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Re-visiting Design and Development of a Low-Cost Computer on Wheels to support healthcare delivery for Low-Resource Settings

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Background and Purpose: Unlike implementations in high-income country settings which span the entire breadth of a health facility, electronic health record (EHRs) implementations in low- and middle-income countries (LMICs) have mostly been disease specific. Since most disease-specific clinics are ambulatory in nature, the inpatient setting has been largely ignored with regards to EHR implementations in LMICs. Computers on wheels (CoWs) has improved access in high-income country hospital settings, but may not be financially feasible in LMIC settings. Here we describe the design and development of a low-cost CoW that has been done in a low-income country setting.
Methods: We developed a set of functional requirements for a computer on wheels and a design approach for the development of a functional prototype from concept to finished product. We conducted a laboratory function evaluation to assess how the CoW would work.
Results: We designed and developed a CoW comprising a cart, computing platform and a docking station for charging. Our computing platform is based on a Raspberry Pi single board computer with a 7-Inch touchscreen display, thermal label printer and 2-dimensional barcode scanner. The unit is powered by a rechargeable battery providing a runtime of roughly 16 hours between charges.
Conclusions: We have demonstrated that fit-for-purpose solutions that may enhance clinical care in an in-patient setting can be designed and developed in an LMIC setting. This approach can reduce barriers to entry for EMR systems in hospitals by making more affordable and locally supportable solutions available.

Keywords: LMIC, Computer on Wheels, EMR Integration

1 Introduction

The adoption and use of Electronic health records systems (EHRs) promises several benefits and improvements to the quality of care. Since the early 2000s, several publications have described implementations of EHRs in low- and middle-income countries (LMICs). One distinguishing characteristic of EHRs implementations in LMICs has been the disease specific focus of most implementations.[1] This is unlike the implementations in high-income country settings where EHR implementations often span the entire breadth of the health system or facility.

One downside of the disease-specific focus of EHR implementation in LMICs is the ignoring of other aspects of healthcare. Since most disease-specific clinics are ambulatory in nature, the inpatient setting has been largely ignored with regards to EHR implementations in LMICs. An argument can be made that focusing on the ambulatory setting for EHR implementations in LMICs addresses most of the information needs since most patients are treated as outpatients. However, some patients treated in the ambulatory setting are admitted to hospital wards, thus requiring continuity of care among the clinical team. These are often the sickest patients whose care can benefit from well documented medical records such as those offered by EHRs in these settings. The presence of such records can facilitate delivery of healthcare and

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help reduce incidence of adverse events, which the World Health Organization (WHO) estimates occurs in one out of every ten hospitalised patients and are fatal in 30% of all cases.[2]

One approach that has been taken in high-income country settings is the use of computers on wheels (CoWs). These have typically taken the form of placing a desktop or laptop computer on a commercially-available cart, augmented with some form of battery power solution that enables the computer to be powered during clinical rounds. These solutions have been estimated to cost more than $3,000.[3] Jen et al. describe the development of their Very-Efficient Agile Laptop (VEAL) as a lower-cost solution for use in emergency departments in high-income country settings.[3] Their solution comprised a laptop computer, commercially available cart, additional battery to extend the runtime of the laptop, and an ID Badge reader, totalling $2,721 in cost. Whether this cost includes shipping is not stated in their description, but must be considered as a component of the cost, particularly in the context of LMIC settings. One additional observation from their description is the use of a mouse shown in pictures of their CoW, despite the fact that their laptops are equipped with trackpads, suggesting that the addition of the mouse provides an enhanced user experience.

In 2003, we developed a CoW using a mechanics rolling toolbox as the base with a modified Internet appliance mounted on top. In 2015 we developed a second iteration of the CoW that was based on a commercial cart and an android tablet.[4] In this paper, we describe the third iteration of a built-for-purpose CoW for use at the bedside along with initial findings from a pilot implementation. While our development has been done in an LMIC setting the solution also has potential applications in high-income country settings.

2 Methods

We have previously published a manifesto describing an LMIC-first approach to developing EMR systems for low-resource settings.[5] The development of our CoW follows this manifesto with five of the six themes exemplified in the prototype: 1) designing solutions optimised for use at the point of care; 2) taking a process-centric approach; 3) emphasis on low-power consumption; 4) emphasis on low cost; 5) a focus on touchscreen user interfaces to maximise usability and efficiency. The remaining LMIC-first theme focused on software development processes, which is not discussed here.

2.1 Setting

The development of the CoW has been undertaken at the Global Health Informatics Institute (GHII) training centre in Lilongwe, Malawi. GHII works at the intersection of science, engineering and global health to address problems of global health importance. GHII has a fully equipped electronics laboratory and a mechanical engineering workshop capable of doing rapid prototype development.

2.2 Functional requirements

We came up with the following list of functional requirements based on our experience working in an LMIC inpatient setting for the past several years:

1. Locally manufactured so as to minimise shipping costs and maximise maintainability.
2. Create a cart solution that provides additional value beyond just the transportation for the computer, creating a stronger value proposition for the user.
3. The footprint should be sufficiently small to navigate through doorways and between patient beds on a congested inpatient ward.
4. The cart should be sufficiently light in weight and agile to allow it to move easily in tight spaces.
5. The computer should be able to run autonomously for at least 10 hours.
6. Can be recharged easily without dependence on support staff.
7. A 2D barcode scanner to facilitate staff and patient identification.
8. A thermal label printer to allow for the generation of stickers to support different applications e.g. labelling of laboratory specimens.
9. Should provide a touchscreen user interface maximise usability and eliminate the extra space required for an external mouse.

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10. The computer should be firmly attached to the cart to prevent theft and the design should minimise the use of external peripherals that could be easily stolen.
11. All external USB ports should be enclosed to avoid users plugging their phones for charging that could drain the batteries, which could significantly reduce the runtime of the system.

Many of these features are core in our appliance model hardware philosophy previously described. [6]

2.3 Prototyping

We focused initially on the development of a cart starting with sketches of a proposed design followed by a mock-up made from thick cardboard. Following that, each piece was individually modelled in AutoDesk Fusion 360 computer aided design software and a tool path created to cut out each piece on a computer numerical control (CNC) router. As we expected to have several iterative improvements on the design, we used 10mm plywood for the initial construction. Once the design reached a level of maturity, we switched to PVC plastic for the final version.

Our process for developing the computing platform was heavily influenced by other internal projects at GHII that unitized single-board computers and touchscreen displays. We considered display sizes of 10-Inch, 7-Inch and 5-Inch. We selected the 7-inch display as it was more easily integrated with the Raspberry Pi, and roughly half the cost of the 10-inch display, while still providing adequate size for performing simple tasks. We chose to mount the display in portrait configuration to minimise the footprint.

Version 2 of the CoW utilised a thermal label printer that would accommodate auto a 4-inch wide label. We believe that the smaller footprint and lower power consumption of a 2-Inch label printer would be preferable and opted for the narrower printer.

In Version 2 of our CoW we used a handheld barcode scanner with a USB connection to the tablet. In our current version we switched to an embedded scanner that was internally connected. This had the additional benefit that it could be used hands-free.

Based on the dimensions of the components a cardboard mock-up of an enclosure was created, moving to plywood and finally PVC as described above. Finally, we needed to design a way of charging the carts.

2.4 Usability Testing

Our goal was to make a product that the users find value in it and have the willingness to use the product day by day. When we created the first version of the cart, we tested it at Daeyang Luke Mission Hospital. We left one cart with the matron in each of the two different departments for two weeks. After two weeks had elapsed, we went back at the hospital to gather feedback.

2.5 Laboratory Function Evaluation

To assess how long the CoW would work, we conducted a laboratory function evaluation. We developed a simple script that printed a label with a timestamp every 10 minutes. This gave us an objective way of comparing runtime of different battery technologies and power management strategies.

2.6 Ethical Considerations

The development of this manuscript and prototype followed all ethical standards for research without direct contact with human or animal subjects.

3 Results

Our Initial prototype from 2003 (original image captured with a low-res camera) along with our 2016 version and our current version are shown below in Figure 1 for comparison purposes.

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Figure 1 - The Evolution of our Computer on Wheels 2003, 2016 and 2023 respectively

3.1 Features of the CoW Prototype

3.1.1 The Cart

After the cart was used by the healthcare workers at Daeyang Luke Mission Hospital, they provided us with the following feedback: The cart was easy to drive around due to its compactness. The height of the cart suited different nurses, and no one complained. However, there was one comment that was raised to say the top half of the cart was wobbling so much and we addressed this problem by adding a frame with a diagonal section at the back of the cart.

While the cart is intended to support the mobility of the computer, we observed that there were other potential applications that could be concurrently addressed. In particular we noticed that clinicians often move between the bedside and the nursing station to collect medical supplies during ward rounds. To reduce the back and forth between the bedside and the nursing station, we designed the cart to facilitate the transportation of frequently needed medical supplies. In addition, waste management was also observed as a challenge. Moving between the bedside and a sharps box with a used syringe increased the chances of a needle stick. To address this, we designed a section of the cart to accommodate a sharp box. Lastly, we added a space for a waste disposal bin. To maximise mobility and ensure that the cart can navigate tight spaces, we used fully-articulated wheels on all four corners of the cart. Figure 2 shows the cart at various stages of development.

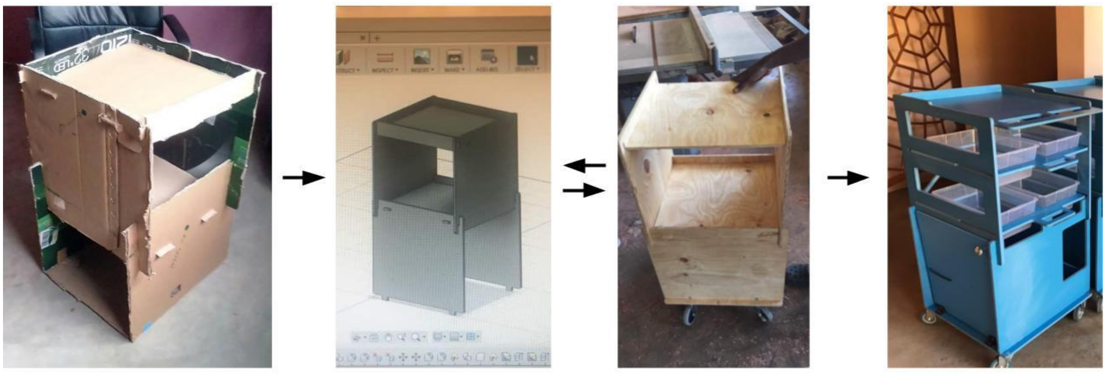

Figure 2 - The Cart at various stages of development

Our design utilised individual pieces that interlock for strength. This approach allowed us to keep the individual pieces relatively small allowing for compact shipping and assembly on-site, similar to the design

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of Ikea furniture.[7] We decided to construct the cart out of PVC as it has the advantage that it is strong, water-resistant, can be easily sanitised, and does not require painting. Assembly of the pieces takes less than five minutes for two people, requiring only eight screws to hold all the pieces together.

3.1.2 The Computing Platform

We settled on using a Raspberry Pi 3B+ single board computer as the computing platform, connected to a 7-inch touchscreen display. We integrated an embedded barcode scanner and a Zebra thermal label printer with a maximum label width of 2-inches. Figure 3 shows the computing platform at various stages of development.

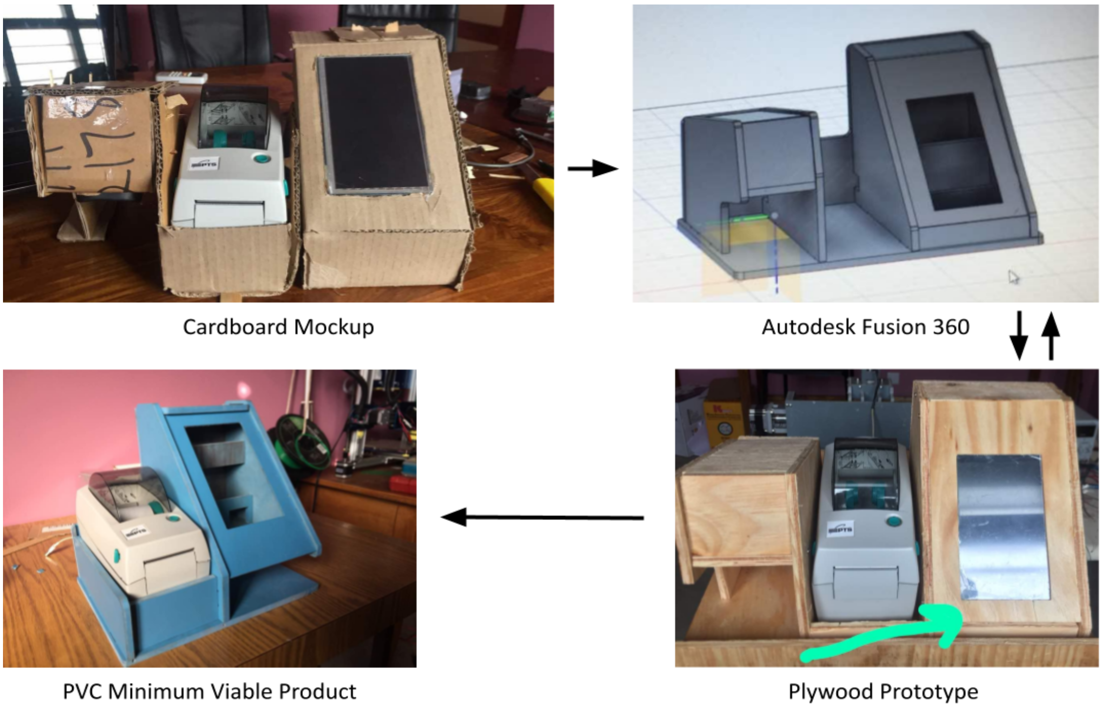

Figure 3 - The Computing platform at various stages of development

3.1.3 Component Integration

As there was a significant amount of electronics integration required, we developed a printed circuit board (PCB), which connected to the Raspberry Pi using the 40-pin GPIO header. The battery charging circuit, real-time clock, and DC/DC converters for the Raspberry Pi and label printer were all built into the PCB. The entire system is powered using a 12-volt, 8Ah Lithium Iron Phosphate (LiFePo4) battery with onboard battery management system.

3.1.4 Power management

To maximise runtime on a single charge, we implemented a number of power saving features. While we wanted to support a feature of printing adhesive labels, we knew that it may be used infrequently. However, while the printer is turned on, it drains a small amount of power even when not printing, amounting to roughly 10 percent of the overall power consumption of the CoW. To accommodate for this, we implemented a power control relay on the PCB that allowed us to turn the printer power on and off in software. With this, we were able to turn the printer on for a few seconds when we needed to print a label, and turn it off immediately after printing. To further reduce power consumption, we made changes to the raspberry Pi configuration file to disable certain unnecessary features such as Bluetooth. In addition, we adjusted the display brightness to an intensity that was still easily visible but sufficiently low to produce power savings. To ensure that the battery is as fully charged as possible at the time a user removes it from the charging station the system is entirely run from the charger leaving the battery at full capacity.

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3.1.5 Connectivity to Existing Clinical Systems

CoWs do not operate independently of other systems. In the majority of settings, CoWs utilise WiFi connections to interface with existing electronic medical record systems. In our experience working in LMIC hospital settings, it has been difficult to ensure complete WiFi coverage in the clinical setting. Due to the structural design of most hospitals, there are often multiple dead-zones in WiFi coverage. We used two strategies to address this information exchange issue. Our first strategy was the encoding of information (e.g., laboratory test order) into 2-dimensional (2D) barcodes that can be printed on labels. With this model, scanning the barcode at the destination (e.g., hospital laboratory) allows the information to be imported into another information system. This essentially eliminated the necessity for connectivity when information is being sent from the CoW to a destination information system. This might have traditionally been done by packaging the information in an HL7 message. We have previously described this approach as a means of health information exchange in low-resource settings.[8]

Our second strategy to minimise the need for real-time connectivity is to push information to the CoW so that no remote database query is needed at the time the user wants to access it. Provided the CoW has periodic access to WiFi it will get synchronised. In this way, it doesn't matter if the CoW happens to be in a deadzone at the time.

3.1.6 Charging Dock

We wanted a solution that was easy to connect to, could be done by the users of the cart and did not depend on a third-party to connect them for charging. Rather than having a cable connected to the cart for charging, we chose to build wall mounted "docking stations". We utilised the magnetic charger concept used on certain models of Apple laptops. Using strong magnets, we were able both hold the cart in place as well as provide the electrical connection for charging. The use of magnetically controlled switches (Reed switches) allowed us to only provide power on the charging terminals when the cart is actually docked. Rather than building separate docking stations for each cart we decided to build a station that could accommodate three carts concurrently. A picture of this "SuperDock" can be seen in Figure 4.

Figure 4 - The SuperDock CoW Charging Station with three CoWs Docked

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3.2 Cost

The cost of materials to manufacture one cart is roughly $160.
The combined cost of all electronics hardware and the PVC enclosure for the computing platform is roughly $650 including the thermal printer and embedded 2D barcode scanner.
The Super-Dock station costs roughly $400 including the charging electronics capable of accommodating up to three CoWs concurrently.

3.3 Initial Findings

Below we describe some of the challenges we faced and discuss how we addressed them.

- One of the first problems we faced was a rapid reduction in battery life. We had initially designed the CoWs using a sealed lead acid battery of the type commonly used in uninterruptible power supplies for computers. When the battery was initially purchased it was able to power the CoW for roughly 8 hours. However, as they were deeply discharged every day, the battery life quickly reduced to the point where we could only achieve 20 minutes of runtime after about 4 months. To address this, we initially had two sets of batteries and swapped that at mid-day. This was followed by an iteration with Lithium-Ion cells building batteries by combining eight individual cells to make a battery. To improve performance, we added a battery management system (BMS). The final iteration used Lithium Iron Phosphate (LiFePO4) batteries with an integrated BMS. With these new batteries we are able to run a CoW for roughly 16 hours and there has been no reduction in runtime in the 18 months since we installed them.
- We observed that under poor lighting conditions the barcode scanner failed to be triggered by motion. To address this issue, we installed LEDs around the scanning area, and turned them on in software when we needed to scan.
- The first iteration of the docking station had charging connections on the side. This design made it difficult to use the cart while docked. In the redesign we moved the charging to the back.
- Version one of the carts did not have a clear indicator that it was charging once docked. This was later resolved by adding a visual indication both on the screen and with a separated LED (Red for charging green for charged).
- The cart was heavier than initially anticipated. To address this, we upgraded the diameter of the wheels to improve mobility.
- We noticed that from time-to-time carts that had been placed on charge at the docking station had become disconnected. We observed that if bumped they easily lost their charging connection. To address this we added a secondary support with an additional set of magnets.

4 Discussion

The “buy or build” question is always difficult. A solution that provides 80 percent of the benefits at 20 percent of the cost is always appealing. However, if closing the remaining gap has significant benefit then building is always the best option. As the current “state of the art” for CoWs is still based on Commercial off-the-shelf (COTS) integration of a cart and computing device, we felt this had sufficient limitations, particularly in terms of cost, we chose to opt for building a solution. While we have created a design that tightly integrates the cart and the computer, the design allows for the cart to be used without the computer where appropriate, and vice versa.

We noted that in the design of the VEAL CoW by Jen et al. they did not incorporate a printer. Since we have identified several use-cases for label printing, we believed that this could be a valuable addition to a CoW used in the clinical setting. One potential barrier to printing was accommodating the power requirements. The thermal label printer used in our design requires an external power supply similar to that used on a laptop. While the printer required 19 Volts DC to operate and the battery powering the CoW is 12-Volts, we were able to step up the voltage using a DC/DC converter. This innovation is generalizable to other CoW designs.

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5 Limitations and Future Work

The development of the custom CoW described in this paper does not include any formal field user effect and problem impact evaluation. This is a major limitation of this work as until the users interact with this CoW, we cannot tell how well it will work. Nonetheless, the main goal of this paper is to share the design of a low-cost CoW that can be easily assembled and maintained in low-resource settings. We believe that others can benefit from having access to this open-design and can further improve upon it. In the future, we plan to deploy the CoW in a clinical setting and conduct formal user effect and problem impact studies using our initial use-case around improving the management of laboratory test order entry and results review as has been described earlier.[4].

6 Conclusion

We have demonstrated that fit-for-purpose solutions that may enhance clinical care in an in-patient setting can be designed and developed in an LMIC setting. This approach can reduce barriers to entry for EMR systems in hospitals by making more affordable and locally supportable solutions available. Additionally the manufacturing and maintenance of the equipment bolsters the local economy, creating jobs and generally strengthening the private sector.

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