device. This time interval was found to give the device enough time to receive and process each message before the next arrives.

4.4 Server Code

The server-side application consists of two components: 1) the code to automatically handle incoming SMS messages and 2) the web interface through which an administrator views and updates data. The current focus was on the former. Django, the framework on which RapidSMS is built, offers a built-in admin web interface for viewing and updating database tables. We used that as the extent of the user interface at this point.

The server's message handling logic is similar to that of the device. When an SMS message arrives, the server first parses it into the header and payload and stores multi-part messages until all parts have arrived. The complete message is processed according to the message type.

Depending on this type, the server may store data from the message, send data out, or both. It may also reply with a message acknowledgment.

Each active device is expected to report its recent activity to the server daily. Once a day, the server should check for devices that missed their last report. How it should handle unresponsive devices has yet to be determined. Depending on the use scenarios for the web interface, the server might display an alert on the web UI or notify the server admin of the unresponsive device via SMS. The device can also send a report for a given day’s activity upon request, so the server might try to obtain the missing report before alerting the admin to the problem.

After developing the device and server code independently, we brought the two halves together with surprising ease. Each had been written according to the same message scheme, with common acknowledgment systems, message headers, and formats for each type of message. In theory there was no reason for incompatibility. Even so, we expected unforeseen issues and were pleased that the device and server quickly began to communicate successfully.

5. CHALLENGES

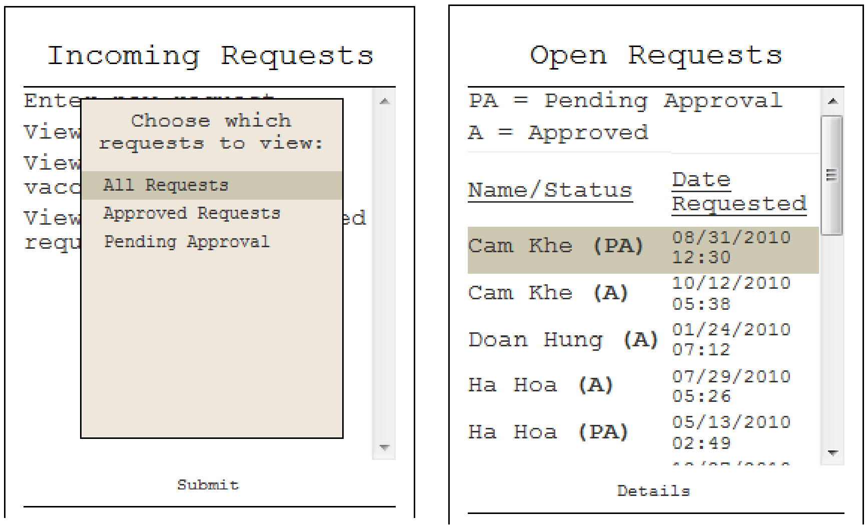
Many development challenges were the result of working with a low-resource device in a low-resource environment. The Vietnam application is much more complex and resource-intensive than the types of applications for which Smart Connect was designed.

The greatest problem we face is a memory shortage. The device needs to store a catalog of up to 10 vaccines, up to seven lots per vaccine at a time, up to 40 locations, several manufacturers, and several shipments. EEPROM is difficult to use for complex and changing data structures, so this data is currently stored in RAM. Unfortunately, the 4KB of RAM on the device is nowhere near enough for these data quantities. During our testing the device ran out of memory with a tiny dataset of just six vaccines, four manufacturers, four locations, and one shipment of 1-2 lots per vaccine. The only apparent solution is to store most data in EEPROM, only loading small amounts into RAM at a time.

EEPROM is also the solution to another problem: data loss. Data stored in RAM is erased every time the device loses power. This is a significant problem in a country where power outages can occur on a daily basis, especially if the application only reports data to the server only once per day. Currently the vaccine catalog, manufacturers, and locations are resent from the server every time the device regains power, but the lots and quantities in stock are not. Storing data in non-volatile RAM will preserve it against power failures.

Another constraint of the device is the 3 x 4 keypad. We originally envisioned being able to enter alphabetic input on the device, such as names of other locations or reasons for stock updates. The application was revised so some alphabetic data, such as names of vaccines and locations, was sent from the server while nonessential alphabetic data was eliminated altogether. The * and # keys were used for scrolling up and down through a menu. We used double-key combinations for other navigational commands, namely Enter to advance to the next panel (0 and #), Back to go to the previous panel (0 and *), and Backspace to erase input (8 and *). On discovering that the firmware could not detect two keys pressed simultaneously, we added a counter to determine how close in time two keys were pressed. Drumming the two keys so they are pressed at distinctly different times but only a fraction of a second apart is interpreted as pressing them simultaneously.

The 20 x 4 LCD character display also required us to scale back our original design. The display can only support a very simple interface that shows a small amount of data at a time, unlike the vision of our original prototype (Figure 6). Whereas the prototype allowed for dialogues to pop up over main menus, the final system has only single-layer displays. The prototype also assumed a much larger screen with a higher resolution that could display different text sizes. Although most of the application works well with the more limited screen, the multi-column form for updating current stock cannot display entire lot numbers, which could make it difficult for the user to select the correct lot. Morever, it is unclear if all text will fit as well on the screen once translated to Vietnamese.



PA = Pending Approval
A = Approved

Name/Status	Date Requested
Cam Khe (PA)	08/31/2010 12:30
Cam Khe (A)	10/12/2010 05:38
Doan Hung (A)	01/24/2010 07:12
Ha Hoa (A)	07/29/2010 05:26
Ha Hoa (PA)	05/13/2010 02:49

Figure 6. Viewing requests for more stock on the original web prototype. This feature was later removed, but it demonstrates UI features of the original design, including submenus and varying text sizes and styles.

Working with the LCD display was all the more challenging because of the minimal, low-level nature of the firmware we received. Support for updating the display consisted of three functions: set the cursor, print any string, or print from a hard-coded list of strings specific to the application. From this we created relatively elaborate scrollable menus that extend off the screen, forms with several columns of data and an input column, backspace support, and other advanced UI features. Designing the data structures and functions to enable this level of sophistication was a time-consuming task.

Another challenge was ensuring the robustness of the SMS communication system. As described earlier, we needed to consider the issues of dropped messages, long messages, and messages sent too rapidly. We also needed to ensure that when the user changed the server number, the new number would be remembered but would not overwrite the old number in EEPROM until the new server had confirmed the number was correct by sending the correct response.

Lastly, we considered security vulnerabilities in the system. When receiving SMS messages, the device ignores any messages not from the server, and the server ignores messages not from a known device phone number. A user can change the server number on the device, but as described previously the new number will not be saved until the server sends the correct configuration reply. If a user modifies the storekeeper number, the change is saved automatically, but the old storekeeper is notified of the change. The device also requires a password to log in, but currently the password is stored only in RAM and not EEPROM. Although the password can be changed, it resets to the default if the device is unplugged. A simple modification to store the password in EEPROM would improve security, but there should be a way for the server admin to remotely reset a device's password in case it is lost.

6. RESULTS

Our application meets most requirements and standards. We built a relatively sophisticated user interface that matches the vision of the prototype, we implemented the required features, and the device communicates successfully with the server. In those respects we have accomplished a great deal.

However, the project cannot yet be called a success. The unforeseen and severe memory shortage currently leaves the system unusable for practical purposes. The application works so long as the data set is sufficiently small, but it fails at the level of a realistic deployment. Fortunately, we expect that storing data primarily in EEPROM will resolve these problems. We are currently working to incorporate EEPROM as quickly as possible.

7. FUTURE WORK

The EEPROM work is our top priority and the primary issue blocking a field test. Several smaller development tasks on the Smart Connect device also remain, such as supporting longer lot numbers that can contain alphabetic characters. There is considerable work to be done on the server application, as our priority was to complete the device application first. The largest server-side task is building the web UI, which also needs to be integrated with the SMS-handling code so that entering or changing data (e.g. new shipments) will force updates to be sent to the devices. Other unfinished work items include handling daily reports from the devices and checking for and responding to devices that missed their last daily report.

8. CONCLUSIONS

Our application demonstrates both the potential and limitations of the Smart Connect device. We have shown that with enough development time, this low-cost system built from simple hardware can support a complex application in nearly every respect. The notable exception is the memory issue, which currently renders the application virtually unusable. We expect to be able to overcome this limitation – but not without considerable extra time investment in an application that has already been challenging and time-consuming to develop. The device was originally envisioned as part of much simpler reporting systems, such as that deployed in Nicaragua. While we hope to find that Smart Connect is capable of handling the full Vietnam application, our experience is that it is best suited for simpler applications.

ACKNOWLEDGEMENTS

I would like to thank Richard Anderson, Nell O’Rourke, and Rohit Chaudhri for their help and support with this project.

REFERENCES

[1] Anderson, R., Blantz, E. Lubinski, D., O'Rourke, E., Summer, M., and Yousoufian, K., "Smart Connect: Last mile data connectivity for rural health facilities," 4th ACM Workshop on Networked Systems for Developing Regions (NSDR), June 2010

[2] RapidSMS, http://www.rapidsms.org/

[3] RapidSMS: Case Studies, http://www.rapidsms.org/case-studies/

[4] RapidSMS: FAQ, http://www.rapidsms.org/ecosystem/faq/

[5] RapidSMS: Overview, http://www.rapidsms.org/overview/

[6] Supported Devices, https://github.com/adammck/pygsm/wiki/