Nowy system robotyczny do zdalnej ultrasonografii – od pomysłu do pierwszego prototypu. Prezentacja projektu ReMeDi

Novel Robotic System for Remote Ultrasonography – from an Idea to the First Prototype. Presentation of the ReMeDi Project.

Artykuł recenzowany

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Streszczenie
Zapotrzebowanie na specjalistyczną opiekę medyczną w dzisiejszych czasach staje się coraz większe. Dodatkowo obserwowany jest rosnący niedobór lekarz w większości krajów na całym świecie. Rozwiązaniem takiej sytuacji wydaje się być telemedycyna. Projekt ReMeDi ma na celu zbudowanie systemu robotycznego do zdalnej diagnostyki medycznej, który będzie wspierać lekarza poprzez umożliwienie zdalnej obecności przy wykorzystaniu inteligentnych i autonomicznych funkcji poznawczych. Ten artykuł skupia się na interfejsach systemu ReMeDi przeznaczonych do zdalnej ultrasonografii i prezentuje prace wykonane w ciągu dwóch lat trwania projektu.

Abstract
Nowadays the demand for specialized medical care becomes higher. Additionally increasing deficit of physician is observed in majority of countries worldwide. The solution for such a situation seems to be telemedicine. The ReMeDi project is aimed to develop a robotic system for remote medical diagnostics, which can support physician by enhancing the (tele-) presence with intelligent cognitive autonomous features. This paper focuses on the interfaces of the ReMeDi system which are dedicated for remote ultrasonography and presents the work done during the two years of the project.

KOMENTARZ RECENZENTA…
Dr hab. n.med Sławomir Grzegorczyn (Zabrze)

The paper presents the project of remote operation of manipulator equipped with ultrasound head. Realization of this project will enable the remote medical examination of patient. For this reason, the article is of large cognitive value and the project has potential future applications in telemedicine.

INTRODUCTION

In the modern aging societies, the demand for specialized medical care becomes higher. Nowadays in the majority of countries worldwide a deficit of physician is observed and the current forecasts alarm that it will increase in the nearest future [actionforglobalhealth.eu]. It has been already reflected in limited amount of experts of various specializations, who are not always available to medical units due to geographical (e.g. provincial hospitals), time (after regular work hours) or other logistic constraints. This situation led to development of several types of medicine-related services performed remotely, ranging from Telenursing, Telepharmacy, Telerehabilitation, Telepsychiatry, Telepathology, Teledentistry, etc. to Telesurgery.

The existing commercial solutions for remote consultations and remote mentoring are, however, limited to merely teleconferencing [RP-VITA, VGO]. There is still no teleconferencing system which would enable a physical interaction between a patient and a remotely located physician to make a tele-examination similar to direct medical examination. In the ReMeDi (Remote Medical Diagnostician) project we develop a multipotential robotic device, which will allow performing a real time remote medical examination. This paper is focused on the crucial part of the ReMeDi project – the robotic system for remote ultrasonography.

Different kinds of medical robots for remote ultrasonography have been developed over the past couple of years. The precursors were Dégoulange with his project Hippocrate [Dégoulange, 1999] and Salcudean [Salcudean, 1999]. There were also other important projects in robotics for remote ultrasonography: OTELO [Delgorge2005], ESTELE [Arbeille 2007] and TER [Martinelli ,2007]. They differ in amount of degrees of freedom (3 to 6), the way of a remote manipulation and the presence (or not) of haptic feedback. Only OTELO project has been recently turned into commercial product called MELODY (AdEchoTech) [http://adechotech.fr/en/products], which can be applied for remote abdominal ultrasonography.

Our goal is to make the ReMeDi robot user-friendly and acceptable by patients and physician as well as support physician by enhancing the (tele-) presence with intelligent cognitive autonomous features. The project is designed on basis of real life scenarios from medical emergency situations, when the lack of medical specialist can lead to dramatic (also fatal) consequences. The robotic device developed during ReMeDi project allows for application of new functionalities of remote presence for remote non-invasive medical diagnostics.

METHODOLOGY

The ReMeDi project follows the development methodology blending ISO-13407 with VDI2206 (V-cycles). Each development cycle consists of the following stages: user requirements and functional design, architectural design, component design and evaluation, system integration and evaluation. Thereby, we follow a user centered (involves user requirements as a starting point), system orientated (considers all functional system requirements) and iterative design (as it allows for the modification of requirements in later design phases and to repeatedly validate the new requirements).

As a medical basis for the analysis of users' needs, 4 use cases – potential clinical situations, in which the application of the ReMeDi system would be especially beneficial were chosen: i) diagnostics of acute abdominal pain, ii) acute heart failure and iii) aortic aneurysm as well as iv) help with ultrasonographer's recovery after work-related musculoskeletal disorders. All the use case scenarios has were carefully analyzed to provide detailed information about functionalities, which are significant for all users of the system.

USER REQUIREMENTS

In the first step of the project the user requirements were defined. The ReMeDi Consortium analyzed the data related to users' needs available in the literature. Non-medical partners observed real medical examinations. For better understanding what people consider as a remote examination and what their expectations are, 4 workshops (moderated discussions) with potential users doctors and patients were organized. The observation and group discussion gather qualitative data in order to explore the users' needs, the survey aims at gathering representative data. The procedures has been described in [Stollnberger 2014; Stollnberger, Moser 2014]. The analysis of the collected information led to a set of user requirements viewed from doctor's, assistant's and patient's perspectives. Some of them are obvious like expectation that "the doctor should obtain all the necessary information for examination" or "the entire work space should be covered by the robot". Physicians underlined that for remote ultrasonography a real-time and sensitive movements with a natural feedback (i.e., feel haptic feedback when robot touches the patient with probe) is very important, but the most crucial is to see the real-time ultrasound image. For patients it is very important to perceive that the robot is controlled by the doctor all the time and the safety is ensured. Very interesting is that almost all patients expect to see the examination results on the display and it important for them, but from the medical point of view this functionality has no value for diagnosis [Stollnberger 2014; Stollnberger, Moser 2014]

Fig. 1. Initial vision of the ReMeDi system

Technical requirements

The main objective of the technical requirements is a precise description and parameterization of every part of the ultrasonographic examination, which could be performed by remote specialists via the ReMeDi system.

Medical examination is a combination of many complex techniques, which involve all physicians' senses, and use a variety of abilities of human hands, eyes and brain. For the technical requirements analysis the ReMeDi consortium had to:

1. choose the stages of ultrasonographic examinations which should be assessed for technical requirements;
2. analyse how doctors technically perform the ultrasonographic examinations;
3. choose and measure parameters, which are crucial for the design of the ReMeDi system;
4. establish how doctors behave and patients react during the standard examination;

For ultrasonographic examination some basic analysis of movements of ultrasonographic transducers were done, but this is not sufficient for the design of the complex robotic system for remote diagnostics. For detailed analysis of direct examination methods, an experiment was performed to collect more precise information on quantitative measurements of the workspace of ultrasonographic examinations as well as applied forces during physician – patient interactions. During the experiment the physicians were asked to perform standard ultrasonographic (echocardiography or abdominal ultrasonography) examination for registration of physical parameters of the examination. For this purpose the Qualisys motion tracking system was used. All doctors wore cybergloves and the USG probes ware equipped with 2 ATI nano force torque sensors. The examinations were recorded by 2 Kinects and Microsoft LiveCam. This experiment provided information about forces and ranges of the doctors' movements.

System Architecture

The findings from users requirements analysis were transferred into the system architecture shown in the Fig. 1. The direct examination by the physician is split into two physical locations. On the patient site (left) a dedicated robotic system equipped with a manipulator with the USG transducer and a force sensor, and an active 3D vision system is placed. The robot is supervised by an assistant assuring the proper and safe robot operation. The diagnostician site comprises a control console with a vision system, haptic input device, an USG control panel and a number of foot switches.

First Prototype

According to the ReMeDi Development Methodology based on the technical specification the first Laboratory Prototype of the integrated system was designed. It consists of the ReMeDi Robot (robotic head and robotic arm) which is integrated with DiagUI including all the stationary components available.

The first prototype of the telediagnostic subsystems should be operated manually by the Assistant and remotely by the Doctor (using joystick). It contains:

- on the patient side: the robot arm, the head, the safety system, the assistant interface, the perception and interaction workstation and the stationary robot base
- on the diagnostician side: the haptic interface with the USG probe and foot switches, the interaction and visualisation workstation with 3D vision system and teleconferencing equipment, and the head pan-tilt controller (joystick).

Patient Site

ROBOT ARM

The arm and elevation mechanism are designed to have the workspace allowing to conduct palpation, auscultation and ultrasonographic examination. The arm kinematics, especially the wrist, was designed to match the rotational workspace of the ultrasonographic positions according to the experimentally measured ones. The payload was scaled up to approx. 80N to fit the requirements of the deep palpation. Several reviews f the CAD design were performed by the doctors in order to check the applicability of the arm to the targeted diagnostic procedures.

Fig. 2 (left) shows the arm during an echocardiography examination. The diagnostician (seen on the robot head display (right) is remotely examining the patient mannequin positioned in the left apical position. The robot arm is equipped with a dummy of the ultrasonographic probe.

The controller of the manipulator consists of an electronic control unit (ECU) and of the actuator-powering unit (APU). The ECU is an industrial embedded PC running RT-Linux with a real-time patch and Robot Operating System ROS. It is equipped with extension cards providing necessary I/O ports (A/D, D/A, encoder counters) and communication link (Ethernet). ECU receives the motion commands from the trajectory planner, converts them into motion commands for the motor controllers (desired motor current) and sends them to APU via analogue interfaces. The motion of the motors is read by means of the incremental encoders and fed back to the RT Linux. ECU can work in position/velocity and torque control mode for each wheel. APU

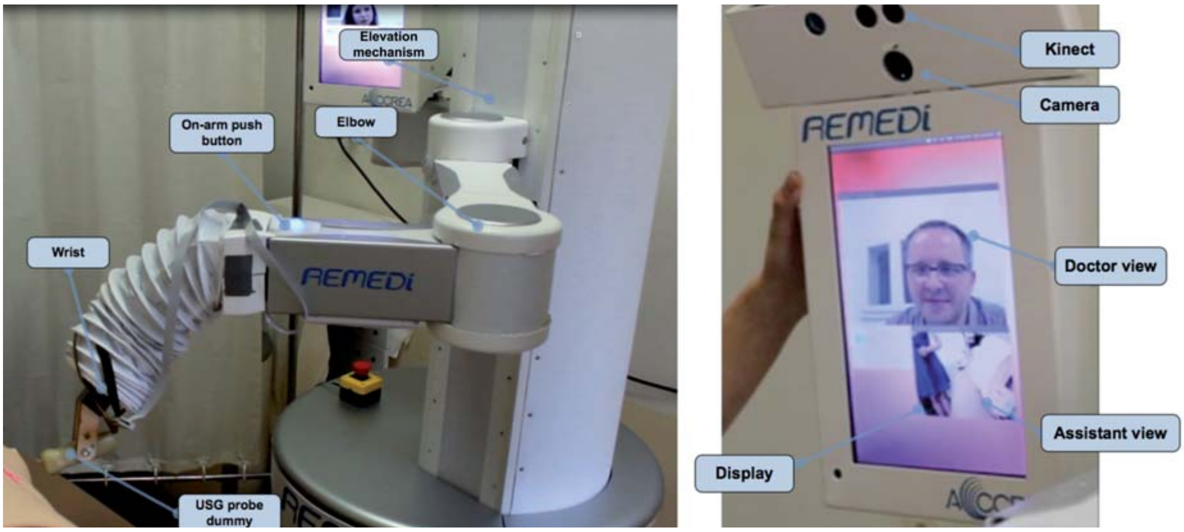

Fig. 2. Robot arm and head

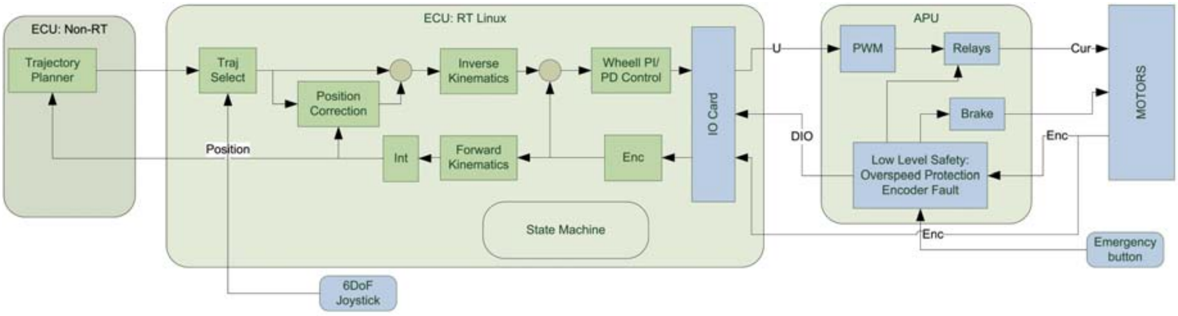

Fig. 3. Manipulator Control system

Fig. 4. ReMeDi robot body

consists of six PWM power amplifiers for the DC motors, and of a low-level security system equipped with an overspeed protection and cable-break and short circuit detection subsystems. The manipulator may be controlled in position and velocity mode. The control loops are running at 1kHz and an impedance control scheme is implemented thanks to the presence of the force-torque sensor. The motion trajectories can be either generated by the trajectory planner of input in a realtime by means of a 6 DoF joystick or a haptic input interface.

ROBOT HEAD

The robot head is a 2 DoF pan – tilt unit equipped with an RGBD camera (Kinect), an RGB camera, a microphone and an LCD screen. The RGBD camera collects the data used further for body pose analysis. The view from the RGB camera provides not only direct stream with the view of the patient, but also is used for the analysis of the facial expressions. The LCD screen shows the diagnostician's face and, in the smaller window, the view of the assistant's window.

In order to find the most convenient position of the head, the pan and tilt angles can be adjusted manually by the assistant or remotely by the diagnostician using the joystick which is a part of doctor interface, as shown later in Fig. 6. In terms of software, the head display constitutes an integral part of the teleconferencing functionality of the gDiagUI, which is described later.

ROBOT BODY

The robot body is designed to cover both the functionality (provide the protection of the patients and the electromechanical systems contained) and aesthetic appearance according to the guidelines of the workshop results with patients. Figure 4 shows the design that users preferred in the requirement analysis phase (left), the rendered simulation on the robot body (middle) and the robot prototype (right).

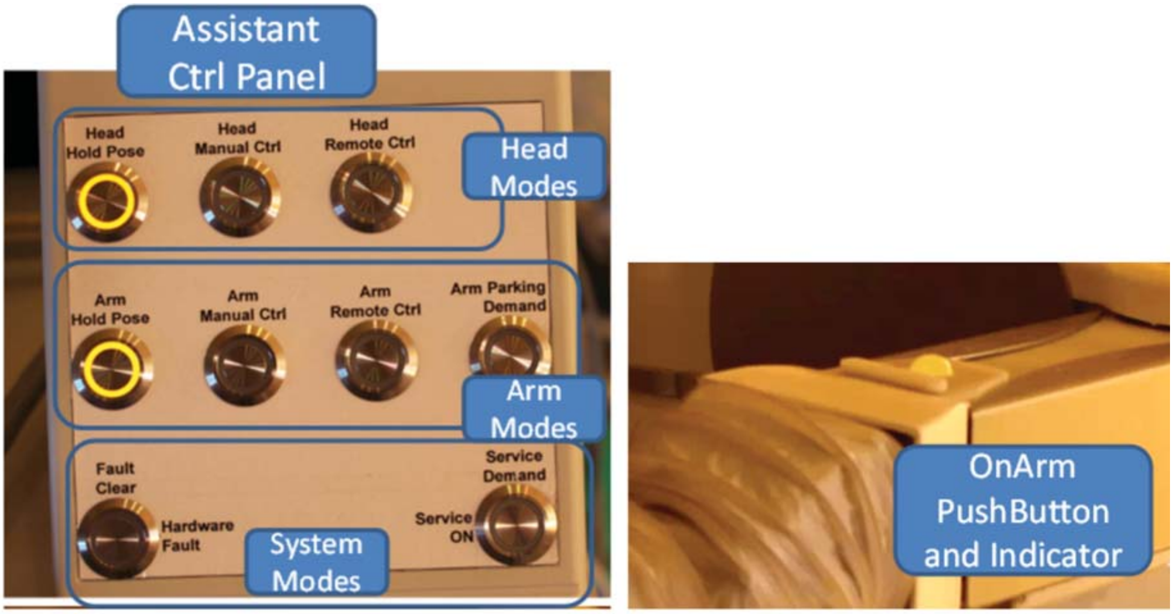

Fig. 5. Assistant Control Pannel equipped with colour light and OnArm PushButton and Indicator

Fig. 6. Safety system: EMG (Emergency Switch) and DMS (Dead Man Switch)

ASSISTANT CONTROL PANEL AND THE INTERACTION BUTTONS

The Assistant Control Panel, shown in Fig.5, is held by the Assistant (it can be placed on the robot body) and is used to switch the control modes of robot head and arm. Both components can be controlled either manually (Manual Ctrl) by the Assistant, or remotely (Remote Ctrl) by the Diagnostician, or can be actively locked in a position (Hold Pose). Additionally, the arm can be automatically parked (Parking Demand) in a position suitable for navigating. The mode that is currently activated is shown by highlighting a corresponding colour indicator. The arm modes can be also switched by (and displayed on) an 'On Arm PushButton and Indicator' located close to the end-effector, as shown on the right of the Fig.4.

SAFETY SYSTEM

Both Patient Site and Diagnostician Site are equipped with Emergency Switches (EMG). These are low level protection systems, that when pressed, interrupt the motion of the moving components and ensure their transition into the safe state. The origin of such an event must be identified and removed and the system must be restarted. In addition to the EMG, when it comes to the remote examination, the system is organized in such way that the Assistant has to hold a Dead Man Switch (DMS) in middle position. When released or fully pressed – the motion is paused and is carried on when the DMS is back in the middle position. Fig. 6 shows a picture of Emergency Button and Dead Man Switch.

Diagnostician Site

INTERACTION HARDWARE

Fig. 7 shows the interaction hardware at the diagnostician site: the haptic input, the joystick and the interaction pedals.

For performance of the remote examination, the Delta-like haptic interface is used, allowing to control the motion of the arm of the robot, at the same time receiving the force feedback, which enables the control of the interaction forces between the ultrasonographic probe and the patient's body. The Joystick is aimed to adjust the head pan-tilt angles remotely by the diagnostician, in order to provide the best viewing angle for the examination. Two interaction pedals are placed at the diagnostician's feet. At current stage of the project, only one interaction pedal is used. By pressing it, the diagnostician couples the haptic interface with the arm of the ReMeDi robot. In case when the change of the workspace is needed, the doctor releases the pedal and can relocate the probe dummy or rest.

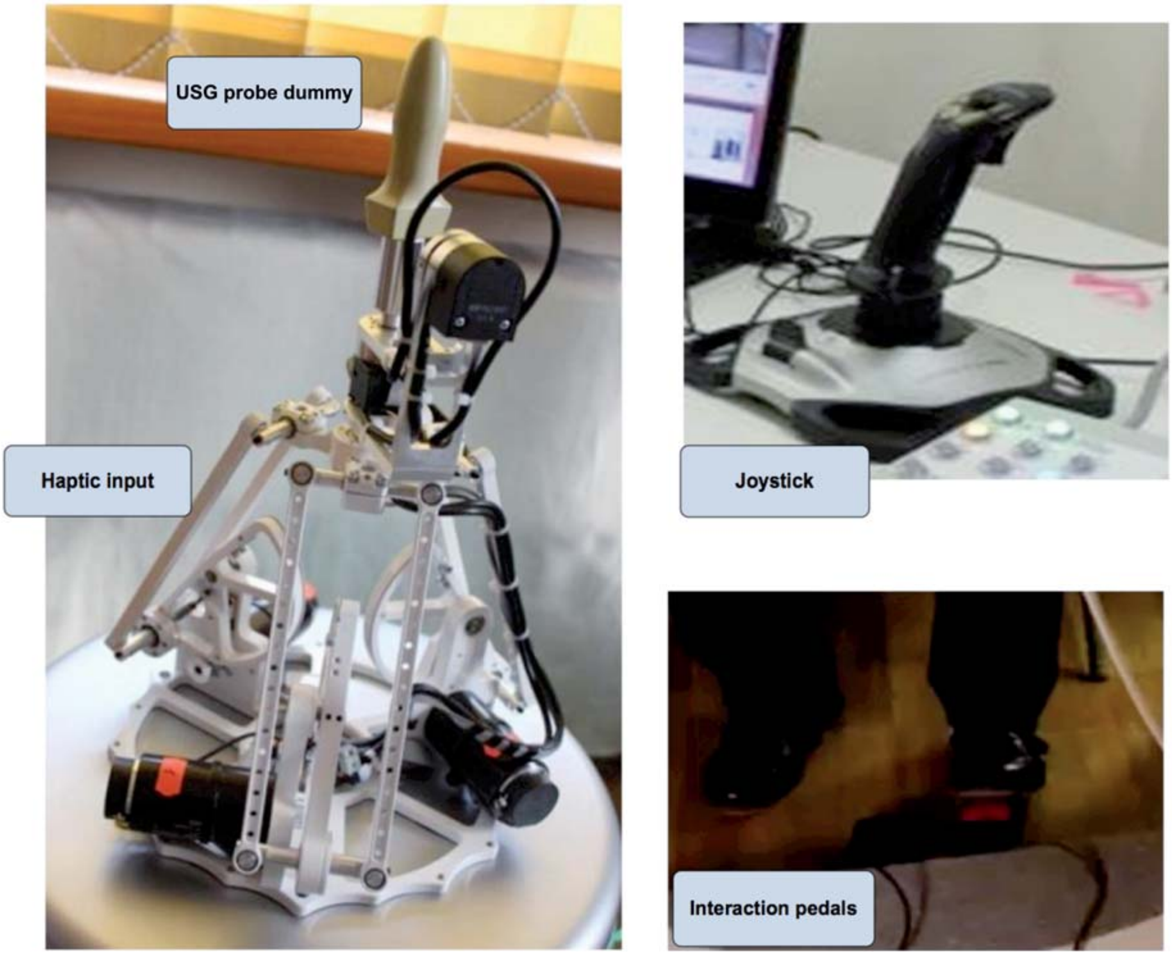

Fig. 7. Hardware components required for the ultrasonographic examination on the diagnostician site

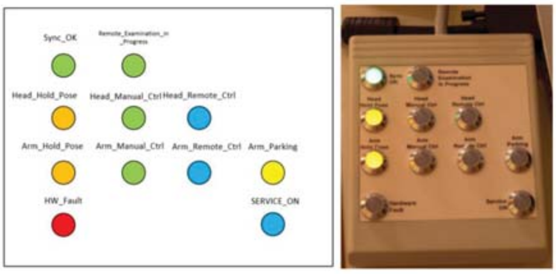

Fig. 8. Status indicator panel at the diagnostician site

DIAGUI (DIAGNOSTICIAN USER INTERFACE)

The main software interface at the Diagnostician site is gDiagUI – the graphical part of DiagUI. The design of this software is described in [Kreczmer 2015]. In order to make the system operational even without gDiagUI activated, and to make the indicators more readable to the Diagnostician, a dedicated hardware panel was built with color diodes corresponding to the state of the main components of the Patient site, see Fig. 8. The diagnostician control panel corresponds with the Assistant control panel and reflect the status of the system, which is set up by the assistant.

TELEMANIPULATION SYSTEM

Using the components described above, a full telemanipulation setup is assembled with all the devices connected either to a local controller or operating in a local network. In this way the telemanipulation system can be tested without the parasite effects of the remote connection. Such a configuration is beneficial for the first pilot tests with end users.

Fig. 9 presents the full telemanipulation setup in use during an USG examination. By placing the diagnostician and the patient sites next to each other, it is possible to test the option with the ‘direct view’, i.e. when the diagnostician can directly see patient, and the ‘remote view’, i.e. using the vision of the teleconferencing system.

The control loop works in a bilateral teleoperation loop as in [Stanczyk2005] with the manipulator under position control and the haptic interface under force control. In order to stabilize the control loop and dissipate the impact energy, a virtual viscosity is added to both controllers.

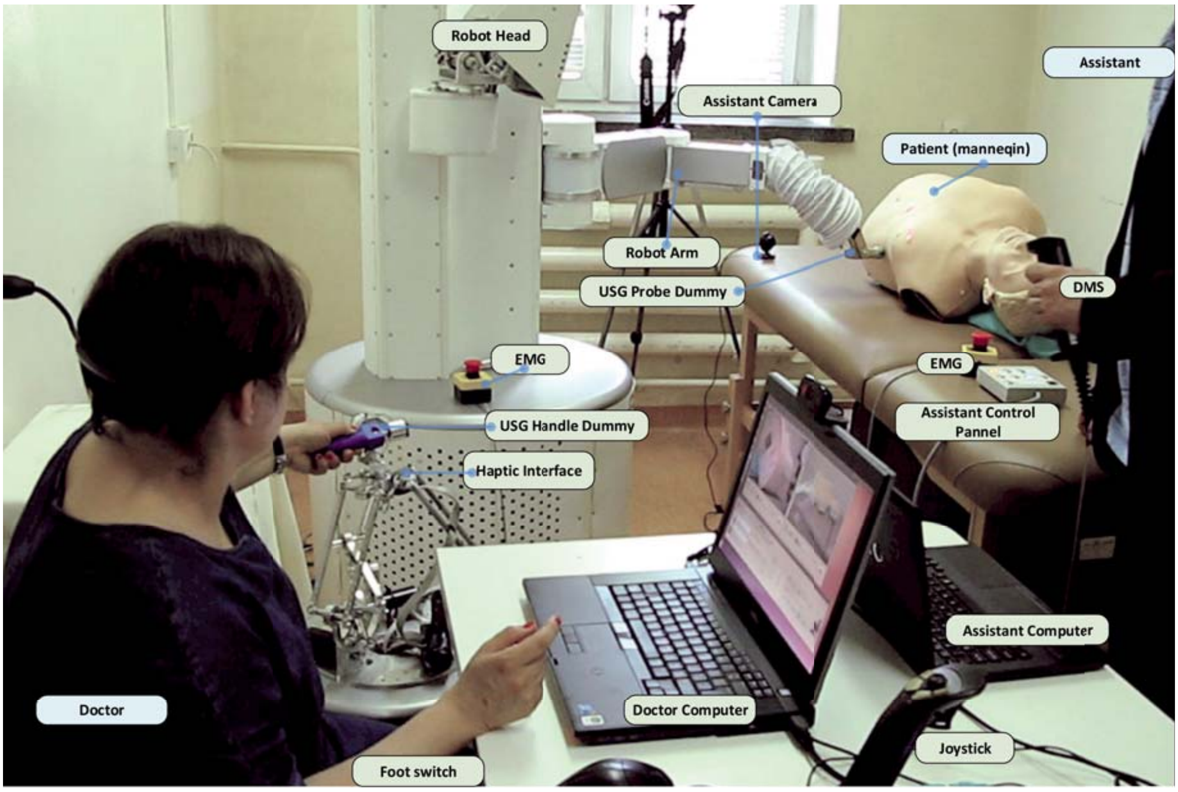

Fig. 9. ReMeDi prototype integrated. Diagnostician and Patient sites

Summary

The first prototype of the ReMeDi system, which is presented in the paper, reflects the user requirements collected during the initial phase of the project. The next step of the project is the evaluation of the first prototype with end-user. All opinions, that will be collected during the tests with real doctors, are going to be used for further improvement of the system. Simultaneously all elements of the system – hardware and software will be developed.

Acknowledgment

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