A Real-time Collaborative Tele-ultrasonography System Applied to Underserved Communities

Abstract: *This paper presents the results of a real-time tele-ultrasonography system applied to communities far from high-complexity hospitals. Statistics from the Brazilian public health service show a miss rate higher than 30% in obstetric ultrasonography exams in Porto Alegre city, and more than 60% in the Restinga community. Additionally, the time gap of at least 4 months between the local exam request, by the periphery health center physician, and its realization in the main hospital was unacceptable. The PoaS@ude project presents a low-cost tele-ultrasonography system applied at Restinga neighborhood, where examinations are carried on the outskirts' health center accompanied in real-time by a specialist physician located on the reference hospital at the central city of Porto Alegre. During the project, the examination miss rate decreased to less than 10% and the exam waiting time to less than 30 days. Finally, the results obtained during the pilot made the project to evolve towards a permanent service, being the solution easily reproduced elsewhere.*

1. Introduction

Most of the current telemedicine applications have characteristics like "second medical opinion", "access to remote medical knowledge bases" and "remote assistance" (even surgeries [Brell, 2009]). Those are applications that aim, chiefly, to provide technical support to the decision-making of non-specialist doctors, who, often, work in places far from the medical excellence centers.

Tele-ultrasonography real-time applications present specific characteristics that demand more network and processing resources from the base computer system. Real-time in this paper means both sides communicating collaboratively and not feeling uncomfortable with the delay. According to Bartoli (2007), this time should be less than 400ms in IP videoconferences to meet ITU (International Telecommunication Union) standards.

When the local doctor lacks the knowledge or experience at the medical discipline or the ultrasound interpretation, the remote doctor must take the responsibility for the final exam report. To take this responsibility, the remote doctor must have all the resources and information referred to the exam execution, as if he were in the examination room. For ultrasonography exams, the video of the ultrasound (US) probe position on the patient and a good quality video of the ultrasound exam itself are imperative for such a diagnosis. This way, the communication between both doctors must occur synchronously and in real-time.

To obtain the desired quality, several factors related to the network and multimedia areas must be taken into consideration, such as the bandwidth, the audio and video encoding, the processing capability of the involved equipments, and the communication delay. These factors are the key for a good user experience.

Details of the proposed solution are given through the following sections. Section 2 presents related works, followed by Section 3 that quickly describes the scenario and motivation. Further, Section 4 describes the tele-ultrasonography system and Section 5 presents its validation, results, and benefits for the society. Finally, Section 6 concludes the article.

2. Related Work

Most of the Brazilian telemedicine initiatives focus on either the spreading of medical knowledge for health professionals, who act far from the centers, or second medical opinion services. The Federal Government, through the RUTE (University Telemedicine Network) [Rute, 2011], has been making significant investments on the development and online availability of knowledge databases related to health. This is a way for improving the decision quality and reducing the so-called "ambulance-therapy" phenomenon, i.e., where underserved hospitals send patients to the referral city, regardless of previous diagnosis.

In most cases, second opinion services occur in an asynchronous manner, i.e., the specialist receives the patient information and can answer later. It can also be observed that, in the second medical opinion, the responsibility for the exam report belongs to the local doctor, not the specialist. The T@lemed Project [Binotto, 07], for example, works between the southern and northern Brazil focusing on second medical opinion through transmission of medical images to main health centers in a "store-and-forward" way, i.e., not at real-time.

Another situation was presented by Sibert [2008] who performed an experiment of ultrasound images and video transmission in rural emergency situations targeting laryngoscopy. The images are transmitted from the ambulance through mobile phones using the 3G connection. The results showed good acceptance of the system by the doctors. However, it has negative remarks on the low image quality caused by the low bandwidth of 3G.

The PoaS@ude project, presented in this paper, is a telemedicine initiative where the exam report responsibility belongs to the remote specialist doctor located at the referral hospital, i.e., it is the first medical opinion. This feature requires the remote doctor to coordinate and participate at the exam, being a constraint to receive in real-time all the information he would have if he was performing the exam locally.

3. System Motivation

The initial motivation to deploy the telemedicine system specifically at the underserved Restinga district (~100,000 inhabitants), in Porto Alegre (~1.5 million inhabitants), was twofold. First, this community needed immediate assistance, as the missing rate in ultrasonography exams was about 60%. Second, because there was a high bandwidth PLC (Power Line Communication) network installed by the government on that neighborhood. The basic health unit is called Macedônia Center, and it makes about 5,000 medical consultations per month.

In a contact with the Municipal Health Department, it became clear that the inhabitants from Restinga had a considerable difficulty in undergoing more sophisticated medical exams, which are made outside the neighborhood in better equipped health centers that have specialist health professionals. Most of the patients have neither enough money to pay for four to six buses to perform the exam, nor time to spend a whole day in the process. The pregnant women are one of the most affected groups since most have no one to care for their other children during the time they are having routine obstetric exams downtown – located more than 35km far from the neighborhood. Due to this miss rate, the World Health Organization (WHO) recommendation of about 4 exams during prenatal care was not accomplished, and that lack of prevention in prenatal period is responsible for a high number of complications not identified on time, leading to the loss or malformation of the fetus and, even, to the death of the mother.

Thus, the decision was to develop a synchronous telemedicine system for routine and prevention obstetric ultrasonography exams performed at the Macedônia health center, under responsibility and remote real-time monitoring of specialist doctors from the Fetal Medicine Department of the Presidente Vargas Maternal-Infant Hospital, located in the central region of Porto Alegre.

The development team and the medical team defined the following system requirements:

- Good ultrasound video quality, to show ultrasonographies' details (perceptible movements as the heartbeats and the respiratory system). This demand is subjective, and the adequate quality is determined by the doctor when he can distinguish the important parts of the fetus needed to perform the correct examination and taking responsibility for it.
- Audio communication between the specialist doctor and the local resident physician.
- Remote pointer, so that the doctor can pont details to the patient and the local physician (who is with the patient). The remote doctor uses its mouse inside the ultrasound area, and the mouse movements are send to the local place, showing specific areas which the doctor wants more attention.
- A second video showing the hand position of the local physician, focusing mainly in the transducer position on the patient's abdomen.
- A third video of the remote specialist doctor, allowing the patient to see who is talking with her and the local physician.

4. System Implementation

Figure 1 shows a schematic of the developed solution. At the Health Center, there is a non-specialist physician who performs the exam at the patient. At the Main Hospital, it is located the specialist doctor responsible for the report. At both ends, there is audio coding and transmission.

In the health center, the system captures the video signal from the ultrasound and the hand position of the attendant, composing both videos on the same screen. The hand position is encoded in low resolution video. Both signals are encoded and transmitted live, being received by the doctor, who analyses it and communicates by video, audio, and through the remote pointer, giving instructions to the attendant and also speaking with the patient.

The ultrasound equipment allows freezing selected images and storing in DICOM (Digital Imaging and Communications in Medicine) format for future analysis. The equipment also allows making calibrations with the ultrasound and measuring determined areas, as the fetus' head diameter and femoral bone size. This is important for the doctor to get the fetus size, comparing to standards and finding growing anomalies.

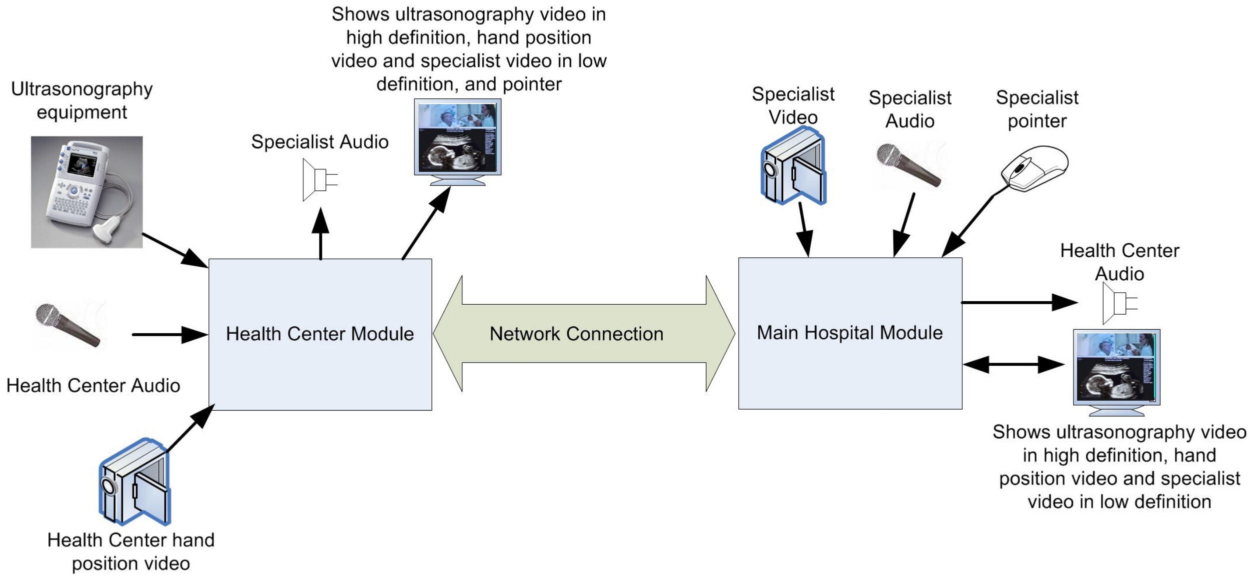
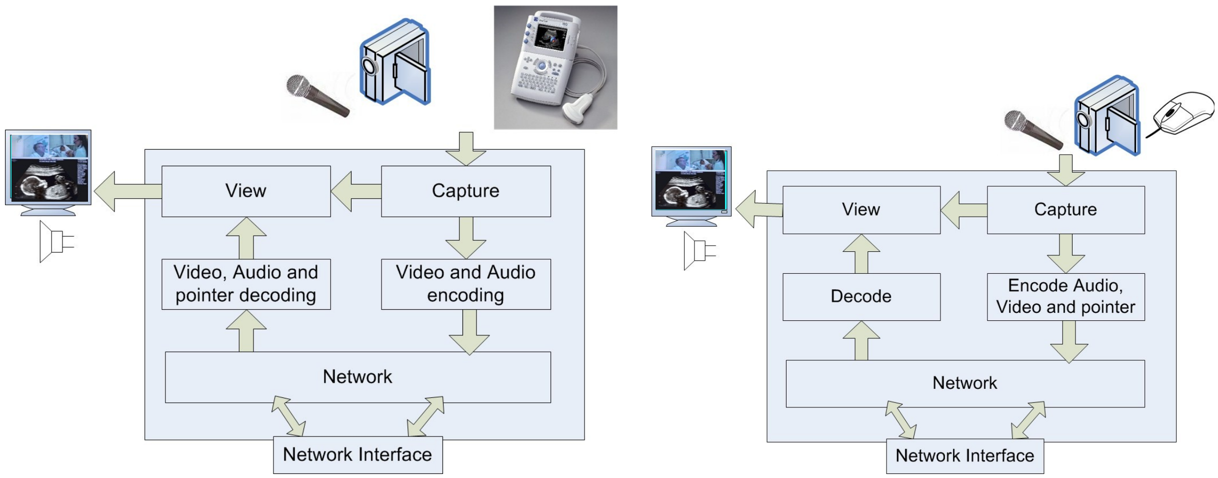


Figure 1: Overview of the developed solution

The system internal structure of the health center is based on libraries developed by the group, and shown on Figure 2a. The description of each library is:

- **Capture**: responsible for receiving the audio and video signals of external equipments, such as camera and microphone, independent from the communication interface (DV, acquisition card or USB). In the specific case of the tele-ultrasonography system, the capture module receives three simultaneous captures: a) the ultrasound video signal; b) the video signal showing the attendant's hand position; c) the attendant audio.
- **Video and Audio encoding**: responsible for compressing the video and audio streams. The generic interface allows working with different video and audio codecs.
- **Network**: implements the point-to-point communication between the local and the remote locations.
- **Video, Audio and pointer decoding**: decodes the video and audio that comes from the main hospital, as well as the pointer signal controlled by the doctor. After decoded, the audio is sent directly to the speakers.
- **View**: presents the user interface, specifically: a) small-sized video of the attendant hand position; b) small-sized video of the specialist; c) large-sized ultrasound image; d) remote pointer image, controlled by the doctor.

The system block diagram placed at the referral hospital is complementary and presented in Figure 2b. The main differences compared to the health center are that it encodes only one video, audio and pointer. Besides that, it decodes the remote audio and video, presenting them on the computer screen.



a) health center *b) main hospital*

Figure 2: Block diagram of the system

The libraries were developed in C/C++ language, since it allows better control on the hardware and queues. It was created a Memory Manager (MM) block, which is responsible for the queue control in the system, managing also the synchronization and semaphores use.

The queues are a key element of the system, and the MM allocates blocks of 20Mbytes for all queues. If the memory is running low, the MM allocates one more block. There are the following queues:

- **Video capture queue**: all captured frames go to this queue. It can store about 10 frames of 720x480 pixels in 4:2:2, but this buffer rarely became full since the Encode block gathers the data from this queue and sends them to be encoded with ffmpeg[1] video. There is another capture queue module which reads the frames from this queue and sends them directly to the output, in order to create de local video preview.
- **Network send queue**: after the video frames are encoded, they go to the network queue to be sent to the destination using UDP.
- **Audio capture queue**: idem to the video capture queue, but for audio.
- **Network receive queue**: used to receive frames from the destination. They are sent to ffmpeg decode, in order to be reconstructed. If it is a video frame, it goes to ffmpeg video decoder. If it is an audio frame, it goes to ffmpeg audio decoder.
- **Video and audio view queue**: after decoding, the frames go to their respective queues (video or audio) and wait for the system to send them to the respective output (video or sound card).

The pointer control has a separate architecture, and executes in parallel with the audio and video encoding / decoding. Another system's library is called "Netcom", which is responsible for all the signaling (in TCP), as, for example, the resolution information to be used, codec's type to be used, keepalive, among other parameters. Additionally, it uses the QT framework, mainly for the graphical user interface.

5. Results and Discussion

To reach the desired system quality, preliminary experiments were performed to validate the effectiveness of the practical requirements [LeRouge, 02]. Using two personal computers (Pentium 3.4 GHz, dual core CPUs with 2 GBytes of RAM Memory), the main evaluated parameters were:

- Video compression using the codecs H.264 and MPEG-4;
- Resolutions of 720x480 and 320x240 pixels;
- 15, 20 and 30 frames per second;
- Bitrate of 500 kbps, 1 Mbps, 1.5 Mbps and 2 Mbps;
- Audio AAC (Advanced Audio Coding) 64 kbps and 128 kbps.

[1] www.ffmpeg.org

The H.264 encoder produced a good video quality, but demanded considerable processing power from the low capacity computers during the video encoding process. It increased the total delay to around 1s, and in some condition caused application freeze. MPEG-4 encoder resulted in a smaller delay (lower than 300ms) and a good video quality, being chosen. This is an application parameter and can be changed if using higher processing power computers.

In relation to the ultrasound video, any resolution below 720x480 was considered improper for using according to the specialist doctor. The main reasons are the artifacts blocking effects and pixel interpolation problems detected in the reconstructed video, which could invalidate a correct medical interpretation of the ultrasound images. Some experiments changing the number of frame per seconds (fps) were also performed in order to define the better relation between frame rate and visual movement video requirements. With 20fps, the result was acceptable according to the doctor. However, better results were achieved using 30fps. Regarding audio experiments, the AAC codec with 128 kbps provided a better audio quality.

The experiments were also performed changing the overall connection bitrate for audio and video. Tests used 500 kbps, 1 Mbps, 1.5 Mbps and 2 Mbps. The best cost-benefit was obtained using 1 Mbps, which was the bitrate established for the system.

The transmission delay was measured based on the clock, which was recorded while transmitted. The overall one-way delay was about 300ms, which meets all the communications needs between doctor and patient. It can be considered real-time, according to the definition stated on the beginning of this paper.

Using these parameters, the video showed perfectly the fetus' movements and met the original need of verifying the heartbeats and the automatic breathing movements, crucial for checking the fetus' health. Figure 3 depicts the environment at the health center, where the local physician places the ultrasound probe according to the doctor's remote guidance. It shows the ultrasound equipment on the right, near the patient, and the system just on the left side of the physician.

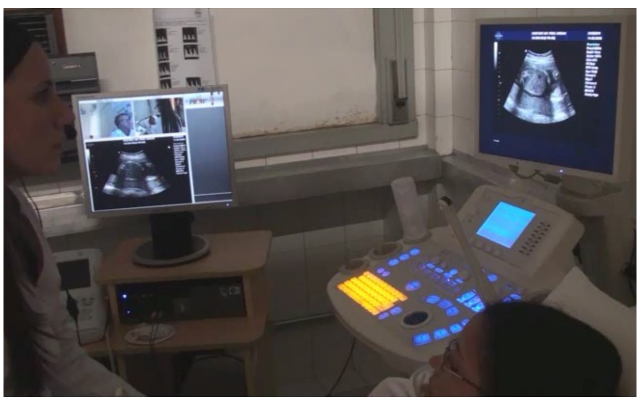


Figure 3: Examination at the Macedônia Health Center

Figure 4 presents the referral hospital, showing the remote specialist doctor that guides the other physician through audio and mouse pointer. From the figure, it is possible to visualize the ultrasound exam as well as the small images showing the probe position and the non-specialist physician. The remote mouse pointer is used to show specific points when he/she is commenting by audio.

During the first month of use, 40 patients were interviewed to collect subjective opinions about their experience. The mentioned major advantages were related of being close to home and the smaller waiting time to perform the exam. The women interviewed did not feel the attendance was impersonal for the fact of talking to the health center doctor, and viewing the specialist in the small video (left on the figure).

Figure 4: Remote attendance by the hospital doctor

The system was released on April 30th, 2008 and it is performing around 40 monthly tele-ultrasonographies at the Macedônia Center. Besides, it was expanded to four more districts, attending monthly about 100 patients, and attended more than 2,000 patients up to now. The consultations identified about 10% of cases that required immediate treatment due to bad fetus formation, what would be disastrous in the case of treatment without the PoaS@ude. These patients were informed of the results and immediately referred to the specialist at the referral hospital. Additionally, from the original 4 to 5 months waiting time at Restinga, the patients are now waiting about 30 days, accomplishing with the WHO recommendation, and the examination miss rate decreased from 60% to 10%.

For comparison purposes, a qualitative analysis is performed with similar systems on Table I. It is important to emphasize that our system is the unique that presents 3 videos for the examination process, including the probe on the patient which is very important to associate the ultrasound image with the correct probe position.

Table I: Qualitative comparison

	Real-time	**Chanels**	**Bitrate (Mbps)**	**Ease of usage**	**Cost**
PoaS@ude	yes	3 videos, 1 audio	1	high	low
[Binotto, 07]	no	1 video	0.5	medium	medium
[Pyke, 07]	yes	1 video, 1 audio	0.65	medium	low
[Kim, 07]	yes	1 video	0.6	low	low

6. Final Remarks

This paper presented a new tele-ultrasonography system connecting a high populated poor district with a reference hospital. The solution uses a MPEG-4 or H.264 video codec, AAC audio codec, resolution of 720x480 pixels to the ultrasound and 30fps. The smaller videos use a resolution of 320x240 pixels. The measured delay was ~300ms, maintaining the real-time sensation, being better than the 400ms case for the IP standard videoconferences.

The public that was benefited by PoaS@ude is divided in 2 groups: pregnant women residing in the peripheral areas of Porto Alegre and non-specialist physicians, who act in health centers far from the central area. The benefit for the first group is the reduction of the absences in prenatal exams and the consequent early diagnosis of pregnancy problems. The second group improves their training because of the constant contact with specialist doctors.

All the patients who made ultrasound exams manifested their contentment about being able to perform the prenatal exams close to their homes, saving money from the transport and being able even to take their other children to the health center. Even more important was the examination waiting time reduction.

A system case specific evaluation form was created to interview doctors and patients. The information gathered from the doctors was focused on technical and medical data, which was the basis for the system parameters establishment, like the chosen video encoding method. Basically, for the patients, the evaluation form analyzed the improvement of 5 factors. The patient was asked to give grades, from 0 to 5, to: informality on the procedure, medical care quality improvement, waiting time improvement, logistics improvement, financial saving. The informality factor average was 0.4 and the other factors achieved a grade higher or equal to 4.

Although it is clear that High Definition videos are ways better than Standard Definition, it is necessary to adapt the technology to the real scenario of the communities in order to deliver a practical and useful tool. This way, PoaS@ude is intended to be low-cost and of easy replication over different bandwidth infrastructures, like other underserved and rural regions. This way, standard hardware equipments allow a rapid penetration of the system by requiring low-cost video cameras and computers to encode regular video resolution over limited bandwidth.

This project was the basis for two ongoing extensions: a) VideoMed project, intended for generic remote assistance, where the ultrasonography video is replaced by any kind of video or image, and the physicians can cooperate and interact remotely; b) Assisted surgical low-cost operating room, where the supervisor can assist, interact, and guide a novice surgeon during initial surgeries, in a process called “tele-mentoring”.

Finally, PoaS@ude is also part of the students’ effort on telemedicine at the Federal University of Rio Grande do Sul, whom have won the first prize at the 2011 IEEE Presidents’ Change the World Competition. Additionally, it accomplishes with at least two of the Millennium Development Goals of the United Nations: reduce child mortality and improve maternal health.

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