Opstillingen som benyttes her er meget lig vores. Her ligger fokuset på hvilke robotter den er sat sammen af. Her arbejder robotten efter et forprogrammeret forløb, hvor den tager en del 2D billeder og sammensætter dem til 3D billeder bagefter.
Konklusionen går ud på at sonografernes main udbytte er at den vil mindske deres arbejdsskader og gener.

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# Interface Design and Control Strategies for a Robot Assisted Ultrasonic Examination System

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**Summary.** This paper presents a new robotic system designed to assist sonographers in performing ultrasound examinations by addressing common limitations of sonography, namely the physical fatigue that can result from performing the examination, and the difficulty in interpreting ultrasound data. The proposed system comprises a robot manipulator that operates the transducer, and an integrated user interface that offers 3D visualization and a haptic device as the main user interaction tool. The sonographer controls the slave robot movements either haptically (collaborative tele-operation mode), or by prior programming of a desired path (semi-automatic mode). A force controller maintains a constant contact force between the transducer and the patient's skin while the robot drives the transducer to the desired anatomical locations. The ultrasound imaging system is connected to a 3D visualization application which registers in real time the streaming 2D images generated by the transducer and displays the resulting data as 3D volumetric representation which can be further examined off-line.

## 1 Introduction

Ultrasound has been used in the medical field since the late 1950s and has become one of the most widely used medical imaging techniques in modern medicine, with diagnostic and interventional applications across disciplines. Most ultrasound systems found in today's clinics and hospitals consist in a hand-held probe containing an array of transducers that convert electrical signals into ultrasonic waves, and appropriate signal reception means. When the transducer is pressed against the skin, it directs small pulses of inaudible, high-frequency sound waves into the body. A very sensitive microphone located in the transducer then listens for the echoes that occur as the sound waves are reflected at the interface between the different layers of tissue they encounter. The delay and intensity of the reflected sound waves are instantly measured and converted into a density profile in the direction of travel of the sound. In the most common form of ultrasound imaging (B-Mode), the process is repeated in multiple directions within a 2D plane in order to create real-time, 2D pictures on the monitor, as illustrated in Fig.1.

Ultrasound technology is relatively inexpensive and portable, especially when compared to other techniques such as computed tomography (CT) or magnetic resonance imaging (MRI). Correctly performed medical ultrasound (US) also poses no known risks to the patient, in contrast to methods based on X-rays or on radioactive isotopes. However, in order to obtain the technical and clinical advantages offered by sonography, highly-qualified personnel trained

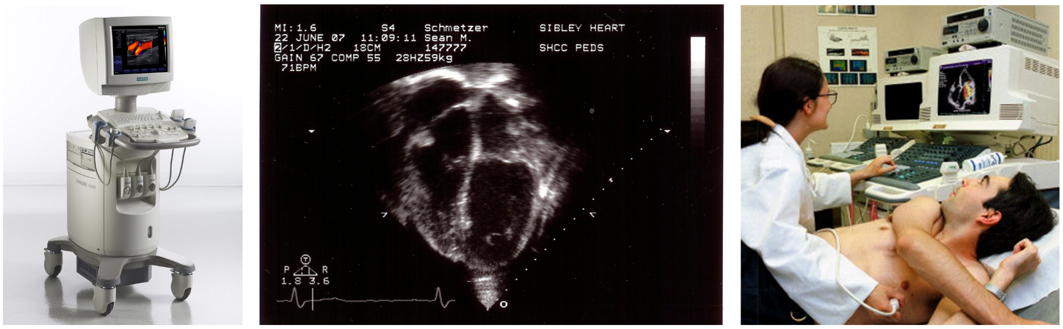


**Fig. 1.** (a) Ultrasound imaging device (b) Ultrasound image of a heart (c) Operator holding transducer on patient.

to properly operate transducers and accurately interpret the resulting images are required. In particular, operators must display highly sensitive skills in order to maximize the ultrasound data signal-to-noise ratio, which is affected by the reflection and transmission characteristics of sound waves in human tissue. Ultrasound procedures are also physically challenging for the medical personnel, as they need to hold transducers in often awkward positions for prolonged periods of time, resulting in high incidences of musculoskeletal injuries and disorders (e.g carpal tunnel syndrome) [3]. With obese patients, image acquisition is made more difficult by the fact that sound attenuation increases exponentially with fat thickness, therefore reducing the quality of the images. To compensate for the signal loss, sonographers need to apply even higher forces on the transducer, consequently increasing their risk of muscle injury.

The idea of using robotics technology to address the challenges and limitations of manual examination goes back to the early 1990s with the first use of industrial robots configured as medical tool holders. The Hyppocrate platform [8] was based on a Mitsubishi robot (PA-10) on which a transducer was mounted as the end-effector. Due to their limited force sensing capabilities, early systems often failed to offer sufficient compliance, dexterity and control performance. New robot designs were developed to better match the force requirements and back-drivable capabilities often absent on highly geared industrial robots. Various designs and clinical applications of similar concepts are discussed in TER [9], Otello/Teresa [10], and UMI [11]. In [12], UBC presents a parallel kinematic design which aims at reducing the weight and bulkiness found in earlier systems, while still conserving a relatively large workspace.

Among the few ultrasound robots that have actually been tested in clinical environments, none have been commercialized so far. There are two main barriers to the clinical adoption to robot-assisted ultrasound techniques. Firstly, different medical fields require different ultrasonic acquisition techniques and different applications call for different robot architecture [12], making it difficult to adapt existing robots to the task at hand. Secondly, and possibly more importantly, the robots themselves are often more expensive than the ultrasound imaging devices they assist, making such solutions prohibitively expensive for the health-care industry.

In 2007, the robot manufacturer KUKA launched a commercial version of the DLR light-weight robot (LWR) which was specifically developed for interactive applications involving people and robots. With its 7 degrees-of-freedom and a workspace comparable to the human arm, the LWR integrates torque sensing directly at each joint, making it an ideal platform for applications that require compliant motion and force control capabilities. Also, as the technology becomes more widely understood and available, the LWR price point is expected to drop to a level that is in line with the cost of current ultrasound imaging workstations. As a result, the LWR can be expected to become a successful industrial robot for human-centered applications in general, and is a promising candidate for robot-assisted ultrasound examination in particular.

In this paper we explore the combination of a 6 DOF robot manipulator in the context of ultrasound examination. In section 2, we present a new collaborative control approach that allows the operator to instinctively drive the manipulator haptically through a force-feedback device, while the robot maintains optimal pressure at the point of contact. Section 3 introduces the overall control architecture, and in Section 4 we describe how the real-time 2D ultrasound data is fed to a software module that registers each planar image in 3D space and presents the operator with a 3D volume of the data acquired over time. The 3D model can be saved and explored post-acquisition using the haptic device. In sections 5 and 6, we present preliminary experimental results and discuss the benefits and limitations of the proposed system.

## 2 System Overview

The system is composed of three main elements: the ultrasound imager, the robot manipulator and the Master User Console, with its haptic user interface.

The ultrasound imager is an off-the-shelf Acuson Antares Premium model from Siemens Medical. The imager itself is connected to the Master User Console computer, while the transducer is mounted on the robot. The nominal position and orientation of the transducer with respect to the robot end-effector can be adjusted through a series of set screws.

The system is designed to operate different types of robots. In the context of this paper, we have evaluated a 6 degrees-of-freedom PUMA robot manipulator from Unimation with a 6 degrees-of-freedom force sensor mounted at the robot end-effector and a 7-degrees-of-freedom LWR robot from KUKA/DLR.

Both robots are able to carry the ultrasound transducer at the end-effector. The robot controller of the PUMA is a stand-alone computer running the local control loop on QNX at 1 Khz. The LWR is a 7 degrees-of-freedom robot composed of harmonic drive gearboxes with custom design actuators. Individual joints are connected via carbon-fiber structures, and each is equipped with a motor position sensor, a joint position sensor and a joint torque sensor. Communication to the LWR robot is performed through KUKA's fast research interface, which allows position and stiffness control at a rate of 1 KHz. Similar to the human arm, the LWR has seven degrees of freedom, which provides higher flexibility and makes it possible to cover a larger, more uniform workspace than traditional industrial robots.

Both robot controllers can communicate with the Master User Console over an insulated TCP/IP network. The network-based communication shows a worst-case transmission delay of less than 0.1 ms.

The Master User Console hosts the main computer running Windows 7. It is responsible for the real-time ultrasound image acquisition and processing, as well as for all user interaction tasks. It is composed of 2 main elements: (1) a haptic device and (2) the graphical user interface (GUI).

The haptic device used is a 6 degrees-of-freedom omega.6 haptic device developed by Force Dimension. The device provides up to 12 Newton of force and has a cylindrical workspace of approximately 110 mm in depth by 160 mm in diameter. The haptic device is connected to the master computer through a USB 2.0 interface which provides a communication rate of up to 4 KHz.

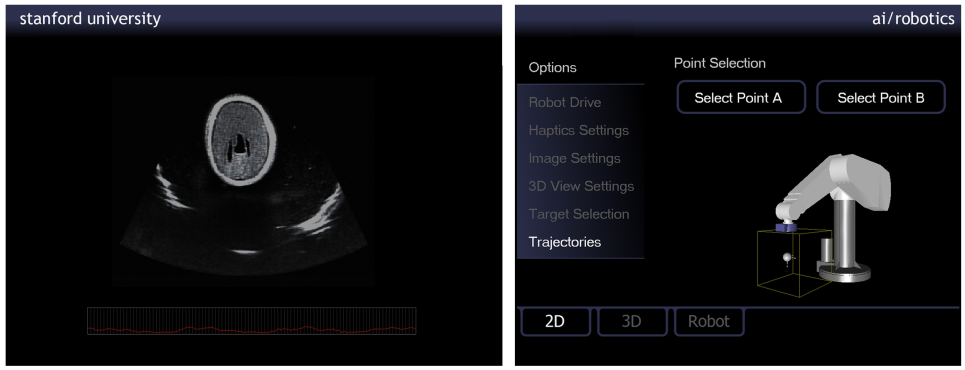


**Fig. 2.** Screenshot of the main interface: (Left) Visualization screen displaying a live 2D ultrasound image. (Right) Command screen which combines all operating modes and user settings of the application.

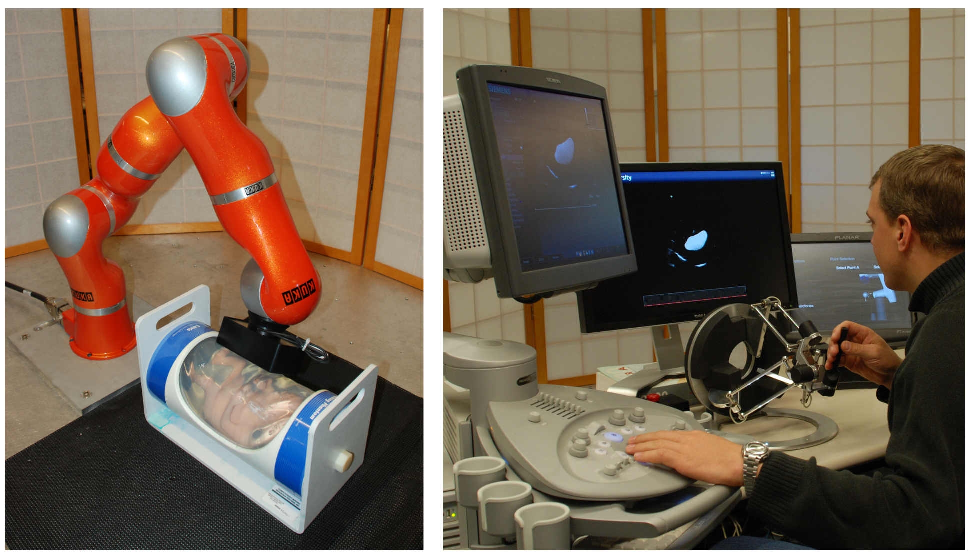

**Fig. 3.** Overall system: (Left) LWR robot manipulator examining phantom model of a foetus. (Right) Master User Console composed of the ultrasound imaging system (US) with 3D visualization and 6-DOF haptic interface.

The application GUI spans over two computer displays. The primary display is used to render the live ultrasound data in real time. The data rendering can be configured to either 2D mode, displaying a stream of ultrasound images, or to 3D mode where a reconstructed volume generated from image data acquired over time is provided. In 3D mode, the user can change the point of view in real-time using a trackball, in order to achieve the best possible analysis of the data. A secondary tactile display is used by the operator to select the different modes of operation. Fig. 2 illustrates a screenshot of the main graphical user interface.

The system is designed to be intuitive to use and requires minimal training. Fig. 3 shows a typical usage scenario of the whole system running with the LWR manipulator.

The system offers different ways of controlling the robot and the transducer, depending on the nature of the examination and its various stages. At any point in time, the operator can switch to one of three different modes of operation, which are referred to as *float*, *haptic* and *automatic*.

In *float* mode, the robot controller maintains the robot in gravity compensation loop by continuously applying torques that compensate for its own weight. This allows the operator to freely move the robot by hand in order to place it in the optimal configuration to reach the target anatomical location. This mode is typically used at initialization when the operator places the robot near the patient, or to manually program a desired trajectory composed of a series of points (see automatic mode below). It also enables the operator to manually acquire ultrasound data, in essence bypassing the whole robotic system.

In *haptic* mode, the operator freely controls the position and force at the transducer by using the 6 degrees-of-freedom haptic interface in real-time. The force applied by the haptic device can be scaled down in order to reduce operators' fatigue, while the system enforces a maximum contact force limit in order to ensure patients' safety. The operator can cover the entire robot workspace by using a button on the haptic interface that acts as a clutch, so that the robot only moves when the button is depressed. If the operator releases the button, the robot maintains the current pose and level of pressure while the operator moves the haptic device to a more convenient configuration. Workspace expansion [6] is also integrated for automatic workspace recentering of the haptic device.

Finally, an *automatic* mode provides controlled motion of the transducer along a desired path while maintaining a user-defined, constant contact pressure. This mode is used mostly for performing 3D sweep scans. The path can be recorded in *haptic* mode by haptically driving the robot along the desired trajectory. Once the path is recorded and validated by the operator, the robot moves back to the starting point automatically (along the recorded trajectory) and replays the trajectory while maintaining a set contact pressure. The movement velocity, as well as the contact pressure, are selected by the operator on the GUI.

In all three modes, the images acquired by the ultrasound system are continuously digitized by the Master User Console computer. Each image is labeled with the position, orientation and contact forces measured by the robot, and stored locally for post-examination analysis. The 2D scans are then used to reconstruct a 3D representation of the volume covered by the transducer, and which can be rendered on the GUI in real-time [7]

## 3 Control Architecture

Many control techniques commonly used in industrial robot manipulator design rely on position or stiffness control [13]. Such techniques are not appropriate for robot-assisted ultrasound examination, which requires precise control of the contact pressure between the patient skin and the transducer. In the proposed system, we use a force controller that has already been successfully tested on a PUMA robot for haptic-based manipulation [14]. The teleoperation approach is realized by integrating three components: a virtual spring to connect the master and slave systems, the operational space framework to provide the decoupled dynamic controller, and a local contact force controller to realize tracking of the contact force. This approach is illustrated in Fig. 4 and the block diagram is in Fig. 5. In the proposed teleoperation approach, a virtual spring connects the master and slave systems. When the positions of the master and slave system do not match, the virtual spring produces a force proportional to the difference in positions. This force acts as a desired contact force which will be tracked by the

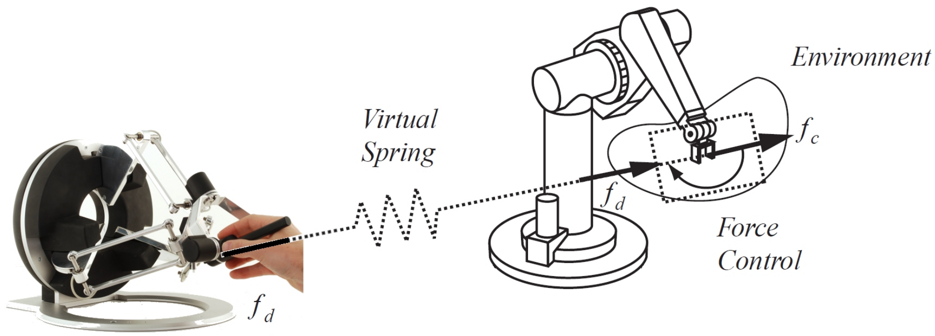


**Fig. 4.** Teleoperation approach with a virtual spring and force control. The desired force, $f_d$ , is produced by the virtual spring based upon the position difference between the master and slave robot end-effectors. The force controller on the slave robot enforces the contact force, $f_c$, to track this desired force while the desired force is fed back to the user at the master device.

local force controlers on each side. Therefore, this approach provides the human operator with contact forces within the bandwidth of the force controller. The robot control on each system is simply contact force control. Even in the free space operation of the slave system, the controller assumes that the robot is in contact with a very compliant environment. The position tracking in free space is implicitly accomplished by the force control and the virtual spring. When the slave robot is in free space, the force control at the slave robot commands the robot to move toward the master's position until the difference in positions is zero since the virtual spring produces the desired contact force in that direction. This approach greatly simplifies the overall teleoperation architecture by connecting a virtual spring between the master and slave and incorporating local force control on each system. Furthermore, the stability characteristics with respect to time delays and the difference between the inertial properties of the master and slave system are improved since the measured contact force is not used as the desired contact force at the counterpart system. Moreover, no switching is required in the robot control structure since the robot is considered to be always in contact with the environment, even in free space. Local force control is the most important part of the proposed approach since telepresence depends on how much bandwidth the force controller has. To deal with uncertainties and time-varying parameters (e.g. dynamic environments), the force control on the slave robot uses Active Observers [15] that modify the Kalman estimation structure to achieve model reference adaptive control. The AOB is designed to cover a medium range of stiffness values. For large variations, on-line stiffness estimation is necessary [14]. This on-line stiffness estimation is important in order to produce a desired bandwidth of the force controller over different environments, such that the teleoperation system can provide the user with a contact force. In addition, the virtual spring stiffness is modified with the change in the estimated environmental stiffness for better telepresence.

## 4 Image Processing and 3D Visualization

Ultrasound transducers are composed of an array of elements which can each send trains of ultrasonic sound waves in controlled patterns. An ultrasound array typically contains between

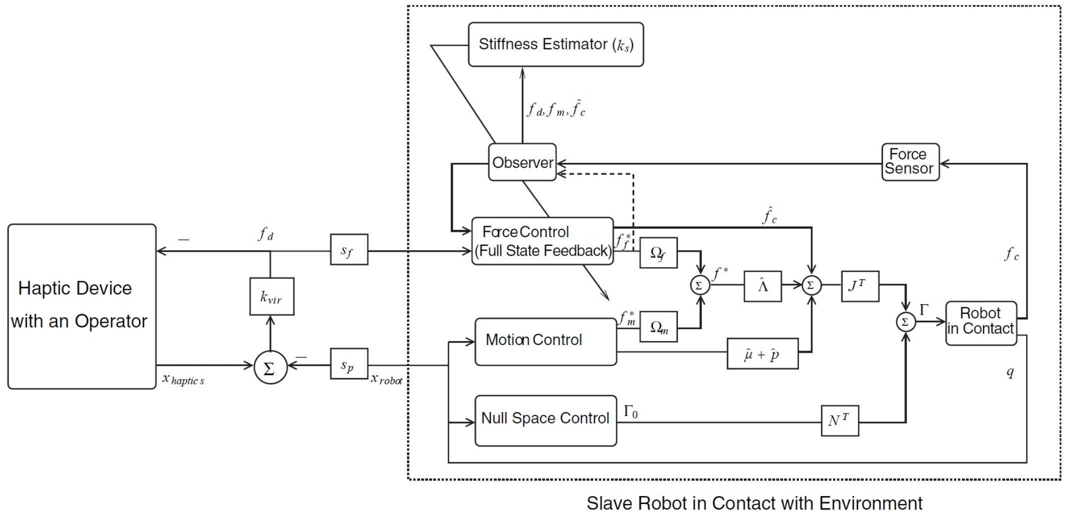


**Fig. 5.** A block diagram for the proposed teleoperation approach. The master and slave system are connected by a virtual spring with a spring constant, $k_{vir}$. The terms, $s_p$ and $s_f$, are the scale factors for position and force, which are used to adjust different workspaces and force magnitudes for the two systems. The block diagram in the dotted block on the right side shows the motion/force control structure for redundant robots.

64 and 512 elements, and comes in either a linear or sector like configuration. The imaging system measures the amplitudes and delays of the reflected ultrasonic wave train and builds monochromatic sonograms, taking into account the geometrical properties of the transducer and its mode of operation. The shades of gray in the image represent the relative reflection coefficients and attenuation of the interrogated tissues. A different class of ultrasound imagers (Doppler ultrasound systems) can also retrieve additional information that represents scalar velocity along the scanned axis, and is used mostly to measure blood flow through through the major arteries and veins of the arms, legs and neck. The velocity information is typically represented by color maps, as shown in Fig. 6.

Images generated by an ultrasound system come in the form of 2D frames in a video stream. The output images are broadcast as a color video signal in either analog or digital form. On modern ultrasound systems, raw image data can be directly accessed in the form of DICOM files through a network connection, making it possible to digitally process the 2D images in real time on a separate computer.

As part of our effort to develop an instinctive interface for haptic navigation and visualization of ultrasound data, we have developed an application that combines in real time the streaming 2D ultrasound images into a coherent 3D volumetric representation of the scanned volume. The reconstructed model can display both colorimetric and gray scale information, and is designed to retain all information extracted from the 2D images in order to maintain the quality of the information required to perform a diagnostic. The volumetric image is generated using a GPU ray casting technique to render the 3D output image in real time.

The reconstruction is only performed with images that are acquired while the robot is in stable contact with the skin of the patient. This condition is determined by reading the measured contact force at the tip of the transducer. If the difference between the desired and

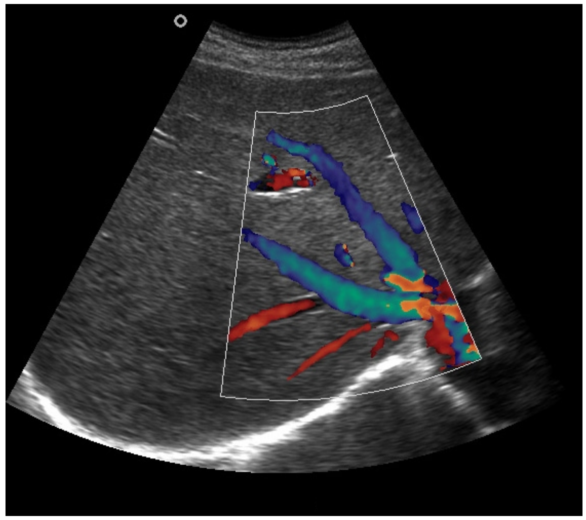

**Fig. 6.** Doppler representation of blood flow in the liver.

measured contact force is below a set threshold defined by the operator (typically of 1.0 N), the image is selected for insertion, otherwise it is discarded. This simple filtering approach effectively prevents images taken during scan transitions from distorting the 3D model, as this is when local deformation of the target area is most likely to occur.

3D reconstruction is carried out in real time and updated every time a new image is available from the ultrasound imager. The reconstruction algorithm operates by keeping track of the exact position and orientation of the transducer at the time of acquisition of each image, relative to the robot frame (see Fig. 7). The 3D volumetric representation is defined by a virtual box of size *(l,w,h)*, which is positioned and oriented to include the anatomical area of interest. The virtual box is discretized into a three dimensional array of voxels with a typical resolution of 512 x 512 x 512, although the maximum number of voxels actually depends on the amount of texture memory available on the graphics rendering hardware. Each voxel is expressed as a *RGBA* quadruplet *(r,g,b,a)*, where *(r,g,b)* describes the color information and *(a)* represents the alpha channel. The alpha channel is used as an opacity channel: if the voxel has a value of 0 in its alpha channel, it is fully transparent (and thus invisible), whereas a value of 255 makes for a fully opaque voxel.

In order to keep track of sampled voxels, a secondary array of same dimensions called the accumulation table is used. Each voxel in the accumulation data contains a single byte that indicates whether the voxel has been defined by a particular scan (value of 255), and therefore cannot be modified, or if it has yet to be defined (value of 0). The reason for using intermediate accumulation values is to support anti-aliasing when the intensities of voxels are partially defined. The *RGBA* values of voxels that have not been sampled are determined by interpolating between their closest sampled neighbors. As a result, the sonographer cannot only extract from the 3D model the 2D views from actual images, but also display 2D images in any arbitrary plane that intersects the target volume in order to assist with diagnosis.

After an image is selected to contribute to the 3D reconstruction, each of its pixels are projected into the 3D robot world frame using the geometrical transformation from the transducer to the volume representation. This transformation is defined by the position and orientation

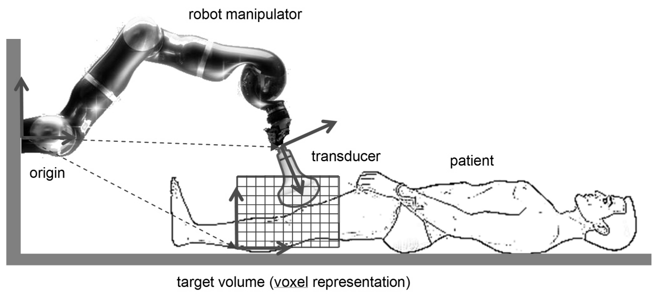


**Fig. 7.** The target volume defines the anatomical area when the scan occurs. Streaming 2D images are acquired from the tranducer and inserted into the 3D voxel representation.

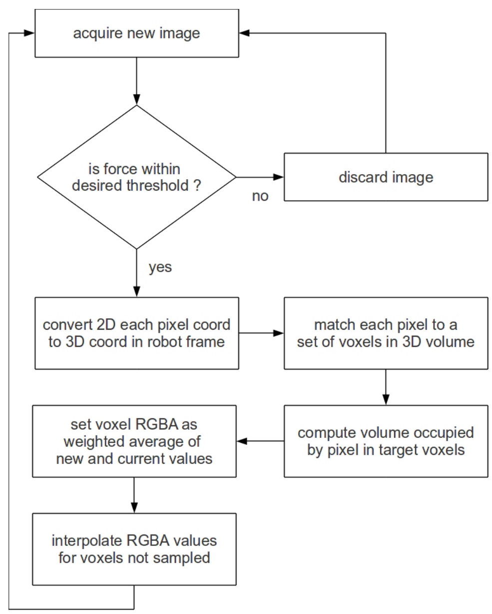


**Fig. 8.** 3D reconstruction dataflow.

of the robot, as well as the geometrical properties of the transducer and image settings programmed on the ultrasound imaging system. Each projected pixel overlaps a set of voxels in the target volume. For each identified voxel, an intensity value is estimated from the amount of volume covered by the pixel. The new colorimetric value of the voxel is computed by a weighted average between the current intensity value and the new one. Fig. 8 shows the dataflow involved in the 3D reconstruction.

At the end of the scan, the accumulation table is parsed to identify any regions that may not have been scanned by the transducer. Missing regions are highlighted to the operator who may then decide if additional scans are necessary.

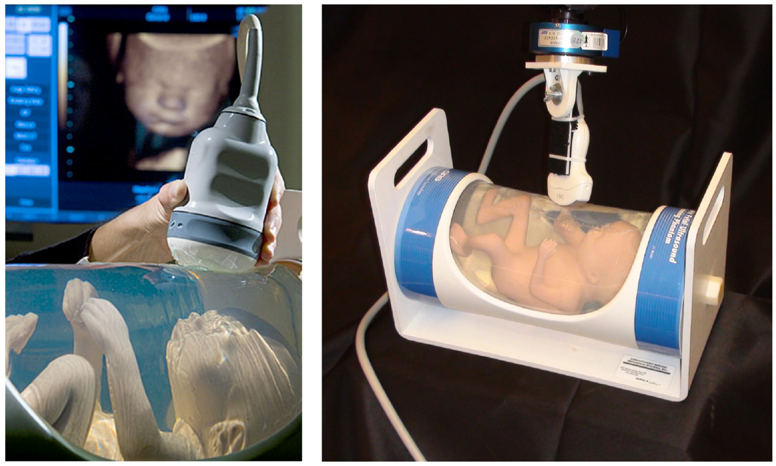

**Fig. 9.** (left) Illustration of the CIRS Model 068 Fetal Ultrasound Biometrics. (Right) View of the robot force sensor, transducer and fetal ultrasound phantom.

## 5 Experimental Results

This section presents the initial experiments conducted with the system after integration. The purpose of these experiments is two-fold: (1) to make an initial assessment of the operation of the integrated robotic/haptic/imaging system, and (2) to obtain some initial qualitative data on system usability, in particular when compared with traditional, hand-held ultrasound examination. For the most part, these experiments are designed to validate the system design and provide the data required to fine-tune the system prior to field testing. The clinical assessment of the system performance is beyond the scope of the initial research phase presented in this paper.

Experiments have been carried out using both the PUMA and LWR robot manipulators combined with the Acuson Antares ultrasound system from Siemens Medical. A transducer of type CH6-2, mounted on the robot end-effector as described in section 2, was used to conduct a simulated mid-pregnancy ultrasound examination. For the purpose of evaluating our system, we selected a CIRS Model 068 Fetal Ultrasound Biometrics Phantom consisting of a fetal model suspended in a non-echoic amniotic fluid-like environment. This choice of phantom was motivated by the fact that it enables assessment of composite measurement techniques and biometric analysis programs common to most ultrasound scanners. The experimental setup is illustrated in 9.

The simulated experimental exam consists in scanning and digitizing the entire fetus in order to build a 3D model. The metrics used to evaluate the outcome of the experiments will include qualitative factors such as model quality (artifacts, missing sections, etc.) and initial feedback on usability by professional ultrasound operators.

The experimental protocol is straightforward: at the beginning of the procedure, the operator is asked to program a desired trajectory for the transducer to follow by selecting a starting point and end point on the target area. Both target points are defined using the haptic device to robotically drive the transducer to the desired locations. At both points, contact forces, position and orientation of the probe are recorded from the robot sensory data. Once the trajectory is successfully entered into the system and validated by the operator, the au-

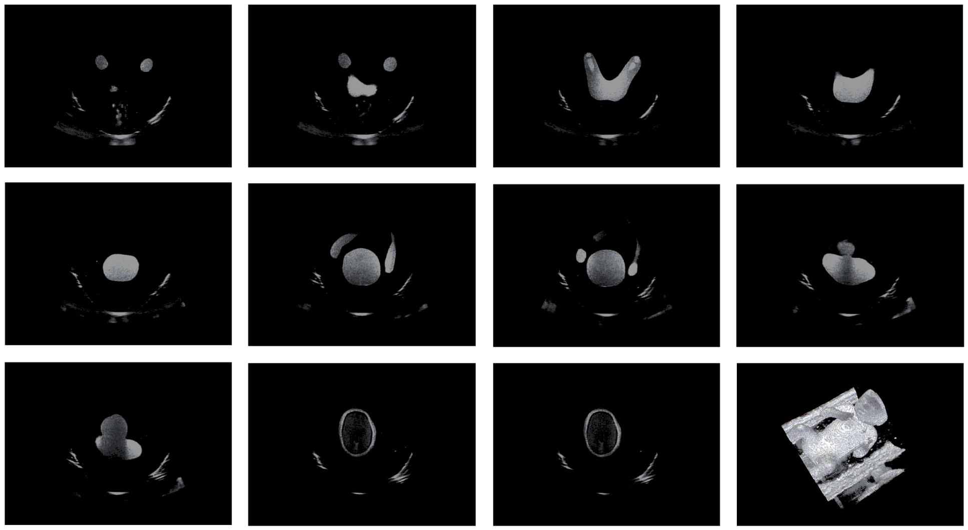

**Fig. 10.** 2D ultrasound images obtained on a CIRS Model 068 Fetal Ultrasound Biometrics Phantom using a Siemens Acuson Antares ultrasound imaging system and an LWR robot. The final 3D reconstructed image is illustrated in the bottom left picture

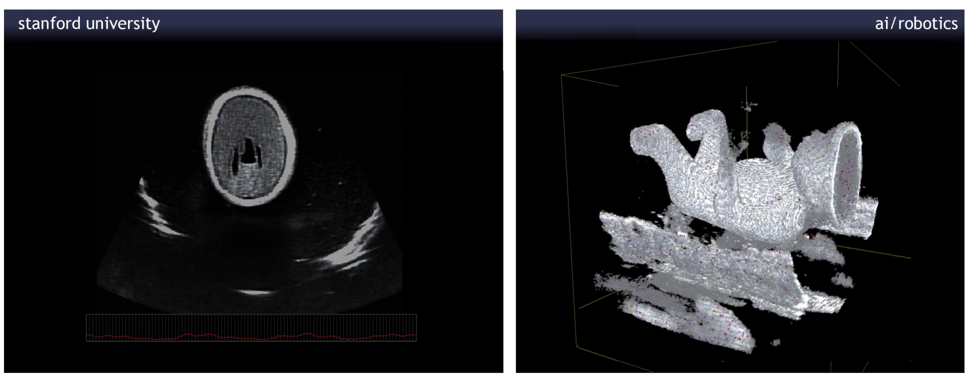


**Fig. 11.** Screenshots of the main user interface. (Left) Live 2D image of the head acquired from the Siemens ultrasound system. (Right) 3D reconstructed view computed in real-time.

tomatic controller is engaged and commands the probe to follow the programmed path, while maintaining the desired force normal to the contact surface.

In this first experiment, the robot followed a linear trajectory 210 mm long with a desired contact force of 4.5 Newton. The desired velocity was set to 15 mm/s, resulting in a total scan duration of 14 seconds. During this period of time, the ultrasound imaging system acquired 702 frames that were combined in real time to produce a full 3D representation of the fetal phantom. A subset of the digitized images is illustrated in Fig.10, with the resulting 3D reconstruction volume in Fig.11.

The same experiment has been repeated several times with various acquisition speeds and contact forces. In order to reduce the amount of friction at the surface of the transducer, and

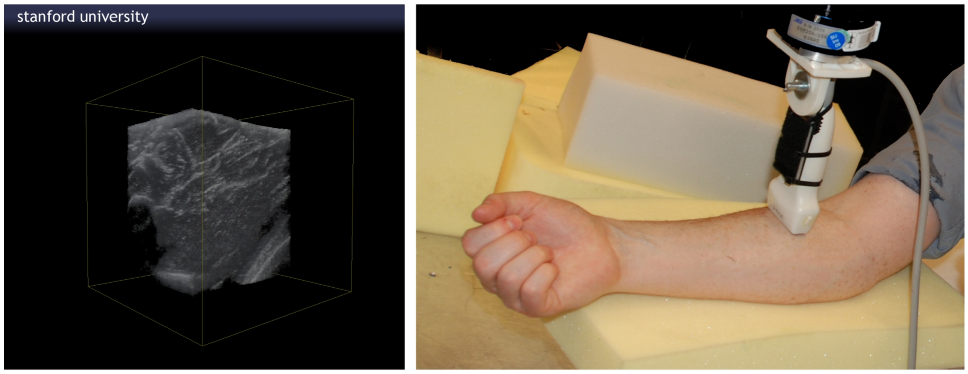


**Fig. 12.** Ultrasound examination of the arm (Left) Generated 3D model. (Right) Ultrasound transducer mounted on a PUMA manipulator.

also to improve sound wave transmission through the transducer-skin interface, we applied a layer of about 5mm of ultrasonic gel on the entire surface to be scanned. By always limiting the velocity of the transducer to a maximum speed of 20 mm/s, we were able to perform multiple scans without missing any sections within the targeted volume.

In order to validate the system performance on a live tissue, the same protocol was followed to acquire a model of a patient's arm instead of the fetal phantom. The transducer was moved along a distance of 120 mm with a constant force of 4.0 Newton on a non-immobilized patient. The resulting 3D reconstructed model is illustrated in Fig.12.

## 6 Conclusion

In this paper we presented a new collaborative robotic system for US image acquisition, which integrates a PUMA or a Kuka LWR robot manipulator, holding a US transducer, with a HGUI (Haptic and Graphical User Interface). The proposed system combines robotic precision and human expertise to facilitate US examinations and build a 3D reconstruction of the anatomical area of interest in real time.

The current implementation on the PUMA robot uses a robotic force control architecture previously developed by the Stanford Robotics Group in order to regulate the contact force at the skin-transducer interface. Experiments show that the use of a force controller and force sensor at the end-effector leads to better results than those obtained with the LWR under standard position/stiffness control approaches, as the latter lacks such a sensor and estimates the force at the tip based on internal joint torque sensors with less accuracy than the dedicated PUMA sensor. The system offers different ways for the operator to control the robot, including direct manual control, scaled operation using the haptic device, and automatic execution of user-programmed acquisition trajectories. All 2D images acquired during examination are combined in real time to produce a 3D model, which can be interacted with during examination, or stored for later use.

The benefits of using such a robotic system for US acquisition include the ability to quantitatively control parameters that affect image quality, such as transducer position and contact forces, more accurately than a human operator. Moreover, autonomous real-time 3D reconstruction enables the system to automatically detect missing sections of acquired data, an issue that currently requires staff to repeat examinations.

From a sonographer's perspective, the main benefit of the system and its haptic-enabled UI are a reduction of the strenuous physical constraints experienced during manual US examinations. Additionally, the combination of haptic device and force control provides the operator with new robot-assisted image acquisition modalities, which can potentially lead to better and/or faster examinations and diagnostics.

Compared to traditional hand-held US examinations, informal tests by clinical staff suggest that the proposed system does meet its goal of reducing user fatigue and is suitable for US examinations. In the next phase of development, the system will be further refined and undergo clinical validation tests in order to assess its potential as a diagnostic and interventional tool. We are also planning to integrate our force control framework directly onto the LWR and mount a 6 DOF force sensor at the end-effector. Finally, we are also investigating combining the proposed system with real-time tracking and registration techniques in order to develop an intelligent, semi-autonomous US transducer holder for perioperative use during surgical procedures that are performed under US guidance.

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