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Over the past 50 years a big effort in research has been made for studying and developing haptic devices for telemanipulation, and nowadays many different architectures and models are available on the market and they are used for a plethora of different applications such as:

- Surgical robotics
- Space robotics
- Service robotics
- Field robotics
- Industrial robotics

But what is a haptic telemanipulator? why we need one? Well, in order to answer such a question it is convenient to start from a specific application such as the control of a flexible robotic endoscope able to perform laser bone ablation (MIRACLE Project).

An haptic telemanipulator is a device able to provide Human Robot Interaction (HRI) i.e. readings of the position/velocity/acceleration intended by the user and at the same time provide him/her with a force-torque feedback. The purpose is to make the user feel like he/she is operating directly the slave even if he/she's thousand of kilometers away. Moreover sometimes, especially in delicate applications like surgery, it is required to enhance the natural performances of the user with an appropriate scaling of velocities and forces.

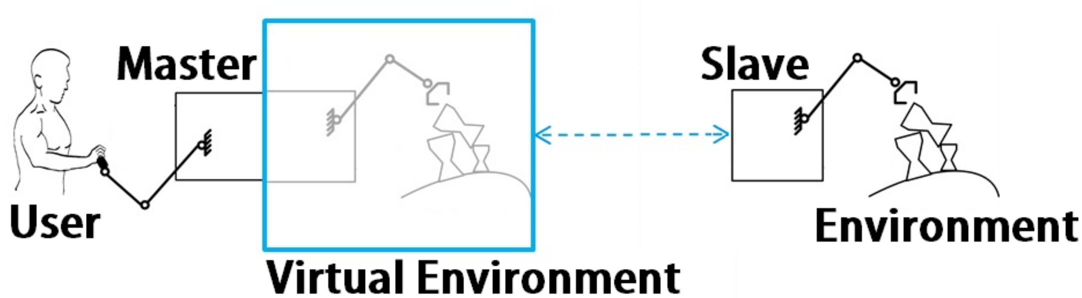

Figure 1: Telemanipulation scenario, in a medical application the User is a surgeon, and the Environment is the body of the patient.

The main requirements for the haptic device of the MIRACLE project are to manipulate the endoscope with sub-millimetre accuracy and the ability to reproduce and scale the interaction forces arising from the contact of the endoscope with the environment. Furthermore the robot must be safe and needs to have safety procedures not to harm the patient in any way, these specifications suggest to design a system running on a Real-Time (RT) framework (i.e. xPC, TwinCAT, ORoCOS) and to use a sound and fast communication protocol (i.e. EtherCAT). In the following sections are described and analyzed the gold standards devices for telemanipulation available on the market and the different control schemes used.

The scenario is shown in Fig. 1 and represent the schematic of the system with all the actors involved: the user is the physician that performs the surgery, the master is the haptic device, the environment is the body of the patient, the slave is the robotic flexible endoscope used to hold the laser, and the light blue dotted line is the communication medium between the master and the slave, it shall even cover long distances thus the bandwidth is of primary importance.

1 Architectures

There are several definition of haptic telemanipulator but the one provided above is (to the author humble opinion) the most complete and clear for the medical application proposed, let's consider two big families of telemanipulator:

- Robotic Manipulators
- Wearable Devices

The first is the most conventional, the device is made out of mechanical parts like gears, joints, and rigid links, it has to be somehow hinged to the ground and the user is constrained to stay in proximity of the telemanipulator. There are two main sub branches of the group: serial and parallel architecture, respectively.

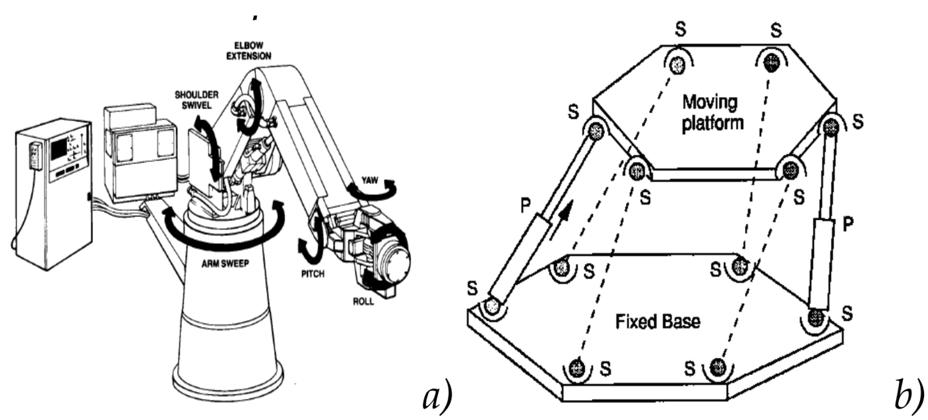

Figure 2: Examples of robotic manipulators: a) is a serial robot while b) is a parallel one.

The second member of the family is composed by wearable technologies, these devices fit on the user's body and they are not constrained to a fixed point, however the force feedback is hard to achieve and often they are bulky and unconfortable to wear.

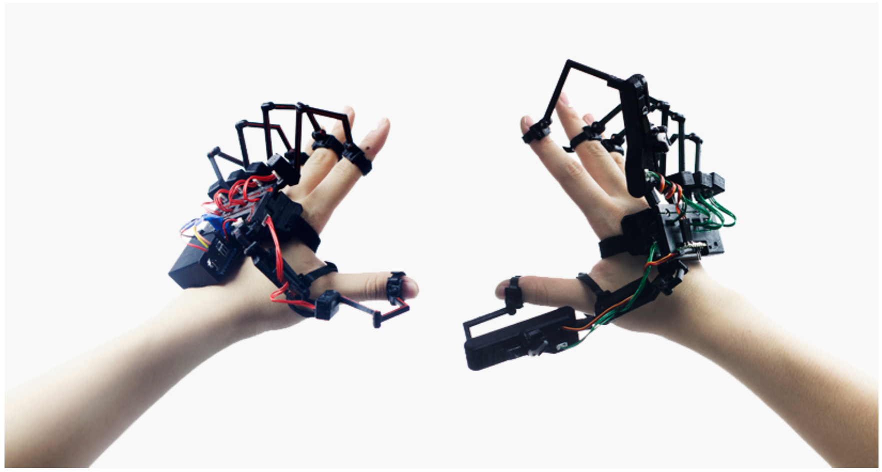

Figure 3: Example of robotics gloves.

1.1 Robotic Manipulators

As described above the Robotic Manipulators family consists of all the devices that are locked to the ground and behave like a joystick, they can provide higher stiffness and accuracy with respect to wearable devices.

A famous classification of robots is defined according to their structural topologies. A robot is said to be a serial robot or serial (open-loop) manipulator if its kinematic structure takes the form of an open loop-chain, a parallel manipulator if it is made of a closed-loop chain, and hybrid manipulator if it is consists of both open and closed-loop chains (but we will not discuss the latter family since its characteristics are just the fusion of the serial and parallel architectures). In the following are described the two different topologies with real world examples.

1.1.1 Serial

Serial manipulators are the most common industrial robots. They are designed as a series of links connected in an open chain topology by motor-actuated joints that extend from a base to an end-effector, the main advantages of a serial manipulator are:

- Large workspace with respect to the size of the robot and the floor space it occupies
- Easy direct kinematics

The main disadvantages of these robots are:

- Low stiffness inherent to an open kinematic structure
- Errors are accumulated and amplified from link to link
- Relatively low effective load that they can manipulate
- Hard inverse kinematics for robot with more than 6 degrees of freedom

The two most famous serial telemanipulators are presented below with specifications and details, attention will be given to those parameters which are important in our application, such as stiffness, resolution, and workspace.

Table 1: Characteristics of the Geomagic Touch.

Workspace	$1.344 \cdot 10^{-3}\ m^3$
Stiffness	x: 1.26 N/mm y: 2.31 N/mm z: 1.02 N/mm
Position Resolution	$\sim$55 μm
Force feedback	x, y, z

Geomagic Touch

If you are looking for a serial telemanipulation that is cheap and decently performing, the Geomagic Touch is the right choice (Fig. 4), it costs ≈ 1400 \$ thus is suitable for research and for a first dive into haptics technologies. The Touch is a 6 degrees of freedom (DoF) 6R (6 Rotational joints) serial manipulator with actuators in the first three joints. The motors constraint the movement along the x, y, z axis, hence the robot is able to provide linear force feedback (no torques provided) to the end effector. In order to use it in its full power it is suggested to use some libraries available online like CHAI3D but they will be discussed later on in a subsequent section.

Figure 4: Picture of the Geomagic Touch, the entry level serial haptic interface.

The main characteristics are presented in Table 1, as shown the workspace is large and the position resolution is good as well, however the stiffness (defined in the boxed note below) is not enough to guarantee a safe execution of any kind of procedure involving the contact of human internal organs and the lack of any rotational force (torque) feedback is a big drawback, for these reasons the device is only used for research purposes and not included in any surgical robot available on the market. The Geomagic Touch is an impedance controlled device, it is going to be explained in the section but briefly the robot reads the displacements meant by the user and sends out a force command to the slave.

Stiffness in Robotics: Stiffness is the rigidity of an object, in other words it is the extent to which it resists deformation in response to an applied force. If we represent a stress with σ and a deformation with ϵ, the Hook's law states that $\sigma = K\epsilon$, and in matrix form:

$$\begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} = K_{3\times3\times3\times3} \begin{bmatrix} \epsilon_{11} & \epsilon_{12} & \epsilon_{13} \\ \epsilon_{21} & \epsilon_{22} & \epsilon_{23} \\ \epsilon_{31} & \epsilon_{32} & \epsilon_{33} \end{bmatrix} \tag{1}$$

Thus C is a $3\times3\times3\times3$ matrix(fourth order tensor), but due to the properties of most materials it can be reduced (using **Voigt notation**) to a 6×6 matrix (first order tensor):

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{bmatrix} = \tilde{K}_{6\times6} \begin{bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ 2\epsilon_{23} \\ 2\epsilon_{13} \\ 2\epsilon_{12} \end{bmatrix} \tag{2}$$

Haptic Master

The HapticMaster (Fig. 6) is another commercially available serial telemanipulator with 3 DoF which is interesting because it is an Admittance controlled device, it works exactly in the opposite way respect to the Geomagic Touch: the robot reads the force and it sends out a displacement information (further information will be given in the next section).

The mechanism of the robot arm is built for zero backlash, which yields some friction in the joints. However, the friction is completely eliminated by the control loop, up to the accuracy of the force sensor. The result is a near backlash-free and smooth moving behavior at the end effector.

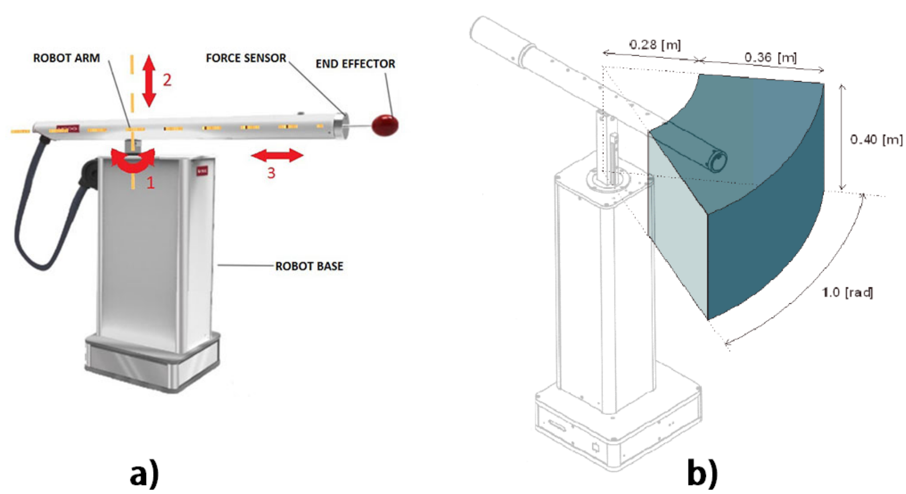

Figure 5: Picture of the HapticMaster, the admittance controlled level serial haptic device: in a) are shown the main parts of the robot while in b) there is the workspace of the end effector.

Table 2: Characteristics of the Geomagic Touch.

Workspace	$80 \cdot 10^{-3}\ m^3$
Stiffness	10-50 N/mm
Position Resolution	$\sim 6\ \mu m$
Force feedback	x, y, z

1.1.2 Parallel

A parallel manipulator is a mechanical system that uses several serial chains to support a single platform, or end-effector. While a serial manipulator uses an open-chain topology, the parallel uses a closed-chain one. The main advantages of a parallel manipulator are:

- High stiffness at the end effector
- Small position error
- High payload
- Easy inverse kinematics

The main disadvantages of these robots are:

- Small workspace
- Hard forward kinematics

The two most famous parallel telemanipulators are presented below with specifications and details, attention will be given to those parameters which are important in our application, such as stiffness, resolution, and workspace.

ForceDimension Family

Figure 6: Devices from force dimension, in order from left to right: Sigma.7, Omega.7, Delta.6.

Force Dimension is the gold standard brand for telemanipulators, they provide with multiple models for every specification, in particular their products with more than 6 DoF are:

Table 3: Characteristics of the Sigma.7 by ForceDimension.

Workspace	$190 \times 130mm$ transl, $235 \times 140 \times 200deg$ rot, $25mm$ grasping
Max Force	$20N$ transl, $0.4Nm$ rot, $\pm 8N$ grasping
Position Resolution	~ 1.5 μm transl, $0.013deg$ rot, 6 μm grasping
Force feedback	x, y, z, ω_x, ω_y, ω_z

Table 4: Characteristics of the Novint Falcon.

Workspace	$7.9010^5 m^3$
Max Force	$3N$
Position Resolution	36 encoder counts
Force feedback	x, y, z,

sigma.7 The sigma.7 is the most advanced master haptic device ever designed by Force Dimension. Its end-effector covers the natural range of motion of the human hand and is compatible with bi-manual teleoperation console design. Its unique custom-designed actuators offer a very high level of forces and torques, making it the most accomplished master device available today. The combination of full gravity compensation and driftless calibration contributes to greater user comfort and accuracy..

omega.7 The omega.7 is the most versatile haptic device ever conceived. Its end-effector covers the natural range of motion of the human hand and is compatible with bi-manual teleoperation console design. The unique design of the omega.x family of devices allows users to upgrade end-effectors depending on their application.

delta.6 The delta.6 haptic device offers an active wrist extension with full force- and torque-feedback capabilities. Built with a modular architecture, the delta.x family of devices are highly accessible systems for developers who wish to extensively customize their device to best meet the specification of their application.

In order to compare this family with the serial one the performances of the Sigma.7 are presented in Tab. 3. The stiffness is very high and the communication frequency is up to 4kHz, allowing the user to render really fine texture and precise virtual environments. The torsional workspace is the largest available and allows the user to feel torques with a large bandwidth.

Novint Falcon

The Falcon (Fig. 7) is a relatively inexpensive 3-DOF haptic device made by Novint for the gaming industry. The controller uses a form similar to that of the delta-robot configuration (the design has been carried on in collaboration with Force Dimension) and because of this form, makes an interesting apparatus for research into control and estimation problems for robots involving parallel linkages. Its low price (< 200\$) makes it very suitable for low budget research and for entry level projects, as a matter of facts it can be easily disassembled and modified. The characteristics of the manipulator are presented in Table 4, the reader will immediately notice that the workspace is very limited as well as the forces that it is able to render.

Figure 7: The Falcon telemanipulator by Novint.

1.2 Wearable Devices

A new trend in haptic manipulation which came out in the past decade is the wearable technology, a new branch of engineering that embeds microcontrollers into devices that are going to fit the human body, examples are:

- Bracelets
- Armbands
- Gloves
- Exoskeletons
- Glasses

The market is already filled with many bracelets that track vital parameters and the movements of the user (iWatch, FitBit, E4 etc..) but wearable devices aimed at telemanipulation are still missing, some products that are trying to enter the market are presented below.

1.2.1 EMG Based

The first family of wearable haptic technologies is the one based on the surfac

1.2.2 Gloves

1.2.3 Voice Coil Actuator

2 Robot Control

2.1 Impedance Control

2.2 Admittance Control

3 Forces rendering

4 Possible Developments