Mohammed Al-Badri*, Svenja Ipsen, Sven Böttger and Floris Ernst

Robotic 4D ultrasound solution for real-time visualization and teleoperation

Latency and framerate of live ultrasound volume transfer in a local network

Abstract: Automation of the image acquisition process via robotic solutions offer a large leap towards resolving ultrasound's user-dependency. This paper, as part of a larger project aimed to develop a multipurpose 4d-ultrasonic force-sensitive robot for medical applications, focuses on achieving real-time remote visualisation for 4d ultrasound image transfer. This was possible through implementing our software modification on a GE Vivid 7 Dimension workstation, which operates a matrix array probe controlled by a KUKA LBR iiwa 7 7-DOF robotic arm. With the help of robotic positioning and the matrix array probe, fast volumetric imaging of target regions was feasible. By testing ultrasound volumes, which were roughly 880 kB in size, while using gigabit Ethernet connection, a latency of ~57 ms was achievable for volume transfer between the ultrasound station and a remote client application, which as a result allows a frame count of 17.4 fps. Our modification thus offers for the first time real-time remote visualization, recording and control of 4d ultrasound data, which can be implemented in teleoperation.

Keywords: 4d, real-time, remote, robotic, ultrasound, telemedicine, teleoperation, volumetric

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***Corresponding author: Mohammed Al-Badri:** Institute for Robotics and Cognitive Systems, University of Lübeck, Lübeck, Germany, e-mail: al-badri@rob.uni-luebeck.de
Svenja Ipsen, Sven Böttger, Floris Ernst: Institute for Robotics and Cognitive Systems, University of Lübeck, Lübeck, Germany, e-mail: ipsen@rob.uni-luebeck.de, boettger@rob.uni-luebeck.de, ernst@rob.uni-luebeck.de

1 Introduction

1.1 Overview

Medical ultrasound imaging is the most common modality used for routine diagnostics to date. Its advantages range from higher safety and real-time capability to low complexity and operation cost as compared to other modalities. However, due to the considerable skill and expertise it requires, ultrasound image acquisition and diagnosis are difficult to be carried out separately, thus making it highly user-dependent [1].

In order to resolve user-dependency, and several other ultrasound imaging drawbacks, image acquisition could be automated and potentially standardized via robotic solutions. This paper is part of a larger research project aimed towards developing a multipurpose robot-supported ultrasound solution for medical applications. It employs a matrix array probe for fast volumetric (4d) imaging, and utilizes force-sensitivity allowing for implementation of safety as well as closed-loop feedback control.

1.2 Motive

Operations such as extracorporeal shock wave lithotripsy (ESWL), where high-intensity focused ultrasound (HIFU) pulses are used to treat kidney stones, use ultrasound for monitoring and controlling the procedure. During an ESWL procedure and due to motion of the patient and/or stones, the operator must continuously monitor the treatment, which could last for as much as an hour, and ensure that the stones stay in the target region of the HIFU beam. This leads to inconvenience for both operator and patient as well as pain for the patient if the HIFU focal point misses the target.

Real-time imaging is necessary in such treatment, as organ motion [2] may occur quickly and at any instant aside from respiratory motion. With real-time 4d visualization, tracking and rapid compensation of motion can be automated through a robotic solution, thus increasing efficiency while decreasing inconvenience. Furthermore, such system allows the clinician to operate on a patient remotely using a master-slave scheme, in which the clinician takes full or partial control of the procedure while obtaining live feedback.

1.3 Purpose

Although 2d ultrasound has been investigated in a number of applications, no commercial solution supporting real-time 4d ultrasound exists to date. In this paper, the focus is directed towards the system component for real-time remote visualisation of 4d ultrasound with low latency and a minimum framerate of 10 fps.

2 Materials and methods

2.1 System structure

A GE Vivid 7 Dimension ultrasound workstation, which is able to produce volumes in a rate of ten to fifty frames per second depending on beam settings and target region size, was used for obtaining ultrasound volumes using a 3V matrix array probe. We modified the station software in order to enable real-time volume streaming through a network, which was otherwise not possible [3]. Our software allows for intercepting the transfer and using the volume data in a custom code.

The complete robotic ultrasound solution was designed to operate remotely by establishing communication between the system and a client application via Simple Object Access Protocol (SOAP) communication. However, as seen in **Figure 1**, volume data are first sent to a C++ backend before being dispatched through SOAP to further clients for visualisation, storage or analysis. This allows for establishing a Transmission Control Protocol/Internet Protocol (TCP/IP) network, in which a client application can utilize the C++ backend directly. SOAP communication enters the picture when a network connection (either local or over the internet) is required. Although the calculations in this paper cover the local network component, differences with a SOAP network are briefly addressed in the conclusion.

Utilizing the station's gigabit Ethernet interface, which theoretically allows up to 125 MB/s speed, a TCP/IP

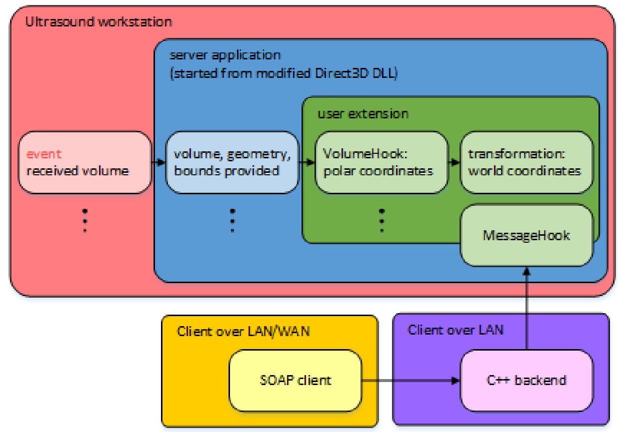

Figure 1: Ultrasound volume pathway from workstation to client applications.

connection was used to transfer volumes between the ultrasound station and a client computer.

2.2 Latency and framerate

With a minimum of 10 fps set as the target framerate, the minimum transmission latency, which is able to achieve this framerate, amounted to 100 ms. Knowing that the size of a produced volume was roughly 800 kB in size, the lowest required speed was therefore 8000 kB/s (~8 MB/s).

Note that acquisition and transmission latencies must be differentiated. Volume acquisition also requires time including beam formation, echo detection, transformation between analogue and digital signals, and so forth. Adding both acquisition and transmission latencies yields the total time of volume visualization at the end-application.

Test runs were conducted with an array of 92 × 20 beams penetrating 16 cm into a water bath. The station yielded ~880 kB volumes with a rate of 17.4 fps, which were transmitted through the gigabit Ethernet connection to a custom C++ client.

3 Results and analysis

During the test runs, the client was able to receive and display volumes at 17.4 fps, similar to the workstation. This indicates that the ~880 kB volumes required a throughput of approximately 15 MB/s with ~57 ms latency.

Factoring in volume acquisition latency, which also equals ~57 ms, total delay amounts to 114 ms for remote visualization.

The gigabit Ethernet interface was able to facilitate the required speed and bandwidth to achieve these results.

It is, however, important to take network activity into consideration. Transmission of other data, such as audio and video, could be taking effect simultaneously, introducing more load to the network.

Furthermore, the number of parameters requested by the client could also influence the size of transmitted data, hence speed requirements. Nevertheless, these differences are very slight and can be neglected in our calculations for two reasons: first, the application in hand (teleoperation) requires only real-time visualization. Therefore only raw volume data and coordinate system information are required. The client can implement a custom code for further processing. Second, the calculated speed for volume transmission (15 MB/s in the aforementioned test) was only a small fraction of what gigabit Ethernet offers.

4 Conclusion

Our software modification of the ultrasound workstation offers for the first time real-time remote visualization and manipulation of 4d ultrasound data.

Using gigabit Ethernet allows for low-latency volume transfer in a rate higher than 10 fps (can be over 10x higher). With volumes averaging 800 kB in size, 10 fps is obtainable using only ~8 MB/s connection speed with 100 ms latency in a local TCP/IP network.

Factoring in additional data and commands in a medical application, gigabit Ethernet would still be able to provide sufficient speed to achieve 10 fps remote visualization.

Adding another client application, connected to the C++ backend using SOAP, imposes higher requirements, as data gain more than twice its size due to format change. This is caused by two effects: first, the data from the ultrasound station is in polar coordinates and needs to be converted to Cartesian space, approximately doubling its size. Second, SOAP encodes the binary image data using Base64 encoding, increasing the required bandwidth by another 36%. With this in mind, a framerate of 10 fps or higher would still be obtainable in our application as data size and required speed are directly proportional – requiring 22 MB/s for a 2,200 kB volume.

Our system can therefore be used to remotely visualize ultrasound volumes in real-time whether in a local or a wide area network. This facilitates telemedicine with live image feedback, in which ultrasound volumes can be used either for remote diagnosis or monitoring and automation of therapy.

In a next step, we will combine the technology with existing medical applications. A plan is also to integrate our volume streaming approach with existing safe communications platforms for medical devices, such as the OR.NET project [4].

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