SELECTED TOPICS IN DESIGN AND APPLICATION OF A ROBOT FOR REMOTE MEDICAL EXAMINATION WITH USE OF ULTRASONOGRAPHY AND AUSCULTATION FROM THE PERSPECTIVE OF THE REMEDI PROJECT

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Abstract:
This article presents a robot for remote noninvasive medical examination. In particular, this robot allows a doctor to carry out an interview, an observation, an auscultation and an ultrasound examination, including echocardiography. The robot has been developed within the ReMeDi (Remote Medical Diagnostician) project funded by the European Union's Research and Innovation 7th Framework Programme. At the beginning of the article, we outline selected results of the user's evaluation of the robot idea together with the requirements regarding the robot. Then the essential system components are presented and a selection of them are discussed in detail. Subsequently we present the integrated system and discuss selected topics concerning the integration. Finally, the document is completed by a description of the users evaluation process.

Keywords: *remote medical examination, telemedicine, medical robot, manipulator, mobile base, control system software architecture, user's study*

1. Introduction

Medicine is a domain of life which poses serious challenges to robotics since many years [3, 5, 22, 23, 26, 35]. It is noteworthy, that the number of robotics applications in this area have been growing continuously for a long time. Nowadays, we can point to numerous research areas such as: robotic surgical systems [40], [22], rehabilitation robotics [24], [13], doctors' assistants [20], patients' assistants [36] or nurse' assistants [21], robotic applications in dentistry, bio-prosthetic [4], laparoscopic instruments and telerounding robots in hospitals [8]. For 30 years also the robotic support of an ultrasonographic examination has become an area of interest of medical robotics [6], [37]. During this time solutions for robotisation and teleoperation of numerous modes of ultrasonographic examination were searched.

Robots allowing for carrying out tasks remotely are an important class of medical robots. It covers the most important systems used in: cardiac surgery, some doctor/nurse/patiens assistants and telerounding robots in hospitals. Telemedicine pays a special attention to such robots and enforces them to possess specific system components. In particular, these are telemanipulation systems, haptic interfaces, augmented and virtual reality, video-conferencing systems.

The significance of telemedicine is emphasised by the World Health Organisation, which has included it to the group of its priorities. Telemedicine includes such services as: telenursing, telepharmacy, telerehabilitation telepsychiatry, telepathology, telesurgery. Their significance stems from the sustainable growth of amount of patients per doctor that is related to ageing of societies. Besides, teleservices ease access to specialists for people from small villages, especially after regular business hours of local health centres.

A robotic system for remote medical examination that includes interview, observation, physical examination and ultrasonographic examination is a new idea in the field of telemedicine. This challenge was undertaken within the frame of the ReMeDi project [39]. To the best knowledge of the authors, robotic systems, which allow to combine different diagnostic activities, have not been developed yet. Although the first robots for teleconsultation *VGO* [43] and teleultrasonography: *MEDIROB* [41], which is dedicated for selected aspects of echocardiography and *MELODY* [42] for abdominal ultrasonography reached the level of commercial products, medicine still needs more complex telemedical solutions which can support doctors in telediagnostics.

This article presents a concept of a robotic system ReMeDi that allows a doctor to carry out remote medical examination that include auscultation and different modes of ultrasounographic examination. Numerous aspects concerning implementation of this idea have been discussed in detail. In Section 2 a concept of the system is discussed. Next, in Section 3, basic system components of the system are presented and some of them are discussed in detail. In Section 4 the integrated system is presented. Finally, in Section 5, selected topics in the scope of components and the integrated system evaluation have been collected. Conclusions are included in Section 6. Organisation of the material in this document refers to individual stages of a V-cycle in the methodology of developing mechatronic systems that is described in the norm VDI2206. This methodology was widely used in the project ReMeDi.

2. The System Idea

The underlying idea of the ReMeDi project is presented in [25] and [39]. In principle, the system has to enable the doctor to carry out remote medical examination in the way that essentially is similar to the traditional examination. A medical examination includes: an observation, an interview, a physical examination and an ultrasonographic examination. In turn, the physical examination covers auscultation and palpation.

These requirements determine a system structure, that is shown in Fig. 1. As in typical telerobotic medical systems, the ReMeDi system consists of two main components located at two physically separated locations. On the local site, the diagnostician interface is placed (Fig. 1(a)) that enables the expert doctor to carry out all the actions necessary for the diagnosis either with or without help of an assistant. On the remote site, the robot (Fig. 1(b)) is positionned for ensuring a telepresence of the doctor at the patient. The robot is equipped with an active 3D multi channel audio-visual communication. It is also capable of physical contact with the patient through a manipulator with a specialised effector. The manipulator should enable the doctor to touch and press any part of the patient's trunk and getting a range of information from this place including reaction forces of the body to pressing. The role of a medical assistant on the patient's site is, firstly, to provide basic medical service to the patient, who can be under severe medical condition and secondly, to support the remotely located medical doctor in an effective medical examination. Therefore, after short training he should be able to perform actions which are not a part of medical examination and cannot be controlled by the doctor e.g. switch on/off of the robot or navigation of mobile platform as well as actions which can make examination faster and safer for the patient e.g. prepositioning of robotic arm, stop the remote examination in case of any hazard to patient's safety.

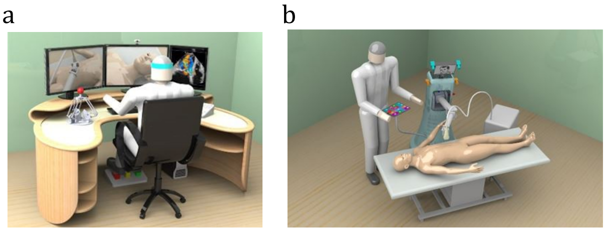

Fig. 1. A basic concept of a system for remote medical examination: a - a diagnostician interface during medical examination, b - a robot performing an examination of a patient under supervision of an assistant.

At the begining of the project, the concept of a robotic system for remote medical examination was evaluated by target users: doctors and patients. The aim of this evaluation was to formulate user's requirements with respect to the system. Some of the results are presented in [32], [31]. In [31] the authors confirm legitimacy and desirability of development of the ReMeDi robotic system in the context of applications in the rural areas. The work [32] presents the methodology of gaining of such information with respect to medical devices. The proposed approach consists in analysis of answers to the research questions of the fundamental nature, that are formulated from four diverse perspectives: literature analysis, users' observations (in their natural activities or functioning), group discussions, collecting of representative data (questionnaires). All data, which were collected during the user requirements analysis, was analyzed by physicians and engineers from the usability as well as technical feasibility point of view. The requirements that have been considered as valuable for medical examination contributed to the final form of the the first prototype of the ReMeDi robotic system concept and were used for functional specification of the system.

Parallel to requirements and specifications the process of evaluation has been planned. For this purpose four clinical situations were selected:

- remote diagnostics of abdominal pain,
- remote diagnostics of acute heart failure,
- remote assessment of aortic aneurysm and therapeutic plans made by the remote team of specialists,
- solution to help in physician's recovery after work-related musculoskeletal injuries.

The choice was done to present all important features and functionalities of the ReMeDi system. The scenarios based on these situations were intended to be case studies.

3. ReMeDi System Components

As a result of the analysis of the basic technical requirements, such as the required contact force of the end effector or the desired workspace, that were obtained on the basis of numerous experiments with users, the decision was made in the ReMeDi project that two separate systems will be developed. The first system will be stationary and intended for the physical examination including palpation only. The second system will be endowed with a mobile base and the physical examination will include ultrasound examination and auscultation.

The decomposition of the system into components was discussed in the work [30]. The basic components are: a diagnostician interface *DiagUI* at the doctor site and a ReMeDi robot at the patient site. Both of them are shown in Fig. 1 and in the diagram presenting the logical architecture of the ReMeDi system in Fig. 2. The diagram in Fig. 2 is one of several SysML internal block diagrams developed in the top-down system design process, applied for the ReMeDi system [30].

The ReMeDi robot, in turn, is decomposed to the following components: a robot central control system, a manipulator, a head, an effector, a control system of the head, a control system of the manipulator, a graphical interface with a video-conferencing system, an analogous interface at a tablet (enriched in components allowing steering the robot by an assistant), perception module and a mobile base. Each of the mentioned system components can be identified as a single block or as a group of blocks in Fig. 2. The ReMeDi robot is shown in Fig. 3.

The diagnostician interface is shown in Fig. 4. Its logical structure is depicted in Fig. 2. It consists of a decision maker module that is supervising its behaviour, 3D visualisation with augmented/virtual reality module, graphical interface module with a video-conferencing system for the doctor together with

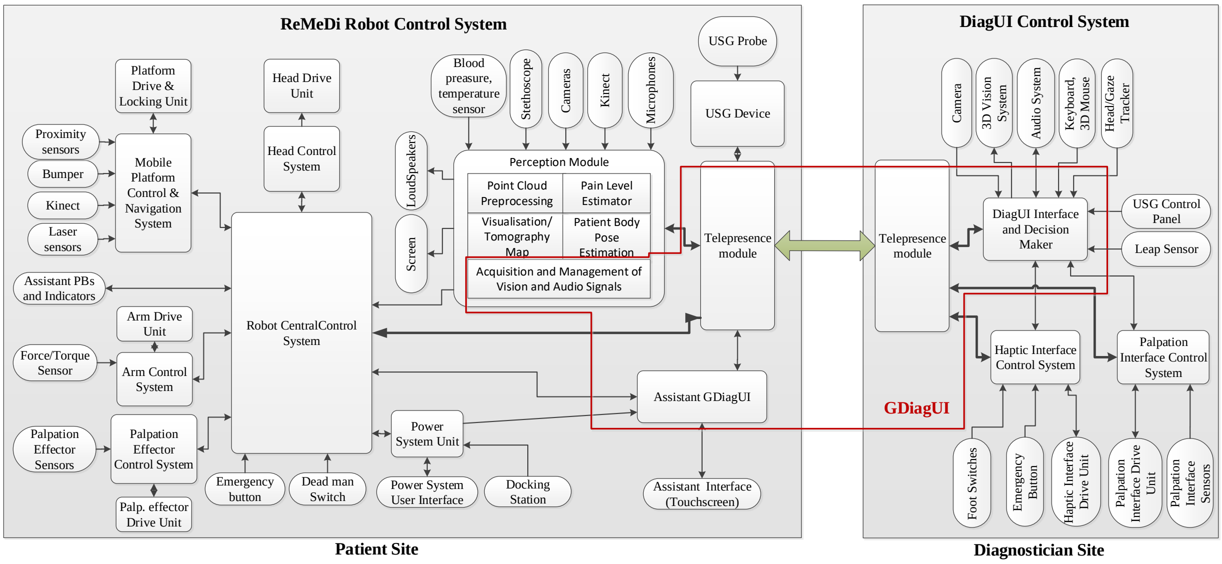

Fig. 2. Logical architecture of the ReMeDi robotic system, [30]

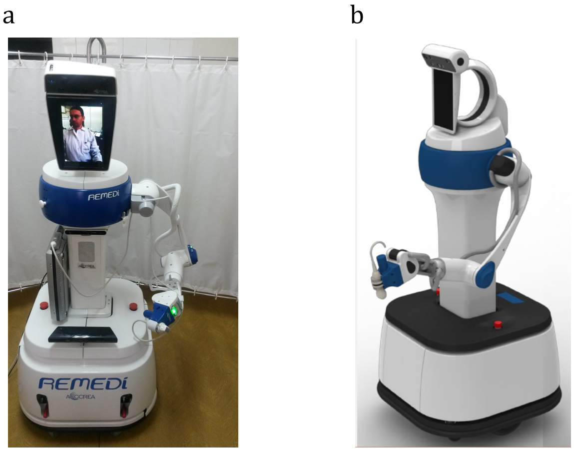
a b

Fig. 3. ReMeDi robot: a – current state, b – project

a component designed to monitor the internal states of the robot, haptic interface and a dedicated controller.

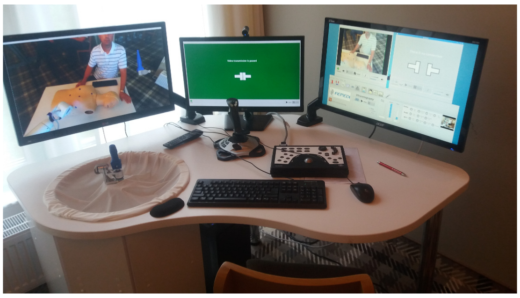

Fig. 4. DiagUI: the current state

Selected components of the ReMeDi system are discussed below. Majority of them are included in the ReMedi robot. It should be noted that we do not discuss a haptic interface applied in the robot. The haptic interface with augmented reality for remote palpation is discussed in [27]. In turn, the haptic interface for ultrasound examination and auscultation is described in the works [2] and [38]. The last of the mentioned works discuss a controller hardware which has been applied in haptic interface for remote palpation.

3.1. Manipulator

A manipulator is a system component that aims at elongation of the diagnostician's arm. The effector has to recreate the motion of the diagnostician's hand and simultaneously has to deliver signals that enable the hand to feel the environment that is in the contact with the effector.

Works on the ReMeDi robot manipulator were initiated by designing a light cable-driven manipulator, [18], at ACCREA (a company based in Lublin which is a commercial partner and a technical leader of the ReMeDi project). On the ground of gained experiences, a large SCARA type manipulator was constructed. It has 6 DOF and is designated for palpation. Straightened arm is 90 cm long. The range of vertical motion is 75 cm. The manipulator allows the effector to act on surfaces with the force 100 N or smaller. The control system enables velocity and force control, leading the manipulator by hand, teleoperation, proper bandwidth. Cables introduce a natural compliance.

The manipulator designed for ultrasound examination, shown in Fig. 5, was constructed by ACCREA on the ground of different design guidelines. The maximal contact force is 40 N. The manipulator is stiff, redundant with 7 DOF (Fig. 5(b)) without prismatic joints. The range of the arm is comparable to the range of the arm for palpation. Kinematics was designed such that the probe in the effector of a manipulator is capable of reproducing the movements of a dummy probe in the hand of a doctor, especially with respect to the orientation.

The electro-mechanical components applied in the manipulator are typical for such construction, but their parameters were designed very carefully by ACCREA. The hardware of the control system is based on JointsController manufactured by ACCREA. The CPU is implemented using STM32F4 microcontroller.

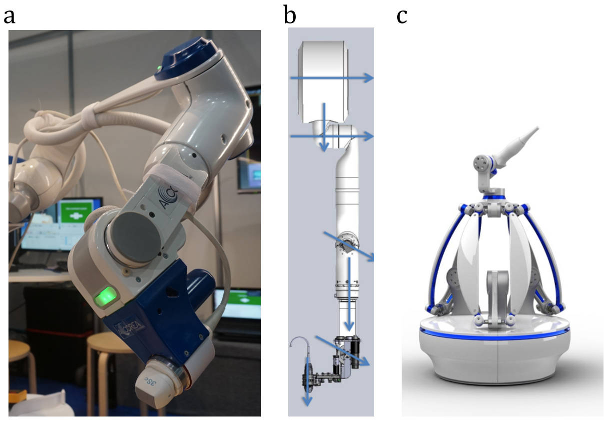

Fig. 5. ReMeDi robot manipulator: a – the current state of development, b – kinematics, c – haptic interface (DiagUI)

The logical architecture of JointsController is briefly presented in Section 4.1. Deployment of control algorithms is distributed between JointsController and PC computer. The applied control algorithms are based on position and velocity feedback control with decentralized feedforward compensation and an impedance control [29]. Communication with PC goes through the UDP protocol. This issue is wider elaborated in Section 4.1.

A multi-axis torque/foce sensor is built-in to the effector. At runtime, the manipulator is coupled with an haptic interface shown in Fig. 5(c). The type of the telemanipulation system architecture is force – position with wave variables [28]. Through the haptic interface a diagnostician moves the manipulator effector and simultaneously feels the remote environment. The detailed information concerning control system of the haptic interface are included in the works [38], [2].

The above concerns to the telemanipulation working mode, in which a doctor steers the manipulator. Besides there is manual working mode in which an assistant handles the manipulator. In this mode, thanks to a redundant degree of freedom and thanks to sensitivity of the manipulator control system to external forces the assistant has possibility of easy reconfiguration of the manipulator's posture without changing the position and orientation of the effector, so that a diagnostician will have assured a good visibility of the effector during the examination. The manual mode include also hand lead so that an assistant can easily locate the effector of a manipulator in the area required by a doctor.

The blue part of the effector in Fig. 5(a) is a fastening housing for an ultrasound probe. If necessary, thanks to suitable mechanical design, this housing can be easily unmounted from the manipulator and replaced by similar one with a stethoscope probe.

3.2. Head and Video Conferencing System

A head of the ReMeDi robot together with a video conferencing system, the cameras and microphones built-in the head, the cameras and microphones built-in DiagUI, together with the assistant's tablet, form the system components which enable the diagnostician an observation and an interview. Simultaneously they give a possibility of remote telepresence near the patient.

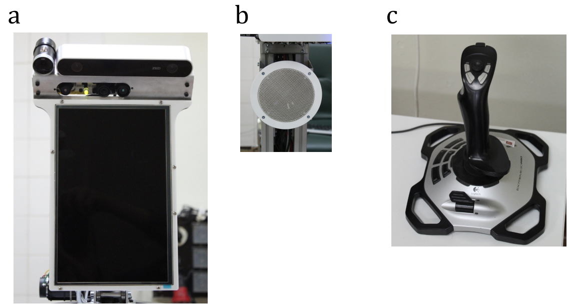

Fig. 6. ReMeDi robotic head: a – assembly consisting of a monitor, cameras and RGB-D sesors mounted, on an active neck, b – a loudspeaker mounted under a monitor b – joystick (DiagUI)

The head, shown in Fig. 6(a) (that can also be seen in Fig. 3), includes Kinect - a sensor with cameras and microphones, a stereo vision camera ZED, and a monitor. A loudspeaker (Fig. 6(b)), located just below, complements the head. The active head drive system has 2 DOF and ensures pan and tilt functionality. The control algorithm offers position, velocity and torque control, and additionally hand leading. The last one is envisioned for an assistant whereas the remaining for a diagnostician who moves them using a joystick (see it in Fig. 6(c) and in Fig. 4). The head is used by the part of the video conferencing system that is designed for a patient.

A prototype of the video conferencing system ReMeDi, shown in Fig. 7, is discussed in detail in [17]. The system consists of three programs, associated to a doctor (Fig. 7(a)), a patient (Fig. 7(b)), and an assistant (Fig. 7(c)), respectively.

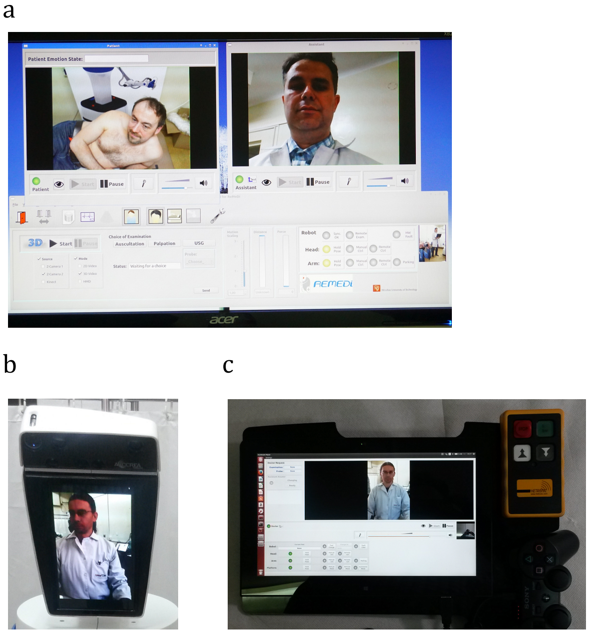

Fig. 7. ReMeDi video conferencing system: a – a doctor program, b – a patient program, c – an assistant program

The *patient program* (Fig. 7(b)) allows the patient to communicate through an audio and video channel with a doctor. It also delivers video streams to the *doctor program* from external medical instruments such as an ultrasound scanner, a cardiac monitor as well as an audio stream from a stethoscope probe.

An assistant can communicate with a doctor independently through audio and video channel. This process is carried out with use of an *assistant program* (Fig. 7(c)). In addition to video conferencing capabilities, this computer program is endowed with a panel designed for management of working modes of the manipulator. Thanks to this an assistant can effectively affect the functioning of the manipulator in reaction to requests of a diagnostician or to requests caused by other important circumstances. It is noteworthy that the *assistant program* supports a protocol of a probe change. It allows an assistant to receive the information concerning doctor's choice of a physical examination mode, that in turn indicates the type of a probe that should be mounted to the robot arm. Then, after the probe is physically mounted, the confirmation is sent back. Then, the doctor program is switched into the mode corresponding to the chosen physical examination.

The *doctor program* (Fig. 7(a)) is more complex. It allows a doctor to communicate simultaneously with a patient and an assistant. It receives and manages audio and video streams from medical devices as well as the stream transmitted from the *patient program*. In addition, an additional source of a video stream with the patient view can be selected and enabled. The program also visualises the state of DiagUI system by a set of indicators. Moreover, it allows the doctor to select a physical examination type and send the relevant request to the assistant so that he/she knows which probe should be mounted to the robot arm in the moment.

The software were developed on the basis of Qt5 and GStreamer 1.0 libraries.

3.3. Mobile Base

While it is typical for the medical equipment that it is moved by personnel force and passive wheels, the conclusions from collected users' requirements indicated that repositioning of the robot should minimally involve the personnel. To meet this requirement the robot is equipped with a self-propelled mobile base (see Fig. 8, Fig. 3 and Fig. 2) allowing remote controlled and semi-autonomous movement. The analysis of target users' requirements [1] has lead to a definition of two distinct functionalities:

- moving between the robot parking lot and examination rooms, which is a *long-distance motion*,
- positioning of the robot next to the patient in the preparation phase to obtain a suitable working area for the robot arm, which will be referred to as *short-distance motion*.

The platform is operated by an assistant with a dedicated panel (Fig. 9).

It is composed of a tablet, mentioned in Section 3.2, a deadman switch and a joystick. A wireless connection between the panel and the robot allows the assistant to control the robot even when they are located in different rooms.

Fig. 8. ReMeDi mobile base

a

b

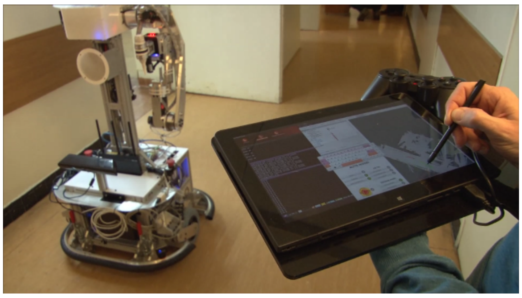

Fig. 9. Mobile base control modes: a – manual, b – "point and click"

The two functionalities of the platform result in two distinct control modes available for the assistant. The *short-distance motion* means fine positioning of the platform close to the patient and precise maneuvering in proximity of a number of other medical equipment located next to the settee. Therefore, for this type of motion a manual mode is provided. The assistant retains a full control of the platform movements through a joystick and buttons of a panel's pad (see Fig.9a). In the *long-distance motion* a lower positioning precision is required. Instead, during the motion between different locations the robot should safely avoid obstacles and people. In response to the requirement of minimal personnel involvement, the control mode for this type of motion reduces an action of the assistant to indicating the target location on the map by pointing and clicking (see Fig.9b) or to choosing a predefined target location from a list. The platform then autonomously plans a path to the selected location and performs the movement. The path planning uses standard methods from ROS `global_planner` library. The motion itself does not require additional assistant's intervention unless the area is too cluttered with obstacles or it is too crowded and the robot stops waiting for a manual control. This approach allows the assistant to stay longer with a patient and to perform other tasks such as preparation of the patient to the examination while the platform moves to its destination point.

The design of the platform itself evolved from the prior development of prototypes discussed in [19] and [10], in which numerous configurations of sensory systems and software frameworks were tested. Those led to the current prototype of the ReMeDi platform whose key elements are described below.

The dimensions of the platform are 70×70×50 cm. Its maximum velocity is 1.1 m/s. The weight of the platform is 40 kg with allowable payload of 45 kg. The platform moves on two actuated wheels equipped with a suspension system and four casters. The suspension guarantees contact between the wheels and the ground.

The sensory system includes two laser scanners Hokuyo UST-10LX, placed diagonally at corners of the robot housing, two Kinect 360 sensors, one on the mobile base and one in the head of a robot. The laser scanners are designed for localisation and obstacle detection. Both Kinect sensors enhance platform capabilities of detecting people and obstacles not visible for the laser scanners (above the scanning plane). The lower Kinect additionally provides a cliff-detection, to protect the robot from falling down from stairs.

The control system hardware platform is based on JointsController (a hardware module manufactured by ACCREA) and a mini ITX computer. The first hosts a real-time software (wheels velocity controllers). The latter runs a software for navigation and control that is based on ROS software modules.

To raise the level of safety, the sensory system will be extended with custom ultrasonic sensors for obstacle detection. They will cover the areas that are dead for Kinect, and laser scanners. It is a set of sonar modules (see Fig. 10). These modules are more than an ordinary range finders. They are able to determine a distance to the obstacle and the azimuth angle of echo arrival. Therefore they deliver much more reliable information than popular ultrasonic range finders.

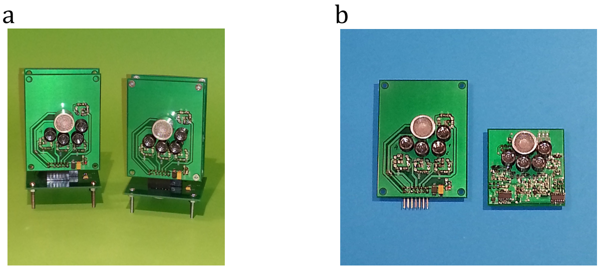

Fig. 10. Modules of a sonar system: a – a tested version of the modules, b – comparison of a front board of the current and new version of sonar module

The idea of the proposed and implemented method of determination of echo arrival azimuth is described in [14]. Its futher developement and experimental results are presented in [15,16]. The sonar module exploits piezoelectric transducers. The size of the front board is a bit bigger than a range finder using electrostatic transducers delivered by SensComp. The size of the new version of the module presented in Fig. 10b is 52×52 mm.

More details of the hardware and software of the platform are presented in [9].

3.4. Supervisory Controllers of ReMeDi Robot and DiagUI System Components

The behaviour of the ReMeDi system is supervised by two high-level control systems: Robot Central Control System (RCCS) and DiagUI Decision Maker (DDM) (see Fig. 2). They handle the ReMeDi robot and DiagUI respectively, wherein RCCS is superior to DDM. In particular, they are directly involved in transitions between working modes of the manipulator, the head, the mobile base, as well as in the protocol of medical examination type change.

Robot Central Control System Robot Central Control System (see Fig. 2) supervises all the other modules of the ReMeDi robot. Based on sensor signals, logical demands of an assistant or a doctor, and status signals from all the lower level components, RCCS makes decisions whether the control systems may be operated or not and what particular system components should perform. These decisions are represented by status signal: RCCS_Status, which is the input signal to all the lower-level decision makers. Since RCCS was designed in the form of a state machine (see Fig. 11) it operates on four main states: *Startup* (enabled just after power on), *Active* (being executed during normal operation), *Shutdown* (executed during systen shut down) and *Failure* (activated when emergency button is pressed or any lower-level component indicates failure state).

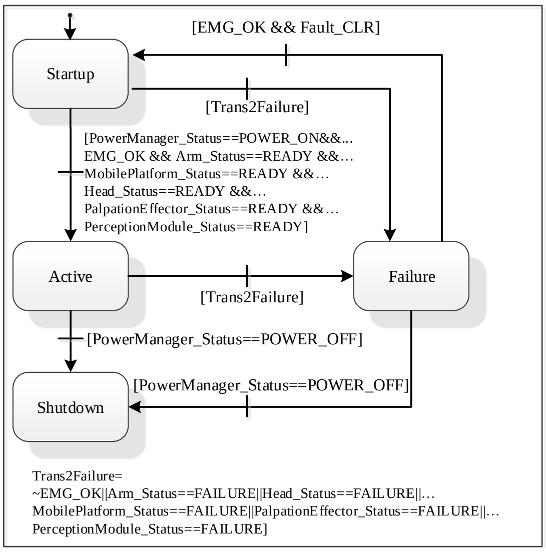

Fig. 11. RCSS: finite state machine

RCCS finite state machine includes more elements than the four states presented in Fig. 11. Each of these states is represented by several substates. The *Active* state is the most important and complex, from the medical examination point of view. Substates of the *Active* state are consistent with medical examination types specified by doctors during preeliminary evaluations. These states can be changed by an assistant (as it was noted in Section 3.2), in response to the request of a doctor, with use of buttons on the assistant panel. More detailed description of RCCS is can be found in [30] .

DiagUI Decision Maker DiagUI Decision Maker (see Fig. 2) is a finite state machine (FSM). The main task of the DDM is to provide means to control and supervise the whole ecosystem of DiagUI application. DDM was designed and tested in Matlab using State Flow toolbox. Finally, the diagram was exported to C++ code where it was embedded into an OROCOS component.

The architecture of DDM is presented in Fig. 12. This finite state machine consist of four main states: *Initialize*, *Running*, *Shutdown* and *Failure*. The Running state, in turn, is implemented as a composition of several other states, such as *SystemReconfiguration*, *ExitFailure*, *Ready*, *ChangeConfiguration*, *Synchronization* and *InExam*.

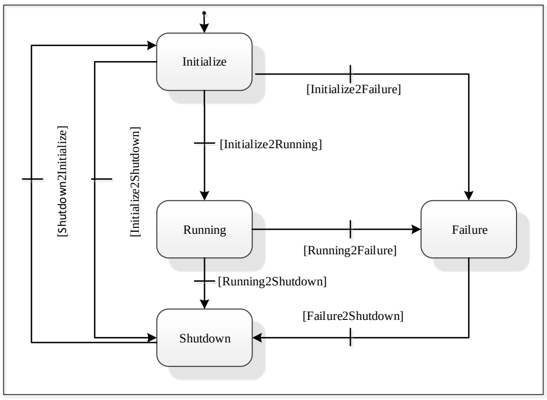

Fig. 12. DDM: finite state machine

DDM returns as the output its state. The state value is a single integer number which contains threefold information concerning the current DDM component state, the current type of the medical examination and whether the ReMeDi robot and DiagUI are coupled or not at the moment. The inputs of DDM are connected to majority of DiagUI components and RCCS. This allows to gather the information about the state of the whole system that is necessary to supervise the behaviour of this system.

The idea of the DDM algorithm is presented through analysis of a typical scenario of activity. The initial state of the finite state machine is *Initialize* in which DDM checks whether the most basic DiagUI components are starting up. After successful initialization a transition is executed which leads to the substate *SystemReconfiguration* of the state *Running*. In this state the DDM is waiting until all the basic components become operational. When the condition is fulfilled the DDM switches to the state *Running / Ready*. This state is temporary and immediately after reaching it DDM performs another transition that leads to the state *Running / Synchronization*. In this state the ReMeDi robot and DiagUI can be coupled (by means of a pedal). When the pedal is pressed by a doctor (i.e. the ReMeDi system is coupled) the DDM switches its state to *Running / InExam*. This state indicates that a medical examination is under way. When a doctor releases the pedal (i.e. the ReMeDi system is decoupled) DDM changes its state to *Running / Synchronization*.

The ReMeDi system can perform different types of examination including auscultation and ultrasonography. Changing between the types of medical examination can occur in any of the four DiagUI states: *Running / SystemReconfiguration*, *Running / Ready*, *Running / Synchronization* and *Running / InExam*. After changes in the system configuration (such as a probe change, approval of changes in the graphical interface by a doctor) the DDM transfers to the state *Running / SystemReconfiuguration*. DiagUI in this state waits until all the required components become ready to work in the mode that is required by the current medical examination type.

4. Integrated ReMeDi system

System components discussed or depicted in Section 3 have been integrated and initially evaluated. In this section we first discuss a hardware - software base that enabled software integration and next we present the integrated ReMeDi system, which allows remote ultrasound examination and auscultation.

4.1. Integration framework

From the developer point of view, the ReMeDi system discussed in Section 3 is a heterogeneous, distributed robotic system composed of many components that operate concurrently, partially in real-time. The components vary in complexity, thus they impose different requirements with respect to hardware and software resources. Moreover, components are being independently developed by the involved partners that usually use different, best known by them tools and methods. For this reason, to make integration of the ReMeDi system possible within a given time, we have applied the Component Based Approach along with suitable development framework [12] that supports this approach.

For the purpose of integration, the ReMeDi system has been described by means of a hierarchical component model, composed of real and abstract components. Real components reflect a physical components (software or hardware) developed by individual partners. Noteworthy is, that it is a bottom-up design process aiming in the direction of a top-down approach applied for the ReMeDi system functional specification in Section 3 and depicted in Fig. 2. These components are treated as a black boxes with well defined interfaces and functionality. Abstract components are used to define hierarchy and structure of the system. Specification of abstract component includes: the interface definition, the list of children (any number of real and abstract components), and the list of internal connection. Every element of the component model is specified in a separate YAML file in accordance with predefined template. The set of YAML files constitute a database that can be processed further to verify a consistency of the system model as well as to generate useful data sets and diagrams (Fig. 13, 14). Moreover, the YAML files are ordinary text files, so they may be easily modified by any common text editor, and managed by any version control system. Consequently, a specification of components can be carried out simultaneously by many people and this process is very flexible with respect to eventual corrections and broader changes.

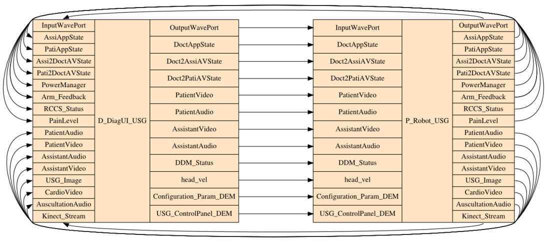

Fig. 13. Top level structure of the ReMeDi system (the counterpart of the diagram in Fig. 2)

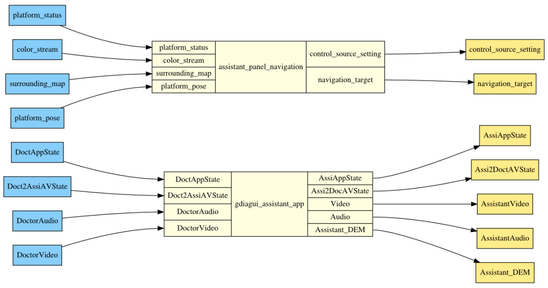

Fig. 14. The structure of the Assistance component (deployed in the assistant panel, see Section 3.2 and Section 3.3)

The ReMeDi integration toolkit is an mixture of hardware and software elements that create uniform environment for development of a distributed, real-time control systems. The general concept of the integration toolkit is presented in Fig. 15. The toolkit consists of well integrated robotics software frameworks (ROS and OROCOS) hosted by a real-time operating system (Linux+Xenomai, FreeRTOS) supporting a real-time network interface (RTnet), and the hardware involving standard industrial PCs as well as custom embedded devices. Computers can be equipped with any number of internal or external devices that extend their functions and communication abilities, while the custom embedded devices can be easily adopted to any specific requirements regarding functionality, resources and dimensions. It is assumed that the computers should perform high level control tasks that require high computational power and many resources while custom embedded devices are dedicated to performing low level control tasks such as: motor control, signal conditioning and sensor fusion. However, this specialization is not obligatory.

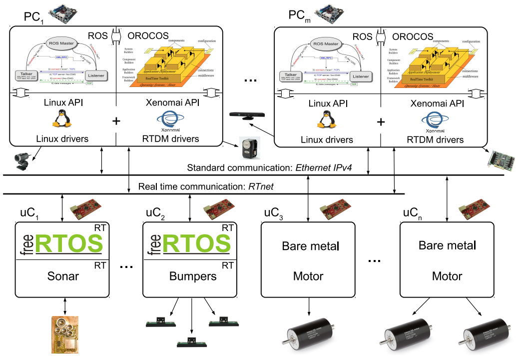

Fig. 15. The general concept of the integration toolkit

In case of the ReMeDi system, the hardware layer includes PC computers along with specialised microcontroller based units. The DiagUI subsystem form one PC computer with one custom haptic interface driver. In the case of the ReMeDi robot we have two PC computers and three microcontroller units: two *JointsControllers* and one *RTnode* [11]. JointsController (see fig. 16 and fig. 17) is a digital, hierarchical multichip controller, which performs robot's low-level motion control – LLMC (it can control up to 12 DC drives and supports: incremental encoder, power unit, and 2 end-switches per drive).

Fig. 16. JointsController overview

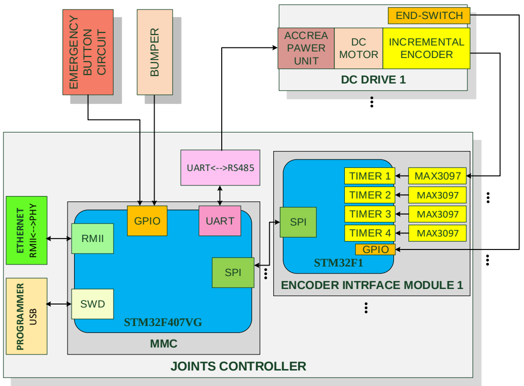

Fig. 17. JointsController structure in low-level motion control system

Almost the whole control strategy of LLMC has been implemented in main microcontroller (STM32F407VG), which performs four basic tasks: 1) execution of the mentioned above control algorithm with frequency 1 kHz; 2) communication with the higher-level controller through Ethernet; 3) communication with DC drive power units through UART;

and 4) acquiring data from encoder interface modules through SPI.

The *RTnode* is modular design, stack based device (Fig. 18).

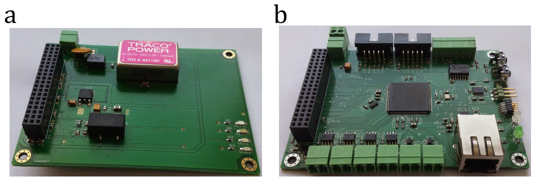

Fig. 18. RTnode device: a – base board, b – power board

It consists of a set of universal hardware modules that implement basic functionality. The motherboard module, which diagram is displayed in Fig. 19, is the fundamental element of the RTnode device, and constitute the base for further device extension. The motherboard provides following universal I/O ports: 4 analogue inputs, 2 analogue outputs, 2 digital inputs, 2 digital outputs, 2 quadrature interfaces, and RTnet communication interface. Motherboard completed with power supply module constitutes a fully autonomous component of the distributed control system. The functionality of the *RTnode* device can by easily modified by proper selection of the additional hardware modules and appropriate software modification. Depending on the modules set, various distributed control and measurement devices can be formed which exchanging data in real time over the network. The *RTnode* used in the ReMeDi system is applied for integration of sonar modules with navigation software and proxemic sensors with onboard safety system.

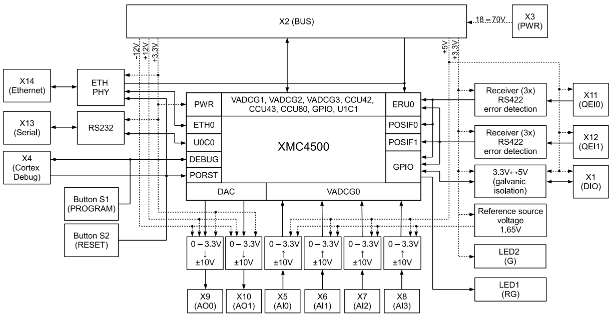

Fig. 19. The general structure of RTnode

RTnode and *JointsController* are custom embedded devices that suit to the needs of the ReMeDi project and allow to apply the integration toolkit from Fig. 13 for development and integration of the ReMeDi robotic system software. *JointsController* is a combination of a DC motors servo controllers and a computational unit, however, it is not designed for real-time data exchange with external computational units. *RTnode* is not a computational unit but it can serve as a real time bridge between PC and a motor servo controller. The underlying design philosophies for these devices are different because they stem from experiences gained in two different EU projects: IURO and LIREC. However, the devices appeared to be complementary and they found application in the ReMeDi robotic system.

The software stack of the PC machines includes two well known robotics frameworks: OROCOS 2.8 [45] and ROS [46] (Indigo or Hydro) hosted by Linux Ubuntu 12.04 (or 14.04) with real-time extension of the Linux kernel Xenomai 2.6.4 [48]. The software stack has been supplemented with real-time drivers [7] for multi-axis torque-force sensor JR3 [49], and multifunctional I/O cards Sensoray m626 [51] and Mecovis [50]. The OROCOS is designed for implementation of software components, which have to run in real-time regime. ROS is envisaged for deployment of the remaining software. In the context of integration, the fact that ROS is widely known and commonly applied standard in robotics is of significant importance. The same is in the case of OROCOS but in a slightly smaller scale. The microcontroller based units perform a low level control tasks that are supervised by a dedicated applications. Software stack include FreeRTOS [44], a tinny footprint, hard real-time operating system dedicated to small embedded devices along with custom application layer. The real-time components communicate between machines through RTnet [47] interface whereas standard components with use of common Ethernet interface.

4.2. Integrated ReMeDi system

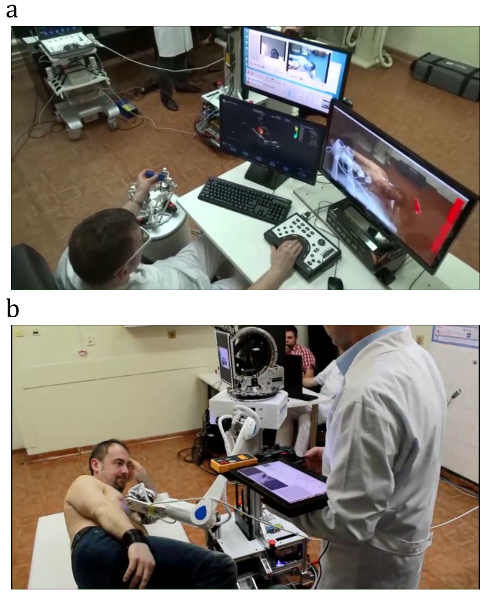

Fig. 20. Integrated ReMeDi system (allowing remote ultrasound examination and palpation: a – DiagUI, b – robot ReMeDi

The first tests of the integrated ReMeDi system are illustrated in Fig. 20. Fig. 20(a) shows DiagUI and a cardiologists from the Medical University of Lublin who carries out echocardiographic examination. In turn, Fig. 20(b) presents a robot in the course of examination of a patient (on the coach) under supervision of an assistant. The doctor is wearing 3D glasses, which allows him watching at the right monitor three dimensional image of the manipulator with ultrasound probe next to the corps of the patient. The image quality enables precise visual assessment of the end effector position with respect to the body. In this context the doctor is aided by augmented reality. The red bar on the side of the screen indicates the distance between the probe and the patient's body.

There are videoconferencing system windows at the left upper monitor through which the doctor can communicate both with a patient and an assistant. The doctor keeps dummy of the ultrasound probe in his/her hand. The dummy probe is mounted to haptic interface. The movements of the dummy are transmitted to movements of the real probe. The reaction forces acting on the ultrasound probe are reproduced by the motors of the haptic interface. Proper operation confirms the picture on the lower monitor. We can see the image obtained from the ultrasound probe, of which suitable quality was confirmed by a doctor.

5. Users' evaluation

The ReMeDi system presented in Section 4.2 needs comprehensive and versatile evaluation, that currently is ongoing at the Medical University of Lublin in Poland. As the final stage of the project is the evaluation, that is based on four use cases listed in Section 2. To date, selected system components have been evaluated: the control system of the mobile base, [1], graphical user interface, [33] and manipulator [34]. In the first two studies usability and safety of components from the perspective of users were evaluated with use of SUS and Godspeed questionnaires. Besides, effectiveness and reliability were studied on the basis of interviews and dedicated technical measures. In the last case evaluation was carried out with use of the "think-aloud" protocol. The evaluation studies were done with use of the mobile base prototype Carol, the first versions of the video conferencing application and the manipulator.

In general, the system components and the basic concept of the ReMeDi robotic system for remote medical examination meet with a favourable response of doctors, nursing staff and patients. However, the participants of experiments had formulated a number of specific postulates, that were taken into account in the current version of the ReMeDi system. Thanks to them, the ReMeDi robotic system evolved to the form that better fits to the needs and expectations of the future users.

Very important and valuable stage of evaluation of the integrated system was constant discussion among doctors and engineers involved in the project. Group of 5 doctors tested the system on the early stage of integration and provided their opinions, which functionalities are satisfactory and which of them still need some improvements form the point of view of the medical personnel. Such a discussions resulted in plenty of small corrections which significantly increased doctors' comfort and patients' safety, but also reduced time of the examination.

6. Conclusions

The article presents a concept of a robotic system for remote medical examination ReMeDi and discusses various aspects of its implementation. The idea of remote medical examination that covers combination of physical examination and ultrasonographic examination is new. The current version of the system allows for remote interview, observation, auscultation and ultrasound examination. The work on remote palpation is ongoing. Development of the ReMeDi robotic system proceeded in tight cooperation with target users, who were engaged during the phase of clarification of the user's requirements and in the course of the evaluation phase.

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