THE TELE-ECHOGRAPHY MEDICAL ROBOT OTELO2

Teleoperated with a Multi Level Architecture using Trinomial Protocol

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Keywords: Teleoperated system, Telerobotics, OTELO medical robot, Tele-echography, Multi level archecture.

Abstract: This paper presents a novel architecture applied to a mobile teleoperated medical robotic system: OTELO2 (MObile Tele-Echography using an Ultra-Light RObot); OTELO2 performs a tele-echography at a distance for the benefit of medically isolated sites. First, this paper presents an overview of the OTELO2 teleoperated system. Then, it describes the modular control architecture used and the integration of the teleoperated layer on this multi level architecture. Finally, it presents the communication links used to control this system, as well as some experimental results.

1 INTRODUCTION

Telerobotics and teleoperation have currently a very important role to play in the medical field especially in non invasive medical application (i.e. tele-echography) needed by the patients living in isolated sites with reduced medical facilities. The aim of the OTELO2 system is to provide people with the best medical examination conditions and thus to have the best diagnostic as possible.

Based on the concept of a mechanical probe holder, OTELO2 is a teleoperated robotic manipulator arm. Teleoperated systems are exposed to possible instability due to the transmission delay of the communication link and to the need of remote safety and maintenance of the robot. The goal of the proposed combined approach, i.e. to use a specific protocol to reduce data loss and to implement a modular architecture to enhance the tele-echography system, is to favor the overall remote medical act for the benefit of the patients.

To control teleoperated system, lots of architectures have been proposed. The "Subsumption Architecture" (Brooks, 1986) is composed of parallel different levels which process information supplied by the sensors in order to determine the control to be sent to actuators. The LAAS architecture (Alami, 1998) is made up of three levels: decisional, executive and functional. Its goal is to homogenize the whole mobile robotics developments and to be able to re-use already designed modules. The AuRA architecture (Arkin, 1998) is made up of two parts (reactive and deliberate), each using distinct method to solve problems. The reactive part is based on sensors and the deliberate part uses artificial intelligence method contains a mission planner, a spatial reasoner and plan sequencer. The OTELO2 architecture relies on the concept of levels initially developed by Brooks and which appear in architectures proposed by AuRA or LAAS. The originality of this architecture is to decompose the control in multi-levels which allows to decompose in clear way the different functions realized and also to decompose each level in several blocks which allow to retail and to separate the connections with the sensors and the actuators.

A description of the teleoperated robotic system, including the "expert" and the "patient" station, is given in the first section. The second section presents the architecture developed to control the robot. The next section presents the communication links between the two stations composing the system and the protocol used to control the robot. The last section presents some experimental result obtained during a teleoperation between Bourges (France) and Montpellier (France).

Charron G., Fonte A., Vieyres P., Fraisse P., Al Bassit L. and Novales C. (2007).
THE TELE-ECHOGRAPHY MEDICAL ROBOT OTELO2 - Teleoperated with a Multi Level Architecture using Trinomial Protocol.
In *Proceedings of the Fourth International Conference on Informatics in Control, Automation and Robotics*, pages 52-58
DOI: 10.5220/0001627600520058

2 THE OTELO2 SYSTEM

OTELO2 is a teleoperated robotic prototype system composed of an "expert" station and a "patient" station. A communication network (e.g. terrestrial or satellite) allows data transmission (i.e. ultrasound images, robot controls, haptic feedback and ambient images) between the two stations (Figure 1).

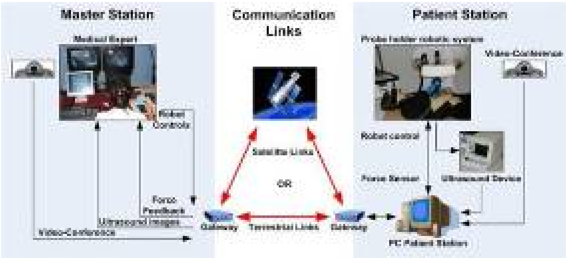

Figure 1: The OTELO2 teleoperation chain.

2.1 The "Patient" Station

The "patient" station is located near the patient at a medically isolated site or in a secondary hospital. It includes a portable echograph device allowing ultrasound frames acquisition and the hardware system for the control of the probe holder robot.

The results of a previous study (Al Bassit, 2003), on the medical gesture performed by a specialist during an abdominal echography, gave the mechanical constraints and characteristics of the robot work space with respect to the tele-echography medical application. The probe must have a spherical displacement around a contact point of the probe with the patient's skin. Displacement amplitudes (Figure 2) are characterized by: a maximal probe inclination of 60° with respect to the normal of the skin plan. (larger inclination is considered useless by the medical expert); a minimal inclination of 35° is necessary, as well as a full rotation of 360° around the probe symmetric axis are needed to fulfill users' requirements. Finally, a translation along the probe axis is necessary to obtain quality ultrasound images and maintain a continuous contact between the probe and the patient's skin. For safety functioning, patient comfort and force control, this displacement amplitude is limited to the interval [-30mm, 10mm]. Hence, the maximal admissible force of the probe on the skin does not exceed 20 Newton.

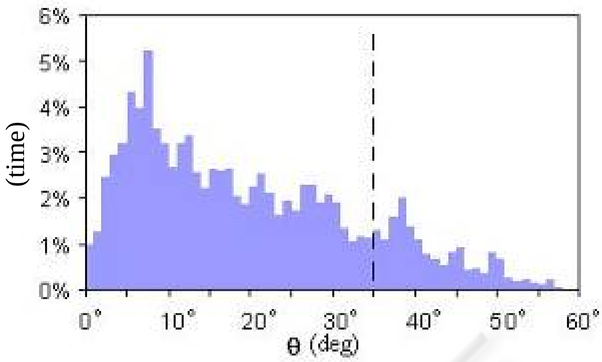

Figure 2: Histogram of inclination angle θ of the probe axis during an abdominal ultrasound examination.

The OTELO2 robot prototype was developed by the Laboratory of Vision and Robotic (LVR) in collaboration with European project partners in order to answer the previously mentioned criteria. OTELO2 is a serial six DOF (Degree Of Freedom) probe holder system; it includes a positioning module (with two prismatic articulations, P1 and P2, with perpendicular axis), a spherical module with distant rotation center (with three revolute pairs R1, R2 and R3, the R1-R2 and R2-R3 angles are equal to α) and a translation along the probe axis (P3, the R3-P3 angle is equal to β) allowing, for a given orientation, to modify the probe/skin contact force (Figure 3).

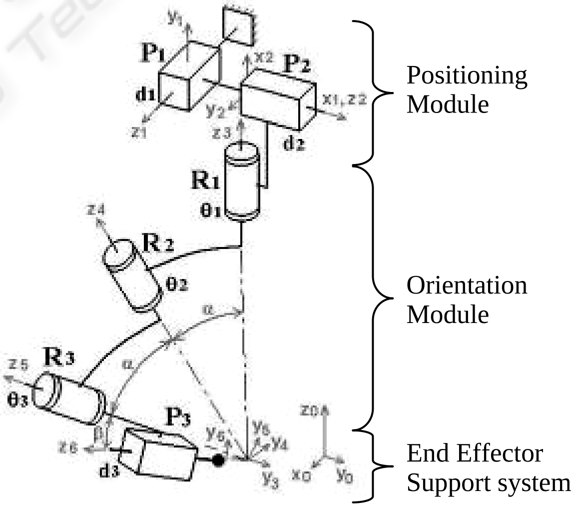

Figure 3: Kinematics diagram of OTELO2 robot prototype.

The α and β angles, respectively 27,5° and 10°, allow a probe maximal inclination of 65° which complies with the medical requirements. The positioning module allows a probe displacement with maximal amplitude of ±25mm for each axis and offers two DOF to search for an organ. The translation amplitude along the probe axis is about 40mm. This axis is coupled with a force sensor giving the force applied by the ultrasonic probe on the patient's skin and enabling its control. The force is transmitted back to the "expert" station in order to ensure the most realistic examination conditions for the medical expert. Finally, depending on the examination type (e.g. ObGyn, Abdominal), various types of manufactured probe can be attached to the end effector of the support system.

The end effector of the remote robot moves the ultrasound probe in order to reproduce the expert gestures which are being analyzed by a dedicated input device (Figure 4). Images coming from the ultrasound system are compressed and sent to the "expert" station, using the H263 protocol, and analyzed by the specialist.

2.2 The "Expert" Station

The "expert" station is located in a main hospital center and is operated by a medical expert. Based on the received ultrasound images, the expert uses a pseudo haptic input device (Figure 4) to control the positions and orientations of the remote ultrasound probe. A videoconferencing system between the two stations allows the medical expert to communicate with the patient, to give instruction to the assistant holding the robot, and to check the good positioning of the robot on the patient's body.

Figure 4: The pseudo haptic input device used to control the orientations and positions of the remote robot.

To control of the teleoperated echography robot was supervised under a novel multi layered and modular architecture. This hardware and software structure was added with specific communication protocols used to control the robot on Internet network. The following section presents the proposed control architecture and its layout. It is followed by the description of the protocol used for data transmission for the robot control.

3 THE OTELO2 SYSTEM CONTROL ARCHITECTURE

For the teleoperated robot and in order to integrate teleoperation layer, it was decided to set up a layered architecture (Novales, 2006). It is a multi level architecture where each level corresponds to a decision/perception loop.

In this section, we present the control architecture of the OTELO2 robot, and the global architecture of the OTELO2 system is described with the two MMI (Man Machine Interface) developed to control the system.

3.1 The "Patient" Architecture

The control architecture of the OTELO2 robot prototype is a three level architecture partitioned in two parts, namely the "Perception" and the "Decision" parts. Each one of these levels correspond to either a software layer or a hardware layer (Figure 5).

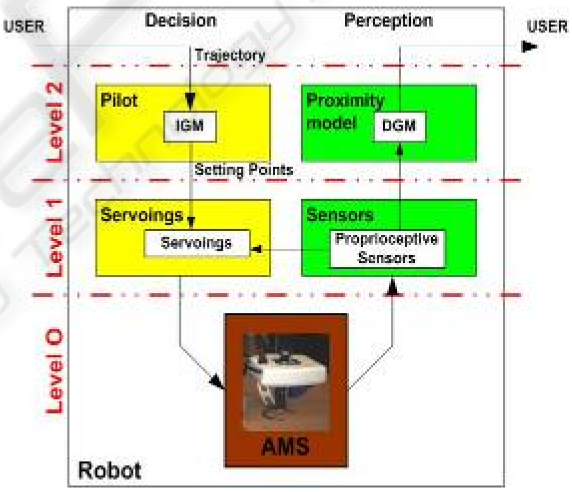

Figure 5: The layered control architecture of OTELO2 robot.

Level 0 represents the Articulated Mechanical System (AMS); it contains the input/output direct interface between the physic world and the robot. This level receives physical data necessary to its actuators and sends information to the sensors at level 1.

Level 1 of the decision part corresponds to the servoings level; it determines the physics data, to be addressed to level 0, from the setting points imposed directly by the upper level.

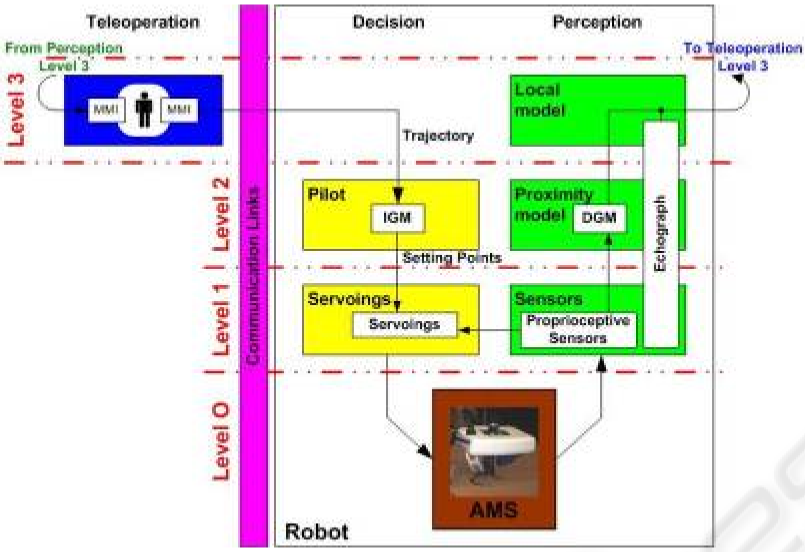

Figure 6: The global architecture of OTELO2 teleoperated system.

The level 1 perception part receives the information supplied by the sensors, and it translates this information to the upper level and to the servoings module. This level ensures the articular servoings with six modules in each part, corresponding to the six axes and associated sensors of the robot.

Finally, Level 2 decision part corresponds to the pilot level; it generates the articular setting points to the lower level from a trajectory (position and orientation of the probe) supplied by the user. The pilot block uses the IGM (Inverse Geometric Model) to generate the setting points taking into account the physical constraints of the system. The level 2 perception part presents a proximity model using a DGM (Direct Geometric Model) to transmit the robot current positions and orientations to the user. We can note, for our application, that there is not a direct feedback loop on this second level. The control loop is accounted for through the distant human teleoperator.

Perception and Decision parts constitute the so-called autonomous part of the robot. A third part, called the teleoperation, is added to the two previous one in the framework of a teleoperated system.

3.2 The Global Architecture

The global architecture includes the Perception, Decision and Teleoperation parts. Each level of the teleoperation part receives the data stemming off the level corresponding of the perception part and can a by-pass the corresponding level of the decision part in order to generate the controls for the lower level.

In the OTELO2 system global architecture (Figure 6), the teleoperation level is located at level 3; it corresponds to the navigation level. This part generates the trajectories which are executed by the robot and are sent to the pilot of the level 2 decision part. Moreover, the echograph device delivers information of a high level (ultrasound images) from its own sensors. Thus, this teleoperation level receives information from the level 3 perception part including the robot positions and orientations, and the ultrasound images coming from the ultrasound probe.

This global architecture offers the possibility of lower control level required for remote maintenance and testing of the teleoperated robot (Figure 7).

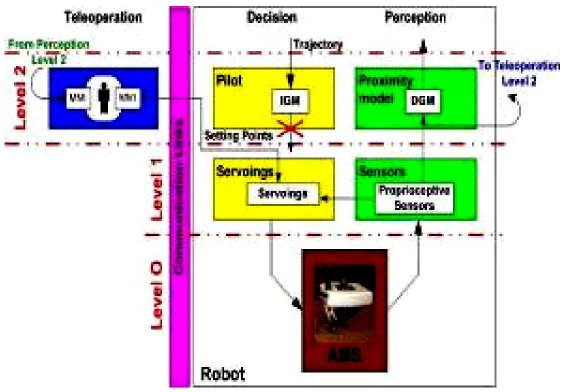

Figure 7: The level 2 teleoperation architecture.

This teleoperation level can control the robot directly, sending articulars setting points. Hence, the user is able to directly and remotely control the robot actuators and is able to detect which of the actuators has a malfunction.

These two teleoperation levels are associated with two MMI allowing an efficient and flexible utilisation of the remote robot.

3.3 Man Machine Interface

With the intention to support the medical expert and in order to ensure the best possible diagnostic, two MMI have been developed for the “expert” station.

The first MMI is a graphical interface provided to the medical expert to visualize the ultrasound images and to choose the appropriate teleoperation level. According to the teleoperation type, the medical expert can control the robot in two different ways. When the expert controls the robot with the high teleoperation level, he/she uses the pseudo haptic input device (second MMI). When the expert controls the robot at a lower teleoperation level, he/she uses a visual interface (Figure 8) to control each individual actuator.

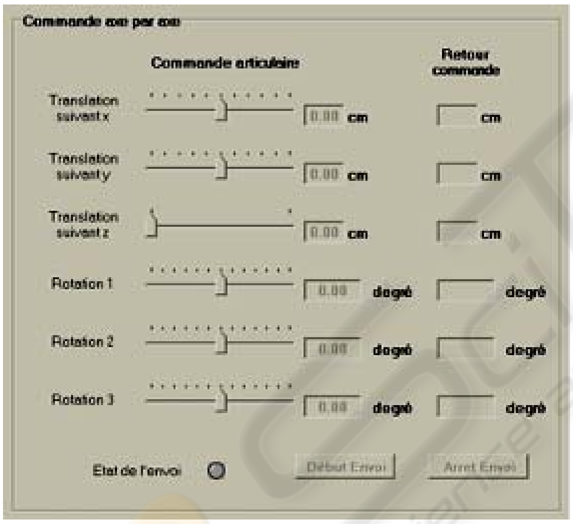

Figure 8: Level 2 teleoperation control interface.

The second MMI is a pseudo haptic interface that resembles an ultrasonic probe. The expert uses the pseudo haptic input device equipped with a six DOF localization magnetic sensor giving positions and orientations.

The pseudo haptic input device (Poisson, 2003) holds a constant stiffness coefficient which provides the medical expert with a rendering of the patients’ body compliance and the force applied by the probe on the patients’ body. The Figure 9 shows the design of the pseudo haptic input device prototype; it includes a force sensor to measure the force applied by the medical expert in accordance with principal axis of the probe.

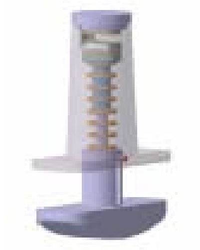

Figure 9: Design of the pseudo haptic input device prototype.

4 THE COMMUNICATION LINK AND DATA TRANSMISSION

The communication between the two stations can be carried out using different communication networks such as satellite, ISDN lines (Integrated Services Digital Network) or the Internet. To perform the robotic tele-echography, three communications protocols are used to transmit all data between the two stations (Figure 10).

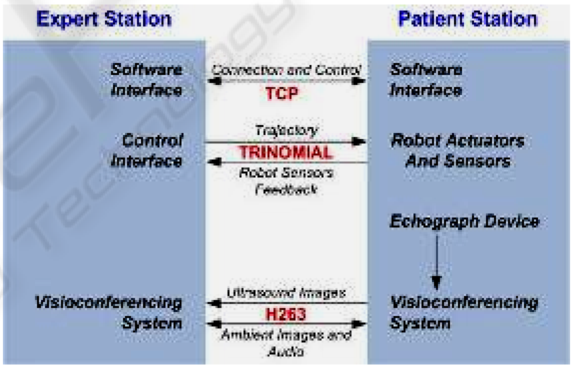

Figure 10: Data Flow representation between the expert and the patient station and selected protocol.

The TCP (Transmission Control Protocol) is an oriented connection protocol. It is used to establish the connection between the two stations, and allows a continuous control of the connection state between the two stations.

To transfer the robot controls, a reliable communication protocol with small transmission delays is needed. Two protocols were firstly considered: the TCP and UDP protocols. TCP ensures reliability in the exchange but can block the communication in case of data loss. UDP protocol (User Datagram Protocol) due to its simplicity generates small transmission delays. However it cannot adapt its flow to the network bandwidth and cannot confirm that data have arrived to the distant site. It was then decided to use a compromise between these two protocols: the trinomial (Xiaoping Liu, 2003). It allows the network not to remain blocked in case of data loss as there is no reemission of the lost data. However, contrary to UDP, trinomial takes into account the transmission delay (i.e. the received data acknowledgement) which allows a modulation of the flow and thus a limitation of the network saturation. In our case, the "expert" station sends the trajectories to the "patient" station using this protocol, and it receives the sensors feedback through the reception of the data acknowledgement.

Finally, a connection is established in order to transmit the ambient images or the ultrasound images to the "expert" station via the videoconferencing system. A bandwidth of 256-384 kbps is required depending on the quality of ultrasonic device to offer the best image quality to the "expert" station.

5 RESULTS

To validate the control architecture and to test the efficiency of our control transmission protocol, a set of tests was performed during a teleoperation between the LIRMM in Montpellier and the LVR in Bourges using the Ethernet RENATER-4 public network; this network provides a flow of about 30Mbit/s.

These results show Round-Trip Time (RTT) between Montpellier and Bourges (Figure 11 (a)), which corresponds to the delays measured between the data transmission and the acknowledgement reception of this data. The RTT varies between 7 and 11 ms proving the efficiency of the chosen data transmission protocol.

Moreover, these results show delays obtained between sending out the control data and the robot position feedback (Figure 11 (b) and (c)) (which include transmission and the time of the servoings). We can see that the system needs approximately 20 ms to reach the desired position.

These results are quite satisfactory and allow us to perform in real time examination in very good conditions without disturbing the rendering of the distant environment to the expert (Arbeille, 2004).

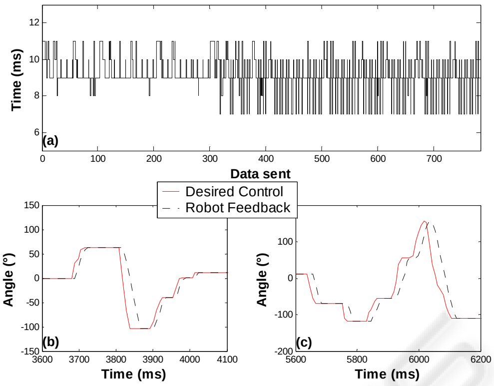

Figure 11: Result during test between Montpellier and Bourges (a) represents the data Round Trip Time, (b) and (c) represent respectively the second and the third axis servoing time delay.

6 PERSPECTIVES

Some improvements (transmission and architectural) have to be considered to provide the medical expert with better examination conditions thus ensuring the best diagnostic as possible.

The communication link (Internet, ISDN, satellite…) used to emit data from the expert station induces transmission delays that can provoke aperiodic data reception and even destabilize the closed loop global system. This can disturb the medical expert medical act when this delay varies too strongly. To avoid that, it is possible to use a FIFO regulator type (Lelevé, 2000) to synchronise the data reception, and thus to provide the expert with a more steady date flow and to adapt more easily his control of the distant robot to the transmission delays.

It is also possible to add an autonomous mode coupled with a level 4 of the teleoperation part, with the intention to realize a full echography of an organ allowing a 3D reconstruction. Thus, the medical expert would select the organ to be investigated and the robot would fallow all trajectories needed to supply the 3D reconstruction wanted by the medical expert. The virtual diagnosis by the expert is made from the 3D reconstruction.

7 CONCLUSION

From a mechanical view point, the OTELO2 prototype robot (Figure 12) corresponds to the criteria imposed by the medical gesture study and experts' requirement; it thus ensures identical examination conditions than to the standard ultrasound one. The modular architecture developed to control it permits easy insertion of new control modules whenever upgrade of the control architecture is needed. Finally, the communication protocol used to control the robot allows small transmission delays and offers moreover adaptability to the network condition.

The experimental results collected during the teleoperation between Montpellier and Bourges show the viability of the tele-echograph system and provided good clinical results.

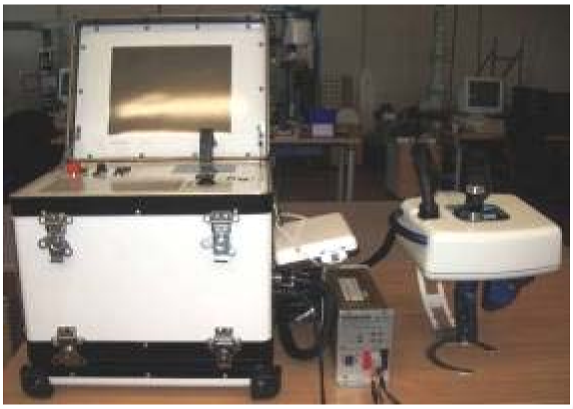

Figure 12: The OTELO2 prototype system.

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