Advanced improves

A multi-disciplinary team of Philips Applied Technologies has developed technology with which medical devices can be remotely controlled while actually feeling the force that is applied on the human body by the device. With this technology the team built an ultrasound scanner allowing the medic to scan in a position that is not causing strains, being able to operate another device as well and without running the risk to be exposed to radiation such as X-ray. The so-called Tele-Operated Ultrasound Probe (TOUP) is now being tested at a hospital in London and first users' reactions are very encouraging.

• *Peter Frissen, Dennis Bos, Kees-Jan Zandsteeg and Kawal Rhode* •

Minimally invasive interventions such as cardiac procedures are typically executed using X-ray imaging for feedback. In many cases, the surgeons would like to use ultrasound as well since it provides additional diagnostic feedback and is also safe for the patient and the surgeon. Some doctors hope that ultrasound could completely replace X-ray in certain procedures in the future.

The use of ultrasound however requires an additional person (termed sonographer or echoscopist) to be present near the X-ray beam. This skilled worker needs to manually manipulate the ultrasound probe during the interventional procedures, which can be time consuming. This adds costs and additional ergonomic and safety issues to the situation. Many sonographers report strain problems in neck, arms and shoulders as a consequence of their daily working routines already. The Tele-Operated Ultrasound Probe system as described in this article provides a solution that enables the use of ultrasound imaging during interventional procedures and that at the same time may be used to improve the ergonomic aspects of the diagnostic routine of sonographers; see Figure 1.

Figure 1. Manual (left) and remote control (right) of an ultrasound probe.

The remote ultrasound probe allows sonographers to manipulate an ultrasound probe from a location some distance from a patient in an upright position, not causing strains. Philips Applied Technologies has leveraged its unique knowledge of haptic feedback and servomechanics to accurately reproduce dynamic forces between the probe and the patient's body in the system's control joystick. This enables the sonographer to feel and manipulates the tissue of the patient very naturally, allowing him to optimize image quality. At the same time, the natural feeling is used to maintain a safe operation. Next to that, the sonographer is out of reach of X-ray beams. Philips Applied Technologies has developed a first sample for clinical studies.

Haptic tele-operation

Tele-operation is defined as the indirect manipulation of an object by a human using two manipulators connected to each other via a controller. A tele-operation system contains in general five parts. In the general nomenclature, the user of the system is the 'Operator'. The operator gives force or position commands to the leading device, the 'Master'. The master is virtually connected via the 'Controller' to the 'Slave' device. The slave interacts with the 'Environment'. A general haptic tele-operation network is shown in Figure 2.

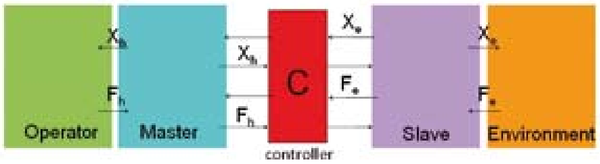


Figure 2. Structure of haptic control.

The interaction between the various elements of the systems will be described shortly. The sonographer operates the system via the haptic master. The actual position of the master in five degrees of freedom (DOFs) is sent to the slave as a setpoint. The slave follows the setpoint while interaction forces with the environment of the three translational degrees are fed back via the master to the operator. In this way, it is possible to locate e.g. ribs of a patient, as illustrated in Figure 3. Forces related to the rotations are very small. Consequently haptic torque feedback is not necessary in this TOUP application.

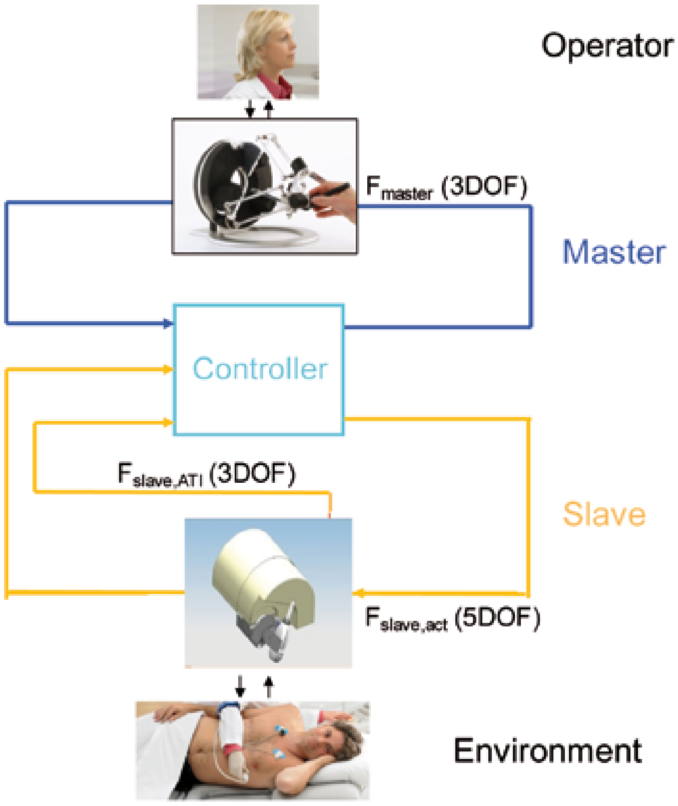
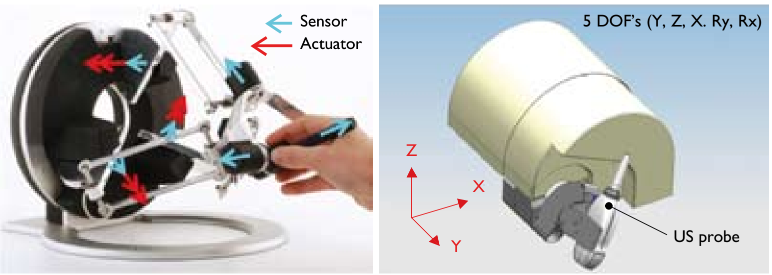


Figure 3. The TOUP system.

Figure 4 shows the master and slave robots of the TOUP system. The master is the Force Dimension Omega.6 and is commercially available. It has six DOFs, three translations and three rotations. The translations are created via the so-called delta structure, with a closed kinematic structure. The delta structure contains three arms which are identical. All arms share the same base and end-plate and consist of a link with a parallellogram. Each arm has internally seven joints. The rotations are mounted on the delta platform with

a rather flexible construction having an eigenfrequency of 20 Hz. Only the translations are actuated.
The slave robot is a proprietary designed and built manipulator optimized for clinical use and safety. It has five DOFs, all of which are actuated and sensed. This slave robot is based on serial kinematics.



Master robot: Force Dimensions Omega.6

Slave robot: Homemade manipulator

Figure 4. Master and slave.

Controller design

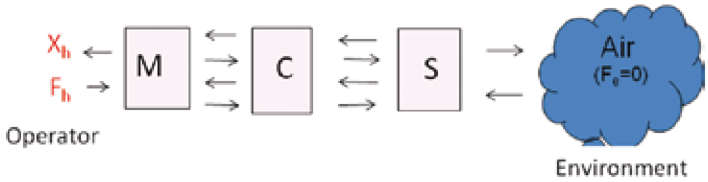
A challenging aspect of the overall system design is the controller. Its design is done by modeling the physics of the system and comparing different controller structures and their effect on the performance. Driven by the different types of tissue encounter in humans, e.g. muscle, fat and bones, the tissue characteristics are taken into account. First, the theory of the haptic feedback system is explained. As illustrated in Figure 3, four systems interact with each other. The master has direct interaction with the human operator and the slave has direct interaction with the environment (see Figure 2). Four channels with information communicate via a controller to the other half of the system. Namely, the force applied by the operator, the position of the operator, the force applied at the environment, and the position of the environment.

The most common notation for the analysis of haptic tele-operation systems is the hybrid parameter matrix. This matrix describes both the position on the environmental side and the force at the operator side as a function of the force (F) and position (X) of the environment and operator, respectively:

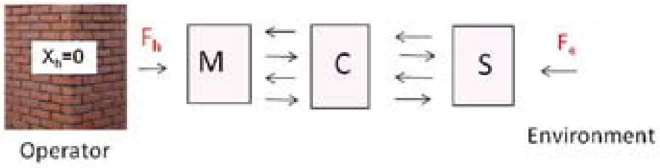
$$\begin{bmatrix} F_h(s) \\ -X_e(s) \end{bmatrix} = \begin{bmatrix} h_{11}(s) & h_{12}(s) \\ h_{21}(s) & h_{22}(s) \end{bmatrix} \begin{bmatrix} X_h(s) \\ F_e(s) \end{bmatrix}$$

The above notation is the so-called two-port notation. Each of the parameters in the matrix can be interpreted physically. The first term h_{11} is the impedance of the system in free movement. Term h_{21} represents the position tracking in free motion, term h_{12} the force tracking in contact and h_{22} the contact admittance. The parameters can be visualized as indicated in Figure 5.

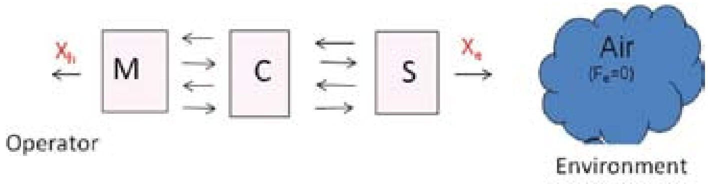
$h_{11}(s) = F_h/X_h$, felt impedance in free motion:



$h_{12}(s) = F_e/F_h$, force tracking with fixed master:



$h_{21}(s) = X_e/X_h$, position tracking in free motion:



$h_{22}(s) = X_e/F_e$, output admittance at slave with fixed master:

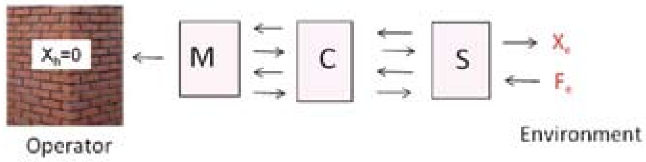


Figure 5. Explanation of the four elements of the hybrid matrix.

Transparency is defined as the ratio of impedances felt by the operator and the environment. The impedance felt by the operator is defined as:

$$Z_{to} = \frac{F_h}{X_h} = \frac{h_{11} + (h_{11}h_{22} - h_{12}h_{21})Z_e}{1 + h_{22}\,Z_e}$$

In case of ideal transparency, the ratio between the impedance felt by the operator and the environment is given by:

$$H_{ideal}(s) = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

In the ideal case, this matrix must be valid for all frequencies. Notice that in the ideal case $Z_{to} = Z_e$. For the TOUP, the so-called kinesthetic sensing is applicable. Kinesthetic sensing goes up to 10 Hz and is mainly used to discriminate shape, size and mechanical properties (of e.g. ribs and tissues).

Experimental results

As mentioned earlier, the performance of the designed haptic tele-operation controller is investigated both by modeling and simulations as well as by means of measurements. The transparency is determined for three different environments, ribcage, muscles and fat. Figure 6 shows the results in z-direction for the slave. It can be seen that the highest bandwidth is achieved for the stiffest environment. The error in transparency for softer environments, muscle and fat, is caused by the inertia of the haptic tele-operation system components. The average bandwidth is about 3 Hz. This is sufficient for the first TOUP clinical tests. Notice also the good correspondence between model and measurement.

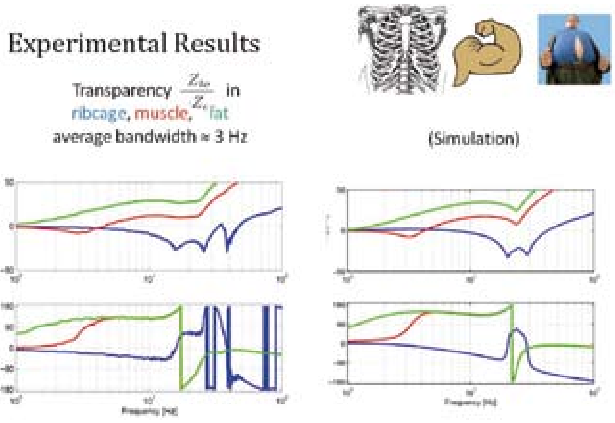


Figure 6. Transparancy of the haptic tele-operation system in Z-direction for ribcage (blue), muscle (red) and fat (green).

Beside transparency, also stability robustness for all frequencies and environments is important. A lot of successful investigation has been done to improve the control design by implementing other control architectures, e.g. by compensating the master and slave dynamics.
A reproducibility for displacement and rotations of 0.1 mm, respectively 1 mrad at the tip of the ultrasound probe is obtained.

Clinical studies

The practical implications of the TOUP system are evaluated during a clinical study; see Figure 7. A patient undergoes a pacing study prior to pacemaker implantation for heart failure; see Figure 8. This study aims to find the best lead position on the hart tissue using ultrasound imaging. More specifically, simultaneously to the TOUP, data is collected of the position of the pacing leads using sequential X-ray images, the intra-cardiac electrical measurements and the left ventricular pressure. The collected data from X-ray and ultrasound are fused. This 'data fusion' provides very rich data to evaluate the outcome of the pacing modes.
An unexpected advantage of the TOUP system is discovered: the position of the ultrasound probe in 3D space is normally gained by an external optical tracking system. This position is required for adequate image fusion. However, the TOUP system knows the position of the probe since it is directly related to the positions of the robot's internal degrees of freedom. This information is tracked during the procedures and used in the data fusion process.

Figure 7: Clinical case of the hybrid system ultrasound (TOUP) and X-ray.

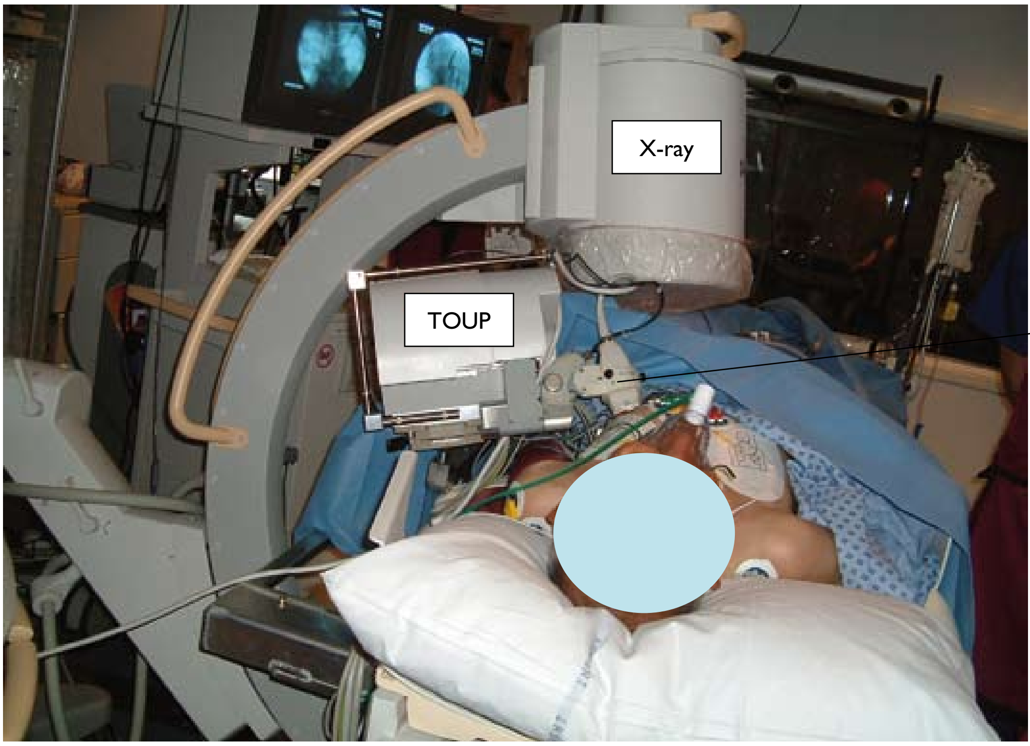


Figure 8. Patient study with X-ray and ultrasound (TOUP) at St. Thomas' Hospital, London.

As an example of the data registration, a part of the left ventricle (blue object) and electrical measurement catheter (pink object) is segmented and overlaid onto one of the 2D X-ray images; see Figure 9. By a visual inspection, the registration is well within the clinical accuracy requirement of 5 mm for these types of procedure.

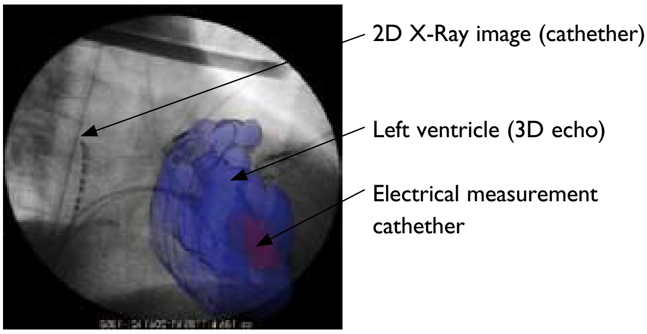


Figure 9. Data fusion of X-ray and ultrasound.

Conclusion

A challenging aspect of the overall system design is the controller. Its design results in a successful performance with measurements executed on different tissues. Ultrasound is a completely safe and well-established imaging modality that provides high quality heart images. There is much recent interest in exploring the use of ultrasound for guiding cardiac catherisation procedures. By developing the TOUP, an elegant solution is made available for the safe and robust use of ultrasound within the catheter laboratory. Recently, the research team at King's College London and St. Thomas' hospital explored the use of the TOUP during several different types of catherisation procedures. Furthermore, the ultrasound probe can be manipulated precisely in a comfortable position, which leads to considerable reduction of physical stress for medics.

Acknowledgment

The project is executed by Philips Applied Technologies in cooperation with:

- Eindhoven University of Technology, Faculty of Mechanical Engineering, Department of Dynamics and Control Technology (Eindhoven, the Netherlands);
- King's College London, Department of Clinical Science and Imaging (London, UK);
- Philips Healthcare (Best, the Netherlands).

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Information

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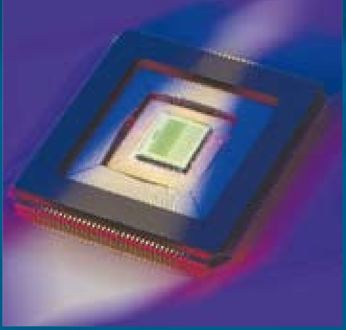

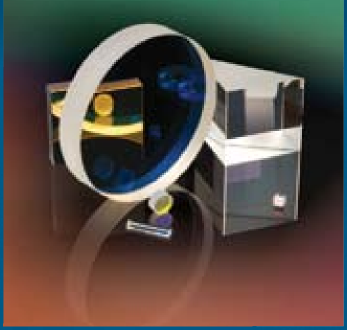

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