Iris: A Low-Cost Telemedicine Robot to Support Healthcare Safety and Equity During a Pandemic

Sachiko Matsumoto[1(✉)], Sanika Moharana[1], Nimisha Devanagondi[1], Leslie C. Oyama[2], and Laurel D. Riek[1,2]

[1] Computer Science and Engineering, UC San Diego, San Diego, USA
smatsumo@eng.ucsd.edu

[2] Emergency Medicine, UC San Diego, San Diego, USA

Abstract. The COVID-19 pandemic exacerbated problems of already overwhelmed healthcare ecosystems. The pandemic worsened long-standing health disparities and increased stress and risk of infection for frontline healthcare workers (HCWs). Telemedical robots offer great potential to both improve HCW safety and patient access to high-quality care, however, most of these systems are prohibitively expensive for under-resourced healthcare organizations, and difficult to use. In this paper, we introduce *Iris*, a low-cost, open hardware/open software telemedical robot platform. We co-designed *Iris* with front-line HCWs to be usable, accessible, robust, and well-situated within the emergency medicine (EM) ecosystem. We tested *Iris* with 15 EM physicians, who reported high usability, and provided detailed feedback critical to situating the robot within a range of EM care delivery contexts, including under-resourced ones. Based on these findings, we present a series of concrete design suggestions for those interested in building and deploying similar systems. We hope this will inspire future work both in the current pandemic and beyond.

Keywords: Healthcare Robotics · Telemedicine · Healthcare management · Human robot interaction · Emergency medicine

1 Introduction

The COVID-19 pandemic is exacerbating many societal inequities, including burdening already-overwhelmed healthcare ecosystems, putting millions of healthcare workers (HCWs) at high risk of occupational harm due to severe stress and the looming risk of infection [1]. The pandemic also worsened long-standing

Work supported by the National Science Foundation under Grant No. IIS-1527759 and the Institute for Engineering and Medicine (IEM).

H. Lewy and R. Barkan (Eds.): PH 2021, LNICST 431, pp. 113–133, 2022.
https://doi.org/10.1007/978-3-030-99194-4_9

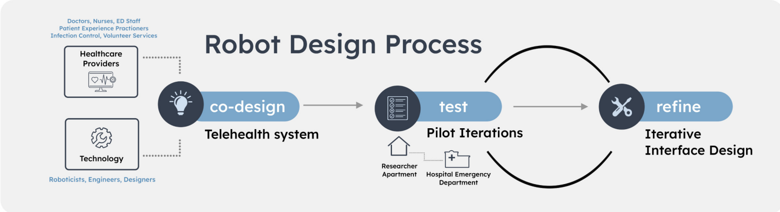

Fig. 1. To build *Iris*, we engaged in an iterative co-design process with stakeholders.

health disparities, with many groups now at an even higher risk of adverse mental, physical, and socioeconomic health outcomes due to a lack of access to high-quality care [2].

Telemedical robots offer great potential to improve HCWs' safety and patient access to high-quality care, but most commercial systems are prohibitively expensive for under-resourced healthcare organizations, and difficult for stakeholders to use.

Also, most commercial telemedical robots are not well-suited (nor designed) for COVID-19 treatment contexts. Most hospitals are busy, noisy, and crowded, some so full of COVID-19 cases that patients are housed in hallways, ambulance bays, or tents, creating difficulties for teleoperators (people driving robots), interactants (people speaking to the teleoperator), and bystanders (people physically near the robot but not directly using it), including: situational awareness (SA), visibility, audiblity, and presence.

Since the pandemic began, our team has been working to address these gaps by partnering closely with key stakeholders to create *Iris*, a low-cost, open hardware/open software telemedical robot platform (Fig. 1). We co-designed *Iris* with front-line HCWs to be usable, accessible, robust, and well-situated within the emergency medicine (EM) ecosystem (the "front door" for COVID-19 treatment). We tested *Iris* with 15 EM physicians who used it to conduct patient interviews and exams. They reported high usability, provided detailed feedback critical to situating the robot within a range of EM care delivery contexts, and provided insights on supporting longitudinal robot deployments.

Based on these findings, we present concrete design suggestions for those in the robotics community interested in building and deploying similar systems, including the importance of supporting: (1) system durability, given the unique needs of the emergency department (ED) environment, (2) adaptability, so users can easily adjust the system to fit their unique clinical settings, and (3) familiarity, trust, and presence, so the operators and interactants feel comfortable with remote care delivery.

Our code, designs, and research instruments are publicly available at https://github.com/UCSD-RHC-Lab/IRIS. We hope this work will inspire roboticists to utilize *Iris's* open source/open hardware platform and deploy similar systems to support their local communities.

2 Background

Even before the COVID-19 pandemic, most healthcare systems worldwide were in a precarious state. In the US, HCWs were overburdened, overworked, stressed, and chronically under-funded, leading to high rates of adverse mental health outcomes, including suicide [1,3]. Many hospitals experienced overcrowding, particularly in the ED representing a public health crisis [4]. This is all exacerbated by the pandemic; HCWs now have the added worry about contracting or spreading the disease, leading to stress, anxiety, depression, and insomnia [1]. EM HCWs have been particularly negatively affected, because most COVID-19 patients first present in the ED [5].

The pandemic also brought to light substantial health disparities in how patients access care and their treatment. In the US, African Americans, Latinos, and Native Americans experience a disproportionate risk of adverse health outcomes compared to other groups [2]. Many of these individuals are likely to seek care at under-resourced facilities, which were already operating in poor conditions or closing pre-pandemic.

Pre-pandemic, some healthcare systems explored telemedicine to help address these issues, often in the form of video teleconference (e.g., Zoom) [6,7], and many increased their use with the pandemic. Unfortunately, this requires patients to have access to technology, knowledge of how to use it, and broadband internet access, which a large percentage do not [8]. For HCWs, the rapid deployment of telemedical technology also increased their cognitive burden and workload, both due to needing to themselves receive training and provide it to patients and their families [9].

In both the research community and commercial sector, many have explored the use of mobile telemedical robots over the years, even more so recently, including performing telerounds in hospitals, remote teaching, and monitoring patients at home [10]. They have seen multiple new clinical uses since the start of the pandemic, including patient admissions, social support, etc. [11–15], and use in prior pandemics [16].

Telepresence robots provide several advantages over static telemedicine devices. They offer operators more independence, since the operator can move on their own, which can also increase their field of view and social presence [10,17]. They are also safer for HCWs, since operators do not need to expose themselves to infectious diseases by going into the patient's room to deliver a telemedicine device.

However, many telepresence robots currently on the market have significant barriers to use. Few were designed for hospitals or were co-designed with stakeholders, which can make them more difficult to use in hospital settings. Additionally, many are prohibitively expensive, and ones designed for hospitals tend to be even more costly (e.g., the RP-VITA costs between $4,000 and $6,000 a month). Furthermore, such robots often are not easily customizable to different settings, which can be problematic given that HCWs need systems to fit within their unique care delivery setting [18].

EDs are a particularly difficult environment to situate robots because they are fast-paced and chaotic. For instance, codes, in which a patient needs resuscitation, occur frequently and require quick response and complex team dynamics [19]. Additionally, ED patients often have high levels of acuity, so robots must be particularly well-designed to avoid causing mistakes that could lead to injury or death [20,21].

3 Designing Telepresence Robots for Overwhelmed HCWs

To design a successful system that addresses issues commonly faced by frontline HCWs, we must consider what is affordable, familiar, and usable to them. We engaged in an iterative design process, where we co-designed our system with HCWs, ran remote studies with them, and used feedback to continue to refine our system.

3.1 Design Requirements

Researchers have co-designed robotics technology with ED clinicians for the past few years, including characterizing their workflow and physical space [3,19–21]. We drew on this work to understand how the ED ecosystem changed in the pandemic, which helped us understand the challenges they face, driving our design decisions.

Many members of the hospital's ecosystem represent key stakeholder groups in the robot design space. These include: (1) HCWs, who seek alternative safe methods for conducting patient consults instead of donning and doffing personal protective equipment (2) Patient experience practitioners, who seek to ensure that patients still experience a high quality of care (3) Volunteers, who seek to provide support services to patients and staff, including isolated patients experiencing loneliness, (4) Infection control practitioners, who seek to ensure all staff and patients are safe from the spread of COVID-19 and other diseases. Across all these groups, perhaps the most important design consideration was to ensure any technology we introduced did not add to an overly-burdened workforce [3]; it was critical the system was easy to learn and use.

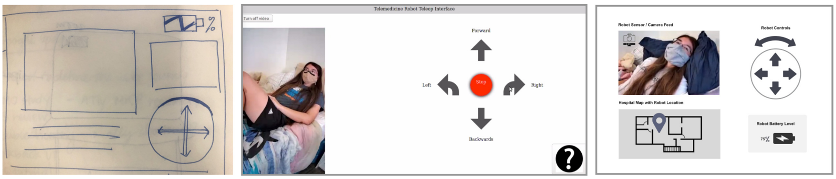

Fig. 2. An iterative evolution of the *Iris* control interface.

3.2 Software and Hardware Requirements

Software Requirements: As the pandemic placed additional pressure on existing stressors of ED staff, our software had to be rooted in addressing these realities. Designing an effortless system meant prioritizing learnability, ease of use, ease of adoption, and accessibility. These design values determined how the user flow, user control, and the screen's UI materialized into the system's visual display and controls for the robot.

We did not want healthcare providers to spend time learning new programs or intricacies of robot control. We took into account technology literacy (can be low among HCWs [3,9]), so it was important our robot had a very short onboarding, setup, and tutorial process for users of all backgrounds and levels of familiarity with technology.

To simplify the number of elements and interactions, while maximizing control screen real estate, we implemented only three components: navigation controls, the robot's video feed, and troubleshooting assistance (see Fig. 2). Arrows on the screen indicate movement in four directions, with a button for an immediate stop. A wide-angle webcam attached at the top of the robot captured the video feed. We added a help button that led users to a short FAQ to aid in troubleshooting. We later removed this troubleshooting button, as several HCWs mentioned they did not find it helpful.

With this minimalistic UI approach, the robot's video feed had the highest importance as its content determined users' driving decisions. The directional control buttons changed to a bright color on selection for clear feedback. Keeping the video and controls side-by-side aimed to keep the users' focus in the same area. We did not want them to have to turn their head or switch their frame of reference when operating the robot.

Hardware Requirements: In designing *Iris*, we focused on five considerations: affordability, ease of sanitation, hospital network integration, physical design considerations, and ease of replicability by other roboticists.

Affordability: We wanted the system to be inexpensive to increase its accessibility for under-resourced health systems, including rural health systems and austere environments. Thus, with *Iris*, we sought to keep costs as low as possible.

Sanitation: We required *Iris* to be composed of materials that were easy to sanitize to reduce the risk of infection and decrease the burden on HCWs. To fulfill this requirement, we consulted a hospital's infection control team.

Hospital Network Integration: We did not want *Iris* to interfere with a hospital's existing network infrastructure, so we designed it to only use a local network. This provides additional security by reducing risks of Internet-based attacks.

Physical Design Considerations: We ensured the tablet and camera mounts were easily adjustable, so HCWs could change their positions to better suit their needs. Furthermore, we made sure the mounts were stable when the robot moved.

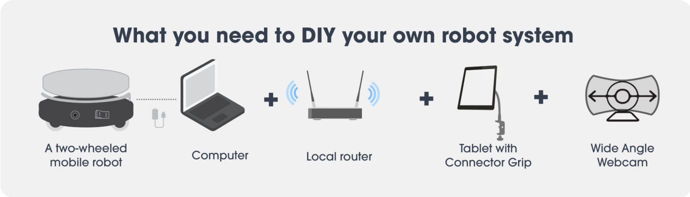

Fig. 3. *Iris's* hardware design is straightforward: a two-wheeled mobile robot with a computer, a local router, a tablet, and a wide-angle camera mounted four feet high on the robot.

Ease of Replication: We selected readily-available hardware components which are easily interchangeable. For example, developers could easily change the type of camera, tablet, or robot base. This allows developers to customize the system to their needs and potentially reduce costs by using components they already have.

4 Implementation

We developed a web-based control interface using Python's Flask framework on the backend, and a webpage with a CSS-styled HTML template on the front-end.

We designed the start up and shut down procedures to be easy for users and require no knowledge of the Robot Operating System (ROS) or Linux. To startup, users turn on the robot and laptop then click an icon that automatically starts the robot's ROS programs. They then turn on the tablet and open a browser, which opens the control interface webpage. The shutdown procedure is simply to turn off the laptop/robot.

We wanted our system to be robust to failures. For instance, if the camera was disconnected or not working the robot would still respond to commands. Also, if the webpage crashed or froze, or if the robot became unresponsive, we created recovery procedures to enable HCWs to simply turn the robot's laptop off and on to restart the system. This is a fairly straightforward procedure that enables people without deep technical knowledge to recover from most problems with the system.

We wanted our system to be low-cost, so we chose low-cost hardware from our lab. The components of our system included a Turtlebot 2 with a Kobuki base, three tablets (one for robot control, two for the hospital's telemedical platform), a computer, a portable router, a wide angle camera, a tablet mount, and a camera mount, as shown in Fig. 3. In total, all components can be acquired for less than $1000.

Additionally, the components of our system are easily interchangeable. For example, a Turtlebot 2 could be swapped out for another ROS-based mobile robot. Similarly, any machine capable of running Ubuntu 18.04 with ROS Melodic may be used; this includes industrial/embedded systems, as well as small form-factor consumer systems.

Fig. 4. Left: The *Iris* platform. Center/Right: A HCW remotely interviews a patient using *Iris*.

We wanted the hardware to be robust to the demands of hospital operation. We securely mounted the tablet and camera to the robot, and put the tablet in a case. The laptop is in a box attached to the robot. This provides protection if the robot crashes or is knocked over. Also, all parts fit within the robot's footprint-nothing sticks out.

Finally, we wanted to ensure all interactants and bystanders could easily determine the purpose of the robot, so made the robot a "costume" (see Fig. 4). We printed a banner that looked similar to scrubs commonly worn by ED HCWs with the words "Telemedicine Robot" prominently displayed and wrapped it around the robot.

5 Evaluation

We ran two studies to evaluate *Iris*. The first was conducted at a researcher's apartment, in which a HCW controlled the robot to remotely conduct a mock patient exam (referred to as *APS*). This was while we waited for approval from infection control before deploying the robot in a hospital. The second was at a suburban ED (referred to as *EDS*).

Study Design *APS:* We used inspiration from pre-pandemic visits to our local ED and patient-room photos sent from stakeholders, to re-envision the researcher's 1-bedroom apartment. Similar to an actual ED, the *APS* set up consisted of a patient room with a bed and an area in the kitchen that we designated as the nurses' station. *EDS:* We conducted the study in patient rooms at the ED.

Procedure: Participants were recruited opportunistically via word of mouth and email by our EM collaborators. All participants gave written informed consent.

APS: After the study's introduction, participants could ask questions. They then practiced driving the robot. The robot started in the kitchen. From there, participants drove the robot to the head of the bed in the experimenter's bedroom. The experimenter laid on the bed, wearing a mask, and used a simulation case script, provided by an EM physician. The participant conducted a patient interview taking this history about the patient's physical state then conducted an examination by having a patient follow instructions. After the patient exam, the participant drove back to the kitchen, and engaged in a short interview and survey.

EDS: The design was similar to *APS*. Participants practiced driving the robot, then drove it from the physicians' work area to a patient room and conducted a patient history and exam with a researcher using the same script. For five participants, the tablet had a low quality microphone, resulting in garbled audio, so they stood near the door where they could hear but not see the patient to do the exam; we addressed this for other participants by using a different tablet. Participants drove the robot back to the work area, and engaged in a short interview and survey.

Measures: We conducted semi-structured interviews to gather feedback about how the robot might work for HCWs in the ED, especially during a pandemic. The interview was split into five categories: patient interview experience, robot experience, system improvements, situating the robot in the ED, and comparisons to existing systems.

We followed our interview with a survey. We used the System Usability Scale (SUS) questionnaire, a validated and effective questionnaire for usability [22]. We also asked demographic questions concerning their medical specialty, experience, age, type of hospital they worked in and comfort level working with robots and technology.

Participants: A total of 15 HCWs participated across both pilots (*APS:* 6, *EDS:* 9; 28–59 years old; three did not provide their age). Participants had one to more than thirty years of experience (mean = 7.2 years); one did not provide this information. Our participants had experience working in a variety of hospitals. In the health system they work for, there are three EDs: one located in a suburban area (referred to as Suburban ED), one in an urban area (City ED), and one in a rural area (Rural ED). All three hospitals have overflow tents constructed on outdoor parking lots to accommodate COVID-19 patients. To preserve participant identities, we use the pseudonyms shown in Table 1.

6 Results

6.1 Situating Robots in the ED

EDs are dynamic environments with unique factors that need to be considered when introducing robots [16,20,21]. Here, we discuss the factors our participants brought up.

Providing Awareness to the Operator, Interactant, and Bystanders in the ED: The physical environment in the ED can make navigation difficult for operators. 8/15 participants (*APS:* 3/6, *EDS:* 5/9) discussed how the hallways in the ED are narrow and can be cluttered with carts and equipment. Dominique expressed concern about how "There is often stuff on the ground, so I worry that [...] if it got under the wheel, would that stop [the robot]?" Trevor was concerned about navigating around people standing in the hallways who might not hear the robot coming up behind them. 10/15 participants (*APS:* 3/6, *EDS:* 7/9) indicated their need for situational and spatial awareness in order to navigate around these obstacles.

The ED is also a very dynamic environment. 7/15 participants (*APS:* 3/6, *EDS:* 4/9) described gurneys, which often house patients in hallways or quickly move down the hallways transporting patients. Daniel described how he often checks over his shoulder to see if a gurney is behind him in case he needs to get out of the way. Luna said patients in hallways can make it "much harder to navigate." Navigating around such obstacles with little warning could be challenging for a robot. Participants also described how there are a lot of people rushing around. To drive the robot, they would need enough SA and visibility to avoid collisions with quickly moving obstacles and people.

Some participants also discussed the benefits of alerting others of the robot's presence. Dominique suggested having a light, flag, or audio signal on the robot so people would notice *Iris* more when it moved. She thought this might help avoid collisions, particularly around corners, where people might not know the robot is coming.

Patients Act in Unexpected Ways Towards Robots: According to Yuri, robots in the ED would have to deal with unexpected patient behavior, "[be]cause [there are] always patients moving, and [you need to be prepared for] patient possibly attacking robot." Trevor described some additional unexpected ways patients may interact with the robot. "There are patients who will urinate on the robot, [and] patients who are very intoxicated [are] just wandering through hallways." For the robot to operate in the ED, it must be robust to these types of interactions with patients.

Infection Control: Participants discussed the importance easily cleaning the robot, especially during a pandemic. Mandy suggested using a cover that could be disposed of between visits to infectious patients. Trevor discussed how the robot would need to endure frequent cleanings. He remembered an ultrasound machine that "broke after three days" because cleaning solution got inside of it. Thus, the robot would need to be easy to clean, durable, and have a clear protocol for how and when to clean it.

Table 1. Participant demographic information and pseudonyms. The abbreviations for Hospital Type are: T: Teaching, NT: Non-Teaching, U: Urban, R: Rural. The abbreviations for Location are: A: Apartment, ED: Emergency Department

Pseudonym	Experience	Role	Hospital type	Study location
Daniel	1–5 years	EM resident	T, NT, U, R	A
Yuri	1–5 years	EM resident	T, R	A
Trevor	1–5 years	EM resident	T, NT, U, R	A
Xavier	1–5 years	EM resident	T, NT, U, R	A
Dominique	11–15 years	EM attending	T, U	A
Nitya	1–5 years	EM attending	T, NT, U, R	A
Aaron	6–10 years	EM attending	T, NP, U	ED
Tobi	1–5 years	EM attending	T, NT, U, R	ED
Mandy	6–10 years	EM attending	T, NT, U	ED
Dennis	16+ years	Physician assistant	T	ED
Luna	16+ years	EM attending	T	ED
Jay	1–5 years	EM resident	T, U, R	ED
Nia	1–5 years	Medical student	T, NP	ED
Rita	1–5 years	EM attending	T, U, R	ED
Neil	–	EM attending	T, NT, U, R	ED

Different ED Care Settings Exist: Participants also told us that there are variations in ED care settings that may affect the robot's effectiveness. 8/15 participants (*APS:* 2/6, *EDS:* 6/9) noted that there are significant differences between the EDs in their health system, and at each location the robot could face different challenges.

One aspect in which EDs differ from one another is their physical environment. Rural ED has narrow hallways, while Suburban ED is comparatively spacious. Participants said other hospitals, such as City ED, are more chaotic and have more obstacles than Suburban ED. Rita also observed that City ED's WiFi is not as reliable. Nitya said the temperatures in Rural ED's overflow tents can reach 115 °F, so they often run air conditioning units, making the environment very loud. She "had to literally scream at people for them to hear me." This suggests the noisy environment could make it difficult for the robot to operate in the tents, since it could be hard for patients and HCWs to hear each other over a video call. In contrast, 5/6 *APS* participants thought the overflow tents in City ED would be a setting where the robot might be useful.

Patients at different EDs may also have different expectations about their care. Nitya speculated that a patient's age and familiarity with their doctor may play a role in these expectations, and how a robot factors into that care. "Specifically out in [Rural ED], [...] people mostly get all of their healthcare from four internal medicine doctors [...They are] used to knowing [their] doctors, having face to face contact. And if [they] come into ER and [are] not just seeing an unfamiliar face [but] also seeing a robot, [it] might be a shock...[younger people] would probably think it's not so far fetched."

Different EDs also have different patient demographics, which may affect how a robot is used. For instance, Nitya described how patients at Suburban ED are generally older, and many have difficulty hearing. She was concerned they might have difficulty hearing the HCW over the video call. Alternatively, Nitya noted that at Rural ED over 50% of patients speak Spanish, and they might benefit from a robot that could "loop in interpreter services." Meanwhile, at City ED, there are sometimes "patients [who] are intoxicated," and some might intentionally or unintentionally bump into the robot.

6.2 Integrating Robots Within HCW's Existing Workflow

High cognitive load is well documented among HCWs [3]. Our participants' experiences reinforced this; many recounted how they were often very busy and everyone in the ED always rushes around. To avoid contributing to HCWs' high cognitive load, any robotic system must be easily integrable into the existing HCW workflow.

Seamlessly Integrating into Existing ED Practices: Physical space management is a concern when introducing robots to EDs. 5/9 *EDS* participants thought *Iris's* small footprint was suitable for an ED environment so it could be easily stored and avoid obstacles (*APS* were not able to see *Iris's* size). However, Aaron was concerned it might not have enough presence in patient rooms and would get lost if it was too small. Trevor discussed how "desk space is real estate" in the ED. In the "doc box," where physicians work when not seeing patients, computers are in high demand. Thus, Trevor suggested the robot be accessible via a tablet, so as to not interfere with people using computers.

Two participants suggested it might be difficult to locate the robot in the ED. Trevor compared it to finding the portable ultrasound machine, saying he could walk around the ED three times without finding it. He noted that "people will forget the robot in the patient's room," making it hard to find. Dennis expressed concern that the control tablet we used in *EDS* would get separated from the robot and lost.

Participants were also concerned about the battery life of the robot. 4/15 participants (*APS:* 3/6, *EDS:* 1/9) mentioned this, saying, "things are always running out of battery" (Xavier). Two participants drew parallels to the portable ultrasound machine, noting that if someone does not charge it, whoever wants to use it next needs to plug it in and "come back half an hour later," which Trevor described as a "huge waste of time." Because of these issues, two participants suggested automatic docking might be a nice feature, and Aaron suggested a "very rigorous plan" around the robot might be necessary.

Pandemic-Specific Workflow: All *APS* participants felt the overflow tents were inefficient and did not adequately support their workflow, suggesting ways robots might help (no *EDS* participants talked about the tents, as they were not using them). One reason Nitya thought "something like [*Iris*] would be useful [was because HCWs need to] run back and forth [and] keep track of both" tents and inside the ED. Trevor described "almost miss[ing] a stroke patient in the department because [he was] in the tent." He also thought it "defeats the purpose [of the tents]" if he is in person with Covid patients.

Nearly all *APS* participants (5/6) felt that the tent was a setting in which a telemedicine robot could be particularly useful. Xavier observed that "most of the patients" at the tent are "pretty healthy," so he would be "more comfortable" just seeing the patient over a video call, whereas patients in the ED typically need "more of an assessment." Trevor described how a system like ours would enable him to check on patients in the tents, but if something more critical came up inside the ED, he could tell the patient in the tent, "Hey, hold on a minute," and quickly switch his focus to the situation in the ED. Similarly, Tobi imagined that she could drive the robot to a patient while on the phone with a consultant and talk to the patient as soon as the phone call was over.

6.3 Robots Supporting HCWs' Ability to Evaluate Patients

Especially in a pandemic, it is important to know if HCWs felt they could thoroughly assess patients remotely. 8/15 *APS* participants (*APS:* 3/6, *EDS:* 5/9) said they got the information needed to assess the patient via *Iris* (though two had slight audio/video issues). Although robot exams were similar to existing telemedical calls conducted over a tablet, participants thought *Iris* gave them increased mobility, letting them get different views of the patient to examine them better, an ability utilized by seven participants (*APS:* 3/6, *EDS:* 4/9). Some *EDS* participants (3/9) also noted advantages of not having patients hold the tablet, such as reduced errors and better visibility of the patient's body.

Being able to see different angles of the patient was especially important when the operator wanted to conduct a physical examination of the patient. 10/15 participants (*APS:* 4/6, *EDS:* 6/9) felt comfortable conducting aspects of a physical exam via the robot. In addition to asking questions verbally, these participants often asked the patient to move their eyes, head, arms, or stick out their tongue. A few participants even asked the patient to stand up and walk in a straight line. However, 9/15 participants (*APS:* 3/6, *EDS:* 6/9) expressed wanting to conduct further physical exams than was possible through the current robot. "A light would have been nice to assess her pupil function. [I would have liked to] look into her throat, and probably in this case would need to listen to her [breathing], but that could also be hard [through the robot]" (Xavier).

6.4 Physical Interaction Is Important

As a result of our study, we noticed how important physical interaction was for patient evaluation. 9/15 participants (*APS:* 1/6, *EDS:* 8/9) said a way to physically interact with the patient could be useful. Daniel said, "[I] would like to have a way to physically interact with [the] patient. Physical exams [are] typically very hands on. [After the virtual interview, I'm] not one hundred percent certain in [the] neurologic exam because I couldn't physically interact [with the patient]." Increasing physical interaction, e.g. by using a telemanipulator, could impact the accuracy of patient evaluations via a robot.

Physical interaction is also important for the patient experience. Based on their experiences, participants speculated that physical interaction with HCWs makes patients feel seen and cared for. Trevor mentioned using a robotic arm to provide more sympathy. He also recounted an experience where he had to stand outside the patient's room. "As long as someone is in there physically with them they appreciate it more. [We] tried [...] call[ing the patient] from outside the room, [...] prison style on phone, but they can see you. They don't like it because you're 10 ft away. [The robot] might be better than that, [but] they still appreciate when there's actually someone there."

6.5 Physicians' Perspectives on Patient Experience

Though a majority of participants saw robots as having the potential to improve patient care, two participants had concerns about the quality of patient experience when using a robot. One concern was the lack of physical presence or interaction with the HCW. Trevor mentioned how facial expressions and body language, such as shrugging, are also limitations that may impact patient experience.

Participants also helped outline current patient experience, with regards to the pandemic. In addition to the "prison-style call" (see Sect. 6.4), nurses facilitate telemedicine calls via an tablet on wheels. However, this method still puts them at risk of exposure to COVID-19. Dennis recalled a colleague who called patients to ask preliminary questions before an exam to reduce exposure, and Dominique described another telemedicine method: "[Having an] intercom [is like a] 'voice of god' into the patient room. [...][It's] alarming [because] you can't see [the person]." Designers must consider the patient experience during telemedicine to avoid alarming patients, which could detract from their care, while still ensuring the patients feel seen and HCWs are protected.

6.6 Use Cases Ideated by Participants

Participants often ideated new uses for systems like *Iris* we had not considered. These ideas provide inspiration for ways we can make our system more useful for HCWs.

Providing More Compassionate Care: Dominique highlighted that a robotic system could help HCWs provide more compassionate care for patients while minimizing exposure to infectious diseases. She described how "there's that stigma, like if you're a physician and you're there with someone who's infectious, you want to get the f- out of there." Yuri shared how while working in a pandemic, he has had to consider jeopardizing patient experience for the sake of minimizing his exposure, thinking "Do I need to see this person less or do I need to expose myself more?" Using telemedicine would help HCWs feel more comfortable spending time with patients because there is less risk, which would provide more support for isolated patients.

Integrating with Translators: As mentioned in Sect. 6.1, 3/15 participants (*APS:* 3/6, *EDS:* 0/9) discussed integrating translation services with our system to assist with communicating with non-native and sign language speakers. Yuri noted this might affect using a robot: "Using an interpreter and robot at the same time would be challenging. Like if [you're] speaking to a patient who doesn't speak English or uses sign language." Integrating the robot with pre-existing interpreter services or offering the ability for a translator to join the call would be beneficial to the robot's functionality. This also can have an impact on health equity and access.

Assisting ED Flow: Two participants also envisioned using the robot for delivering medication and supplies. For instance, Trevor suggested, "if you could have grooves for medication cups, [that] would be useful because then [nurses] can send in meds." Using the robot to deliver items to the patient reduces HCW's' risk of exposure.

Additionally, implementing some autonomous care delivery tasks on the robot could support HCWs providing more compassionate care. For instance, Dominique discussed needing to make sure a patient can walk and eat before discharge, but this is often neglected for more important tasks. Tobi also suggested using the robot for discharge instructions. Having a robot complete delivery tasks would be useful in an ED's hectic environment, as it could speed up patient discharge and save time for the HCW.

6.7 *Iris*-Specific Feedback

Generally, participants found *Iris* easy to use. 12/15 participants (*APS:* 5/6, *EDS:* 7/9) had little to no robotic experience, but ten stated that the system was easy or straightforward to use. On SUS, our system scored a mean of 76.67 (s.d. = 15.79) among *APS* participants and 78.33 (s.d. = 12.2) among *EDS* participants, implying *Iris* is usable [22].

Participants generally said navigation was intuitive and the controls were easy to use. All participants were able to complete the task. The controls had a small learning curve; participants expressed no concerns navigating after a few initial button clicks.

11/15 participants (*APS:* 5/6, *EPS:* 6/9) reported no difficulty seeing and hearing the patient, who was wearing a mask. There were a few times where the speaker had to repeat what they were saying; however, this can happen normally in face to face conversations, especially ones involving masks.

Nearly all participants wanted the video on the interface to be wider to aid with navigation and provide a better view of the patient. Many participants indicated that they had limited situational awareness, saying they were concerned about crashing the robot or thought they might have been able to get closer to the patient but were not sure.

Lowers Cognitive Burden through ease of use and learnability	**Strengthen System Durability** to withstand unpredictable events and conditions in the ED	**Embraces Platform Adaptability** to be adjustable across many different healthcare settings	**Cultivates Familiarity and Trust** through culturally conscious and locally relevant design
Supports Accessibility to make system inclusive through multimodal forms of feedback and interaction	**Reinforces Built Environment Integration** to prompt easy adoption of system into existing HCW workflow and physical settings	**Support Situational Awareness** through visual, auditory, and physical cues to provide information critical for robot navigation in the Emergency Department	

Fig. 5. Design recommendations for situating a telehealth robot in the ED.

Participants also wanted a camera that could pan, tilt, and zoom without moving the robot, and some requested a rear view camera.

7 Discussion

Our results provide important considerations for deploying telehealth robots in the ED during a pandemic. Based on these findings, we provide seven design recommendations, including situational awareness, accessibility, and familiarity and trust (see Fig. 5). We also briefly explore the implications of our findings with regard to health equity and access. Finally, we discuss ideas for future work.

7.1 Design Recommendations

Co-designing with key stakeholders in the ED ecosystem and running a remote apartment study with *Iris* yielded additional insights and considerations for telehealth robot design, as described in our findings. Here, we present what we have learned to be the most integral parts of situating a teleoperated robot in the ED. The following design suggestions discuss various aspects of human-robot interaction (HRI) crucial to the operator, interactants, and others around the ED.

Situational Awareness: In the ED, SA is critical for all key stakeholders (teleoperators, interactants, and bystanders). Most prior work focuses on teleoperators' SA and information the robot acquires to carry out the commands or activities. However, interactant and bystander SA are equally important.

Interactants and bystanders may be alarmed by seeing a robot. To mitigate this, the robot should clearly convey its purpose. Emphasizing the presence of the operator, as discussed below, could also be helpful. Bystanders also include HCWs, who will be engaged in safety critical tasks. Because HCWs already have high cognitive load, the system should not place the burden of attention on HCWs. Therefore, we must account for the bystanders' awareness of the robot for successful deployment in ED settings.

Making the robot more visible and audible is critical to operator, interactant, and bystander SA, and can be realized through non-verbal communicative cues. Designers should consider employing a combination of cue types to support patients with hearing and vision loss (common among the majority of older patients).

Visual Cues can help direct attention to the robot, especially when in motion, helping bystanders avoid colliding with it. Multiple cues may be helpful, both via the robot's features (e.g., lights or gaze cues to indicate directionality), and physical indicators on the robot (e.g., paper photographs of teleoperators affixed to the rear of the robot, flags). *Physical Cues*, such as motion and/or haptics, can also be helpful for supporting SA.

Finally, *Audio Cues* can be integral in supporting SA, and can alert people to the presence of the robot and what task state it is in. For the ED, it is important to carefully consider how to design sound, as both a noisy robot and a quiet one could add to HCWs' cognitive burden, and interactant/bystanders' discomfort.

System Durability: The robot needs to be robust for use in safety critical functions. The robot may encounter environmentally austere conditions, including extreme temperatures (e.g., inside COVID tents). Inside the ED, there may be many obstacles, including: uneven surfaces and debris, crowded hallways, etc. The robot also has to endure frequent decontamination required for repeated use, especially during a pandemic. Additionally, from Yuri and Trevor's experiences we learned that the robot needs to withstand patients who might be under the influence and attack the robot.

Additionally, the robot system must be robust to failures to maintain people's trust. Trust is often primarily influenced by robot performance [23], so the system must perform as expected for people to use it. This is especially important because we do not want to compound the high stress of HCWs by also making them worry about a robot.

Accessibility: The system needs to be accessible for all stakeholders. For example, most hospitals are populated with older adults, who experience high levels of hearing loss. Since hearing aids are expensive and easily lost, many will not bring them to the hospital. All staff and patients wearing masks has also made communication difficult for many, as it's difficult to read lips and infer expressions. Unfortunately, due to social stigma, many individuals will not admit they cannot hear well, causing them to miss important instructions, impacting their ability to make informed medical decisions. Having the robot support textual feedback and subtitles could help address these issues. This can help support deaf interactants of all ages, as well as non-native English speakers, who can be supported through interpretation/translation services.

External sound design should be embedded to provide visual accessibility. The system needs to relay audio reinforcement and feedback for those who may be blind, experience low vision, or color blindness to indicate the robot's presence.

Trust, Familiarity, and Presence: The robot should be perceived as acceptable and trustworthy, as this will affect its ultimate adoption [23]. Technology familiarity can play a role, as embodying new concepts within older ones can help build familiarity [24]. Familiarity can also be cultivated by technology being locally, culturally, and socially relevant to an individual's lived experiences, e.g., as created via stakeholder-centered, co-design processes [19]. Additionally, robot designers can add images to robots to reassure patients, similarly to how HCWs displayed pictures of themselves to patients who could not see their faces due to PPE.

In the case of using telemedical robots to provide care in a pandemic, cultural awareness is particularly important for designers. Many groups have deep distrust of healthcare in general, where it is already a struggle to have them seek care, and thus may be particularly discouraged to learn their care is being delivered via a robot.

Finally, conveying presence [17] is an important aspect of creating trust and necessary for successful robot-mediated telehealth, which can be conveyed via mobility and spatial awareness. This helps the operator feel comfortable in the remote space, and that interacting remotely is not a barrier to providing care.

It is also crucial for the interactant to sense the presence of the teleoperator, so they feel they are being seen and receiving quality care, a factor our participants felt was important to cultivating trust. Highlighted by Trevor's prison-style phone call experience with a patient, visibility of the HCW alone might not be enough to express presence-patients still highly value physical presence. As seen in previous research [17], the physical embodiment of the robot can help more closely mimic face-to-face interaction and enrich the operator-interactant communication.

Platform Adaptability: The robot needs to have the ability to be adaptable for different operators and interactants, and for different contexts [3,18,19,21,25,26]. It needs to be flexible and adaptable to the various use cases discussed by participants.

The system should exhibit adjustable software and hardware capabilities. This will allow the system to be personalized to various ED needs depending on the physical conditions such as light and sound. Additionally, the system should be adjustable to the various types of exams HCWs might need to conduct. For instance, HCWs might add a light to the robot to better conduct neurological exams, as participants mentioned.

Robots need to be adaptable to different types of healthcare delivery, hospital settings, and locations of care. This can mean urban or rural hospitals, crowded or uncrowded, noisy or quiet, etc. They should also be adaptable to different interactants, such as populations of non-native speaking groups needing translation capabilities.

Built Environment Integration: Locating the robot within physical space is a critical part of effectively using it within the ED. The system should not add more burden for HCWs by making the robot difficult to find and recharge. In a busy ED, HCWs need an easy way to track and locate the robot and its connected interface. For example, designating a physical docking location is a simple but pivotal aspect of integrating the robot into the ED that can ease anxiety and streamline system management [27].

Cognitive Burden: It is important that the system reduces cognitive burden. The control interface should have a short learning curve, fulfilled through recognizable and familiar UI controls. The operator should not have to manage multiple programs nor spend time troubleshooting. The robot should be designed to reduce the cognitive load of interactants/bystanders, such as by including aforementioned communicative cues.

An interesting design tension which came up in our findings was Trevor's desire to use the robot to support task switching. This was already a substantial patient safety problem in the profession pre-pandemic, with EM HCWs being interrupted every six seconds, leading to many adverse events [16,20,21]; we certainly had not forseen the possibility that the robot could exacerbate this problem. Designers should consider this possible dual-use of the robot and consider ideas for mitigation.

7.2 Implications for Health Equity

One of our goals in designing *Iris* was to support health equity; many of our decisions were made with accessibility and community engagement in mind. We ensured our system was low cost and easy to use, made our hardware and software open source, and designed the system to be adaptable to different contexts. We hope this approach can help build broader community support and involvement, such as from local hobbyists and makers [28], many who want to support their local healthcare systems during a pandemic but might not know where to start.

Additionally, people can adapt the system to their unique local contexts, which is critical for the system to be well-contextualized to and adopted across different healthcare environments [18,29]. Developers can add, remove, or adjust features to best fit the environment in their healthcare setting. For instance, some might add a speaker to amplify the call volume if the robot is in a noisy ED, whereas those using the robot in a quiet ward at night may not want the robot disturbing others. They also could build a robot using systems they already have to decrease costs, for example, adding a boon with a camera and mini-screen to an old Roomba. Or they might add culturally-relevant "costumes" to their robot to help improve patient experience.

7.3 Limitations and Future Work

Our work had several limitations. First, no patients participated, so our feedback is centered on the physician's (teleoperator's) experience, and their interpretation of the patient's experience. Also, most of our HCW participants were EM physicians, who have different needs and expectations than other HCWs (e.g., nurses, technicians, volunteers). This is something we plan to address in our future work, by including patients, family members, and other stakeholders in the co-design and evaluative process [24,30–32], as we have in other projects [24,32].

In this study, *Iris* was entirely teleoperated. While we one day would like to have a system which supports shared autonomy, due to how crowded hospitals currently are, our stakeholders required a fully teleoperated system. However, in the future, we plan to design a shared control system for *Iris* to further reduce the cognitive load on HCWs, such as by supporting low-level navigation and obstacle avoidance tasks.

Our work raises many open questions for future HRI research. For instance, how can designers improve the quality of robot-mediated interaction in healthcare? What are key ways to convey presence and provide SA to operators providing and interactants receiving remote care, particularly given potentially challenging environments (e.g., noise, crowdedness)? Additionally, these questions may be informed by exploring increasingly active research areas in robotics, including soft robotics, haptic feedback, and virtual/augmented reality-based interfaces, all of which could improve care delivery. Finally, more work needs to be done to determine how robots can best support health equity, an emerging area of research in HRI and Healthcare Robotics [32].

We hope our work inspires others to design accessible, equitable, open hardware, open software systems. Our study provides valuable insights into situating telemedicine robots into the ED, particularly during a pandemic. We hope others in the robotics community can leverage these insights to improve healthcare in their communities.

References

1. Spoorthy, M.S., Pratapa, S.K., Mahant, S.: Mental health problems faced by healthcare workers due to the COVID-19 pandemic–a review. Asian J. Psychiatry **51**, 102119 (2020)
2. Hooper, M.W., Nápoles, A.M., Pérez-Stable, E.J.: COVID-19 and racial/ethnic disparities. JAMA - J. Am. Med. Assoc. **323**(24), 2466–2467 (2020)
3. Riek, L.D.: Healthcare robotics. Commun. ACM **60**(11), 68–78 (2017)
4. McKenna, P., Heslin, S.M., Viccellio, P., Mallon, W.K., Hernandez, C., Morley, E.J.: Emergency department and hospital crowding: causes, consequences, and cures. Clin. Exp. Emerg. Med. **6**(3), 189–195 (2019)
5. Whiteside, T., Kane, E., Aljohani, B., Alsamman, M., Pourmand, A.: Redesigning emergency department operations amidst a viral pandemic. Am. J. Emerg. Med. **38**(7), 1448–1453 (2020)
6. Kane-Gill, S.L., Rincon, F.: Expansion of telemedicine services: telepharmacy, telestroke, teledialysis, tele-emergency medicine. Crit. Care Clin. **35**(3), 519–533 (2019)
7. Hayden, E.M., et al.: Telehealth in emergency medicine: a consensus conference to map the intersection of telehealth and emergency medicine. Acad. Emerg. Med. **28**, 1452–1474 (2021)
8. Benda, N.C., Veinot, T.C., Sieck, C.J., Ancker, J.S.: Broadband internet access is a social determinant of health! Am. J. Public Health **110**(8), 1123–1125 (2020)
9. Zhai, Y.: A call for addressing barriers to telemedicine: health disparities during the COVID-19 pandemic. Psychother. Psychosom. **90**(1), 64–66 (2021)
10. Kristoffersson, A., Coradeschi, S., Loutfi, A.: A review of mobile robotic telepresence. Adv. Hum.-Comput. Interact. **2013**, 1–17 (2013)
11. Shen, Y., et al.: Robots under COVID-19 pandemic: a comprehensive survey. IEEE Access **9**, 1590–1615 (2020)

12. Sierra Marín, S.D., et al.: Expectations and perceptions of healthcare professionals for robot deployment in hospital environments during the COVID-19 pandemic. Front. Robot. AI **8**, 102 (2021)
13. Esterwood, C., Robert, L.: Robots and COVID-19: re-imagining human-robot collaborative work in terms of reducing risks to essential workers. ROBONOMICS: J. Autom. Econ. **1**, 9 (2021)
14. Chai, P.R., et al.: Assessment of the acceptability and feasibility of using mobile robotic systems for patient evaluation. JAMA Netw. Open **4**(3), e210 667 (2021)
15. Fossati, M.R., et al.: LHF connect: a DIY telepresence robot against COVID-19. Strateg. Des. Res. J. **13**(3), 418–431 (2020)
16. Kraft, K., Smart, W.D.: Seeing is comforting: effects of teleoperator visibility in robot-mediated health care. In: Proceedings of the 2016 ACM/IEEE International Conference on Human-Robot Interaction, pp. 11–18. IEEE Computer Society (2016)
17. Rae, I., Mutlu, B., Takayama, L.: Bodies in motion: mobility, presence, and task awareness in telepresence. In: Human Factors in Computing Systems (CHI), pp. 2153–2162 (2014)
18. Gonzales, M.J., Cheung, V.C., Riek, L.D.: Designing collaborative healthcare technology for the acute care workflow. In: Proceedings of the 9th International Conference on Pervasive Computing Technologies for Healthcare, PervasiveHealth, pp. 145–152 (2015)
19. Taylor, A., Lee, H.R., Kubota, A., Riek, L.D.: Coordinating clinical teams: using robots to empower nurses to stop the line. In: Proceedings of the ACM on Human-Computer Interaction, vol. 3, no. CSCW, pp. 1–30 (2019)
20. Taylor, A.M., Matsumoto, S., Xiao, W., Riek, L.D.: Social navigation for mobile robots in the emergency department. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 3510–3516 (2021)
21. Taylor, A., Matsumoto, S., Riek, L.D.: Situating robots in the emergency department. In: AAAI Spring Symposium on Applied AI in Healthcare: Safety, Community, and the Environment (2020)
22. Bangor, A., Kortum, P., Miller, J.: Determining what individual SUS scores mean: adding an adjective rating scale. J. Usability Stud. **4**(3), 114–123 (2009)
23. Washburn, A., Adeleye, A., An, T., Riek, L.D.: Robot errors in proximate HRI: how functionality framing affects perceived reliability and trust. ACM Trans. Hum.-Robot Interact. (THRI) **9**(3), 1–21 (2020)
24. Moharana, S., Panduro, A.E., Lee, H.R., Riek, L.D.: Robots for joy, robots for sorrow: community based robot design for dementia caregivers. In: ACM/IEEE International Conference on Human-Robot Interaction (HRI), pp. 458–467 (2019)
25. Ahumada-Newhart, V., Olson, J.S.: Going to school on a robot: robot and user interface design features that matter. ACM Trans. Comput.-Hum. Interact. (TOCHI) **26**(4), 1–28 (2019)
26. Fitter, N.T., Strait, M., Bisbee, E., Mataric, M.J., Takayama, L.: You're wigging me out! Is personalization of telepresence robots strictly positive? In: Proceedings of the 2021 ACM/IEEE International Conference on Human-Robot Interaction, pp. 168–176 (2021)
27. Cesta, A., Cortellessa, G., Orlandini, A., Tiberio, L.: Long-term evaluation of a telepresence robot for the elderly: methodology and ecological case study. Int. J. Soc. Robot. **8**(3), 421–441 (2016). https://doi.org/10.1007/s12369-016-0337-z

28. Hofmann, M., Lakshmi, U., Mack, K., Hudson, S.E., Arriaga, R.I., Mankoff, J.: The right to help and the right help: fostering and regulating collective action in a medical making reaction to COVID-19. In: Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, pp. 1–13 (2021)
29. Jang, S.M., Hong, Y.J., Lee, K., Kim, S., Chiên, B.V., Kim, J.: Assessment of user needs for telemedicine robots in a developing nation hospital setting. Telemed. e-Health **27**(6), 670–678 (2021)
30. Kubota, A., Peterson, E.I., Rajendren, V., Kress-Gazit, H., Riek, L.D.: Jessie: synthesizing social robot behaviors for personalized neurorehabilitation and beyond. In: Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction, pp. 121–130 (2020)
31. Kubota, A., Riek, L.D.: Methods for robot behavior adaptation for cognitive neurorehabilitation. Annu. Rev. Control Robot. Autonom. Syst. **5**, 1–27 (2021)
32. Guan, C., Bouzida, A., Oncy-Avila, R.M., Moharana, S., Riek, L.D.: Taking an (embodied) cue from community health: designing dementia caregiver support technology to advance health equity. In: Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, pp. 1–16 (2021)