Haptics as a Key Technology in Man-Machine Interface

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The haptic senses include many different modalities: sensing of force, texture, temperature, body posture etc. While optical display screens and acoustic signals are standard interface modi for machine to man communication, haptic interfaces are still at a research level. But many practical and commercial realizations are now emerging. This article gives some examples from the biomedical robotics field, namely surgery telemanipulators, rehabilitation devices and assist devices. But research results from haptic interfaces could benefit many other domains, including the automotive.

Key Words*: Haptic interface, Man-Machine Interface, Human-Machine Interface, Man-Machine Interaction*

1. Brief Background on Haptics

Haptics, from Greek “äπτω” = “I touch”, is one of the “classical” five senses described by Aristoteles. Of these, touch is the only one common to all living organisms. While humans (or any other organism) can live without sight, hearing (Helen Keller), taste or smell, they cannot live without the sense of touch.

Of these five senses, touch (or “haptics”) is the most complex one. It includes at least six modalities, for each of which physiologists can identify separate receptor cells or organs.

- Force sensing
- Texture sensing
- Proprioceptive sensing, i.e. perception of bodily joint positions and muscle postures
- Temperature sensing, combining temperature and heat sink capacity of the sensed object
- The vestibular system (sensing of the direction of the gravity acceleration)
- Pain sensing (nocioception)

A subtle combination of the first three modalities allows the distinction of slippery or sticky.

A combination of the first four haptic senses allows the distinction of wet/dry.

Reflecting on the complexity and richness of haptic perception, it is surprising that these senses have somehow often been underestimated in comparison to vision and hearing. It is true, that the sheer information quantity of the visual sense seems overwhelming from the engineering point of view. This is partly due to the fact that this information quantity can be technologically estimated with seemingly “good” accuracy, although there is room for much debate also in this field. The optical “refresh rate” is somewhere between 30 and 50 Hz, perfectly sufficient for smooth video streaming, with the corresponding number of pixels and colors. The perception limits, it seems, can be defined with a certain accuracy. Such considerations will give a number of bits/sec.

Similar reflexions are even easier for acoustic perception: A frequency range of about 16 Hz up to 20 kHz, a dynamic range of up to 100 dB, all this can again be translated into bits/sec. The discussion on compression formats and perceptual thresholds illustrates however the shaky value of such estimations.

Now, to how many bits per second correspond the six modalities of haptics listed above? Almost needless to say that this is still an open question, estimates rely on a great number of assumptions.

2. Haptics as Man-Machine Interface

A man-machine interface consists of input and output devices. The words “input” and “output” obviously interchange their meaning when seen from the human or from the machine side. Most common input devices (from man to machine) are keyboards, buttons, joy-sticks, steering wheel, pedals. The most common output device (from machine to man) is a visual display (watch, tachometer, lamp or LED, display screen). Add to this acoustic devices, microphone as input and speaker as output and we might cover well over 90% of man-machine interface. Thus we see a very different situation for the two interaction directions

1) [human → machine]
2) [machine → human]

While the first direction of interface, [human → machine] , is essentially haptic, the second one [machine → human] is to a large extent optical or acoustic, and only very indirectly haptic. (Of course we feel the vibrations and accelerations in a car, but this is a secondary effect, not essential for operating the car). The important haptic interface of the driver and the car is through the command elements, the steering wheel, the pedals, the "feel" of handles, buttons, knobs. There we see a real and important haptic interface in action: The original function of the steering wheel is clearly only a command function, to give the direction of driving. Of great importance is however the secondary function, i.e. the haptic feedback the driver gets from the steering wheel. This is essentially a force feedback, including some vibrational content (is the engine running or not? At what speed?). Or imagine having to brake with a kind of joystick with no haptic feedback, where braking torque is only proportional to position and not to force on the pedal. It would seem quite awkward, and we would have to rely all the more on the haptic feedback signal of deceleration the car is giving us. However, with some practice, one can become proficient at operation on visual feedback only: Think e.g. of video-game addicts.

These few examples have introduced the importance of haptic interface in an every-day setting such as driving an automobile. Haptic interface have actually been a somewhat isolated topic of research for many years (see e.g. Hayward1)), but recently the number of conferences (World Haptics, Euro Haptics, Asia Haptics) and publications on the topic is rapidly increasing. I will now come back to some examples outside the automotive domain.

3. Application Examples in Biomedical Technology

3. 1 Surgery Robotics

Surgery has developed from open surgery to mini-invasive surgery and, since about 10 years, to robotic surgery. This development is very logical, as the surgery tools have become more and more sophisticated, in line with technical progress. Two essential pioneering developments in surgery have come from outside the field of surgery proper:

1) Anaesthesia, pioneered by Hanaoka Seishu2) in late Edo period (early 19th century) Japan and
2) Asepsis, discovered mid 19th century by Semmelweiss in Vienna.

The 20th century has then seen the development of endoscopy introduced on a large scale by Karl Storz in Germany and Olympus in Japan. Endoscopy (seeing inside the body through rigid or soft tubes) has quickly led to the techniques of mini-invasive surgery, for as doctors could see, they also wanted to operate through little holes. This is why the word "endoscopy" then acquired the meaning of not only seeing, but also operating through small orifices, natural orifices as well as small perforations. Needless to say that such mini-invasive techniques, while very beneficial to the patient (less trauma, less scars, less infection, shorter hospitalization), are much more demanding for complex surgical manipulation. Simple gestures such as suturing need intensive training when done endoscopically.

Instrument makers now succeed in building endoscopes which include a micro-camera and two tweezers of seven degrees of freedom each. The total number of degrees of freedom of such an endoscope (two tweezers, camera, endoscope position) then easily exceeds twenty. Such an instrument needs two to three surgeons to operate.

To the engineer, the solution out of this dilemma is obvious: Motorize the instrument and build a command console for the surgeon. The surgery instrument thus becomes a telemanipulator (sometimes also called "master-slave system"), similar to the devices designed 60 or so years ago for the handling of dangerous (e.g. radioactive) substances. Such a teleoperated surgery system is called, somewhat abusively, surgery robot. It is of course not falling under the usual definition of "robot" as autonomous (or automatic) machine, strictly speaking it is just a telemanipulator. But it has the huge advantage that the surgeon can again operate with his two hands in a natural way, not having to turn 20 knobs.

This situation explains the success of the DA VINCI surgery robot from Intuitive Surgical inc. (**Fig. 1**) in the last 10 years. So essentially the surgeon has regained the mastery of his tools as he had it in open surgery, but now in a mini-invasive ("endoscopic") mode, a bit as if he would be "inside" the patient with his hands. The cognitive neuroscientist would say, the surgeon "embodies" his tool in an efficient way, i.e. the motor cortex of the surgeon's brain identifies the tool as part of the surgeon's body. This will be discussed briefly in **section 3. 4**.

However today's surgery robots still have absolutely no force feedback, they rely only on visual feedback through the endoscope camera, often only 2-D, sometimes 3-D vision. This sets clearly the agenda for research in surgery robotics: We as engineers will need to develop a true haptic interface, i.e. measure the forces at the tip of the operating tools (with sterilizable and if possible disposable force sensors) on the "slave" side of the telemanipulator and a kind haptic joystick (or handle) on the "master" side (the command console), with a true force-feedback. This will give back to the surgeon the full sensation of working with his hands inside the body, especially if such an interface can be made multimodal (adding temperature, pulsation etc.)

Fig. 1 DA VINCI surgery "robot" (or telemanipulator) from Intuitive Surgery inc
Up to now, such commercial telemanipulators have no force feedback, they rely only on visual navigation by the surgeon, seated at a console in the operating room, nearby the patient. Such devices have become very popular among surgeons and patients as well, as they allow a very intuitive manipulation of mini-invasive surgery tools.

3. 2 Rehabilitation

Another important domain of biomedical robotics where haptic human-robot interface is at the very core is the field of rehabilitation robotics. With the rapidly increasing aging of the world population (especially of course in Japan and Western Europe), the need for professional physiotherapy is growing much faster than the supply of able therapists. It is established that stroke-patients and patients from orthopaedic surgery (hip replacement) need intensive and permanent physiotherapy in order to regain (or not to loose) their physical abilities. Also spinal cord injury patients (over the whole range of spinal cord injuries) are in great need of daily physiotherapy. The effectiveness of robotic tools for rehabilitation has been clinically proven in many research publications, the number of such studies is rapidly increasing. But the cost of actual devices is still much too high and the complexity of operating such tools is at the present too high to release them for unsupervised training, ideally at home. Such devices, whether for the hand, the arm or the leg are complicated to fit to the patient, so the much needed assistance to the physiotherapist is only slowly progressing. Moreover, as therapy is so important to regain motricity after an accident (vascular, nervous or other), it is also essential to come up with device motivating the patient to use them regularly. We show here an example of a 2-dof rehabilitation device for the hand developed at our lab and interfacing with a game in virtual reality (VR) on the "slave" side of the manipulator. (**Fig. 2**)

Fig. 2 Two degree-of-freedom (d.o.f) hand rehabilitation device designed at EPFL Robotic Systems Lab for hemiplegic children
As with most rehabiltation devices, besides an ergonomically correct kinematics, motivation of the patient is a key feature. In this case, the task consists of maneuvering an object through a labirynth. Kinematics and multi-d.o.f.force feedback are adjustable over a wide range.

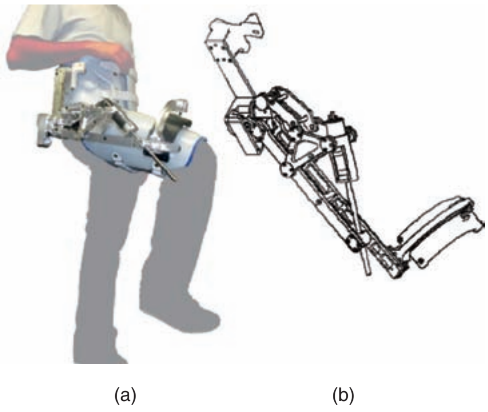
3. 3 Assist Devices

Exoskeletons as human-assist devices appear in science fiction dreams since quite some time. In the last decade, several such systems are appearing, many of them in Japan. While Honda's walk-assist system (**Fig. 3**) seems to be targeted, among others, for factory workers, Cyberdyne's HAL (**Fig. 4**) is promoted as both, assistance for elderly and "human enhancement", i.e. increasing the physical force of a human e.g. to carry heavy loads. This last function is of course closely embedded in biomedical robotics as an assist device for the daily care of elderly and persons of reduced mobility, e.g. for a nurse carrying a disabled patient.

While there are several encouraging pioneering devices and research projects in this domain, carried out at many institutions, practical commercially available devices at affordable cost have yet to be developed. One of the main challenges of such devices is the control. The exoskeleton "Rex" from New Zealand, designed for patients with complete lower limb paraplegy, is statically stable and is controlled by joysticks. It stabilizes the patient in an upright position, but it is extremely slow (about 6m per minute). The Cyberdyne HAL is controlled by EMG, i.e. electrical signals picked up from the muscles of the corresponding limbs. This seems to work reasonably well for healthy patients, it could also be a hopeful approach for some partially disabled patients. The research question is about how much autonomy the system should have to really assist the wearer in his/her intention to move and were to take the signals from. Here we drift away from the topic of haptic interfaces, this is a question of Brain-Machine Interface (BMI), another rapidly expanding research topic. It will not be investigated further in this article.

Fig. 3 Walk assist device from Honda

Fig. 4 "Robot Suit" human assist device HAL from Cyberdyne, Japan
It is controlled through EMG signals, i.e. electrical potential signals taken from the muscles (electromyogram).



(a) (b)

Fig. 5 Assist device for the hip joint designed at EPFL Robotics Systems Lab
This device is intended for elderly patients, e.g. for re-mobilization after a hip joint operation or for stroke recovery. The kinematic design aims at providing high torque for the sitting-to upright transition and for stair climbing while being as "transparent" as possible for normal walking.

In **Fig. 5**, an assist device for the hip joint of elderly is shown. The mechanical design of the kinematics is such that there is high torque for the sitting to standing transition and on stairs, while, for normal walking, the device should be as "transparent" as possible. In this context "transparent" means that the device should not hinder normal walking. Technically speaking, the device should be back drivable, at least in the normal walking mode. We are currently experimenting with designs allowing the motor to run always in the same direction, thus avoiding acceleration losses. The core is a system with light weight brakes and clutches to reach the oscillating movement of the leg. In designing such a system, the complex joint kinematics of the human skeleton must of course be thoroughly understood and accommodated.

3. 4 Research in Cognitive Neurosciences

Cognitive neurosciences have already been evoked in **section 3.1** on surgery robotics, when referring to "tool-embodiment" of a surgery tool by the surgeon. This is just an example of a topic of great interest in neuroscience. "Embodiment" is the mechanism by which the sensori-motor system (and our brain in general) integrates our limbs, especially our hands, arms, legs and feet as part of our body. The amazingly efficient operation of the complex multi-dof control of the human body relies on this "embodiment" mechanism, which could, from the engineering point of view (and with much simplification) be described as the constitution of a dynamic model of the body in our brain, especially (but not only) in the sensori-motor cortex. Moreover, it is well known from intensive research by cognitive neuroscientists that the skilful appropriation of a tool (fork, chopstick, cutter, screw-driver, surgical tool, music instrument, tennis racket, bicycle, car etc.) relies exactly on this embodiment mechanism. Roger Federer "embodies" his tennis racket, for his brain it has become part of his body. It is more than just a metaphor to say that the violin has become "part of the body" of a great artist, it is true in a scientific sense that his brain considers his music instrument as part of his body.

From this description, it is only a small leap to the idea of studying mechanisms of embodiment with the help of robotic (or mechatronic) tools such as haptic interfaces, joysticks, telemanipulators etc. opens a wide new field of research. With a telemanipulator, we can operate in a virtual environment (Virtual Reality, VR) just as well as in a real environment. For experimental work, we thus have the huge advantage to have to realize only the master side in hardware, the experimental set-up to be manipulated can all be in software, in VR. **Figure 6** shows such an experimental setup, where the mechanisms of embodiment can be studied in a controlled environment and in complex scenarii.

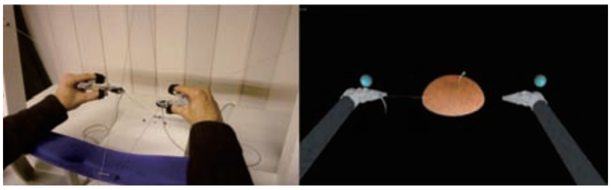


Fig. 6 Telemanipulator acting in a Virtual Reality (VR) environment
The haptic master console designed by Dr. Marc Vollenweider gives three-component force feedback to two hand-held tweezers over a tetrahedral cable arrangement. In this way, there is a large workspace, large force feedback capacity, but no inertia to the manipulator, as the heavy motors are in the fixed base. The tweezer's orientations are measured, but there is no torque feedback. Realistic force feedback is possible in this way. This device has been developed as a trainer for surgical robotics and is now used for experiments in cognitive neuroscience, but it has a large potential for applications in other fields.

4. Other Application Examples (including automotive)

After all that has been said, the importance of haptics for the man-machine interface in the automotive application field seems obvious. Especially the link to cognitive neurosciences provides a promising approach for future research activity: indeed, driving a car, getting to know it and "feel" at ease in it are all indications of various degrees of "embodiment" of a car by our brain. In other words, our brain quickly builds a sort of internal model of certain relevant aspects of a car, so that, in some sense, one can say that "it (the car) becomes part of our body". For these mechanisms to be efficient, for safe, comfortable and pleasant driving, the haptic "feel" of the commands of a car are thus essential. The progressive stiffness, the appropriate amount of viscous damping, the end-stop characteristics of steering wheel, accelerator and brake pedal are essential elements in this context, they are (or should) accordingly be fine tuned very carefully. Although to a lesser degree, such reflections apply also for secondary input devices such as knobs, buttons, handles, seats, the "feel" of closing the door etc. Major car manufacturers devote considerable attention to such questions.

Other fields of application where haptics is essential are e.g. the design of input elements such as keyboards, touch screens, musical instruments, household appliances, sports equipment. In all these domains, a thorough analysis of the haptic properties of the interface can lead to decisive improvements and can sometimes translate into spectacular marketing successes or failures.

5. Conclusions

Our mind, our image of ourselves as an individual is completely determined by the sum of our sensory inputs. Of these, the various modalities of the haptic senses (in a large sense) are, in certain ways, more basic than optical and acoustic data inflow. This is now well accepted by roboticists as well as by researchers in cognitive neuroscience.

Research in haptic man-machine interface has therefore become an active branch of robotics, biomedical and mechatronics engineering. Besides pure research interest, such as evidenced e.g. through the link to cognitive neurosciences, many practical fields stand to benefit from a better understanding of the interplay of human physiology and mechatronics. As examples, the importance of haptic man-machine interfaces in robotic surgery, rehabilitation and assistive devices have been presented. The focus on haptics is also crucial in many other domains, specifically in the automotive industry.

*1 DA VINCI is a registered trademark of Intuitive Surgical, Inc.
*2 ROBOT SUIT HAL is a registered trademark of CYBERDYNE Inc.

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