Biomedical Data Mining

Extended Abstract

# Clinical trials and evaluation of Cardiac ultrasonography over 4G wireless network using a teleoperated robot

Sotiris Avgousti and Panicos Masouras

**Abstract**

A wearable tele-echography robot (MELODY) with four levels of-opportunity that allows a clinical master to inspect a ways off a patient by ultrasound was assessed and tried over 4G portable organization. At the master side, the clinical master utilizes a fake test to control the genuine test which is constrained by the mechanical arms at the patient side and situated on the patient's body by paramedic faculty. The correspondence between the two destinations is worked with by a videoconferencing join. The telerobotic framework has now been clinically tried and popularized. The exploratory arrangement of a wearable tele echography robot, the MELODY framework over a 4G network interface used to quantify the framework execution is portrayed. The assessment and examination of the significant clinical ultrasound video and the pertinent issues characterized as far as the normal throughput and jitter delay are researched. A far-reaching video coding guidelines examination for heart ultrasound applications is performed, including H.264/AVC and HEVC utilizing an informational index of nine cardiovascular ultrasound recordings. Both level headed and emotional (clinical) video quality appraisal were performed.

This Letter proposes a start to finish versatile tele-echography stage utilizing a compact robot for far off heart ultrasonography. Execution assessment explores the limit of long-term evolution (LTE) remote organizations to work with responsive robot tele-control and ongoing ultrasound video web based that meets all requirements for clinical practice. Inside this unique situation, an intensive video coding principles examination for heart ultrasound applications is performed, utilizing an informational collection of ten ultrasound recordings. Both unbiased and abstract (clinical) video quality appraisal exhibit that H.264/AVC and high effectiveness video coding principles can accomplish indicatively lossless video quality at bitrates well inside the LTE upheld information rates. Diminished latencies experienced all through the live tele-echography meetings permit the clinical master to distantly work the robot in a responsive way, utilizing the remotely conveyed heart ultrasound video to arrive at an analysis. Considering starter results reported in this Letter, the proposed robotised tele-echography stage can accommodate dependable, distant determination, accomplishing tantamount nature of involvement levels with in-medical clinic ultrasound assessments.

**Keywords:** biomedical ultrasonics, cardiology, medical robotics, telemedicine, Long Term Evolution, 4G wireless networks, teleoperated robot, end-to-end mobile teleechography platform, portable robot, remote cardiac ultrasonography, long-term evolution, LTE wireless networks, responsive robot telemanipulation, real-time ultrasound video streaming, video coding standards, video quality, teleechography sessions, cardiac ultrasound video, robotised teleechography platform, remote diagnosis, in-hospital ultrasound examination

## INTRODUCTION

Providing the desired quality levels of specialised healthcare across the population is a challenging task. This task becomes even more daunting in remote, often isolated areas and developing countries, where the physical presence of specialised physicians is limited. At the same time, already dispersed rural hospitals, due to

Sotiris Avgousti and Panicos Masouras
Cyprus University of Technology, Cyprus, E-mail: sotiris.avgousti@cut.ac.cy

the lack of appropriate infrastructure and personnel, cannot intercept the ever growing need of patients moving long distances towards the nearest regional hospital. For this purpose the European Union (EU) and the World Health Organization (WHO) have identified the development of mobile health systems and services as a top priority. The latter initiative aims at reducing healthcare expenditures while increasing the quality of healthcare services, and hence patients' quality of life (QoL).

Ultrasound imaging is an integral part of many clinical applications ranging from typical ultrasound examinations (cardiac, foetus, carotid artery, abdominal aortic aneurysm etc.), to medical emergencies and surgical decision making. As a result, there is a great demand for this technique to be available even in the absence of ultrasound specialists, as in the case of most isolated areas, developing countries, and emergency/disaster incidents. On the other hand, this specialised healthcare method has been traditionally expert-dependent, involving a high-level of training.

Over the past decades, numerous mHealth medical video communication systems have been developed to address this issue. Such systems rely on trained ultrasound technicians and/or paramedical staff to acquire an ultrasound video (perform the on-site examination), while a remote medical expert assesses and provides the diagnosis based on the communicated ultrasound video in real time. Over the same period, tele-operated robots for remote ultrasound examination have also witnessed a significant growth. Such systems further benefit from the fact that no additional specialised personnel are required to remotely perform an examination and provide a clinical diagnosis.

Despite the plethora of such systems and services, however, their adoption in standard clinical practice remains limited. As debated in, the primary reason is that they do not provide a comparable quality of experience (QoE) level to that of in-hospital ultrasound examinations. The latter is largely attributed to underlying video compression and wireless networks technologies. Mobile tele-manipulated robots performing remote ultrasound examinations typically convey the following data: (i) robot control commands in the form of x, y, z vectors, which have low-bandwidth requirements, but are delay sensitive and loss intolerant, (ii) ultrasound video data which are bandwidth demanding – as the they communicate the clinical information –, are also delay sensitive although to a lesser extent, and minor losses are tolerable, and (iii) ambient audio and video information which require moderate bandwidth, and being not so critical, in most cases certain delays and losses are tolerable. Based on the afore-mentioned, data rate and latencies found in early 3G wireless networks and video encoding capabilities of video coding standards prior to H.264/AVC, essentially prevented the wider adoption of mHealth tele-robotics systems in standard clinical practice.

In this Letter, the objective is to develop a reliable, robotised tele-echography platform over emerging 4G and beyond wireless networks. The goal is to investigate the hypothesis in that wider adoption of such systems and services in standard clinical practice can be materialised once providing clinicians with comparable QoE to in-hospital examinations. The approach is to exploit open-source video encoding technologies for low-delay diagnostically lossless ultrasound video communications and responsive robot tele-manipulation over commercially available 4G-long-term evolution (LTE) networks. The contributions of this Letter, which significantly extend prior work in, are summarised in the following areas:

i. *Video coding standards comparison for cardiac ultrasonography*: Open-source video coding standards comparison for cardiac ultrasound video wireless transmission. Here, the objective is to examine the capabilities of different video compression standards for use in robotised tele-echography systems. Performance evaluation is based on objective metrics (e.g. peak-signal-to-noise ratio (PSNR) and BD-rate algorithm) and clinical assessment by a senior cardiologist. Clinical evaluation involves assessment of both B-mode and colour Doppler mode cardiac videos.

ii. *Robot-control and ultrasound video data communications over 4G wireless networks*: The capability of commercially deployed 4G-LTE networks to simultaneously accommodate (i) responsive tele-manipulation of the robot situated at the patient's site by the remote medical expert and (ii) low-delay, ultrasound video communication at the acquired video resolution and frame rate encoded at different compression levels is examined.

iii. *Real-life scenarios using the proposed end-to-end mobile tele-echography platform*: The primary focus of this Letter concerns the development of a robotised tele-echography platform that will be evaluated using realistic real-life scenarios. For this purpose, experiments are performed using two healthy volunteers.

## METHODS

### Robot control and manipulation

For the needs of this Letter a portable robot with 3 DOF was used. The MELODY system is based on the earlier Teresa system and was commercialised by AdEchoTech.

The remote medical expert uses a dummy probe to control the actual probe, which is situated and manipulated by the robotic arms at the patient side. This operation involves low-bandwidth control and force commands such as moving the probe along the x and y axes (i.e., sideways and vertically, respectively), replicating the positioning movements of the ultrasound probe on the patient's body of an on-site examination. The key concept here is low-delay and hence responsive control, achieving a QoE level comparable to typical examinations in standard clinical practise. The data are conveyed between the robot master–slave stations over the LTE wireless infrastructure.

### Ultrasound video encoding

The ultrasound device at the patient's side is connected to a frame grabber which allows capturing raw ultrasound video at the video resolution and frame rate that is displayed on the device's monitor. The video is then fed to the open source mHealth video communication platform designed for medical video pre-processing, encoding, and communication. The software allows frame rate reduction (for lowering bandwidth demands and encoding time where applicable) and encoding at different compression levels (e.g., bitrate demands) using different video compression standards. Based on FFMPEG software, the platform allows encoding the raw ultrasound video using the MPEG-2, MPEG-4 part-2, H.264/AVC, and high efficiency video coding (HEVC) compression standards, using open-source implementations, namely mpeg2video, xvid, x264, and x265, respectively.

The software is installed on a laptop at the patient's side. At the remote end (expert's side), the same software is used for post-processing, decoding, and rendering of the clinical content using the VLC media player. The medical expert reviews the displayed ultrasound video on the laptop's monitor for navigating the probe to the suitable positions for performing the appropriate diagnosis according to the examined ultrasound video modality.

### Ambient video

Ambient video and audio may be also communicated from patient to expert side and vice versa. The latter is particularly helpful for the medical expert to provide further instructions to the carer with respect to the robot position while communicating directly with the patient. The proposed system supports commercially available software for communicating audio and ambient video (e.g., Skype). Moreover, it provides customisable interfaces for real-time ambient video streaming of well-known high-quality outdoor video cameras such as the GoPro camera (particularly useful for disaster incidents scenarios, not examined here).

### Wireless transmission over emerging wireless networks

The objective here is to investigate the capability of commercially available 4G-LTE wireless networks to communicate diagnostically lossless medical video at the acquired video resolution and frame rate, while conforming to strict delay requirements. To overcome the design limitation of the MELODY robot, which requires a dedicated channel for communicating the robot control specific data, a 4G router (D-Link-DWR921) equipped with a machine-to-machine enabled card is used. The latter configuration allows us to communicate both robot control and ultrasound video

Sotiris Avgousti and Panicos Masouras
Cyprus University of Technology, Cyprus, E-mail: sotiris.avgousti@cut.ac.cy

data over the same wireless channel (in addition to ambient video and audio data), and hence translates to a significant enhancement over previous experiments using the MELODY robot. The hub, which is connected to the 4G router and provides Ethernet connections to the robot and laptop(s) equipped with the mHealth video communication software is introduced for experimental purposes in these series of experiments and is not an essential element in the proposed mHealth Tele-Echography platform.

Wireshark, an open-source cross-platform network protocol analyser is used for monitoring both robot control and video data across patient and expert sites. The latter allows for QoS measurements including throughput analysis, estimating packet end-to-end delay and delay jitter, as well as total packet losses.

**Mobile tele-echography platform quality assessment**

Scenario 1

The first scenario aims to demonstrate the significant benefits of employing emerging video coding standards both for video communications and storage. Most ultrasound devices today still depend on successful, but soon obsolete video coding standards for storing the necessary video loops during an ultrasound examination, such MPEG-1 and 2. The adoption of DICOM recommendation for using the H.264/AVC standard for storing and network transmission remains extremely limited. In the contrary, they rely on high-quality –often uncompressed – images to revisit a clinical case.

A video coding standards comparison including the latest, HEVC standard, using open-source implementations that can meet the encoding requirements of real-time medical video communications is performed. The objective is to investigate the bitrate demands reductions for equivalent clinical quality achieved by emerging video coding standards.

Scenario 2

The second scenario aims to assess the readiness level of adopting the mobile tele-echography platform in standard clinical practise, for scenarios where wireless infrastructure is required. For this purpose, both technical and clinical evaluation is performed. The scenario includes: (i) a training phase, where the medical expert familiarises with the proposed platform and robot tele-operation, and (ii) a remote cardiac ultrasound examination using the tele-operated robot following the clinically established protocol. During the training phase, the medical expert is asked to rate the responsiveness of the tele-operated robot while maintaining line-of-sight with the patient (and hence robot). The second subtask of the training phase is for the medical expert to familiarise and assess the wirelessly communicated ultrasound video delay with respect to the ultrasound video displayed on the device's screen (having no delay and therefore serving as the ground truth). The dual objective is (i) for the medical expert to become accustomed to the incurred delays of tele-echography attributed to robot control data and ultrasound video communication delays, and then (ii) assess the quality of clinical QoE compared with in-hospital ultrasound examinations.

**RESULT AND DISCUSSION**

This section provides preliminary experimental evaluation results of the proposed mobile tele-echography system over currently deployed 4G-LTE systems in Cyprus. A data set composed of ten cardiac ultrasound videos (2 healthy male subjects × 5 videos per subject), including B-mode, colour-Doppler mode, M-mode, and pulsed/continuous Doppler mode video loops is considered. The ultrasound videos maintain the original video resolution output from the ultrasound device monitor: 800 × 600, while there is frame rate reduction from 44 to 30 frames per second compared with the original video. The videos were acquired during two live tele-echography sessions. We first provide and discuss the results obtained from the video coding standards comparison, followed by the performance evaluation of the end-to-end mobile tele-echography platform.

A video coding standards comparison in terms of output clinical quality and associated bitrate demands was performed. More specifically, the most widely used standards were investigated, namely MPEG-2, MPEG-4 part 2, MPEG-4 part 10 (or H.264/AVC), and the emerging HEVC. All videos parting the data set were encoded at the following bitrates: 256, 512, 1024, and

2048 kbps, using the default profiles and encoding settings found in FFMPEG, producing a total of 160 video instances (4 compression levels × 4 video coding standards × 10 ultrasound videos).

A video quality boxplot of all investigated video coding standards for a given target bitrate. Each of the illustrated boxplots corresponds to PSNR scores of the ten cardiac ultrasound videos of the examined data set. Moreover, Fig. 3 shows a rate–distortion graph of all investigated video coding standards and bitrate points using averaged values over the whole data set. As evident from both graphs, newer video coding standards such as HEVC and H.264/AVC significantly outperform older standards such as MPEG-4 part 2 and MPEG-2. They achieve higher PSNR ratings while having less bitrate requirements. The trend is the same for all investigated videos. The latter observation strongly highlights the potential gains in storage capacity once ultrasound machine vendors adopt recommendations such as DICOM Sup. 149 and rely on the compression efficiency of the HEVC standard. More importantly, mHealth systems such as the proposed platform can capitalise coding efficiency towards communicating larger volumes of clinical content, providing equivalent clinical quality to in-hospital examinations.

The most important issue raised by the medical expert and prevented higher overall rating and hence clinical QoE is the robot initial positioning on the patient's chest and navigation towards obtaining the cardiac ultrasound. During routine clinical practice, this step involves small movements where the medical experts reposition the ultrasound probe on the patient's chest, to obtain a clear view of the heart (and hence ultrasound video). This view may be obstructed by chest bones and slightly differs per patient. It does not extend over a few seconds. However, during remote ultrasound examination, the medical expert has to instruct the carer holding the remote robot, as to where to (re)position the robot holding the probe on the patient's chest, which in inherently slower. The afore-described process was the major drawback documented throughout this preliminary experimentation cycle and is primarily attributed to the robot design.

Following the training session two live tele-echography examinations were performed to evaluate the proposed system's performance. For a more realistic assessment of clinical video quality and experienced network-attributed delays, the clinical evaluation setting involved the laptop and ultrasound device monitors situated side by side. The physician, however, was not in LOS with the patient.

The medical expert first proceeded with assessing the induced delay by the LTE network for communicating the cardiac ultrasound video. As deducted by the medical expert's rating, the incurred delay was within acceptable levels to appropriately navigate the ultrasound probe and proceed to the ultrasound examination. This observation strongly highlights commercial LTE channels capacity to accommodate medical video communication systems and services in a manner that was only feasible using wired infrastructure up to a few years ago. As the medical expert quoted, having completed the initial training, video communication delay is not expected to be an issue during remote tele-echography examinations.

As the medical expert commented, cardiac ultrasound videos communicated at a bitrate of 512 and 1024 kbps using the MPEG-2 standard do not qualify for clinical practise, as there is an evident loss of clinical information. Video quality is significantly improved at 2 Mbps, however, there still exist some loss of clinical information. Overall, the MPEG-2 standard using the investigated video compression levels at the clinically acquired video resolution at 30 fps, can only be used for pre-diagnosis purposes. It is important to note here that the medical expert emphasised that a safe conclusion can only be drawn using a larger number of clinical cases.

## CONCLUDING REMARKS

Preliminary results provide a strong indication that the proposed robotised tele-echography platform can be used to provide reliable, remote diagnosis over emerging 4G and beyond wireless networks. Commercially available long term evolution 4G wireless networks in Cyprus facilitate packet round-trip times (latencies) that are well within the stringent, low-delay requirements for responsive robot tele-operation and real-time medical video streaming. At the same time, available data rates, both in the uplink and downlink, linked with new video

Sotiris Avgousti and Panicos Masouras
Cyprus University of Technology, Cyprus, E-mail: sotiris.avgousti@cut.ac.cy

coding standards efficiency allow for diagnostically lossless video communication at the acquired video resolution and frame rate. Based on the afore-described observation, it is envisioned that mHealth tele-echography systems will be adopted in standard clinical practice, increasing the level of healthcare provision, especially for rural hospitals, emergency incidents, and in developing countries, where the presence of specialised medical personnel is not feasible. To achieve this however, requires that both paramedical personnel and medical experts undergo the appropriate training that will be ultimately integrated into medical education.

Ongoing work focuses on concluding the assessment of open-source implementations of all video coding standards, including the new HEVC standard, and investigating the efficiency of the proposed system over a larger number of clinical cases. Extending the proposed research to different ultrasound video modalities is currently planned.

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