A Collaborative Video-Conferencing System for Improving Care During Neonatal Transport

by

Irene Fan

Submitted to the Department of Electrical Engineering and Computer Science in partial fulfillment of the requirements for the degree of Master of Engineering in Electrical Engineering and Computer Science at the

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Abstract

The need for real-time telemedicine to support urgent care is growing. The primary focus of our work has been on improving the care provided to critically ill infants born at community hospitals who need to be transported to tertiary care centers for specialized neonatal treatment. Providing real-time effective communication between community physicians, transport teams, and specialists will lead to better decisions about where to transport patients, better patient care during transfers, and reduced time to proper treatment upon arrival at the receiving hospital.

There are a number of challenges in implementing a system that meets these needs: creating a reliable high-bandwidth channel on a moving ambulance by aggregating unreliable low-bandwidth cellular channels, providing a user interface that can be easily and effectively used by physicians, and instrumenting the incubator in which the infants are transported.

We have built a bi-directional near real-time video-conferencing system designed to facilitate better communication between physicians and transport teams. In addition to providing much higher-quality video than current mobile telemedicine applications, our application provides collaborative and domain-specific features not offered by a regular teleconferencing system: doctors and transport team members can save and email snapshots and video clips for further analysis and discussion, zoom in on different portions of the video, switch between several cameras for different views of the patient and a vitals signs monitor, and set the video transmission parameters (e.g., frame rate and latency).

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Chapter 1

Introduction

MANTiS (MIT Ambulatory Neonatal Telemedicine System) is a collaborative video-conferencing telepresence system for improving the care provided to critically ill infants during their stabilization and possible transport to tertiary care centers, which provide highly specialized services. Over the last few decades, neonatal care has moved toward the model of a regionalized system that stratifies care into levels of complexity ranging from basic to subspecialty neonatal care [37, 38]. Expectant mothers at high risk of giving birth to extremely premature or seriously ill babies are generally transferred, as per the Committee on Perinatal Health recommended standards [37] confirmed by subsequent studies [21, 15, 34], to Level III subspecialty neonatal intensive care units (NICUs) prior to delivery. However, many seriously ill newborns are still delivered at community hospitals that lack the specialized expertise needed for optimal patient care.

We have designed MANTiS to help improve patient care in these cases where ill babies are geographically separated from the neonatal specialists who best know how to treat them. During initial patient stabilization within a hospital, MANTiS can be used to connect community physicians with specialists to determine appropriate treatment plans and also whether transport is necessary for the ill baby. MANTiS also enables the transport team and specialist to communicate from a moving ambulance during patient transport using bi-directional near real-time video, by striping the video over the cellular data network.
In addition to providing higher-quality video than current mobile telemedicine applications, MANTiS provides collaborative and domain-specific features not offered by a regular teleconferencing system: specialists, physicians, and transport team members can save and email snapshots and video clips for further analysis and discussion, zoom in on different portions of the video, switch between several cameras for different views of the patient and the vitals signs monitor, and set the video transmission parameters (e.g., frame rate and latency).

1.1 Motivating application

It is not economically feasible for most community hospitals to staff neonatal physicians around the clock to provide the advanced level of care needed during the initial stabilization of a critically ill newborn. In community hospital settings, an ill newborn is often first cared for by a primary care physician or advanced practice nurse. This physician or nurse may have the skills to resuscitate the baby but lack the clinical specialty experience and training to determine whether transport is necessary and, if it is, provide care confidently until the transport team arrives. If the tertiary care center to which the baby will be transported is far away, then substantial travel time may also be required. Therefore, there may be a significant period of time when neonatal critical care expertise is needed but unavailable to the infant.

Currently, community physicians, nurses, and transport team members can consult neonatal specialists via telephone and radio. Telemonitoring of the sick baby from the time of initial assessment through the end of the transport process can improve the quality of patient care during this critical time. Telemedicine has the potential to enable needed neonatal critical care expertise to be provided in real-time, allowing a team consisting of both on-site and remote medical providers to work together to meet the newborn’s needs.

A collaborative approach between the community pediatrician and a neonatologist during the initial assessment of the infant would determine which patients could be properly cared for in the community hospital setting and which would benefit from
transfer. Such an approach would streamline medical resources and allow infants with less severe illnesses to remain at the birth hospital with their families. Telemonitoring would also enable a neonatal specialist to provide ongoing expertise during the stabilization of a critically ill newborn. With real-time audio and video linkage to the care site as well as continuous transmission of vitals signs data and radiographic studies, the specialist has the information needed to give and adapt clinical advice as the infant’s condition evolves. Upon the transport team’s arrival at the community hospital, the baby would already have a care plan in place, developed under the guidance of the neonatologist waiting to receive the patient at the tertiary care center.

Continued telemonitoring of the infant while en route to the tertiary care facility would provide for a virtually seamless exchange of information between the transport team and the NICU team that will ultimately manage the patient. En route monitoring would also enable additional subspecialty consultation to be provided, should it be needed in the case of a newborn’s condition deteriorating during transport. The ability for the transport team to work with the tertiary care team to provide rapid assessment and intervention could greatly enhance the care of these critically ill newborns, particularly when the transport times are long.

1.2 Requirements and challenges

Given the more technically challenging nature of the mobile use case, we have predominantly focused on developing MANTiS as a mobile telemedicine application. We are confident that we can port the application to the less challenging community hospital environment for future evaluations that we will describe in Section 7.4.

A mobile real-time video telemedicine application has several requirements:

- continuous high-quality video, which in turn needs a mobile and reliable high-bandwidth communications channel;
• a user interface (UI) that can be easily and effectively used by physicians with little training;

• additional tools to facilitate both immediate and deferred collaboration with other specialists, who may not have access to the application.

These requirements are accompanied by several challenges. For instance, a high level of user-friendliness in the UI is key to widespread adoption by the medical community as a tool to help improve patient care. The application needs to be designed to meet the physicians’ and transport team’s needs at every step of the infant stabilization and transport process.

In transmitting video, bandwidth is a major challenge; video requires much more bandwidth than what is used by a phone call. In previous stages of MANTiS’s development, it was realized that while wireless wide area networks (WWANs)—and in particular, cellular data networks—are not the ideal network infrastructure for this type of application, they are the most feasible option given the mobile and geographic requirements [18]. A custom networking infrastructure would be financially prohibitive. Another option, the 802.11 wireless network, offers lower latency and loss rates compared to the cellular network, but any wireless detected by a moving ambulance during patient transfer would be spotty at best.

Our choice, the cellular data network, has its challenges. Cellular data networks provide widespread coverage, but are characterized by long round trip times (RTTs) and high loss rates. In addition, they are optimized for downloading rather than uploading data, which we need to do when sending video from an ambulance to a hospital. Despite these drawbacks, the widespread coverage of cellular data networks makes them the best choice.

The video transmission should be smooth and near real-time. A few dropped packets should not significantly affect video quality, but latency needs to be minimized for the video to be as “real-time” as possible. Doctors need smooth, continuous video to evaluate patient movements, and although the amount of latency and video
quality can be traded off, both need to meet the users’ baseline expectation for the application to become a viable tool in the field.

1.3 Contributions

We developed MANTiS to facilitate improved collaboration—between community physicians, transport teams, and neonatal specialists—in the context of neonatal patient care. MANTiS helps physicians and transport team members to communicate with specialists before and during patient transport by linking them with bidirectional video which can be striped over the cellular data network. From the tertiary care center NICU, specialists can use the application to switch between different video streams that together provide a full view of the ill baby. Specialists can also see the patient's vitals signs data from another video stream. They can zoom in on the current video as well as save snapshots and video clips. The saved materials are posted to a web server for central storage and easy access; the web server simplifies the sharing of snapshots and video clips with any other specialists consulted for a second opinion, who may not be present or have access to the application.

We collaborated with neonatal intensivists from the Boston, MA area on this project, and we iteratively shaped MANTiS’s software and hardware features, as well as the user interface, around their feedback. During this process, we borrowed a transport incubator—a temperature-controlled enclosed crib for the baby used in both the hospital and transport settings—from Children’s Hospital Boston, the largest healthcare provider for children in Massachusetts [13]. We equipped the transport incubator with the cameras, laptop, and networking hardware needed to send patient video. We also worked with the Children’s Hospital transport team to conduct initial test deployments.

To obtain a stable high-bandwidth mobile communications channel, we built MANTiS upon technology that allows bi-directional video to be striped over cellular data networks. Tavarua, the video-streaming subsystem, was already developed in the earlier stages of this project [18, 43]. Tavarua itself builds on two compo-
ponents: Tribe [43], which provides the low-level interface to the network hardware; and Horde [44, 42], which performs network striping to provide communication over several channels.

At this point, we have prototyped MANTiS based on the collaborating physicians’ feedback, overcome various deployment challenges, and tested the technology in the Children’s Hospital transport ambulance. The current version of the system is ready for a more formal evaluation.

1.4 Thesis organization

Chapter 2 delves more extensively into the current state of neonatal intensive care. It also covers related work in both the clinical application of telemedicine and past telemedicine endeavors. Chapter 3 gives an overview of MANTiS and its underlying subsystems, while Chapter 4 outlines MANTiS’s major software features and the design decisions behind them. Chapter 5 describes challenges encountered in preparing MANTiS for test deployment. Usage trials are discussed in Chapter 6. Finally, future work for MANTiS and conclusions about the project are presented in Chapter 7.
Chapter 2

Background

Telemedicine has the potential of having a significant positive impact in many areas of medicine. It should prove particularly useful in situations where specialized medical knowledge is needed. Oftentimes, the clinicians (i.e., physicians, nurses, and paramedics) who have initial contact with the patient have the capability to administer treatments but lack the specialized knowledge to prescribe an appropriate care plan. Cardiac, trauma, stroke, neonatal, and geriatric emergencies, among others, all fit this model, and their current medical practices could benefit from our telepresence-enabling technology. In developing MANTiS, we have chosen to focus on the case of neonatal critical care for several reasons: the existing medical need, its characteristics which lend to a simpler deployment model, and our collaboration with neonatal intensivists on the project.

2.1 Neonatal intensive care

Specialized care for ill newborns has improved with the emergence of a regionalized system that organizes the levels of neonatal care delivered in hospitals. The identification of prenatal complications and subsequent transfer of expectant mothers to facilities with neonatal specialty services has demonstrably improved outcomes by ensuring that at-risk infants are born at hospitals with the expertise, staffing, and resources to provide them with the appropriate care [19].
Unfortunately, some premature and critically ill babies are still delivered in centers not fully equipped to care for them, necessitating transport to a tertiary care facility. Although the level of transport care given to a sick newborn has greatly improved due to the establishment of regionalized transport teams consisting of advanced practitioners, the transport process remains inherently risky. In particular, transport may increase the risk of mortality—a 1998 Australian study examining outcomes of infants less than 30 weeks’ gestational age transferred from one tertiary care facility to another due to NICU congestion demonstrated that the mortality rate of the transferred infants was significantly greater than that of matched infants who remained at the hospital in which they were delivered [16].

The discipline of neonatal transport medicine as a specialized practice has co-evolved with the establishment of regionalized organization of neonatal care [17]. Most of the focus of this specialty has been on the equipment required for transport, the care delivered by the transport team upon arrival at the referring hospital, and the subsequent care delivered during transport to the receiving hospital. There is limited data available on the initial assessment of the infant at the time the transport team is called and on the condition of the baby during the transport process, perhaps due to the difficulty in standardizing care for the ill neonatal population in this time window. What is clear is that during the period of time the transport team is en route, the receiving hospital receives only a partial picture of the state of the baby and its provided care, from what can be described over cell phone and radio.

We believe telemedicine can improve outcomes in neonatal intensive care medicine by helping to identify critically ill babies, improving patient care before and during the transport, and shortening time to treatment at the receiving hospital. The experience community physicians gain from the enabled collaboration with neonatologists can also translate into improved general patient care at community hospitals.
2.2 Related work: Clinical applications of telemedicine

General interest in telemedicine has increased as healthcare has become increasingly specialized. Patients needing specialized care are often far away from the handful of tertiary care centers scattered around the country that have the resources to treat them.

Telemedicine applications can be roughly characterized as either synchronous or asynchronous. Asynchronous telemedicine does not require the simultaneous availability of the source and recipient of patient information. It often involves the acquisition of medical data, e.g., an x-ray, that is then transmitted to a specialist for analysis at a later time. Synchronous telemedicine, on the other hand, requires that the source and recipient be simultaneously available and linked in a way that enables real-time interaction. Our application is designed to support synchronous telemedicine.

Situations in which the patient is stable and no immediate interaction is needed are well suited to asynchronous telemedicine. Radiology and pathology, for example, make extensive use of asynchronous telemedicine. Situations in which the state of the patient may be changing rapidly, e.g., obstetrics and neonatal care, are better suited to synchronous telemedicine.

Synchronous telemedicine has become a promising tool in bringing specialty services to patients located far from the specialized medical services available only at major hospitals. For example, in the area of pediatric cardiology, a 2002 study showed that real-time transmission of neonatal echocardiograms from community hospitals to cardiologists in a tertiary care center was a reliable and efficient way to send images and could positively impact the immediate treatment of critically ill babies [45]. Real-time interaction allowed the cardiologist to guide sonographers to obtain more useful views during the study as well as provide immediate interpretation for the referring doctor. Rapid identification of heart defects—which are responsible for nearly one-third of newborn deaths [25]—and application of the appropriate therapy can be life-saving.
Extending the use of telemedicine to create “virtual critical care” has gained acceptance in adult medicine. A virtual department of critical care has been established at UMass Memorial Medical Center in Worcester, MA with the goal of delivering collaborative, interdisciplinary patient-focused care [33]. Critical care patients are managed around the clock by specialists on-site or via telemonitoring.

Synchronous telemedicine has also been used to improve the care of pediatric critical care patients in underserved rural areas. A 2003 study illustrated the use of telemedicine to facilitate the partnership between a university-based pediatric intensive care unit and a rural medical center [32]. A previous model of employing a pediatric critical care physician without the presence of other pediatric specialists became nonviable, and a new telemedicine-based consultation system was designed to meet the patient care needs. This health care delivery model, deployed in a region with sparse medical resources, was shown to have a high level of satisfaction amongst both health care providers and parents.

2.3 Related work: Technology for telemedicine

Our goal is to make MANTiS a real-time mobile video telepresence system. Such a system requires mobile, high-bandwidth communications technology with good quality of service. Other existing telemedicine applications have different communications technology requirements, or are bound much more tightly by bandwidth constraints.

As mentioned in Section 2.2, some tertiary care centers have established stationary links with smaller community hospitals to provide remote specialized care. The TeleStroke program [1] at Massachusetts General Hospital (MGH) uses a stationary video-conferencing system that enables specialists at MGH to conduct stroke evaluations on patients at remote partner hospitals as well as offer treatment advice to on-site physicians. Its teleconferencing facilities require high bandwidth, low latency, and reliability, which—because it is a stationary application—can be met by a broadband internet connection. In the case of the Remote Evaluation of Acute isCHemic Stroke (REACH) program developed in rural Georgia, and now incorpo-
rated as REACH Call, Inc., community hospitals call a central dispatch center, which then pages an on-call specialist [47, 28, 2]. The specialist can connect to the community hospital from any broadband-enabled computer and remotely perform stroke skills tests, review computerized tomography (CT) images, and advise the community hospital physicians in determining a diagnosis.

With respect to mobile systems, the communication channels of several early mobile telemedicine applications utilized satellite technology [40, 27, 46, 36]. However, the deployment cost and inherently long packet latencies associated with satellite technology limited the adoption of these applications.

The current widespread growth of inexpensive cellular data networks has made them the medium of choice for many mobile telemedicine applications. However, many systems transfer only telemetry data via the cellular data network [29, 30, 39, 35, 24]; others, such as the British Lancashire Ambulance project [23] and the European Union’s AMBULANCE project [41], additionally transmit images. These low-bandwidth systems use few—in most cases, one—cellular data channels and suffer from high network loss.

Researchers at the University of Maryland developed a system that enabled neurologists at the receiving trauma center to diagnose acute ischemic stroke from video clips of patients transmitted during transport [48, 22, 26]. The system used proprietary hardware that took advantage of multiple cellular data channels but achieved a frame rate of only 8 frames per second at data transfer rates of 8.8 kbps. Latencies averaged between 10 to 15 seconds.

A mobile telemedicine system using commodity hardware was developed at the University of Massachusetts, Amherst [20]. The setup uses a single cellular modem, allowing for average data rates of 70-80 kbps for combined transmission of telemetry, audio, and video. At this data rate, they can only transmit a single video stream of 160 \times 120 frames at 4.2 fps, or three streams at 1.5 fps. When the video data is transmitted at 3 fps, the average latency is in excess of 3 seconds (with even larger latencies likely at higher frame rates).

A team at the International Institute of Telecommunications in Montreal, Canada
recently developed a mobile telemedicine application targeting trauma patients, which also transmits audio, video, and vitals signs over the cellular data network [14]. While the development of MANTiS has focused almost exclusively on establishing an aggregated WWAN channel suitable for transmitting bidirectional real-time video, this system has taken a more general approach. It calls a specialist based on the patient's pathology and integrates medical devices to combine transmitted video with vitals signs data, e.g., ECG and pulse oximetry, which MANTiS does not. However, because this system utilizes only one 3G network, it achieves video rates of between 5-15fps at less than 115kbps; in comparison, MANTiS sends 15-25fps at 300-800kbps of video. This system also has a strong focus on securing the communication channel with encryption, something MANTiS currently does not do but which could easily be incorporated in a future prototype.
Chapter 3

Overview of MANTiS

MANTiS is designed to support communication between a specialist at a specialist node and a community physician or transport team member at a patient node (i.e., where the patient is located). Communication for each case of patient stabilization and/or transport takes place in the context of a session. Unlike a phone consultation, a session involves multiple data streams—video, audio, email—and can have saved state that can be accessed after the session has ended (snapshots, video clips, etc.).

In the case of transport team members consulting specialists in the receiving NICU during patient transport, communication takes place between a mobile patient node (such as the ambulance) and a stationary specialist node, using the cellular data network. In the situation where both the patient and specialist nodes are stationary, e.g., when a physician at a community hospital collaborates with a tertiary care center specialist to determine the best course of treatment for an ill baby, both end users can use stable and fast broadband networks.

In this chapter, we will give an overview of MANTiS, as well as describe the systems MANTiS extends: Tavarua, a video and communication subsystem that allows high-quality bi-directional video to be striped with low latency across the cellular data network; Horde, the network-stripping middleware; and Tribe, the device abstraction layer for the network interfaces.
3.1 MANTiS

The specialist and patient node hardware setups and user interfaces reflect the differences in responsibilities, environments, and resources on each side. As we will discuss in Chapter 4, we designed the application to give the specialist node more control over the session than the patient node. Here, we describe the configuration of MANTiS's specialist and patient nodes, as well as the application usage model.

3.1.1 Hardware

The specialist node consists of two computers with a broadband internet connection, and a webcam pointed at the on-duty specialist for bi-directional video. The first computer is dedicated to running the MANTiS application. The specialist may use the webcam, which is connected to this machine, to demonstrate procedures to be performed.

MANTiS runs under Linux, an operating system with which some users may not be familiar. Consequently, we use dedicated machines—at both ends—to run our application, so that the user need not interact extensively with the underlying system.

We assume the specialist also has convenient access to a second nearby computer that she would already have been using for general computing, e.g., checking email. She can use this machine to access MANTiS’s web server in order to view screenshots or play back video clips. Any web browser may be used for this purpose, and no other specialized software is needed.

The patient side of the application is centered around the transport incubator. The transport incubator we borrowed from Children’s Hospital is a scaled-down intensive care unit on a wheeled frame. The transport incubator consists of a temperature-controlled plexiglass crib outfitted with a respirator, drug pumps, and a vitals signs monitor for obtaining physiological data such as heart rate, ECG, and pulse oximetry.

As shown in Figure 3-1, we instrumented the apparatus with a laptop, cameras, and networking hardware.
Figure 3-1: Transport incubator outfitted with laptop, cameras, and networking hardware, to be used as a patient node.
**Laptop.** The laptop for running the patient side of the application, as well as the network hardware, are arranged in the limited space on top of the respirator’s gas tanks. Because of vibrations in the ambulance during transport, we use a ruggedized laptop.

**Cameras.** The cameras for viewing the baby are attached on the railings securing the drug pumps, which happen to be centered over the plastic crib. They are focused on the head, torso, and body of the patient. The cameras are affixed by clamps so they can be adjusted on a per-patient basis. Camera adjustment is sometimes necessary since neonatal patients can range from 12 to 22 inches in length and might not always be placed in the plastic crib in the same orientation. To capture vitals signs data, another camera is attached to a metal arm that swings down to face the screen of the vitals signs monitor.

**Network interfaces.** We currently use three cellular network interfaces: two from Verizon [3], and one from Sprint [4]. The models of the interfaces vary slightly, but Verizon and Sprint both use CDMA EV-DO Rev A networks. Two of the network interfaces are USB-based, and the third one is PCMCIA-based.

The incubators used in the community hospital setting do not necessarily have the same setup as the one we outfitted. Incubators that are not used during transport do not need to be self-contained. For instance, the IV pumps or respirator might not be attached, and the frame may also differ. The patient node permanently stationed at a community hospital can use a desktop instead of a laptop. Rather than the cellular network interfaces, it can utilize available wireless LAN or broadband internet connections.

On reason we have focused on the special case of neonatal transport for the initial deployment of this general telemedicine system is because it is simpler from an application deployment standpoint. Since the baby is always in the transport incubator, all equipment can be installed around the crib. Camera positioning in the general mobile telemedicine case, on the other hand, is more complicated due to variations in ambulances and transport team habits.
Children’s Hospital has a dedicated transport team that picks up referred patients in a specialized transport truck (Figure 3-2) and brings them back to the hospital for critical care. The transport team’s extensive experience makes Children’s Hospital a good partner to work with during the application test deployment phase—they transport approximately 1000 critically ill and injured young patients annually [5]. Since the transport team always picks up the patients to be transferred, only one transport incubator at Children’s Hospital needs the patient node equipment installed for a test deployment.

Figure 3-2: Ambulance used by the Critical Care Transport Team at Children’s Hospital Boston.

3.1.2 Usage

When a community hospital physician consults a specialist, she starts the session by choosing the appropriate hospital to contact and then pressing a button. On the specialist’s end, the program waits to be contacted, at which point it automatically accepts the connection and establishes the session. In this scenario, if both nodes are using a wireless LAN or wired internet, the specialist should be able to view the video of the baby at a high resolution (currently 512×384 pixels) and low latency (~1 second) without encountering any video artifacts or corrupted frames.
During the session, the physician and specialist can communicate via the bi-directional video as well as the audio channel, which is currently a regular cell phone call as will be discussed in Section 5.2. Both the physician and specialist can use the UI to select between connected cameras on the transport incubator. The specialist can switch between cameras for different views of the baby or to check the vitals signs data, while the physician, who is in direct contact with the ill baby, might use this feature to direct the specialist toward a specific issue. The specialist can digitally zoom in on the video, enlarge the video, and save and email snapshots of video frames. Both the physician and specialist can also save video clips of the video stream at the patient node. The saved materials are posted on a web server, and the specialist may send links of some snapshots or video clips to other specialists for further consultation.

Using MANTiS, the physician and specialist can together determine both the baby’s condition and whether transport to a tertiary care center is necessary. If the baby needs to be transported, the specialist can continue advising the physician while an ambulance is on the way to the community hospital, helping to stabilize the critically ill infant and continuing to devise an appropriate treatment plan.

When the ambulance arrives at the patient’s location, the community physician disconnects and allows the transport team to re-establish the session with the specialist. The transition can happen either before or after the baby is loaded onto the ambulance’s transport incubator and then into the back of the ambulance. The transport team needs only to press a button to re-establish contact with the appropriate hospital, and then, if needed, to adjust the cameras so that together they provide footage covering the baby’s whole body.

During transport, the transport team and the specialist continue communicating via the bi-directional video and a cell phone call. Because the system is now transmitting video over the cellular data network, the specialist may want to adjust video transmission parameters—namely frame rate, latency, and resolution—depending on the sort of detail she wishes to analyze. For example, if the transport team notes that the baby has spina bifida, the specialist might choose to increase the resolution and
latency while decreasing frame rate to get image-quality video. On the other hand, in the case where a specialist is trying to diagnose neonatal seizure, she may choose to decrease latency and increase frame rate for smoother video at the cost of lower image quality. The specialist can further maximize the use of the limited available bandwidth by using unidirectional video and ceasing to send video from her node.

At the end of each session, videos of the entire session are transcoded and loaded onto a web server, so that they are available for review in a post-transport reconciliation meeting. A detailed security policy for this web server is beyond the scope of this thesis, but we discuss some possible security considerations in section 7.3.

3.2 Tavarua

Tavarua, the underlying video subsystem of our telemedicine application, was developed in the earlier stages of this project. It provides the video-conferencing logic for the application and handles all video encoding and decoding.

The main function of Tavarua is to provide high-quality streaming video. It uses a slightly modified version of the H.264 codec for video encoding and decoding. H.264 provides the best video at low bit-rates, but each I-frame spans many packets. The loss of any one packet will corrupt the entire frame, and the ffmpeg/x264 decoder used often crashes when asked to decode corrupted frames [43].

To work around packet losses, the area of each frame is split into subframes that are encoded and decoded independently of each other via H.264. The encoders are run out of phase with each other and do not all begin encoding on the same frame. Under this method, each I-frame component spans fewer packets, and less data is corrupted due to packet loss. Also, packet losses only corrupt subsections of the video rather than destroying entire frames.

Horde provides Tavarua with continuously updated information about the amount of available bandwidth in the system, allowing the video server to adjust the encoding process accordingly. Tavarua also dynamically accommodates hot-plugging and unplugging of video cameras at any time.
3.3 Horde

Horde is the middleware that provides the application with network striping, a process that splits up data from a single source and sends it over several smaller channels to be recombined at the destination. Multiple cellular providers offer overlapping coverage regions, which can be exploited to obtain a robust, higher-bandwidth connection. Most other work done on network striping assumes the channels below are stable and homogenous, which is not the case in our application; the WWAN channels used in MANTiS each have different bandwidths and varying latency. Horde allows the application’s data streams to provide information about desired performance while hiding many low-level details. It then stripes the data accordingly over the set of network channels; for example, more timely data is sent over faster channels.

Horde maintains multiple congestion control sessions—one for each underlying network link. This strategy allows Horde to adapt to varying conditions between individual links and to apply different congestion control schemes optimized for certain types of WWAN links.

3.4 Tribe

Tribe is the device abstraction layer that aggregates remote network devices over a local area network and presents them as local devices to higher layers. It allows the system, for example, to use many PCMCIA WWAN interfaces when the number of slots on the patient node’s laptop is limited. Meeting MANTiS’s minimum bandwidth requirements may demand the simultaneous use of several WWAN interfaces. Tribe is useful when hardware restrictions prevent us from connecting all the network interfaces we need to the laptop.

Tribe uses lightweight routers with extra PCMCIA slots and implements a protocol that allows the laptop to manage these routers and the active interfaces connected to them. Tribe adapts to WWAN interfaces disconnecting and reconnecting at any time, which can happen not only from bad reception, but also in the case of cards
physically being inserted or removed from the system.

At present, we do not need to use Tribe or the routers, because we are only using three interfaces and they can all be connected to the laptop without any hardware or operating system-related issues. However, if we need to, the integration of Tribe allows our application to easily scale to many more WWAN interfaces. In lab experiments, we have scaled up to eight network interfaces without running into problems.
Chapter 4

Software Features and User Interface

We designed MANTiS to facilitate better communication and collaboration between transport teams, community physicians, and specialists. We worked closely with neonatal intensivists to solicit feedback on what would make MANTiS more useful to them, and iteratively built the user interface around their feedback. Besides the near real-time video supplied by Tavarua, MANTiS supports switching between multiple cameras, zooming video, saving and emailing video clips and snapshots, and fine tuning video transmission parameters. Other features include near-fullscreen video, instant messaging, network information, and an option to switch between bidirectional and unidirectional video.

As mentioned in Section 3.1.1, the specialist and patient nodes of MANTiS each have dedicated machines for running the application. The specialist node also has a second machine for general computing, which can be used to access the web server storing video clips and snapshots. MANTiS is always in one of two modes: either it has an ongoing session, or the system is idle and waiting for a connection to be established between the specialist and patient nodes.

In this chapter, we describe in detail the user interfaces and software features for the specialist node, patient node, and web server. We also highlight the ways MANTiS differs from a typical teleconferencing system.
4.1 Specialist node

The start of the session is driven entirely by the patient node; the specialist node simply waits for an incoming connection. The user interface during this period is shown in Figure 4-1.

![Figure 4-1](image)

Figure 4-1: UI for specialist node, prior to session.

Once the connection is established, the specialist’s user interface changes to show the video and controls, as shown in Figure 4-2.

4.1.1 Bidirectional video

The specialist and patient nodes each display the video streams they are sending and receiving. The specialist is primarily focused on the neonatal patient and vitals signs data; she needs the video of herself only for visual feedback that the gestures she is demonstrating are centered on camera. On the patient node, the transport team is predominantly preoccupied with the patient, but occasionally needs to refer to the video of the baby to know where the specialist is currently directing her attention.
Figure 4-2: UI for specialist node, during a session.
The video being sent from the hospital is important as a means for the specialist to demonstrate a procedure to be performed.

In order to minimize miscommunication, the specialist and transport team always view the same video streams (including, for the patient’s video, zoom settings, camera selection, etc).

4.1.2 Switching between cameras

The grid of buttons on the right side of the user interface allow the specialist to switch between active cameras on the transport incubator. The system software in MANTiS allows an arbitrary number of cameras to be connected; however, the user interface for our trial deployment with neonatal patients allows for up to four active cameras. The camera denoted “Telemetry” captures data from the screen of the vital signs monitor. Up to three more cameras are mounted on the transport incubator to give the specialist a full view of the patient. Two cameras—for the upper and lower body, labeled “Head” and “Torso,” respectively—suffice for most cases. An additional camera labeled “Feet” can be used for larger babies. A premature infant born at 25 weeks is \(~12\) inches long, whereas a large term infant can be up to \(~23\) inches in length.

The sensitivity of each camera button depends on whether the corresponding camera is active, as shown in Figure 4-3. The button of the currently selected camera
is colored blue. The specialist and transport team can each determine which camera
is being viewed; a change by either side will trigger a corresponding change on the
other party’s view.

Originally, only the UI on the specialist node had camera-switching capabilities;
however, our collaborating physicians suggested this feature would also be useful for
the transport team. Using this feature, the transport team could check the cameras at
the start of the session and ensure that they were providing a full view of the patient.
The buttons would also allow the transport team to verify that all connected cameras
were active. During the session, the transport team could switch views to better
direct the specialist toward what they thought currently needed critical attention.

4.1.3 Zoom video

The zooming feature, activated by the “Zoom” button, is available only to the spe-
cialist. It allows a digital zoom onto the current video stream. Normally, the system
captures video at the best resolution offered by the currently active camera, then
downscales it to the user-specified resolution before encoding; when zooming, the rel-
evant portion of the video is selected before downscaling occurs. The specialist uses
this feature to get a closer look at the patient, e.g. at a skin lesion or a wound site.

As shown in Figure 4-4, clicking the “Zoom” button activates the zoom feature,
and a blue-bordered rectangle appears on the patient’s video. The rectangle can be
moved with the mouse and enlarged or shrunken with the scroll wheel. When the
specialist left-clicks on the patient video, it will zoom to where the rectangle was; the
zoom can be cancelled with a right mouse click. Pressing the “Reset zoom” button
brings the video to the original view.

4.1.4 Fullscreen

When the specialist does not need access to other system features, she may want
the patient video to take up more screen real estate. For this scenario, we provide
a fullscreen mode, which brings up a new window with an enlarged patient video as
Figure 4-4: When the “Zoom” button is clicked, a blue-bordered rectangle appears. The rectangle can be moved with the mouse and its size adjusted with the scroll wheel. The video zooms to where the rectangle was upon a left-click on the patient video.
shown in Figure 4-5. Fullscreen mode is triggered by the “Fullscreen mode” button located in the grid of buttons below the patient video. In this mode, the specialist’s video and network statistics are displayed in a small column on the right-hand side.

![Figure 4-5: Fullscreen mode on the specialist node UI.](image)

4.1.5 Video clips

The specialist node saves both the outgoing and incoming uncompressed video streams for the entire session, and our collaborating physicians have noted that a video of the entire transport session would be useful during a post-transport reconciliatory meeting.

During the session, portions of the patient video stream can also be saved as video clips. Pressing the “Save video clip” button brings up the window shown in Figure 4-6. To save a video clip, the user selects a clip length and, optionally, supplies a description for the video. As soon as she presses the “Save and post” button, the application saves the most recent video segment to the web server. If, for example,
the clip is specified to be 2 minutes long, the application generates a clip from the
most recent 2 minutes of the video. The intention is that the specialist can record
some event of interest right after she sees it. For example, a specialist who notices
the patient having a seizure can save a clip of it to send to a neurologist. The process
of saving a video clip can be initialized from both the patient and specialist nodes.

Figure 4-6: Video clip-saving window on the specialist node UI.

A traditional teleconferencing system assumes all relevant parties are available
during the meeting; however, in the case of patient transport, the specialist may not
arrive at the specialist node until after the start of the session. With this feature,
the transport team can save video clips of significant events the specialist missed to
bring her up to speed. During the session, the specialist may also want to save video
clips for further analysis, or, as described above, for a third-party consultation.

In the current version of MANTiS, video clips are only stored at the specialist
node. Generating a video clip involves copying a portion of the saved video stream
and converting it to a format suitable for playback in a web browser, specifically .mpg.
The video clip's name is labeled with a timestamp and any user-supplied descriptors.
Video streams are not saved at the patient node because of the large size of the
uncompressed video files of the whole session and our assumption that the laptop
used at the patient node is more constrained in resources than the computer at the
specialist node. Instead, when the transport team saves a video clip, a message is sent
to the specialist node with the relevant information, and the job is processed at the
specialist node. Because the starting frame can only be approximated due to latency,
the program adds some buffer before and after the specified segment to ensure the desired content is included.

Video clips are encoded and saved in a separate thread. Since saved clips can be as long as five minutes in length, clip-saving jobs are queued up and run asynchronously. The queue prevents an overload of concurrent threads that could affect the decoding of the received video, and hence video quality, at the specialist node.

4.1.6 Snapshots

The snapshots feature allows the specialist to save currently displayed video frames for further analysis. For example, if the specialist asks that a transillumination test be conducted, she may want to take snapshots during the test in case a second opinion is needed later.

When the specialist presses the “Save screenshot” button, a burst of snapshots is saved. A sample snapshot burst is shown in Figure 4-7. Multiple images are saved to provide backup options in case the saved frame is not ideal, e.g., due to occlusion or motion blur. For example, if the specialist wants a snapshot of the baby’s face while the baby is moving waving her arm, the burst feature increases the chance of having some snapshot without the baby’s hand in the way. The system aims to save a burst of images that is close in time, so that the images are relevant to the specialist, while still providing backup options. Currently, the burst consists of the 5 frames following the received request, although any corrupted frames detected by the decoder are not saved. In choosing burst size, we tried to strike a balance of having enough images to bolster the likelihood of a relevant, uncorrupted snapshot, and having too many images. Too many images would increase the difficulty of pinpointing a desired snapshot.

Snapshots are viewed in a separate window that appears when the “Show screenshots” button is pressed, as shown in Figure 4-8. Snapshot thumbnails are displayed in the scrolled window in reverse chronological order, and each burst of snapshots is grouped by the color of the border around the image. Snapshots are shown by clicking on the corresponding thumbnail; the currently displayed thumbnail is indicated by
Figure 4-7: A sample snapshot burst. The order of the five frames is top to bottom, left to right. The bursting feature provides the user with backup options in case one of the saved frames is not ideal, such as the fourth frame in the shown group.
its yellow border. Snapshots can be browsed using the left and right arrow keys to go to the previous and next thumbnail, respectively. Saved snapshots are also available on the web server.

Figure 4-8: Viewing snapshots in the specialist node UI. The selected snapshot can be emailed as an attachment, as described in Section 4.1.7.

The snapshot feature is available only on the specialist node. Taking a snapshot requires more precision than saving a video clip, and the latency in the sent video would make it difficult to pinpoint which frames the transport team wanted saved as snapshots. If we used the same buffering technique to ensure that the correct frames were saved, the bursting frequency would cause an overload of snapshots to be generated.

MANTiS adds a timestamp to both video clip and snapshot names. These timestamps are generated with respect to the session start time, for convenience in figuring out at what point during the transport they were saved.
4.1.7 Email

Email capability is only available at the specialist node, although it would be easy to generalize for both nodes, as we will discuss in Section 7.1. The email feature makes it easy for specialists to send saved snapshots to third parties for further consultation and is currently integrated in the window triggered by the “Show snapshots” button, as shown in Figure 4-8.

The email feature stores previously used email addresses for future convenience, and automatically generates a message subject and body which can be further edited by the user. The currently selected snapshot is attached with the email. MANTiS uses Gmail [6]—Google’s webmail service—for an SMTP server to send emails. For better protection of patient privacy, however, a local SMTP server could be used in the future, as we mention in Section 7.1.

4.1.8 Video transmission parameters

Adjustable video parameters include frame rate, latency, and resolution. When both sides of the application are connected to fast wired or wireless networks (i.e., network latency <100ms), the option for packet retransmission can be selected, and video can be sent with the lowest latency option (~1s) in conjunction with the highest frame rate (25fps) and VGA resolution. During transport, however, patient video is being striped over cellular data channels with limited bandwidth and a high loss rate. In this situation, adjustment of video transmission parameters can help physicians make the most of the available bandwidth to get video quality more suitable for what they are trying to view.

Video transmission parameters are adjusted at the specialist node. MANTiS offers three modes for adjusting video parameters: simple mode, advanced mode, and auto mode. Physicians with different levels of familiarity with video characteristics will want different levels of control over the parameters.
4.1.9 Simple mode

Simple mode offers physicians three general options, where each option is a different group of frame rate, latency, and resolution settings. Currently, all the simple mode settings have the same latency, but are geared toward different balances between frame rate and resolution, ranging from a higher frame rate with lower resolution to a lower frame rate and higher resolution.

With simple mode, physicians can easily associate each of the three options with a network strength and desired type of video. The summarized options are less intimidating than having to change each parameter individually, especially if the physician does not have a good sense of what each different frame rates, latencies, and resolutions entail.

The simple mode buttons are grouped with the auto mode button in a panel on bottom left corner of the specialist's user interface, as shown in Figure 4-9. If one of the modes in the simple mode panel is selected, it is colored blue.

![Simple and auto mode buttons in the specialist node UI. If one of the modes in the simple mode panel is selected, it is colored blue.](image)

4.1.10 Advanced mode

Advanced mode is for physicians who want fine-grained control over the video. The advanced mode panel is shown in Figure 4-10. Each of the video parameters can taken on a variety of settings. Physicians can choose among frame rates of 5, 10, 15, 20, and 25 frames per second; latencies of 0.5, 2.5, and 5 seconds; and five resolution options ranging from Tiny at $192 \times 128$ pixels, to Max at $640 \times 480$ pixels (i.e., VGA
resolution). These parameters are selected using radio buttons, and the changes take effect when the “Apply” button is pressed.

![Advanced mode panel](image)

Figure 4-10: Advanced mode panel in the specialist node UI. Frame rate, latency, and resolution parameters are selected via radio buttons, and the changes take effect when the “Apply” button is pressed.

Because the latency setting only determines the size of the playback buffer, the video latency can be larger than what is selected. When video is transmitted, frames are stored in a playback buffer as they are received, before the video is displayed on screen. The latency setting does not account for network delays; therefore, given the long round trip times of cellular data channels [18], video latency can be affected by network conditions.

### 4.1.11 Auto mode

In auto mode, the video parameters are determined by a heuristic that dynamically considers the number and characteristics of active network interfaces. For example, the system will immediately change settings to serve lower quality video when a card is removed or no longer active. If the system detects a new card, it first waits to check that the connection is relatively stable before increasing the video quality. The number of modems connected is irrelevant when a wireless or wired network is available; in that case, the heuristic knows to adjust for higher quality video.

As mentioned in Section 4.1.9, the auto mode button is grouped with the simple mode buttons.
4.1.12 Resync

Resync, triggered by the "Resync" button, offers a point of synchronization between the sending and receiving nodes. When video is transmitted during transport, the packets are sent over multiple cellular channels, and there is high variance between each channel's performance. The playback buffers used to store received packets, as mentioned in Section 4.1.10, absorb this variance to allow for uninterrupted video playback. A resync is internally generated when the playback buffer empties at one node of the application, or when the number of frames in the buffer consistently falls below a certain threshold; at this point, the other node is contacted, and the system waits for the buffer to be filled to a preset limit before resuming video playback. Some state information is also reset: most importantly, the video encoding rate is reset to a lower bitrate. The resync is used to prevent severely interrupted playback resulting from buffers getting stuck in a near-empty state.

Resyncs are automatically used by MANTiS to ensure consistency; whenever a change is made to the video, it pauses until both sides of the application have acknowledged the change. Resyncs are crucial upon a video resolution change, which requires a new encoder and decoder. MANTiS also automatically resyncs video during changes in camera selection and video zoom.

Because the internal logic is tuned to avoid all unnecessary resyncs, it may fail to detect a scenario that needs a resync. In this case, the user can utilize the "Resync" button as a soft restart for the video. When the video begins to be continually jerky or corrupted, the user should first attempt a resync, and then switch to a lower video resolution if the video quality does not improve.

4.1.13 Instant messaging

MANTiS has an instant messaging feature, shown in Figure 4-11, that provides an extra medium through which the transport team and the specialist can communicate. Right now, the audio channel in MANTiS is established with a regular cell phone call, as discussed in Section 5.2. This connection is less reliable than the aggregated one.
over which video is striped, and thus is more susceptible to disconnection when the ambulance drives through areas of low cellular coverage. In case of a dropped call, the transport team and specialist can send messages via the instant messaging box until the ambulance reaches an area where the audio link can be reestablished. From our patient tests on the Children’s Hospital transport truck, we found that instant messaging is also useful when noise in the ambulance (e.g., from the respirator or truck engine) renders the audio channel difficult to use.

If implemented as best practice, the instant messages could provide written confirmation of medical orders, e.g., the specialist sending messages to affirm the use of certain medications. The transport team could also use the instant messaging feature to log additional notes about the session.

4.1.14 Network data

The UIs on both MANTiS’s patient and specialist nodes display network data for the patient node, as shown in Figure 4-12. The network data consists of the send rate and receive rate in kilobits per second. It also shows the number of active network interfaces at the patient node. Network data for the specialist node is not displayed, since it is assumed that the specialist node is located at a hospital and connected to a fast network.

The send rate is also graphically represented by a bar indicator; the higher the send rate, the more bars depicted in the indicator. The bars are colored red if the send rate
Figure 4-12: Network data on the specialist node UI, showing that the patient node is sending 951 kbps and receiving 24 kbps with one active network interface. In this case, the patient node was using wireless ethernet to send high-quality video.

is <300KB/s, green if the send rate is >700KB/s, and black otherwise. These network bars are not necessarily a straightforward indicator of available bandwidth, since even when the aggregated channel is capable of providing more bandwidth, the sending rate will be low—and the network bars colored red—if the video has no activity or is of low quality. However, the bar indicator can be a fast visual confirmation for both the transport team and specialist when the video freezes up in a situation where there is no bandwidth, such as when the ambulance is driving through a long tunnel.

4.1.15 Unidirectional video

The “Use unidirectional video” button triggers the specialist node to stop sending any video to the patient node. The specialist may elect to use this feature when there is limited bandwidth and she does not need to demonstrate any procedures to the transport team. The button’s label will change to “Use bidirectional video” when pressed, so it acts as a toggle between the two options.

4.1.16 Ending the session

The “End session” button ends the current telepresence session. When pressed, both sender and receiver UIs will return to their pre-connection states.
4.2 Patient node

The in-session user interface for the patient node is simpler than the corresponding window on the specialist’s side of the application. One reason we decided to give the specialist more control of the application is because of the fundamental asymmetry in system resources at the two nodes. We assume that the specialist, rather than the transport team, needs to pay more attention to the baby’s video stream to both offer advice and prepare for patient arrival. Since the transport team is concurrently treating the critically ill baby during the session, we designed the patient node’s UI to require minimal interaction.

Prior to the start of a session, the patient’s side of the user interface is shown in Figure 4-13. The user at the patient node—whether a community physician or a transport team member—can use a drop-down menu to select the hospital to connect to. Tavarua attempts to connect to the selected hospital once the “Start” button is clicked.

![UI for patient node, prior to session](image)

Figure 4-13: UI for patient node, prior to session. When clicked, the “Start” button becomes a “Cancel” button for canceling the establishment of the connection.

The user interface at the patient node switches to the one shown in Figure 4-14.
when the session commences\textsuperscript{1}. The patient node UI also displays both the video being transmitted to and received from the tertiary care center. The four buttons beneath the patient’s video on the left side of the UI select the camera from which video is to be sent.

![UI for patient node, during a session. A preset image is used in place of the video when no video streams are detected.](image)

Figure 4-14: UI for patient node, during a session. A preset image is used in place of the video when no video streams are detected.

Pressing the “Save video clip” button activates the feature described earlier in Section 4.1.5. Network data—with the patient node’s sent and received data rates, and active interface count—is displayed beneath the specialist’s video (see Section 4.1.14).

Like its counterpart on the specialist node’s UI, the “End session” button severs the connection between the two nodes. The user interface switches back to the pre-session window in Figure 4-13 if the button is pressed by either side.

\textsuperscript{1}The video received from the specialist node in Figure 4-14 has been altered, because of screenshot-saving issues with the X-windows drivers on the laptop.
4.3 Web server

The web server is the central repository for the snapshots and video clips saved during each session. The web server provides centralized and easily accessible storage for session materials, and the browser used to access the files also provides a video playback mechanism for our application. The snapshots and video clips can be viewed from any device with an internet connection, including smart-phones; no access to or knowledge of our application is required.

A directory is created for each session as shown in Figure 4-15, and named with the timestamp of the start of the session. Each session directory contains separate images and videos folders. The saved snapshots are displayed as a gallery as shown in Figure 4-16, for easier browsing. Videos are listed in the videos folder (see Figure 4-15) and can be played back in a web browser with the appropriate plug-ins.

Figure 4-15: Web server screenshots. A directory is created for each session, and contains separate image and videos folders. The videos folder lists the generated video clips.
Figure 4-16: Snapshots from each session are stored in galleries on the web server.
In our current deployment setup, the web server is on the machine used for the specialist node.

4.4 MANTiS versus typical teleconferencing systems

Typical teleconferencing systems are closed systems. It is assumed that all relevant participants are available and present during the session, and the video is not recorded and made available for playback purposes. Absent individuals can be briefed via another medium (e.g., email) afterwards if they need to know what transpired during the session. In our case, if the specialist is not physically present at the specialist node, it is helpful for her to see video clips of the patient’s condition; a verbal or written briefing would lack a key component of the telepresence session. If the specialist were to describe the events to a third party, it would also be most helpful to show them the original video of exactly what happened during the session.

A typical teleconferencing system assumes nothing significant is happening unless both parties are present. In our system, the transport team is present but busy during patient transport; their focus is foremost on the baby rather than on the connected party. Also, it is useful to send video to hospital even if the specialist is not there to view it, because the information may be useful to her later.

Most video conferencing systems assume symmetry—both in the communications network and the usage by the connected parties—but MANTiS has several asymmetric characteristics. In terms of network resources, the specialist node is connected to a reliable high-speed network while the patient node relies on the cellular data network during transport. Hence, video clips and snapshots are stored at the specialist node so it is easier to forward this information. In a typical system, video transmission parameters have one static setting based on assumptions about the transport network; MANTiS assumes a network with dynamically changing attributes, and therefore allows video transmission parameters to be changed throughout the session.
In our usage model, the specialist at the specialist node has more time to focus on the session because she does not have immediate hands-on responsibility for the neonatal patient. Also, the monitor she uses at the specialist node has more screen space than that on the patient node’s laptop. As such, we designed the UI with more features under the control of the specialist. We assumed that the transport team would only want to push a button to start the session before leaving it to run with minimal interaction.
Chapter 5

Preparing for Deployment

The core technical challenge in this telemedicine application is sending high-quality near-realtime video over the cellular data network. This thesis, however, focuses on the interdisciplinary challenge of prototyping a useful medical tool built on top of the video-striping technology. In the previous chapter, we discussed the software features built atop Tavarua to make the system a richer collaboration tool for medical professionals. We also had to select and incorporate appropriate hardware, as well as overcome various practical roadblocks, before we could conduct test deployments of MANTiS. In this chapter, we will elaborate on some of the deployment challenges encountered: camera placement and method of attachment, wire management, audio, lighting, ease of setup, accident-proofing, and choice of hardware.

5.1 Camera placement and wire management

From a deployment perspective, the case of neonatal transport is a simpler case of the general problem of telemedicine during transport. In general patient transport scenarios, the ambulances can be of various sizes and outfitted in different ways, making it difficult to standardize camera placement and attachment methods. In the case of neonatal transport, all the equipment can be attached to the transport incubator. In particular, the size and fixed placement of the baby gives a simple solution to the issue of camera placement.
Together, the webcams used in MANTiS should ideally give a full view of the patient; at the same time, they cannot be in the way of the transport team, nor should they be placed where their view could be blocked by transport team members during en-route patient care. With the transport incubator, there are no occlusion issues. The baby is in a set location, and cameras mounted on top of the crib give a full view of the patient without getting in the way of transport team members, who interact with the baby from the windows on the side of the apparatus. Since all our equipment can be attached to the incubator, we also don’t have to worry about laptop placement and wire management for devices that would otherwise be placed in different corners of the ambulance.

5.2 Audio channel implementation

There were several deployment considerations regarding audio. We designed the system to concurrently stripe audio along with the video stream, and from a technical perspective, the audio channel had much less demanding requirements than those of the bidirectional video. Several logistical complications arose as we readied for deployment, the first of which had to do with microphone usage and placement. We originally planned to use the microphones on the transport incubator, and we brainstormed how to place microphones to capture both the ambient audio (e.g., the baby’s cries) and the communication between specialist and transport team. This issue became irrelevant when we borrowed the transport incubator and realized the noises and vibrations from the respirator would overpower any other audio picked up by the microphones.

Another overarching issue was audio latency: a latency of a few seconds would take getting used to and could potentially cause miscommunication. We considered giving the transport team headsets and using a “push to talk” model of communication, but in the end these issues led us revert to using a regular cellphone call for the audio channel. As discussed earlier in Section 4.1.13, we implemented the instant messaging feature as a backup medium of communication.
5.3 Obtaining patient vitals signs data

The capture and transmission of vitals signs data turned out to be another issue that did not surface until we were preparing for deployment. The transport incubators currently used by Children’s Hospital are equipped with the Welch Allyn Propaq Encore device [7], which monitors vitals signs including: electrocardiogram (ECG), respiration, pulse oximetry (SpO2), non-invasive blood pressure (NIBP), temperature, heart rate, etc. Our collaborating physicians noted the usefulness of directly seeing these vitals signs, some of which are difficult to verbally describe. However, this monitoring device has no video output or data port, only a small printer.

To get around the issue, we use a dedicated camera pointed at the screen of the vitals signs monitor to capture the data. This simple technique has the benefit of being a viable solution for any type of vitals signs monitor, regardless of the availability and format of a digital output. Since there is no place to attach a camera in front of the vitals signs monitor in the transport incubator’s current setup, we constructed an arm (as shown in Figure 5-1) that could rotate the camera into place when needed. The camera could not be fixed in the lowered position because anything projecting from the transport incubator’s frame could potentially cause problems when the transport incubator was being wheeled through doorways. The rotating arm makes it easy to move the camera up into a nonintrusive location above the transport incubator in case it gets in the way of the transport crew during patient care.

5.4 Lighting

Besides the issue of corrupted or missing packets, the bidirectional video quality is also strongly affected by the lighting conditions of the cameras’ environments. Lighting conditions are straightforward to control at the specialist node; however, ensuring good lighting is more complex on the ambulance with its varied light settings and the possible influence of natural light from the ambulance windows. Issues we encountered included lighting levels, resulting video colors, and reflections.
5.4.1 Lighting levels

For our webcams to produce high-quality video, there has to be sufficient lighting. Patient details could be lost in a darkened video, and low light also causes a drop in frame rate. Too much light also negatively affects patient video, washing out colors and details. The Children's Hospital transport ambulance has several different lighting settings, so we tried out different combinations during mobile tests to determine what would give the best quality video. These mobile tests were run during the day, and we noticed it was important to have enough artificial lighting in the ambulance such that any changes in natural light levels from the windows (e.g., when passing through shadows or tunnels) would not greatly affect video colors.

Before our first test deployment, our concerns led us to buy a commercial strip light for additional lighting on the transport incubator; the halogen lamp already attached to the transport incubator was too bright. As it turns out, the strip light was not necessary in this particular deployment situation given the amount of available lighting in the ambulance.
5.4.2 Video colors

Light source, webcam, and monitor settings all affect video color. For instance, the webcams we are using have auto color correction, which is why they produce good video within a range of environments. If we want MANTiS to have diagnostic-quality video, however, it is important for the specialist to know the exact color of the patient. Neonatal patients frequently suffer from slight asphyxiation, characterized by blue hues in the skin. To calibrate video colors, we keep a color wheel in both the transport incubator and at the specialist node, as shown in Figure 5-2. The specialist can confirm the baby’s color by matching it on the transport incubator’s color wheel, then looking up the matched color on her corresponding wheel.

![Color Wheel](image)

Figure 5-2: Color wheel for calibrating video colors.

5.4.3 Reflections

Reflections are another lighting-related challenge. The webcams facing the patient are clamped outside the crib, and pick up reflections from the clear plexiglass. If a reflective area happens to be located over the baby, part of the patient’s image is effectively lost.

The reflections are often a byproduct of the environment in which the transport
incubator is located, e.g., by overhead lighting. However, the baby can also be a source of reflections. Neonatal patients are frequently wrapped in saran wrap during transport as a cost-effective way to help the baby retain body heat and skin moisture. Under more serious circumstances, it is also used to protect babies with underdeveloped epidermises. Reflections off the saran wrap can be picked up by the webcams.

Currently, we have had to deal with reflection issues on a case-by-case basis. When the incubator is not in transport, reflections from overhead lights can be avoided with thoughtful transport incubator placement. During transport, small pieces of paper can be taped over the top of the incubator where overhead lights are reflecting. The paper eliminates the reflective spots for the webcams but does not obstruct the transport team’s view of the baby, which is mostly via the sides of the crib due to drug pump placement on top of the incubator.

5.5 Ease of setup

When outfitting the transport incubator, ease of setup was a significant consideration. Once the transport team arrives at the tertiary care center, they can do nothing that would reduce time spent caring for the critically ill baby. We minimized the time and work needed to contact the specialist node at the receiving hospital from the patient node, and we designed the equipment setup so as to not interfere with the transport team’s current patient care routines. In terms of software, the transport team only needs to make the appropriate hospital selection in the pre-session UI and press a button to start the connection (see Figure 4-13). When the session starts, the transport team checks the connected cameras via the user interface and may adjust the webcams if needed. From that point on, the specialist can take charge of available features.
5.6 Accident-proofing the patient node

One issue we overlooked when starting trial deployments of MANTiS was accident-proofing our application in the event the ambulance is in a traffic accident during transport. MANTiS’s deployment does not raise new safety issues for the baby, since all the equipment at the patient node is attached to the outside of the plastic crib. The transport team, however, was understandably concerned about firmly attaching the added hardware to the transport incubator, which is locked into place in the ambulance upon loading.

In this regard, we have plans to build a laptop mount on top of the respirator gas tank enclosure, then securely affix the network hardware to the laptop’s cover to save space. The cameras on top of the transport incubator are already clamped to a railing used to secure drug pumps, so they are both secure and adjustable. There are still concerns with updating the rotating arm for the vitals signs camera: it is currently made of aluminum and could possibly shear off in event of a crash.

5.7 Hardware selection

One important consideration when designing MANTiS was the decision to use only conventional, off-the-shelf components. Several major previous telemedicine efforts have been thwarted by this issue, including the project at the University of Maryland that enabled acute ischemic stroke diagnosis from transmitted video clips [48]. By using commercial cellular modems and conventional webcams, MANTiS can reap the gains of continuing technological advances.

Our hardware choices have not been without their own challenges. For cameras, we chose a current high-end mass-market webcam, the Logitech QuickCam Pro 9000 [8]. However, we have frequently run into unexpected problems with the camera’s driver during development. When we plug several of these cameras into the laptop mounted on the transport incubator, the driver prevents the cameras from all running at full resolution. We have also experienced some driver incompatibility issues over the
course of development because most drivers are written for Windows or Mac operating systems.

Cellular modems introduce their own complications. Recently, with the advent of the Apple iPhone [9], AT&T [10] data networks have been overloaded with traffic, at least temporarily. Our previous setup consisted of five network interface cards: two from Verizon, one from Sprint, and two from AT&T. The congestion of the AT&T 3G networks significantly degraded the prior aggregated channel’s network performance, and we have temporarily removed the two AT&T cards from our system, instead relying more on Verizon and Sprint’s CDMA network.
Chapter 6

Evaluation

In the process of prototyping MANTiS, we solicited feedback from the neonatal intensivists with whom we have been collaborating, and also tested the application in a moving ambulance. We conducted stationary evaluations of earlier system prototypes in the lab, then ran mobile tests of the current system in the Children’s Hospital transport truck. Section 6.1 describes the first demo of the system to the physicians, which we conducted in the lab. In this phase, we also visited Children’s Hospital to evaluate cellular signal strength and lighting conditions in the transport truck. We then updated the system with several requested features; Section 6.2 describes a subsequent assessment by one of the physicians. Section 6.3 describes tests in the moving transport truck without the physicians present. Section 6.4 details the final testing phase, in which another physician evaluated the system in the moving truck.

6.1 Initial demo

The physicians first saw a prototype of our application in the lab. We set up the specialist node in one office and the transport incubator in a nearby common area, and ran the system off the lab’s wireless network to demonstrate both MANTiS’s software features and our hardware setup on the transport incubator.

The physicians were enthusiastic about the application and its possibilities, but requested several additional features:
• **Vital signs.** Originally, we used only two cameras: one to show the baby’s head and torso, the other for the baby’s lower body. The physicians noted that it would be useful if they could also see the baby’s vital signs, either next to or in a picture-in-picture format within the current streaming video. Upon finding no data ports on the vital signs monitor, we decided to try using a camera to capture this information. Camera placement was tricky given that the camera needed to be far enough away to capture the screen of the vital signs monitor, yet not stick out from the frame of the transport incubator in a way that would prevent it from going through doors and hallways. We decided to address this issue by mounting a camera on a gooseneck arm.

• **Video clips, email, web server.** The physicians liked the snapshot feature and requested an analogous video clips-saving feature for capturing events such as seizures for further review. They also wanted to be able to email saved snapshots to other physicians. Up until this point, we had assumed an application usage model where the transport team and specialist were both present; we realized a video clip-saving feature would also be useful for recording important patient events in situations where the transport session had started and the specialist node of the application was unstaffed.

With these ideas, we began to further develop the collaborative aspect of the application. We decided to use a web server as a way to store the images and video clips from each session, so they could be easily shared with physicians who did not have access to our application. For instance, if the neonatal specialist wanted to discuss the infant’s seizure with a neurologist, the neurologist could immediately access the web server from any device with an internet connection and browser, including a smart-phone.

• **Adjustable cameras.** We were informed by physicians that the critically ill infants being transported could vary significantly in size, between 12 inches and 22 inches, and they were not always loaded into the transport incubator in the
same orientation. We realized we needed movable cameras to ensure the video streams were always centered on the patient.

- **Camera buttons for patient node.** The physicians requested buttons on the patient node of the application for switching between cameras. This feature would allow the transport team to direct the specialist’s attention to specific issues.

- **Color wheel.** During discussions of common critical neonatal symptoms and treatments, physicians mentioned asphyxia and the importance of correctly gauging the color of the baby, leading them to suggest the usage of the color wheel for color calibration between the two nodes of the application.

- **Accident-proofing.** Originally, the cameras were attached to the top of the transport incubator with velcro; one stipulation of borrowing the transport incubator was that we could not permanently modify it, e.g., by drilling holes. The laptop and network hardware were balanced on the respirator tank. We realized we needed secure hardware mounts when the physicians brought up the issue of securing hardware in a way that minimized risk to crew and patient in the case of an en-route automobile accident.

After implementing the requested software features, we verified that the updated code base and the new user interface worked in the mobile setting, by testing it in a commercial van during nighttime drives through Boston, in a manner similar to mobile tests conducted on Tavarua [43]. To prepare for tests in the Children's Hospital transport truck, we went and evaluated lighting conditions and cellular signal strength inside the truck. We were concerned about having sufficient lighting for the cameras; also, we wanted estimates of signal strength to see if data transfer from the ambulance was seriously hampered. The truck provided several lighting options which would suffice for the purposes of our application. Preliminary measures of signal strength from inside the ambulance showed manageable but significant degradation compared to outside the vehicle, suggesting that we should experiment with adding an external
<table>
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<tr>
<th>Interface</th>
<th>Download</th>
<th>Upload</th>
<th>RTT</th>
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<tbody>
<tr>
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<tr>
<td>AT&amp;T Option GT Max</td>
<td>Test</td>
<td>0.02Mbps</td>
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### Inside the ambulance

<table>
<thead>
<tr>
<th>Interface</th>
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<td>87ms</td>
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<td>AT&amp;T Option GT Max</td>
<td>Test</td>
<td>0.04Mbps</td>
<td>228ms</td>
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### Outside the ambulance

Figure 6-1: Download rates, upload rates, and round trip times (RTTs) for each of our cellular network interfaces as measured from inside and outside the Children's Hospital transport ambulance. Verizon and Sprint use the CDMA EV-DO Rev A network, and AT&T uses GSM HSDPA. We ran our tests using online network throughput estimator speedtest.net; it uses TCP while our system uses UDP, but was sufficient to give us an estimate of data rates for comparison purposes.

antenna to the ambulance in the future. Figure 6-1 shows download rates, upload rates, and round trip times for each of our cellular data modems as measured from inside and outside the ambulance when parked at the Children’s Hospital garage.

The network throughput estimator we were using from speedtest.net [11] failed to get statistics for the AT&T network, possibly because AT&T is throttling its network. Combined with the slow upload rate and high round trip times, we decided to stop using the AT&T cards.

### 6.2 Stationary system evaluation by physician

We ran the next test once we had implemented the features requested at the previous meeting with the physicians. The test was run in the lab with the same setup as the previous one; this time one of the physicians interacted directly with the user interface and provided usability feedback. The physician liked the interface and found it straightforward to use. Two aspects she found non-intuitive were the lack of clear
feedback when saving snapshots, which made it confusing as to whether the snapshot burst had successfully been saved, and how to email the saved snapshots. The email interface was difficult to find because it was bundled with the snapshot previews in the window triggered by the “Show screenshots” button. The physician liked the gooseneck arm solution to capturing vitals signs data, though during setup we found that the arm’s multiple degrees of freedom made it difficult to quickly adjust into place such that the camera was centered and in focus on the monitor.

When she tried out the web server, the physician emphasized the utility of the session directories containing saved snapshots and video clips—and having everything time-stamped—and began brainstorming further data integration for transport reconciliation sessions. With this feature, she mentioned that neonatal specialists would have more objective measures for treatments, e.g., time elapsed from when a medicine was given to when it started taking effect, when reviewing cases.

Since the system again ran smoothly, we began preparations for mobile tests in the Children’s Hospital transport truck. We made plans to further update the UI, but the work was not completed before subsequent tests. However, we did finish modifying the arm to its current swing-down design, which drastically cut down its setup time.

6.3 Mobile ambulance test, without physicians

In the first mobile ambulance test, we evaluated the system without the physicians present. We loaded the outfitted transport incubator into the Children’s Hospital transport truck, which then drove from MIT around Cambridge and Boston on routes typically taken to and from the city during transports, including driving past Children’s Hospital. We set up and monitored the specialist node of the application from the lab.

During this experiment, we lost video connectivity in a few tunnels, but otherwise had continuous connectivity of reasonably high quality. Figure 6-2 shows the received data rates for both the patient and specialist nodes of the application. The received
data rates for each node encompass all incoming packets, including video, system messages, and network overhead.

The Tavarua subsystem allows for the patient node to send video over all active cellular data channels and receive video via a single channel. As such, the specialist node’s received data rates generally far surpass the patient node’s received data rates. The specialist node’s received data rates do not directly correspond to video quality, because the video encoding rate can decrease even when there is sufficient bandwidth, e.g. for still images. However, data rates below $200\text{kbps}$ indicate degradation in video quality, and rates above $500\text{kbps}$ indicate qualitatively good video. The patient node’s received data rates are limited to $\sim100\text{kbps}$ because it utilizes only one channel; data spikes significantly above $\sim100\text{kbps}$ are due to network buffering characteristics. The drop in data rates around 45 minutes into the test was due to loss of connectivity in a tunnel.

Interestingly enough, MANTiS’s video connection was much more stable than the regular cell phone connection used to communicate between the ambulance and the specialist node. The cell phone call dropped several times in situations when we were still receiving video from the ambulance. The instability of the audio channel and the level of noise in the ambulance led us to add the instant messaging feature.

From the specialist node, we verified that all the software features worked as expected. We had the person on the ambulance lightly shake our test doll to simulate seizures, and we were able to see smooth movement in the video. The only other issue that surfaced was that the glare from the overhead ambulance lights created a distracting reflection in part of the camera’s field of view. We temporarily covered the relevant spots on the top of the plastic crib with small pieces of paper, but have yet to find a permanent solution.

6.4 Mobile ambulance test, with physicians

Satisfied with the video results from our first mobile test, we ran a similar test with a different physician evaluating the user interface. The physician used the specialist
Figure 6-2: Received data rates for both patient and specialist nodes of the application for the first mobile test. The drop around 45 minutes into the test was due to loss of connectivity in a tunnel.
node set up in the lab while we again loaded the outfitted transport incubator into the Children’s Hospital truck. A similar route was driven.

![Image](image_url)

Figure 6-3: Zooming in on the test doll’s simulated skin lesion.

The physician reported that she found the UI easy to use, and emailed snapshots of the test doll to members of the Children’s Hospital transport team. She was enthusiastic about being able to view saved video clips on the web server from her mobile phone. In addition to simulating seizures, we simulated a skin lesion on the baby by drawing a small mark on the doll’s face and utilizing both the zoom and snapshot features for closer examination. The zooming capability was limited by the camera resolution, but the simulated skin lesion, as seen in Figure 6-3, was relatively clear in the snapshots.

The received data rates for both the patient and specialist nodes during this session are shown in Figure 6-4. Results are similar to those in Figure 6-2 from the previous test, except it was a shorter session in which the ambulance did not drive through any long tunnels. Representative frames from high and low quality video are shown in Figures 6-5 and 6-6, and two sample snapshots are shown in Figure 6-7.

Overall, the physician seemed satisfied with the application and was eager to proceed to future deployment stages. From this test, we made plans to further accident-proof the system and begin the procedure for setting up a specialist node at Children’s Hospital’s neonatal intensive care unit.
Figure 6-4: Received data rates for both patient and specialist nodes of the application for the second mobile test.
Figure 6-5: Successive frames of qualitatively good video from the mobile ambulance test with physicians, from top to bottom, left to right. The bright spot on the test doll’s left shoulder is from the camera capturing a reflection of the overhead ambulance lights.
Figure 6-6: Successive frames of corrupted video from the mobile ambulance test with physicians, from top to bottom, left to right.
Figure 6-7: Sample snapshots from two separate bursts. The ambulance was moving when these snapshots were taken, but the pictures within each burst looked identical. A sample snapshot was selected from each.
MANTiS is a fully functional prototype that we believe is ready for field testing. Some technical and logistical tasks are remaining, as is a formal evaluation of MANTiS’s impact as a communication-enhancing tool that increases accuracy of diagnosis and appropriateness of treatment for patients.

7.1 Software

The remaining software-related tasks fall into three categories. Some are straightforward to implement and have not been finished because of time constraints. Other tasks should clearly be implemented but present real challenges. For the remaining tasks, we will have a better idea of whether and how they should be done when we have more deployment experience.

Simultaneous viewing of patient and vital signs videos

One of the features the collaborating physicians who interacted with MANTiS requested most was the ability to simultaneously view synchronized patient video and vital signs data, for instance in a picture-in-picture form. Given our current model of capturing vitals signs data from the screen of the vitals signs monitor using a camera, this feature requires the simultaneous capture and integration of two video streams. Implementation will involve significant code changes in Tavarua: right now, the code
initializes all the active cameras, then captures from one camera at a time. As such, this is an important but challenging feature.

**Saving more comprehensive records of patient transport sessions**

MANTiS currently creates a separate directory on the web server for each transport session, containing saved snapshots and video clips. The inclusion of the instant messaging log, sent emails, and any information currently recorded by hand by the transport team would turn the directory into a comprehensive, centralized record of the session. If the instant messages were used to provide written confirmation of medical orders, they would enable objective insight into en-route patient treatment and effects when combined with the recorded video of the session. Compliance with established medical practices could also be confirmed from the saved data.

With these changes, the audio transcript would be the last missing record from the session. Although we outlined the reasons for using a regular cell phone call as the audio channel in Section 5.2, sending audio over the aggregated channel available to MANTiS might improve the current state of audio communications, in addition to making it easier to record. As mentioned earlier, the cell phone calls failed several times during each of our ambulance tests, in contrast to the much more stable video channel.

The instant messaging log and sent emails can easily be saved. We will need more deployment experience to decide on the optimal audio channel implementation and how to best transform the session directory into a comprehensive record of the patient encounter.

**Application alerts**

A specialist might not be present at the specialist node at the start of a transport session. As such, it would be useful for MANTiS to alert the appropriate physician(s) of a new session by playing a sound and sending a page.

Also, auditory and visual alerts should be implemented for the arrival of any new instant messages. On the ambulance end, the transport team’s predominant focus
is on the patient. If a specialist is present at the specialist node, she is preoccupied with monitoring the video of the patient or engaging in a variety of other tasks. Right now, incoming messages are easily overlooked.

Such alerts are straightforward to add to the application.

Adding email capability to the patient node

With the current user interface, it is not immediately obvious how to send emails: the email feature is bundled with the snapshot display in the window brought up by the “Show snapshots” button as described in Section 4.1.6. Adding a separate “Send email” button and decoupling the two features would clarify the user experience. The window brought up by the new button would contain the email fields currently located in the snapshot display window, allowing users to send emails without attaching snapshots. It would also have a scrolling window of thumbnails—similar to the current snapshot thumbnails—as well as a listing of saved videos. Each item would have an adjacent checkbox to enable selection as an attachment.

Right now, the email feature is only available on the specialist node of the application. The collaborating physicians requested that email functionality also be added to the patient node as a means for the transport team to communicate with the specialist and any third parties not present at the session. An email window on this side of the application would offer fewer attachment options, because it only has records of the video clips it requested to save rather than access to all the saved session materials.

Future additional features for a more fully developed email module might include an importable address book and autocompletion for email addresses. Given more time, the basic email feature would be simple to incorporate into the application, but it would take more work to make the address book compatible with the users’ current systems.
Optimizing video settings

More experiments are needed to optimize both the suggested settings for the preset “simple modes” as well as the “auto mode” heuristic for adjusting video parameters based on detected network information.

We aim to have each simple mode embody tradeoffs in a way that is clear to the user. There are four main video parameters: color, latency, frame rate, and resolution. However, simple modes only adjust frame rate and resolution, because the current cameras come with a color-correcting feature and latency is set to the medium buffer size. To determine the settings associated with each mode, we would work with physicians to adjust advanced mode parameters for a photo-quality diagnosis where a faster frame rate is not crucial, and also for a diagnosis such as labored breathing where resolution is not as crucial. The third simple mode would be an average of the other two options.

More experimentation is also needed to determine the expected network conditions. We would like to use this information to refine our auto mode heuristic, which unlike simple modes, tries to get good video quality at any given moment without relying on a priori assumptions.

7.2 Hardware

In the ongoing process of selecting the most effective hardware to use on the transport incubator, there are still many options to explore:

- **Mobile computer.** We are considering a ruggedized tablet computer in place of the current laptop; if the transport team prefers a touchscreen to a keyboard, the tablet will allow us a different interface in a smaller form factor.

- **Cameras.** The current limitations with zoom and resolution quality lie with our choice of cameras, and could be mitigated with higher-resolution cameras that have optical zoom functionality. With future general deployment in mind, the option of wireless cameras could also be considered; they would remove
the hassle of wire management when cameras are be positioned around the ambulance or stretcher.

- **Hardware encoder.** Taiwan-based computer manufacturer Quanta [12] has expressed interest in this project and offered hardware encoders that are much more efficient than the current software encoders in use. During transport, the latency of the system is dominated by delays in the cellular data network and would not improve much with faster encoders, but the hardware encoders could theoretically enable the transmission of HD-quality video.

The accident-proofing issue, described in Sections 5.6 and 6.1, must also be solved before we can deploy the system. Secure mounts are needed for the mobile computer, cellular modems, and other networking hardware. The aluminum vitals signs camera arm should be replaced with an arm more resistant to shear from the impact of a crash. The arm also needs to lock into place in both its raised and lowered positions to prevent unexpected movement.

We are investigating other options for locations to mount the hardware. The collaborating transport team emphasized that the laptop's current location—the top of the respirator tank—is precious real estate to the transport team. A tablet computer's flexibility could enable it to be mounted on the side of the transport incubator or elsewhere in the ambulance.

Reflections on the plastic crib of the transport incubator, as described in Section 5.4.3, still need to be eliminated.

### 7.3 Security

Thus far, the development of MANTiS has not fully addressed the security issues of protecting patient data; for instance, the saved patient data on the web server needs to be protected by appropriate authentication and authorization mechanisms. However, we believe that the patient data striped over the cellular data network is secure enough for deployment. The cellular phone system offers a modicum of security
in its digital channels, and the splitting and striping of video and system data over multiple cellular channels should provide adequate obfuscation. A person who taps into any one of the channels cannot find out much about the data being sent. In the case that our users find the obfuscation from network striping insufficient, we can easily add encryption to Horde. Regarding the audio channel, a regular cell phone call should be permissible, given that it is currently the primary way for the transport team to communicate with specialists in the receiving NICU.

As described in Section 4.1.7, MANTiS currently uses Google’s webmail service, Gmail [6], to send emails. Emails should instead be sent via a local SMTP server.

7.4 Future experiments

MANTiS is designed to enable communication that will lead to increased accuracy of diagnosis as well as appropriateness and timeliness of treatment for critically ill infants. To measure the application’s impact on patient treatment and current clinical practices, we plan to continue with a more formal evaluation of the system. Besides some of the technical issues described in the previous sections, e.g., accident-proofing and security, a few main logistical tasks remain before we can begin a formal evaluation: installing the specialist node at Children’s Hospital Boston, negotiating arrangements with and installing specialist node equipment at a chosen pilot community hospital in the region, and obtaining permission to evaluate our application on patients. The evaluation itself will be conducted in several phases using a series of increasingly realistic experimental setups that will culminate in deployment with patients.

We will likely examine secondary markers rather than direct outcomes when evaluating MANTiS’s impact on neonatal care. We will use questionnaires to indirectly measure the application’s effectiveness in improving communication and coordination between transport teams, physicians, and specialists during transport. Trials to determine direct outcomes, e.g. declining transport rates or fewer cases of specific
common treatments, would have to be conducted over a long period of time and require that numerous factors be controlled.

7.4.1 Phase 1: Basic concordance of clinical opinion

The success of a telemedicine encounter is largely contingent upon the remote specialist having reliable high-resolution video transmission of the patient. As such, concordance of clinical opinion between two subspecialty trained neonatologists—one at the patient bedside and one conducting a remote examination—would be an important preliminary test to determine if the system transmits information of sufficient fidelity that the specialists would likely reach similar assessments if both were at the bedside.

In the first phase of the evaluation, we would be evaluating the quality of information transmitted by MANTiS. A telemedicine triage link would be created within Children’s Hospital. One neonatal specialist would remotely monitor a patient from the specialist node of the application, set up in a designated area within the hospital. The patient would be assessed in the outfitted transport incubator by another bedside specialist. In this test, MANTiS would use the hospital’s network rather than the cellular data network, to simulate the scenario of physicians at community hospitals communicating with specialists at tertiary care centers.

To validate the reliability of the transmission, we would check that the two specialists reached the same conclusions regarding treatment for the patient. The specialists should produce the same diagnosis of the patient’s symptoms, e.g. agreeing that the baby had a seizure. They should also have similar subjective analyses on factors such as patient responsiveness, degree of respiratory effort, gestational age, and presence or absence of cyanosis and edema.

This type of mock triage system has been trialed in the context of assessing feasibility of telemedicine for use in the assessment of pediatric emergency room patients. In a study at the Childrens Hospital of Pittsburgh in 1998, it was shown that a reliable telemedicine link could be established such that pediatric patients would be assessed accurately [31]. The ability of the remotely connected physician to detect
abnormal findings ("sensitivity") was reported to be 87.5%, and the ability to detect normal findings ("specificity") was reported to be 93%. Given the considerable advancement of technology since the time of this particular study and the high quality of transmitted video measured during Tavarua’s development [18], we are confident that our current telemonitoring system should provide at least equal, if not improved, results.

We would use a questionnaire to obtain other feedback with regards to the physician and transport team’s experiences employing the system, e.g., aspects of system performance and ease of use. During the experiment, we would also record which application features were most utilized by physicians.

### 7.4.2 Phase 2: Consultations from the pilot community hospital

The second testing phase would evaluate MANTiS’s impact when the ill baby is at the community hospital. We would install the specialist node of the application at a chosen pilot community hospital in the Boston area. Prior to use on patients, simulations would be conducted with the neonatal care teams at both sites. These would familiarize all providers with the application as well as establish a communication protocol that would allow the providers to relay information efficiently and effectively. Patients who complied with the informed consent protocol would be enrolled in the pilot study after clearance from the respective institutional review boards.

During this phase, we would collect case studies to determine whether physicians thought the application-provided link to neonatal specialists benefitted patient treatment. We would record the frequency of consultation and the number of transports, noting cases where transports were requested or cancelled as a result of consultation. We would also collect case histories of patient care plans affected by consultation, e.g. cases in which specialists prescribed medicine to be administered to the patient prior to transport.

As in Phase 1, we would gather information about application usage patterns
to get a sense of how often different parts of the software were used. We would check factors such as the number of sent emails to gauge MANTiS’s usefulness as a collaborative tool. The same questionnaire from Phase 1 would be administered for each patient encounter, but would additionally note parameters such as ease of communication.

7.4.3 Phase 3: Consultations during transport

In the final phase, we would evaluate MANTiS’s impact on patient transport. Upon the arrival of an enrolled patient, the first responding physician at the community hospital would initiate the interactive teleconsultation session. If it was determined that the baby would require transport to Children’s Hospital, the Children’s transport team—equipped with the mobile patient node—would be mobilized. The tertiary care physician and on-site physician would continue consultation until the transport team’s arrival, at which point they would assist in stabilization of the patient and start the process of moving the patient to the outfitted transport incubator on the ambulance. The transport team leader would re-establish the session with the tertiary care physician.

Again, we would utilize the previously outlined methods to gather data on the utility of our application. Community physicians, transport team members, and specialists would all complete questionnaires regarding the patient encounters. We hope the communication and collaboration enabled by MANTiS would increase the overall sense of preparedness for the patient encounter.

7.5 Summary and Conclusion

In developing MANTiS, we have created a collaborative mobile telemedicine application to improve the care of extremely premature or critically ill babies at sites where there is limited specialized expertise and during transport to a tertiary care facility. Our application enables clinicians—whether they are at a community hospital or in a vehicle—to quickly obtain a consultation with the neonatal specialists who are most
knowledgeable and experienced in caring for critically ill babies. We adjusted the application according to feedback from collaborating neonatal intensivists in order to create a relevant tool for them.

By building our application on top of Tavarua, a subsystem that stripes high-quality bi-directional video over the cellular data network in near real-time, we harnessed its technology in a user-friendly form for physicians and clinicians. We added additional collaborative features to tailor the mobile video-conferencing application toward our neonatal treatment case: email, to send snapshots of the session; a web server, to store saved session materials for convenient access in third-party consultations and post-transport review; and instant messaging, as an additional medium for communication. We also outfitted a transport incubator for deployment and overcame various challenges to conduct preliminary tests in a moving ambulance. We believe the system is now ready for formal evaluation and deployment.

Although we have focused on the case of neonatal transport, MANTiT could easily be generalized to other medical scenarios where the clinician who is the patient’s first point of care may lack the specialized expertise to determine optimal treatment. For instance, in the case of stroke where prompt delivery of the correct therapy can dramatically improve a patient’s potential recovery, MANTiT could allow a paramedic to confirm a patient’s symptoms with a specialist and decrease the time to treatment.

MANTiT can be further generalized for use in any mobile scenario where the most accessible communication infrastructure available is the cellular data network and a high-bandwidth, stable communication channel is needed. MANTiT already offers higher-quality video than current mobile telemedicine applications and, given its use of commodity hardware, its teleconferencing capacities will continue to improve with any ongoing improvements in the cellular data network infrastructure.
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