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Telerobotic Systems in Medicine: Challenges and Potential

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Introduction

Telerobotics is part of the wider field of telemedicine. The ultimate goal of telemedicine is to provide specialized healthcare services over long distances. The possibility of consultation diagnosis, treatment, and medical intervention from a distance, may greatly impact the quality of life of patients located in isolated areas where access to specialized medical services is limited. Practically, a specialist can examine or operate on a patient at a different geographic location without either of them having to travel. Costs and inconvenience are avoided while improved access to information becomes possible. Moreover, the physician can provide services while at a more comfortable working environment. Apart from medically-isolated areas, telemedicine is also expected to play a role in removing barriers to healthcare provision in developing countries, in areas of natural disasters, and war zones where consistent healthcare is unavailable or there is no time to transport a patient to a hospital. The primary objective of this study was to present a systematic review of telerobotic systems and highlight their challenges but also their potential.

Methods

The general Telerobotics framework. The MELODY (AdEchoTech) system is a commercial platform for tele-ultrasonography that has been used extensively in our experimental investigations. Here it is used as a paradigm for the relevant concepts. It consist of three parts:

- Expert system (master station)
- Patient system (slave station)
- Communication link for the data transfer

Operation. At the patient's site the lightweight robot is held and positioned by a paramedic over the patient. The ultrasound probe is attached to the robot and it is manipulated using the available 3 DOF, following a master/slave control approach. At the master site, the medical expert moves a fictive ultrasound probe as required for an echographic examination. This motion is sensed and transferred in real time via a communications link to the robot's site where the manipulation system replicates this motion. Data are transferred between the two stations.

The overall tele-ultrasonography system

The Melody telerobotic system

Enabling technologies for telerobotic systems:

- **Telemanipulation systems.** Telerobotics applications mostly involve articulated (serial and parallel) robot configurations but other forms were also considered including snake-like robots. The number of degrees-of-freedom is directly associated with the application requirements. Operation of telerobotic systems is commonly based on a man-in-the-loop control approach and involves a master/slave architecture. The use of force-reflecting haptic feedback is a significant enhancement that allows the operator to sense the forces applied by the remote manipulator on its environment.
- **Network systems.** In a telerobotic system, the master station controls a remote robot by sending position commands and accepting force and visual feedback, in addition to information on slave robot position and status. The communication system must support three types of data flows: (1) Real-time control data; (2) Medical video stream; (3) High-level management data.
- **Medical video communication systems.** Medical video dominates over robot control data and other biosignals, both in terms of bandwidth requirements, as well as processing needs. An optimum trade-off is required that satisfies the medical video quality requirements without compromising the teleoperation process via over flooding available bandwidth. Communication delays and information loss are inherent to long-distance teleoperation. They may severely impact the stability and performance of the controlled system.

Classification of telerobotic systems:

- **Short-distance telerobotic systems**. Even though the operator's site is alongside the patient, it is in fact separated from the robot unit, while guidance is based on the acquired images and the transmitted sensory information. A most advanced short-distance telemanipulation system is the da Vinci Surgical System (Intuitive Surgical, Inc.) that was developed for minimally invasive laparoscopic surgery. It operates on the basis of a master–slave control concept and it is suitable for various procedures (urological, cardiac, gynecological, etc.).
- **Long-distance telerobotic systems**. The operator and the manipulator site are geographically separated. The link between them is established either via an existing communication infrastructure or via a dedicated temporary network (wired or wireless). For the Melody system mentioned above the expert's hand motion is sensed and the information is transferred in real time via a communications link to the robot's site, where the manipulation system replicates this motion. The telerobotic system is enhanced by integrating a videoconferencing system which is used for visual and auditory interactions. The connection between the two remote sites for data/image transmission is performed using a TCP connection. Four kinds of data are transmitted: (1) Synchronization flags, (2) Robot control data, (3) Videoconference data, (4) Ultrasound video.

Study overview:

This study included a systematic bibliographic review of medical telerobotic systems based on publications between the years 2004 to 2015, for which more details can be found in [2],[3]. Therein, are documented significant advances achieved in this area, prevailing concepts are discussed, and future challenges are highlighted. The review covers not only clinically approved, commercial systems but also experimental approaches. Telerobotic systems are classified into short-distance ones and those operating in long physical distance, as described above. The considered short-distance telerobotic systems were further categorized with respect to their application field (general surgery, neurosurgery, cardiac and thoracic, urologic, etc.). The development stage of the various systems was also taken into account (experimental, clinical, commercial).

References

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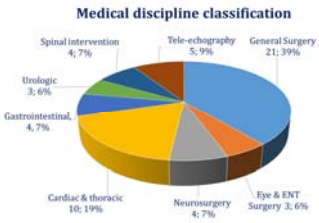
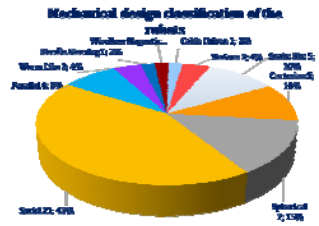
Results

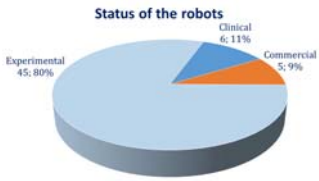


Telerobotics have been employed for a wide range of diagnostic and interventional applications in different medical disciplines. Even though some general-purpose telerobotic systems have been developed the majority are application/anatomy specific. Major fields of application include: general surgery, cardiac and thoracic, neurosurgery, urologic and gastrointestinal surgery.

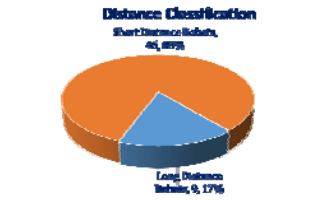
Inherent advantages and auxiliary functions often implemented on medical robots are also relevant to telerobotic systems, further enhancing their capabilities and functionality (steady-hand, accuracy, motion scaling, biomotion compensation, etc.).



Robotic systems used for telerobotic applications are diverse in terms of kinematic structure, degrees-of-freedom, and actuation methods. Serial articulated robots is the main type used in telerobotic applications but also other forms have been used, including parallel robots and snake-like ones.
A serial robot consists of a number of links interconnected with actuated revolute, prismatic or other type of joints. At the inboard end of the kinematic chain is the base of the robot and at the outer end is the end-effector e.g., an interchangeable surgical tool.
A parallel manipulator consists of several serial chains to support a single platform (the end-effector). In general, serial robots can have a large workspace and good dexterity. The kinematics and control of parallel robots are in general more complex but they are suitable for high-speed displacements and accurate positioning.
Constant curvature or snake-like robots are continuously curving systems particularly useful when required to access through narrow passages and operate in confined spaces. Actuation often involves continuously bending actuators or the use of tendons. Concentric-tube robots are also included in the same family.



Despite remarkable achievements demonstrated by a plethora of the examined telerobotic systems, yet only a handful of them have reached a commercialization stage, and even fewer have been adopted in clinical practice. This fact signifies that further efforts are required to address both clinical and technological challenges. An existing difficulty for the introduction of medical robotic technologies remains the inertia of ongoing medical practice. A prerequisite for commercialization is to obtain regulatory approvals, which usually takes a significant amount of the development time and cost. For the device to be marketable, it must also be accepted by third-party payers in the health-care system, including insurance companies. Another significant issue that limits the adoption of telerobotic -and robotics technology in general- in clinical practice is the high cost associated with the acquisition and maintenance of such systems.



Telerobotic systems are categorized as "short-distance" and "long-distance" depending on the physical distance separating the operator and the remote manipulator. In the case of short-distance systems, even though the operator's site is alongside the patient, it is in fact separated from the robot unit, while guidance is based on the acquired images and the transmitted sensory information. In principle, this arrangement enables operating the manipulator from a larger distance as well. Short-distance systems are mostly associated with a physical barrier case. In the long-distance category, the operator and the manipulator site are in fact geographically separated.

The large majority of existing systems have been short-distance ones showing that further work is required for the telerobotic systems to effectively contribute in telemedicine.

Conclusions

Medical telerobotics is an emerging field expected to have a significant impact on healthcare. A study on existing telerobotic systems highlighted the status of the field. Summarizing the above results:

- Telerobotics have been considered for various diagnostic and interventional applications in different medical disciplines.
- The majority of the existing telerobotic systems are application/anatomy specific rather than general-purpose systems.
- Existing telerobotic systems are diverse in terms of kinematic structure, degrees-of-freedom, and actuation methods.
- Among the developed telerobotic systems very few have reached a commercialization stage, and even fewer have been adopted in clinical practice.
- The large majority of existing telerobotic systems have been short-distance ones.

Indicative of its potential is the fact that telerobotics are relevant to a wide range of applications and medical disciplines. It is also noticeable the fact that the large majority of existing systems have been short-distance ones and the potential of operating them remotely remains largely unexploited. This fact signifies that the ultimate goal of employing robotic manipulation in telemedicine, in order to provide specialized medical services remotely, has not been accomplished yet. Benefits of using long-distance telerobotics will particularly apply to rural areas, emergency incidents, military operations, and in developing countries, where specialized medical personnel is not available.

Future developments in the field of telerobotics will require addressing specific clinical as well as technological challenges following an interdisciplinary approach. Technological challenges are related to three basic enabling technologies: robotic manipulation, vision systems and telecommunications. For the transition from short-distance to long-distance telerobotic systems a major role is played by the telecommunication links. Latest telecommunication technologies should be embraced to ensure efficient, reliable and safe transmission of data.

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