Human-Centered Design of a Cyber-Physical System for Advanced Response to Ebola (CARE)

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***Abstract*— We describe the process towards the design of a safe, reliable, and intuitive emergency treatment unit to facilitate a higher degree of safety and situational awareness for medical staff, leading to an increased level of patient care during an epidemic outbreak in an unprepared, underdeveloped, or disaster stricken area. We start with a human-centered design process to understand the design challenge of working with Ebola treatment units in Western Africa in the latest Ebola outbreak, and show preliminary work towards cyber-physical technologies applicable to potentially helping during the next outbreak.**

I. Introduction

This research is aimed at developing a medical cyber-physical system (CPS) and its operational procedures to respond to current and future Ebola (or other infectious disease) outbreaks. Our overarching goal is to enhance the safety of Ebola workers by minimizing their contact with the virus by systematically augmenting CPS technologies in treatment clinics. To achieve this goal we are working to design, develop, and validate a human-in-the-loop medical cyber-physical system for monitoring patients, insuring compliance with relevant safety protocols, and collecting data for advancing research on infectious disease control with the use of technologies. We are developing and integrating a system composed of a connected sensor network and a mobile robot platform for telemedicine by leveraging recent advances in the medical CPS research [1]–[3] and our existing research work on smart environments for independent living, and human-in-the-loop robotics [4], [5]. Rather than a design-from zero approach, we primarily focus on interoperability and integration of existing standardized hardware and software systems to realize a testbed for verification and validation of medical CPS. We collaborate with research partners at University of Massachusetts Medical School, to understand the specific challenges of working in infrastructure-degraded environments and critically analyze potential technological solutions.

Our long-term vision of a future Ebola treatment clinic (ETU) is composed of suspected, probable, and confirmed Ebola wards each of which is augmented with a sensor network and multiple teleoperated robots. This research focuses on the design and realization of a system in a single Ebola ward, shown in Figure 1. The research has the following interconnected aims:

1) Create new knowledge, methods, and tools to better understand the operational procedures in an infectious disease treatment clinic
2) Design, implement and validate a treatment ward augmented with a medical CPS for patient monitoring
3) Design intuitive control interfaces and data visualization tools for practical human-robot interaction
4) Design, implement and validate traded, coordinated and collaborative shared control techniques [6] for safe and effective robot navigation
5) Evaluate acceptability and effectiveness of the technology among health care workers and patients

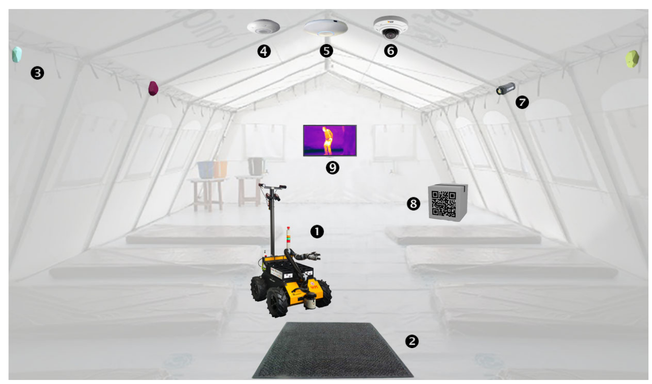

Fig. 1. Potential layout of a future medical CPS integrated into a portable Ebola treatment facility includes: (1) a teleoperated robot for materials handling and decontamination, (2) pressure sensitive mat for occupancy awareness, (3) Bluetooth low-energy (BLE) localization beacons, (4) microwave and infrared motion sensor, (5) wireless communication network, (6) panning camera, (7) infrared camera for remote temperature monitoring of patients, (8) barcoded and tracked equipment and consumables, and (9) telemedicine interface for no-contact interactions with both medical staff and family members.

We closely collaborate with medical experts to generate use cases and develop a set of verifiable design requirements. The system in its full form will be composed of vision and IR-based motion sensors, proximity sensors for tracking patients, a telemedicine robot equipped with a medical sensor module (blood pressure sensor, pulse oximeter, noncontact temperature sensor, etc.) which can be utilized by the local and remote medical staff for consulting with the patients. Moreover, the mobile robot can provide logistics support inside an Ebola treatment center by tracking and delivering essential supplies to patients such as food, water and medicine. The occupancy and motion tracking sensors can be utilized to provide surveillance and a means to detect any

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breach of protocol for patients in isolation. We employ user-centric, modular and reconfigurable design principles that enable scalability of the system.

II. Challenges of ETUs in West Africa

The 2014-15 Ebola outbreak in West Africa was centered on the countries of Guinea, Liberia, and Sierra Leone, and was the first outbreak of such scale and magnitude. The total reported cases during this outbreak is significantly more than the reported cases of all other previous Ebola outbreaks. A total of 25,550 reported cases and 10,587 deaths have been recorded until April 5, 2015. Of those cases, 12,138 were in Sierra Leone, 9,862 in Liberia, and 3,515 in Guinea [7]. Most of the information presented in this paper is directly relevant to Liberia because UMass Medical School Medical School, whose doctors we regularly interact with, sent significant medical help to Liberia. It is also relevant to Sierra Leone and Guinea due to the similarity in how the disease progressed there in comparison to Liberia.

West Africa is a region that had serious health challenges before the Ebola outbreak that made the situation more difficult to handle effectively. In [8], a thorough review of the demographics and health of the nation is presented. Of relevance to this work, the survey notes that electricity is almost nonexistent in rural areas of Liberia; 55 percent of households nationwide have no toilet facility available (private or shared); and only 56 percent of rural households have access to an improved water source. Also of importance during the 2-week survey period, the authors noted that 31 percent of children under the age of 5 exhibited a fever. Unfortunately this highlights one of the biggest challenges ETUs face. Fever is a symptom of both malaria and Ebola, and segregating the patients with the two diseases is difficult in the degraded conditions but essential to stopping the spread of Ebola.

In order to better understand the operations and challenges of ETUs, we conducted a thorough interview with Dr. Steven Hatch of UMass Medical School. We summarize the points and concepts that he highlighted for us as the most important for any solution that aims to improve the operation or conditions in the ETU. Dr. Hatch spent two tours, approximately a month long each, at an ETU in rural Bong County, Liberia and has first-hand experience responding to the Ebola outbreak at its height. He described to us the general environment of the ETU, what a typical workflow in a day looks like, and ended with a couple specific challenge areas that any design team should be aware of.

His main message though centered on the fact that we know very little about how to effectively respond to an Ebola outbreak. The previous outbreaks were small and contained, little information was collected for dissemination to other researchers, and thus led to ineffective response and significant knowledge gaps at the beginning of the outbreak. He emphasized that only through direct experience did he learn that while the disease is spread through a variety of the bodily fluids, it is not bleeding that is usually a problem, but in fact the large quantity of diarrhea and vomiting that necessitates careful clean up. He notes that a likely reason for the significantly higher survival rates seen in Western aid workers treated in the West and people infected by Marburg virus (similar to Ebola) in Germany in 1967 is due to the better facilities for handling that waste, hinging mainly on the availability of flushing toilets. In addition, Dr. Hatch notes that in his experience the patients that survived best were those who managed to hold fluids down and aggressively hydrate whether through oral intake of fluids or intravenously (IV). Ebola does not spread particularly easily, requiring direct exchange of bodily fluids. Ebola has a reproduction number of between 1.5-2.5 meaning one patient will on average infect about 2 other people if no measures are taken [9]. Compared to measles or influenza, Ebola is significantly more difficult to transmit.

The ETU in Bong County was relatively small, especially compared to some of the much larger ETUs closer to the urban areas. ETUs are all different sizes, manufactured with different materials, and follow different procedures depending on the organization that runs the ETU. There is little standardization or commonality between the approaches even on questions, such as balancing the risk between providing patients with IV fluids and reducing risk of accidental needles injuries to the aid workers. The Bong ETU was built of a steel frame covered in wood and blue tarps, leading to a scene that Dr. Hatch described as having a very “artificial” look. A total of about 30 patients at a time were in the ETU spread between the “suspected” ward where people are held until their test results come back. They sometimes used “probable” ward if tests aren’t conclusive, and finally the “confirmed” ward where the test results are confirmed. In the “suspected” ward, no reuse of equipment or supplies is allowed to minimize the risk of infecting someone who doesn’t have Ebola in the ward. Dr. Hatch noted that there is no power grid; all the power for the ETU comes from generators that run 24/7 with fuel mostly provided by the United States Navy.

A typical work day at the ETU consists of periods of work inside the wards in full personal protective equipment (PPE), paperwork, logistics activities, and personal care. Due to the heat and humidity, staying hydrated and not overexerting while wearing PPE are critical to the safety of the aid workers. In reality, few medical decisions are made in the ETU. Medical care consists mainly of providing fluids orally or through IV to dehydrated patients, examining and monitoring patients, and providing antibiotics, anti-anxiety, anti-nausea, and malaria medications. The tasks that need to be done while wearing PPE involve hanging IV bags, taking blood for tests, cleaning and disposing of waste, and bringing the deceased to the morgue. During the daylight hours, staff presence inside the ETU is frequent but not complete. Staff must be in PPE and present any time a patient is connected to an IV bag so they can be monitored for any complications that potentially arise.

Dr. Hatch specifically highlighted two areas that are of particular concern and need to be kept in mind. The first is that records keeping is challenging in the ETUs due to the fact that all materials inside the wards, must stay inside. This means that charts cannot be taken out, and must be manually transcribed by voice across the 2 meter “no man’s land” separating the wards from the rest of the ETU or memorized. The more faithful information that can be extracted and tracked can significantly improve the immediate response to an outbreak by quickly disseminating information to national health ministries and non-governmental organizations (NGOs). In addition, the information can be used by researchers after the outbreak has subsided to study new operation procedures, methods, and approaches to prevent or stop outbreaks earlier. The fact is that few people in the world had first-hand experience dealing with Ebola before the outbreak in West Africa. Such information can be used to generate new training materials so more people are prepared to respond to the next outbreak.

Finally, significant cultural challenges remain. It is not likely that direct robotic interaction with patients would be acceptable to either the aid workers or the patients. Simple but effective solutions are key, that do not scare patients, but at the same time provide valuable data and useful services. Many patients believed that chlorine spray, used to disinfect surfaces, was in fact used to kill people. More rural areas believe Ebola is a disease introduced by Westerners. These are challenges that any deployed systems will have to address in a manner to ensure more effective operation of the ETU.

III. Human-Centered Design

Given the immense challenges highlighted above, we quickly realized that we needed to modify our traditional approach to problems to comprehend the design space. The challenges around the Ebola outbreak are at the intersection of technology, sociology, and individual people which means that only a holistic design process that considers the multi-faceted problem as a whole will be successful. To tackle the design challenge, we employ the human-centered design toolkit from IDEO [10] which guided the team through a series of design exercises to capture and rank information based on its relevance. The toolkit led us through a process that aimed to satisfy the categories of constraints posed by desirability, feasibility, and viability. A successfully deployed system will satisfy all three of these categories simultaneously. Figure 2 shows the output of design challenge identification task as an example.

The first step of the design process involved identifying a specific description of the design challenge. After several hours of discussion centered on information gathered through background research, interviews, and videos/reports from Liberia, we identified the following challenges ranked in order of importance: tent lifecycle from the perspective of patients/medical professionals/administrators, safety, ease of use/intuitive operation, reliability/resiliency, and increased situational awareness while outside the wards. At the end of the exercise, we succinctly summarized the design challenge: The mission is to deliver a safe, reliable, and intuitive emergency treatment unit to facilitate a higher degree of safety and situational awareness for medical staff, leading to an increased level of patient care during an epidemic outbreak in an unprepared, underdeveloped, or disaster stricken area.

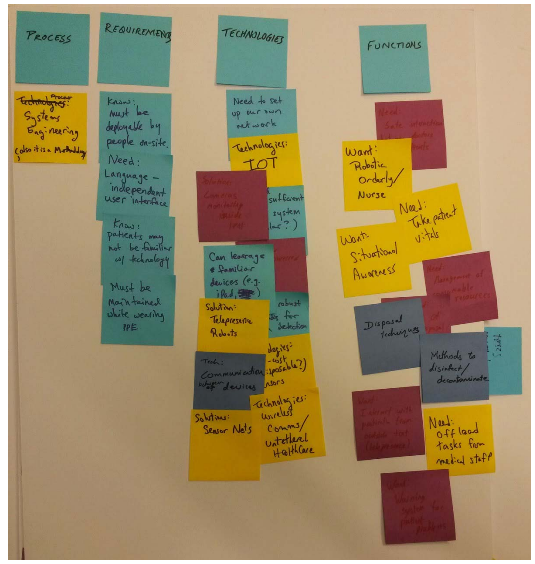

Fig. 2. An example board capturing the information generated during the design challenge identification part of the human-centered design process.

The design challenge identification is particularly useful for getting the entire team on the same page. The process of working through a series of statements to get more than 10 people to agree on, naturally forces members to consider other aspects of the problem and have a more holistic understanding of the challenge at hand. After the challenge identification task, the team continued to use the toolkit to capture existing knowledge about the approaches currently used in Liberia, and also generate a list of relevant stakeholders/personas. We are in the process of generating design personas of technically proficient visiting medical professionals, local medical professionals, Ebola-suspected patients, confirmed patients, community/family members, and NGO/ETU administrators. We feel these personas provide significant converge of the design space, and are used to evaluate potential solutions from the perspectives of the relevant stakeholders themselves.

IV. Technology Use Cases

In order to rapidly prototype and test various solutions to the design challenge, we built a small ETU testbed consisting of a tent, cots, buckets, networking equipment, several sensors including motion detectors, temperature sensors, Kinect/camera, and also a teleoperated tracked robot. Figure 3 shows an open-source implementation of a person detection algorithm, OpenPTrack[1]. The ETU testbed allows us to quickly prototype small modules such as the person tracking and evaluate their effectiveness through various methods such as direct interviews with relevant users, role playing, or critical analysis with respect to the generated personas.

[1]http://openptrack.org

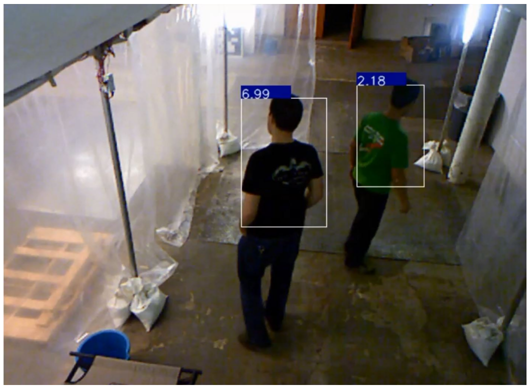

Fig. 3. An open-source implementation of a person detection algorithm showing how multiple people can be tracked inside an ETU with a commercially available depth sensor such as the Microsoft Kinect.

Person tracking within an ETU would be useful in several potential scenarios. It can be used to remind doctors and nurses to visit specific patients they may have not checked on recently. It can also be used to track the patients so their activity levels can be monitored. It is common for patients in the ETU to empty their own bucket in the latrine, and the system can be easily programmed to alert a doctor or nurse if someone hasn't gotten up in awhile, indicating their condition may be degrading significantly. Finally, person tracking would be useful to administrators since it can give real-time information about occupancy as patients enter and leave the ETU, and also provide localization information about where the doctors and nurses can be found in the case of an emergency.

One of the other use cases we have quickly prototyped is a repurposed mobile robot system to enable remote decontamination of areas or materials shown in Figure 4. The Ebola virus can live on moist surfaces and because of the high humidity in West Africa, surfaces can be a serious source of spreading the infection inside the ETU. A solution of bleach is sprayed on surfaces to disinfect them, and this is a task that can be accomplished with robots, freeing the people in PPE to focus on caring for patients.

Fig. 4. A teleoperated robot demonstrating a decontamination operation. Many tasks that do not involve contact with patients such as logistics, materials handling, and decontamination can be accomplished using teleoperated or semiautonomous robots to enhance the safety of workers.

V. Conclusion

We are working on integrating the entire sensor and networking system on a series of nets that can be retrofitted inside existing ETUs. Cellular networks in Liberia can provide 3G level of bandwidth in data connections, so network connectivity to the Internet will require careful management but is not a significant roadblock. We will continue prototyping and testing other technological use cases within our testbed as we generate new ideas and use the information from the testbed to evaluate their effectiveness with our medical partners and consultants.

We have presented our preliminary work on developing a next-generation ETU that will lead to increased safety for medical professionals and patients while hopefully enabling doctors to stop the outbreak quicker and cure more people the next time a problem like the Ebola outbreak in West Africa appears. With careful attention to generating culturally acceptable and adaptable technological solutions, the international and national agencies will be better prepared and equipped to handle the next outbreak.

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