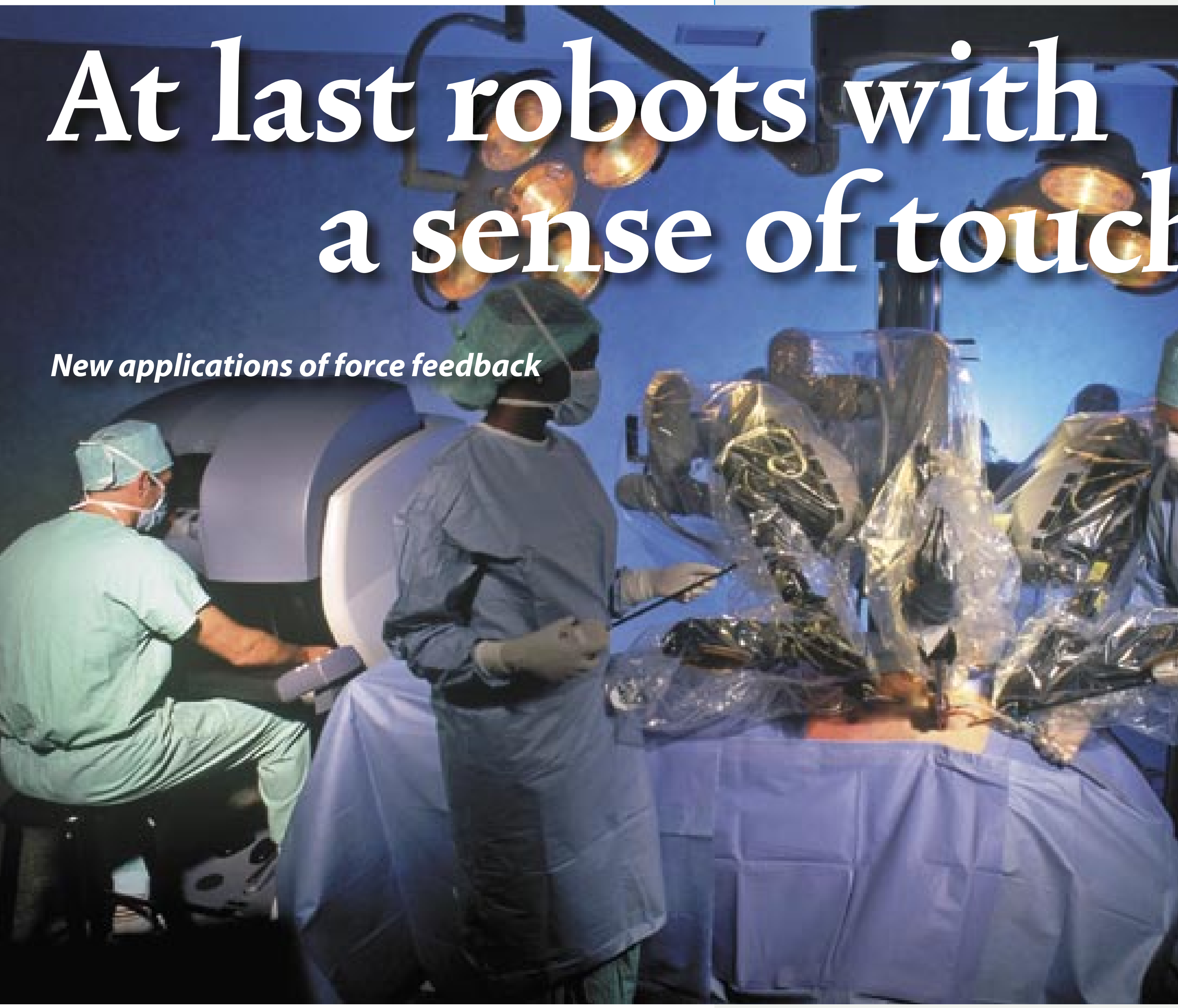
At last robots with a sense of touch

New applications of force feedback



For a number of years surgeons have been using robotic arms to carry out precision operations. These technical appendages can operate without any tremors, and according to the manufacturers, they offer up to ten times the precision of the human hand. The downside is that surgeons using robot arms cannot feel what they are doing. Until now, that is. Countless research groups are looking into the possibilities of force feedback, i.e. transmitting the reaction force acting on the robot arm back to the surgeon. A lot of progress has already been made with soft structures, but hard structures remained a problem. Researchers at TU Delft have succeeded in building a first prototype that can grasp both hard and soft structures while enabling the remotely operating surgeon to really feel what he is doing.

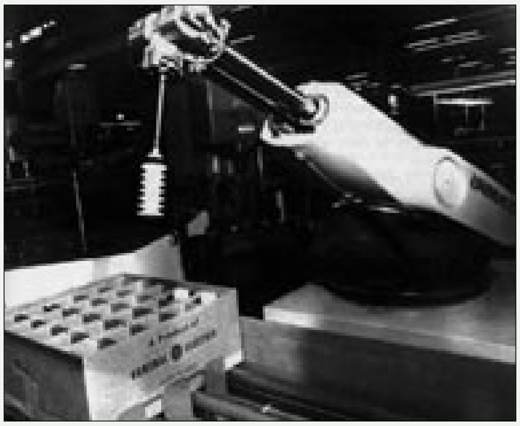
By Bennie Mols

Seated at the console of Intuitive Surgical's Da Vinci telemanipulator, a surgeon controls the robot arms. On the console's display he is presented with a stereo image of the operating area inside the patient. The surgeon's hand movements are scaled down and reproduced exactly by the instruments held in the robot arms. However, the surgeon's hands do not feel anything of what he is doing in the operating area. The rest of the medical team can follow the surgeon's movements on the extra monitor (upper right). During the operation the telemanipulator is shrouded in plastic covers to maintain a sterile environment.

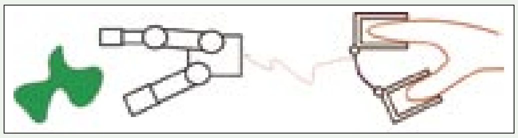
The control console of the Da Vinci telemanipulator includes two joystick-like grips which the surgeon uses to control the robot instruments. Feedback from the operating area to the surgeon is a purely visual affair.

Photograph: Intuitive Surgical Inc.

In 2001 surgeons at a London hospital operating on the prostate of a 61-year old man were the first to use three robot arms controlled by joysticks and a console in the operating theatre. The robot arms had to manoeuvre inside a one centimetre wide opening. Two small cameras attached to one of the arms provided a view of the operating area.
This type of operation requires maximum precision, which is something the robot arm is good at. The robot even filters out the natural tremors that affect even the best surgeons. The first robot operation in the Netherlands, on a gall bladder, took place at Utrecht University Hospital in late 2003. Elsewhere in the world, robot arms have even been used for basic heart surgery such as pericardial operations and heart valve repairs. For more complex heart operations human surgeons still outclass robots.

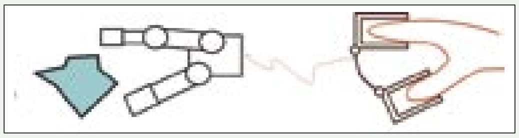


The first industrial robot, the General Motors Unimate, was introduced in 1961, and instantly reshaped industrial production processes. Today some 750,000 industrial robots are in operation, all of which are rigid, hard, and heavy.

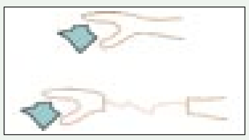


The classic remote surgery approach consists of a soft master interface (on the right) and a hard robot slave. This works well as long as the objects to be handled are reasonably soft.

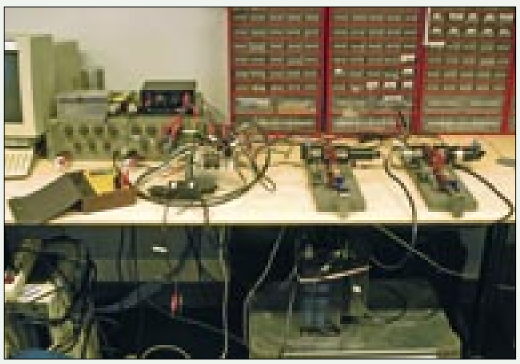
An illustration of the contact instability that occurs when a rigid robot comes into contact with a rigid environment. The robot oscillates violently onto and across the contact surface. This behaviour is known as the hammer effect, and can even present a hazard to bystanders.



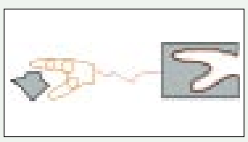
The classic remote surgery approach does not work with hard objects, because the forces acting between the rigid robot and the rigid environment build up too fast for the control system to keep up with. The result is contact instability.



The ideal remote surgery system involves extending the hand of the operator with all its muscles and tendons. In this theoretical case the operator experiences the correct interaction with the object manipulated by the system.



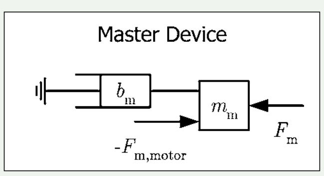
The experimental set-up used at the Delft Biorobotics Laboratory to test the soft/hard theory. On the right is the master, with the slave to the left of it.



The approximation of the ideal remote surgery system as envisioned by the Delft Biorobotics Laboratory uses a soft slave hand that mimics the hand of the surgeon and a hard master hand that mimics the slave environment.

Close-up view of the master (the operator interface). The force is measured as close to the finger as possible. The system also measures the position and speed of the motor.

The master interface is approximated using a simple model in which the energy losses are represented by a viscous element (b_m), while the mass attached to the motor is represented by m_m, on which the forces of the motor (F_m) and the operator (F_m) act.



Movements in miniature

All remote surgery operations were performed using the Da Vinci machine, a commercially available robot, over two hundred of which have been sold. A surgeon operates it by holding a pair of grips that control the remotely operated robot arms which perform the actual operation. A video display provides visual feedback. Robot arms used in keyhole operations already have many advantages. They can remove surgeons' natural tremor, but they can also perform complex movements by exactly reproducing the surgeon's arm movements through a wrist joint in the instrument and the robot arm to which it is attached. A major drawback of the system is that the remotely operating surgeon cannot feel what is happening. He does not know whether he is operating on hard tissue or on soft tissue, since no contact sensation reaches his fingertips. To make the surgeon really aware of what is going on you need a force feedback system. When the instrument at the end of the robot arm comes into contact with a surface, the system feeds back the reaction force acting on the instrument to the joystick operated by the surgeon. This is also known as a haptic system. Researchers at the Delft Biorobotics Laboratory of the faculty of Mechanical Engineering and Marine Technology have been working on the development of just such a system.

The use of force feedback in robot arm control systems is not limited to medical applications. The European Space Agency (ESA) is developing robot arms for use on board spacecraft. Muscular dystrophy patients can be helped by fitting wheelchairs with force feedback robot arms. Force feedback robot arms are even used in robot rehabilitation. Force feedback enables us to control motor vehicles and aircraft using a joystick, which is a safe and relaxed way of operating things. Theme parks use the principle to create lifelike interactive attractions, and underwater operations would not be the same without force feedback systems. The TU Delft researchers are collaborating with a number of other parties, among them ESA, the Academic Medical Centre (AMC), and Exact Dynamics, Didam to ensure that their research follows real world needs as closely as possible,

Hammer effect

"In our laboratory we design robots inspired by biological functions," says Dr. Ir. Richard van der Linde, who supervises the research into haptic systems for remote control applications. Van der Linde previously developed the world's first autonomous two-legged robot driven by artificial muscles which needs less mechanical power than humans do. He is a part-time assistant professor at TU Delft, and is also employed by Altran Technology Consultants. In 2001 NWO, the Dutch Organisation for Scientific Research, awarded him the Veni, Vidi, Vici innovation impulse award for his research into biocompatible designs. The award money he received is now being used for the current research into force feedback in remote control systems.

Van der Linde: "The aim of biologically compatible remote control is to give the robot arm mechanical properties identical to those of the human hand. When you push your hand against something, it will flex while still enabling you to feel the difference between a hard and a soft surface. Even in contact with a hard environment, the hand remains stable."

This stability has proved to be a major problem when a robot arm is used to grasp a hard object while at the same time transmitting the sense of touch to the human hand operating the robot arm by remote control. Swedish doctorate student Göran Christiansson let me feel for myself what can happen if you use a traditional, rigid robot arm. I grab hold of the control arm and move the robot arm to pick up a hard object. As soon as the robot arm touches the object, it starts to hammer its surface like mad.

"Now you know why we call it the hammer effect," Christiansson says. "When the rigid robot arm comes into contact with a hard surface, the lightest movement results in a strong reaction force. The measuring and control systems simply cannot quantify the force and displacement involved: they cannot send commands back to the control arm in time to stop things going wrong. If the phase of the action becomes opposed to that of the measurement system results, the robot arm will start to jerk violently."

Crusher

Since traditional robot designers were aiming at accurate sensors, rigid structures, and fast control systems, instability upon contact with a hard surface became a common phenomenon. The lack of stability of the classic, rigid robot arm is not the only problem. If a rigid arm is used to handle a fragile instrument, it often ends up crushing the instrument when the robot lacks the

delicate sense of touch that humans have. As the robot arm makes contact with the object, the forces start to build up very rapidly because the robot is so heavy, rigid, and strong. This can also result in systems that form a potential danger to humans and the robots' surroundings. The contact between the human hand and the control arm is much slower because it is light, flexible, and soft. A system like that is much less capable of causing damage to its environment. Light and soft systems also tend to be less expensive to make.
The problems outlined above mean that the classic, rigid robot arm will only work well in contact with soft objects. In surgery for example, any contact with bone could spell disaster, while not all tissue is soft either. The surgeon may well be looking for a badly calloused section of tissue, or he may be using the robot arm to work with a hard instrument.

Dampened and soft robot arms

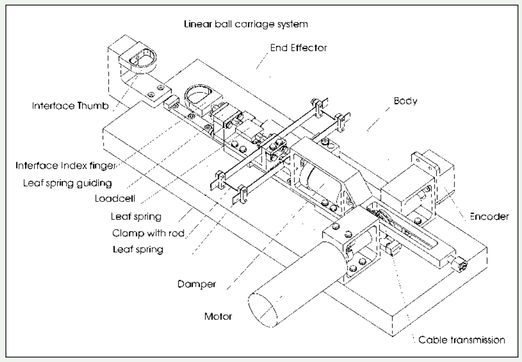
Bearing in mind the biological principles of the human hand, Christiansson, supervisor van der Linde, and supporting engineer Erik Fritz designed and built an experimental model that solves both problems. To begin with, both the operating end (the master) and the robot pincer end (the slave) have only one degree of freedom. When an imaginary surgeon on the master side uses his thumb and index finger to move two grip rings towards each other, an electrical signal transfers the movement to the robot arm, which has also been fitted with a pair of gripper rings that it can move to and fro along one axis. The single degree of freedom involved is sufficient to investigate the force feedback principle.
"When I take hold of a hard object between my thumb and index finger," Christiansson explains, "my fingers will flex slightly, but I can still feel that the object is hard. We are looking at ways of incorporating this underlying biological principle into the robot arm. That is the main innovation."
In technical terms the researchers opted for a pair of leaf springs with adjustable stiffness, with a variable damper set parallel to them. This is the first time that anyone has constructed a robot arm with variable rigidity and damping.
"We recently presented our concept at a conference," van der Linde recalls, "and some of the scientists there just couldn't believe that we were intentionally taking away the rigidity of a robot arm. The thing is that making the robot arm less rigid actually increases its application potential. It will enable surgeons to operate on both hard and soft tissue. Our solution is a full analogue of biomechanical muscle models."

Radioactive materials

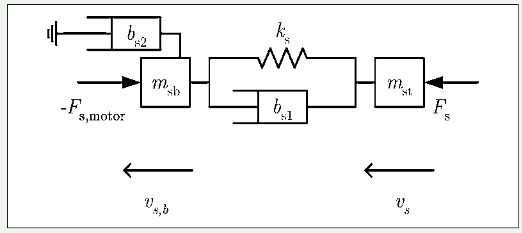
The damper consists of a piston in an air-filled cylinder with a small hole in it, the diameter of which can be varied to adjust the degree of damping. The robot arm consists of a mass connected in series to a parallel damper/spring system, which in turn is connected to another mass. The result is that the robot arm can be made non-rigid.
Christiansson: "The question is, can you use a non-rigid robot to feel that a hard object is just that? You are inclined to think that this is not the case, but as it turns out, it works very well."
The operating end looks identical to the robot end, i.e. it has the same adjustable mass-spring/damper-mass system.
"Even so, the system is easiest to operate with the operating side made as rigid as possible," Christiansson continues, "producing a system that consists of a rigid operator arm and a non-rigid robot arm."
The asymmetrical set-up is a new and promising aspect of the development of robot arms for remote surgery applications. The aim is to make the robot arm a sensitive extension of the human arm. Previous development work on robot arms with force feedback to the operator panel does exist, in particular for handling radioactive material in the nuclear industry, but none included this asymmetrical way of working, using a non-rigid robot arm linked to a rigid operator arm. Instead of recreating the properties of muscles, traditional robotics used powerful but far from subtle electric motors.

Integrating mechanics and controls

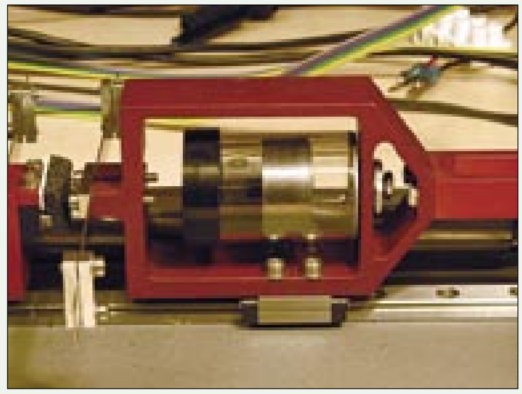
When the slave unit developed at TU Delft makes contact with an object, sensors automatically measure the position of the end point and the force acting on it. The control system at the robot end then processes the position and force information, and passes it to the operating end in the form of an electronic signal. To supply the necessary power, both the master unit and the slave unit have been fitted with DC motors. So a motor supplies the power to push back against the human hand



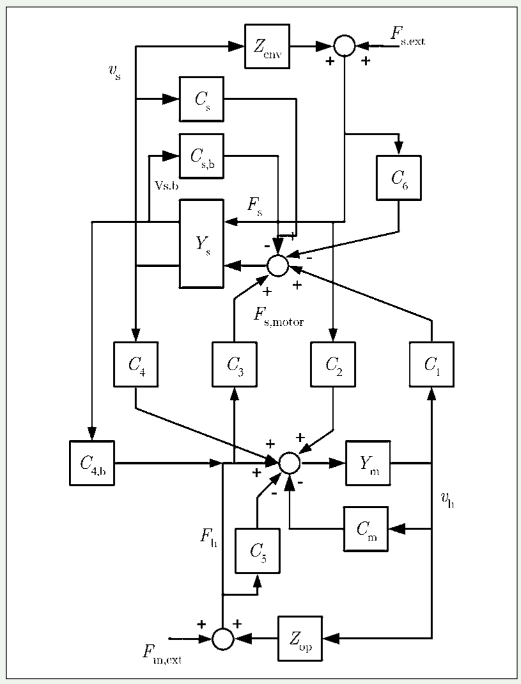
The slave-set-up.



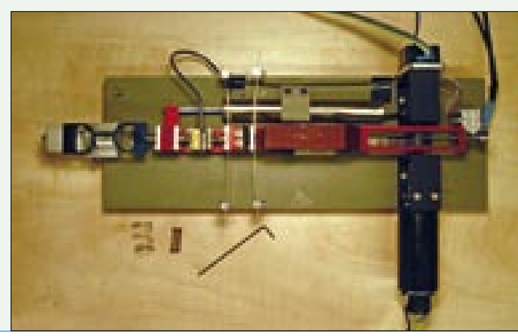
The slave interface is also being modelled using a simple model, with the energy losses represented by a viscous element (b_{s2}), and the mass attached to the motor represented by m_{sb}. In contrast to the master this system includes a spring (k_s) and a damper (b_{s1}) between the tip and the motor. These make the slave soft. Acting on this system are the forces of the motor (F_s) and the operator (F_s).



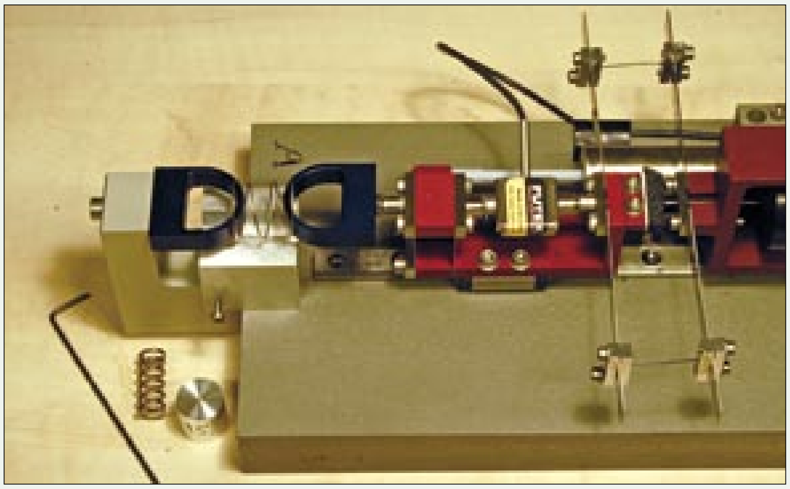
The spring (k_s) and the damper (b_{s1}) from the previous figure have been realised using an adjustable leaf spring structure and an adjustable piston and cylinder combination.



Although force feedback appears to be rather obvious, it requires a complex control system. Even a simple set-up with a single degree of freedom requires some 10 different parameters, as well as models of the environment, the operator, and the set-up. Since none of these models can ever be exact, finding the optimum settings becomes a complex matter which in practice often boils down to trial and error.



The soft slave developed by van der Linde's group features an internal element that gets deformed when a hard object is grasped between the gripper loops. This results in a natural build up of forces between the gripper loops of the slave and its environment.



The soft slave can also handle soft objects. In this case, both the slave and the object become deformed as a result of the contact forces.

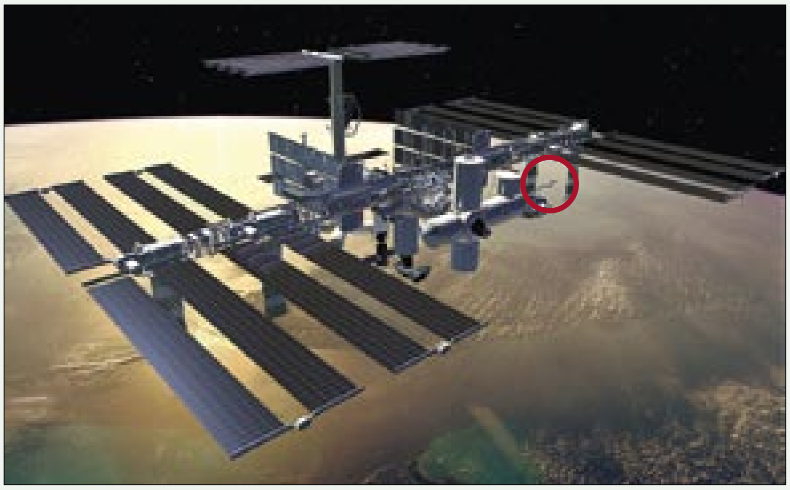


Illustration: NASA

The exterior of the International Space Station (ISS) requires regular maintenance. Since the robots developed so far (such as the European ERA developed by Dutch Space (marked by the red circle) are too unwieldy for maintenance work, astronauts have to venture outside for maintenance work, known as Extra Vehicular Activities.

The Eurobot is controlled by an astronaut from inside the ISS. Force feedback would be a useful feature to prevent the Eurobot damaging the ISS. For this purpose, TU Delft doctorate student André Schiele is working at ESTEC to develop an exoskeleton that will enable astronauts to operate the Eurobot while providing force feedback from the robot to the astronaut.

enabling the operator to actually feel the reaction force. The control system drives both motors. Ideally a human operator should feel exactly what the robot arm feels, however, the robot will operate better at certain frequencies.
Christiansson: "At frequencies up to a couple of hertz we can achieve a force transfer of about 95%, which is very good. At higher frequencies the performance drops rapidly, but this is not a problem for most applications."

Two worlds "In our system we have integrated the mechanics with the control system," van der Linde continues. "The Da Vinci robots now in use in hospitals try to solve everything using pure control systems, i.e. with electronic positioning and correction. My guess is that eighty percent of the world would like to solve robot control along these lines. Control systems are easy to use across distances, and to scale down large operator side movements to much smaller movements at the robot arm end. Even so, apart from the various mechanical alternatives there is still no force-controlled remote surgery system that is robust and fully stable in contact with hard surfaces. There is always the danger of contact instability, which is why we have added a mechanical damper and spring system to an electronic control system, combining the best of both worlds. Mechanics alone, just like pure electronic control systems, just cannot do this."
At the AMC in Amsterdam, fully mechanical master-slave manipulators are being evaluated.
"Surgeons tend to like the idea of a fully mechanical system," says supporting engineer Fritz. "An electronic control system uses motors that can add energy to the system. Most surgeons think that a motor has the potential to mess up an operation. With a fully mechanical solution the surgeon feels completely in control. So, we will have to win over the surgeons first before we can introduce electronic control systems in a remote surgery system."
Moreover mechanical solutions are still less expensive to manufacture.

Sound as additional information Whatever the integration of mechanics and control system looks like, the information arriving at the operator end is always slightly filtered.
"One of the things we still know very little about," says Christiansson, "is which kind of information is most important for certain tasks. For example, what is the information you need to feel differences in human tissue? We don't know yet, but we will have to find out in order to set up our robot arm correctly. How rigid should it be, and how much will it have to be dampened? How sensitive must the sensors and motors be? How will time delays affect the force feedback? All of these are still practically unknown factors."
Christiansson, who took his degree at Chalmers University in Stockholm, is now halfway through his doctorate research. He intends to use the remaining time to find the answers to these questions.
"We will be asking various test subjects to perform experiments with our master-slave setup, so they can tell us what the relevant types of information are."
Fritz adds that if a surgeon looks at a display to see what he is doing he could at the same time be hearing what is happening to provide him with additional information that can help him assess the condition of certain types of tissue.
"It would enable him to integrate the information about what he can feel with what he is seeing and hearing. As a possible result, it could mean that the extra audiovisual information reduces the level of tactile information required," Fritz explains.

Flexible plastic fingers

Once the scientists understand what kind of information is needed to build the right kind of operator arm, the next step will be to create more realistic grips. Whereas current models still use a pair of loops through which you put a thumb and forefinger, future models may well use lightweight plastic fingers.
"At some point in the future they will become small medical instruments, flexible systems, that can be easily attached to a robot and so cheap that they can be disposed of after use," says van der Linde. The system will also have to evolve from its current configuration with a single degree of freedom into a mobile instrument with several degrees of freedom.
Van der Linde continues: "The crucial question really is, how good should good be? Even though you cannot see the forces, you can feel them. This makes it difficult to quantify what the human operator stands to gain from using

robotic manipulators. Anyhow, the main point is that we have now managed to demonstrate using a highly simplified system that our concept with a non-rigid manipulator and a rigid control manipulator offers great advantages over the classic approach.”

According to van der Linde, remote surgery is a newly developing field, even though it has a history that goes back fifty years. And it can look forward to a great future both in medical applications, in the form of touch-sensitive instruments, and in other fields, including micro-assembly, the handling of radioactive material, and underwater robotics.

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Slower and softer, but still better?

The human hand cannot match a robot hand in many ways. Consciously, humans can vibrate their hands at no more than about five hertz, and even unconsciously, as when suffering from Parkinson’s disease, the human hand vibrates at no more than fifteen hertz. The precision of the sensors and actuators in the human hand is low, enabling us to recognise differences between one and ten percent at best. Doctorate student Göran Christiansson has me do an experiment.

“I will give you a little block to hold between your thumb and index finger. I want you to estimate its length. Then I will give you another block, and you will do the same. I then want you to tell me which is the longer one of the two. You may not look, just feel.”

I take first one, then the second block between my thumb and index finger.

“They feel the same to me,” I say.

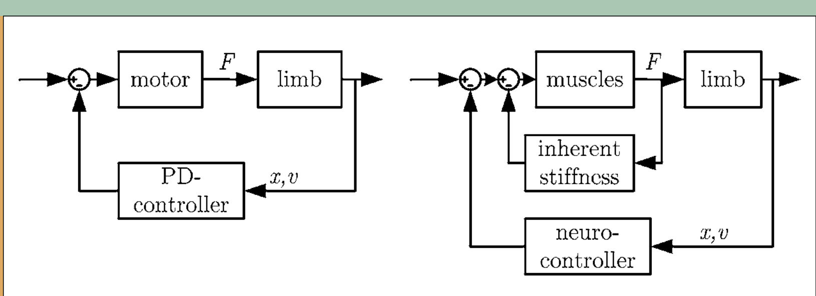
“Wrong, one is three millimetres longer than the other one,” Christiansson laughs.

“A robot would do much better.”

Humans can only feel forces acting with a frequency of less than 300 hertz. The neural delay between the moment the hand registers the force and the moment we respond to a stimulus generally is between ten and one hundred milliseconds long. From the finger, the stimulus has to travel to the spinal cord and back, and sometimes even all the way to the brain and back. The knee jerk reflex for example takes about one hundred and forty milliseconds. When a person accidentally touches a hot surface it takes up to half a second before they realize what is happening and pull back their hand.

“For a robot arm this kind of performance level would be abysmal,” says Christiansson. “It can easily outperform us on all of these counts.”

Nonetheless, the human hand is very stable and has a very finely tuned muscular system. A human hand contains some seventeen thousand sensors, although there is quite a bit of overlap. We use seventy percent of all these sensors to gather tactile information, and the rest is used to perceive pain stimuli.



Photograph: Exact Dynamics

Remotely operated mechanisms are also used for rehabilitation purposes. This picture shows a disabled person suffering from motor deficiency using the Exact Dynamics ARM, a mobile manipulator attached to the wheelchair. Force feedback might be very useful to this user group. In addition, the soft slave principle could improve safety.

Photograph: Exact Dynamics

People use force feedback in many everyday tasks. To perform the same tasks using a robot without force feedback would require lots of training.

The human hand has 22 degrees of freedom and contains over 17,000 sensors. To reproduce the complete range of movements available to the human hand would require complex mechanics, as demonstrated by the hand from the European Teleman project from the 1990s (for which TU Delft acted as secretary; see also Delft Outlook 97.2).

Robots — From big, heavy and cumbersome to small, light, and flexible.

The year is 1921 when Czech playwright Karel Capek introduces the world to the word ‘robot’. In his play ‘Rossum’s Universal Robots’ he describes how robots handle all the chores so humans can spend their time on leisure. It was 1961 before the first robot application appeared on an industrial production line when the U.S. company General Motors used a robot arm, the now legendary Unimate. The idea that humans could rest on their laurels and let robots do all the work for them has of course been relegated to the realm of dreams. Even so, the fact remains that robots can perform tasks that humans simply are not very good at, such as lifting heavy objects, or endlessly repeating the same actions, all with ultra-high precision. For decades traditional robotics focused on strong robots, producing large, heavy, rigid structures. The result was exceptional performance of power, speed, and accuracy, quite a contrast with the sensitive coordination and movements of the human arm with its damping and flexibility built into the muscles and tendons. Whereas our limbs can move lightly and elegantly, classic robot arms appear clumsy and move in sudden jerks. Also, the human nervous system includes a number of ingenious adaptive feedback mechanisms. The control mechanism of a traditional robot arm is essentially different from that of a human arm (see figure below). Biorobotics researchers are looking for ways of improving robot systems for specific tasks by incorporating biomechanical principles in the design of robot arms. The aim is to improve the system’s stability and efficiency and to build lighter and more flexible robots. In addition the biorobot arm is designed to give its operator a sense of actually being in contact with the object or surface the robot touches. This is one of the fields being researched at the Delft Biorobotics Laboratory.