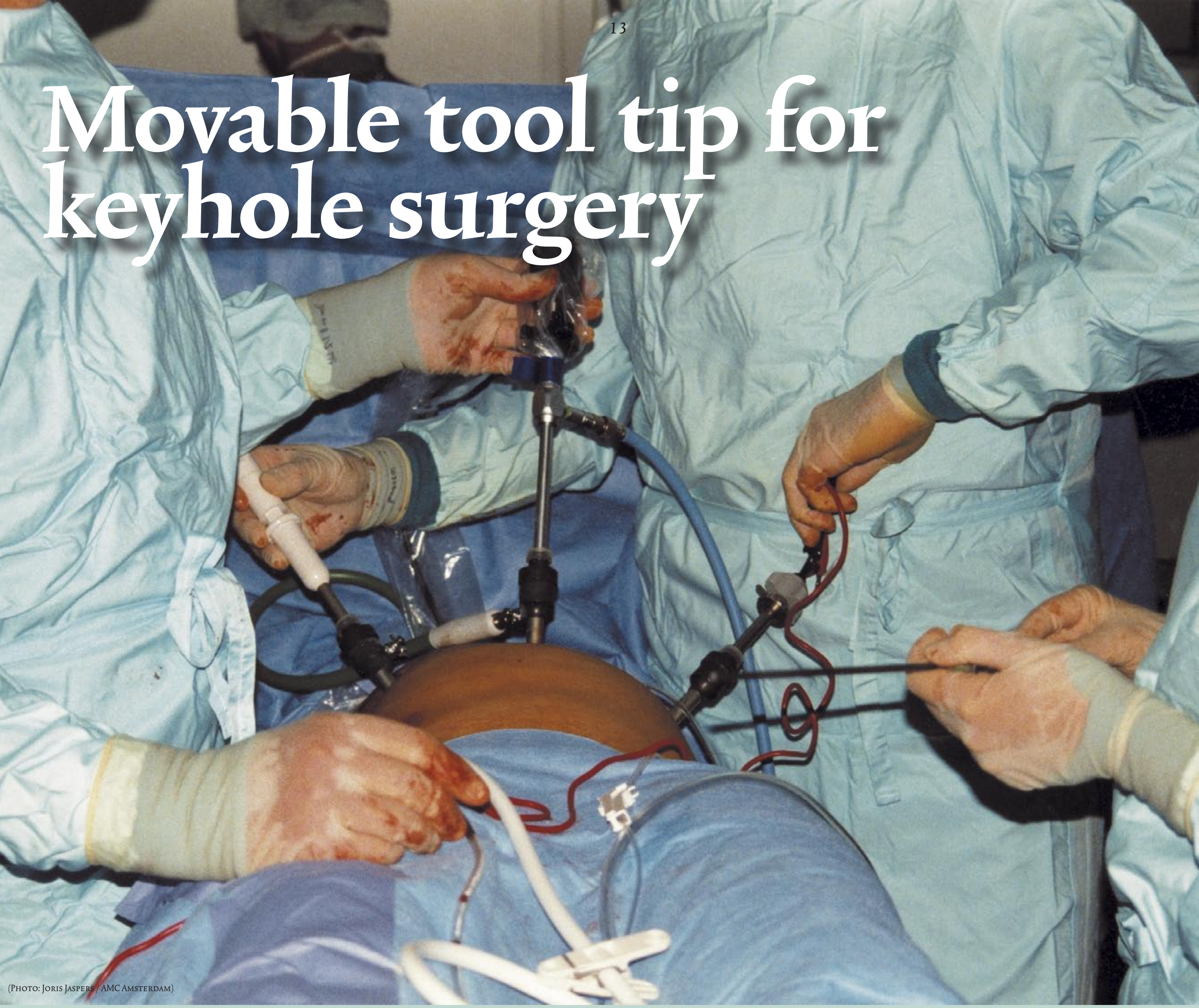
Movable tool tip for keyhole surgery

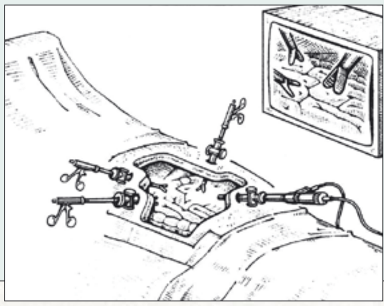


(Photo: Joris Jaspers / AMC Amsterdam)

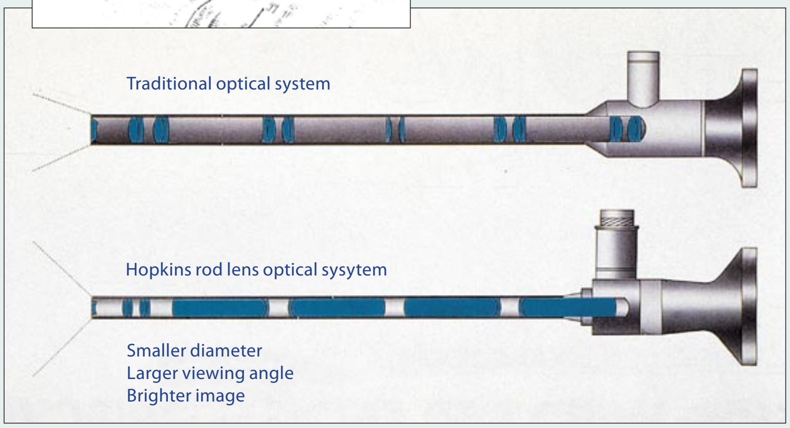
A laparoscopic operation, during which the abdomen is inflated with CO_2 to create more room to work. Three cannulae (tubes containing valves) have been inserted. The surgeon uses the endoscope (in the middle) to look inside the cavity. The other cannulae are used to insert surgical instruments.

A major problem in keyhole surgery, which involves surgeons performing operations through small incisions, is the complex manoeuvring of small instruments. Researchers at TU Delft have built an entirely new tool tip control system, based on the tentacles of squid that will enable surgeons to manoeuvre a camera or instrument in any direction during keyhole surgery. The concept uses nothing but standard parts like cables, springs, washers and tubes, so the cost is less than one percent of the cost of the currently available tool tip systems. The mechanism is easy to miniaturise. A worldwide patent has already been applied for, and the design is now ready for commercial application. Surgeons can't wait to start using the new invention, in particular because it will enable them to use minute instruments during keyhole surgery.

by Bennie Mols

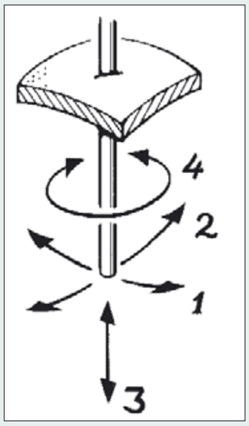


Cutaway view of the abdomen with three laparoscopic instruments, and, on the right, an endoscope. The surgeon operates looking at the camera image from the endoscope, which is displayed on a monitor.

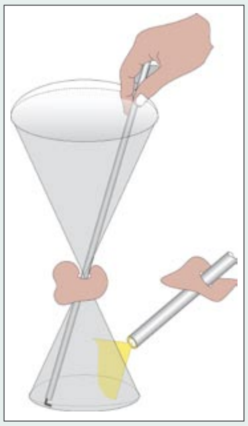


(Photo: Karl Storz)

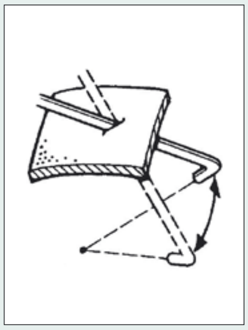
Current rigid endoscopes for laparoscopic surgery.



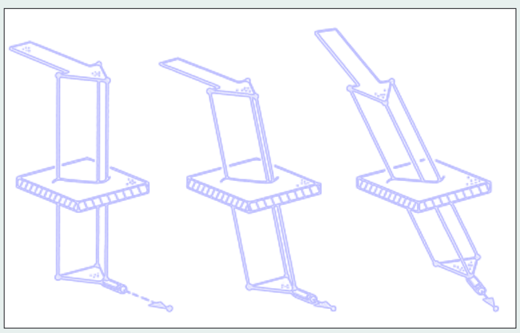
The cut in the abdominal wall restricts the motion of current rigid endoscopes to one translational and three rotational degrees of freedom.



The incision acts as a fulcrum for the movements of endoscopes and instruments. As a result, movements of the hand are both mirrored and scaled.



A rigid 90° endoscope can be used to view organs from several sides. One drawback is that the image will be tilted, resulting in a slight orientation error. This calls for another solution, i.e. a steerable tip.



The principle of the Endo-Periscope is based on parallelograms. The camera (at the bottom) accurately follows every movement of the grip.

Breedveld first tested his ideas in a model made of wood and aluminium. Once he knew how everything worked, he started refining the mechanism and reducing its size.

The aim of the surgeon in minimally invasive surgery is to damage as little healthy tissue as possible and still be able to perform all the necessary surgical actions. In abdominal surgery, for example, a small incision is made in the abdominal wall through which the surgeon first inserts a laparoscope, an endoscope adapted for use in abdominal surgery (laparos being Greek for belly). The laparoscope consists of a tubular instrument with a light source and a camera fitted to one end, which surgeons can use to see inside the abdomen. But a traditional laparoscope (a straight tube without a flexible tip) severely restricts movement. The surgeon can rotate the laparoscope a little bit in three directions, but that is all. Looking at a feature from several directions is simply not an option, even though this is exactly what surgeons want to do. Ideally, surgeons should be able to rotate a small camera or an instrument inserted through a small cut, in the abdomen for instance, in any direction, since that would enable them to see tissue structures from any angle, and operate on them, without having to make a new incision. This requires a movable tip which surgeons can manipulate in a simple way by hand.

Dr Ir Paul Breedveld has been working on designing and building an endoscope tip that can move in any direction at the Department of BioMechanical Engineering of the Mechanical, Maritime & Materials Engineering faculty of Delft University of Technology ever since 1997. After several innovative prototypes the most recent one has just been completed for commercial application.

“I am not just trying to come up with fundamentally new mechanical engineering principles,” Breedveld says. “I also want to make sure that they get used rather than disappear in some drawer to gather dust.”

Too expensive

On a table in his office at the university, Breedveld sets out a display of movable tip controls to show their historical development. The standard laparoscope used by surgeons has a diameter of ten to twelve millimetres, although five millimetres is now slowly becoming the standard. Breedveld’s first prototype had a diameter of fifteen millimetres, whereas the latest prototype only measures five millimetres in diameter. And now the new Delft Cable Ring Mechanism will allow it to become even smaller, down to one millimetre. However, the development involves much more than simply making things smaller; the entire mechanism that bends the tip has undergone a radical change.

Moveable endoscopes were initially developed for gastro-intestinal examinations, with the express purpose of being able to negotiate the twists and bends of the oesophagus, stomach, and intestinal tract. At their business end, these endoscopes feature a movable tip that can be remotely controlled by the surgeon. Breedveld demonstrates how the mechanism of such a classic tip works. It is a complicated system of rings connected to hinges and riveted joints. The tip can twist in any direction and is controlled by means of four thin cables running through guide tubes soldered to the rings. The guide tubes are necessary to make sure the cables can move only along their length.

Breedveld: “A number of companies in Japan manufacture these flexible endoscopes. However, the mechanism is so complicated that even in a country where practically everything has been automated, the things still have to be manufactured by hand.”

This makes the tips expensive: they come at anything from € 300 to € 500 each.

Gastro-intestinal examinations have one big advantage over abdominal surgery, for one. Since the gastro-intestinal tract itself is not sterile (it is a bit like the world outside which has been pushed inside the body), there is no need for the endoscope to be sterilised after use to kill all the bacteria it carries. It does get disinfected, of course, but for use in abdominal surgery anything the surgeon inserts into the body must be meticulously sterile. This means that endoscopes for abdominal use have to pass extreme requirements. The current standard practice for hospitals is to sterilise instruments for twenty minutes in steam at 120° Celsius. Of course, a movable tip system has to be able to cope with that. There is a movable tip system that is suitable for sterilising, but it requires a different, more expensive sterilisation technique, which is something that hospitals would rather avoid. Another company builds a complicated robot system costing well over a million euros that uses remotely controllable instruments. This system also uses a standard, rigid endoscope. For many hospitals however, this option again is too expensive. The challenge lies in finding a new mechanism for a controllable tip that is much cheaper to manufacture. It must be a mechanism capable of doing many different things, and it must use a simple construction."

The tip must be small (preferably no wider than five millimetres, but less is always better), hollow – the surgeon has to able to look through it using an optical system – and it must be capable of bending through a wide angle in any direction, preferably with a small radius.

New spring type During the very first stages, Breedveld used a technical Lego construction set to build a parallelogram mechanism that enabled him to convert the movements of the grip held by the surgeon into a rotary movement of the tip. If the surgeon rotates his hand in a certain direction, the tip rotates in the same direction. Although some translations occur in mirror image, the grip is always parallel with the viewing direction of the camera. The principle worked, so Breedveld knocked together a wooden model with a real camera on the end. The control mechanism worked very intuitively, but it was clear that this mechanism could not be scaled down to anything near five millimetres. Even if it could be done, the mechanism would become too expensive and too fragile to make it useful in the medical world.

During a six-month stay in Japan from 1999 to 2000, Breedveld, constructed a metal prototype together with Japanese colleagues at the Tokyo Institute or Technology that worked just like the wooden prototype, even though is was of a very different construction and no longer used two interconnected parallelograms.

"We came up with a novel type of spring," Breedveld recalls. "Nothing like your classic, helical spring, because you cannot thread a tension cable through it without it slipping out of place. To improve cable guidance, we made a number of rings made of spring steel and spot-welded them together, with the welds alternating at right angles. Each ring has two small holes in it through which the cables are threaded. The resulting 'Ring Spring' is easy to compress, but hard to twist."

The design received an award at the most prestigious European conference on endoscopic surgery. The design was called an Endo-Periscope, because the tip was now free to twist in any direction. The first prototype of the Endo-Periscope had a diameter of fifteen millimetres. Surgeons loved it, but immediately saw a few drawbacks. The grip on one end was an unwieldy big lump, and in its neutral position, the tip curved through 180°. And then of course, the Endo-Periscope had to be slimmed down.

Twenty minutes So, something else was needed. Breedveld and his colleagues set to work and in 2001/2002 designed a variant of the 'Ring Spring' and a much improved grip for the surgeon. The new tip can twist through 120 in any direction, uses four cables running though the spring, and uses a clever compensation spring inside the grip. The freedom of use of the tip has been increased dramatically. At twelve millimetres, this second prototype of the Endo-Periscope was also a bit slimmer.

"We then used this prototype to carry out a number of experiments," Breedveld says. "These show that even persons who have never handled an endoscope before can master the controls of the movable tip within twenty minutes. Another experiment that used a hook instead of a camera also yielded very positive results. The test subjects were able to twist the tip just like their wrist, and could easily go through complicated stitching routines with it. When they managed to do that, we saw for the first time that our research, which from the very start had been focused on using a camera for viewing, could also be very useful for the manufacture of small remotely controllable instruments."

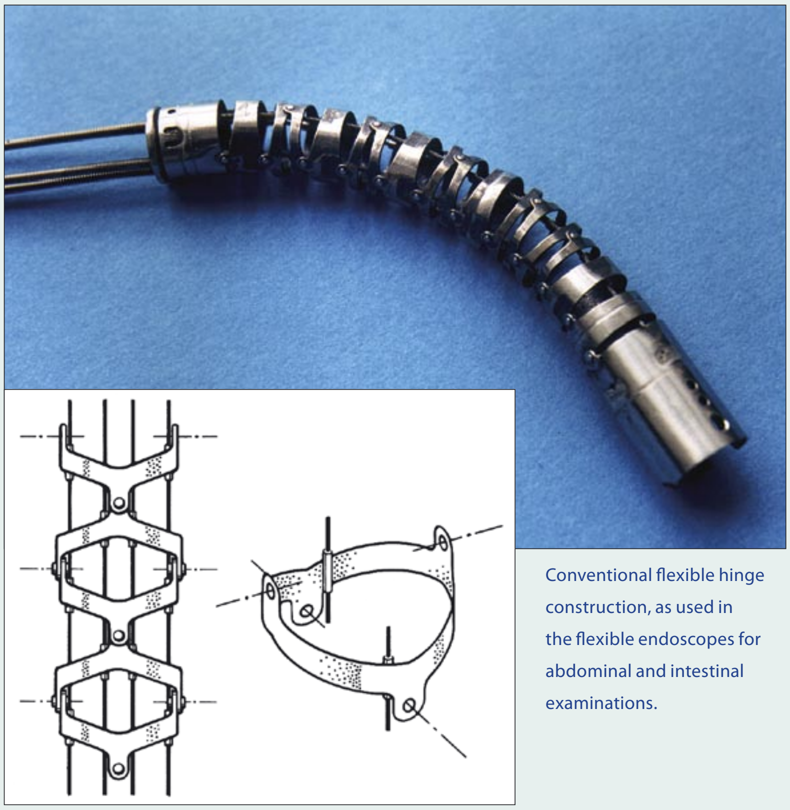
"Unfortunately, we cannot make the Ring Spring much smaller in diameter without raising the cost quite a bit. All in all, it meant that we had to go in search of a completely different mechanism – again."

Squid arm A second line of Breedveld's work was the search for mechanisms that can propel themselves through the intestinal tract. Breedveld and some students under his supervision went to look at mechanisms to be found in the natural world around us that might possibly be used in an artificial mechanism.

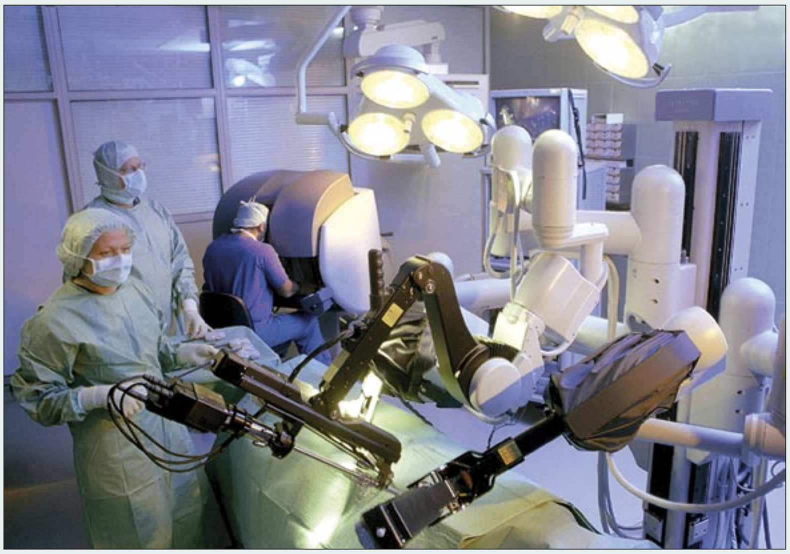
"This eventually brought us to the tentacles of a squid. A squid does not bend its tentacles with four strings of muscles; instead, it uses a whole ring of muscle

(Photo: Olympus Nederland, Leiden)

For intestinal examinations flexible endoscopes are used like these two colonoscopes made by the Japanese firm Olympus.



Conventional flexible hinge construction, as used in the flexible endoscopes for abdominal and intestinal examinations.

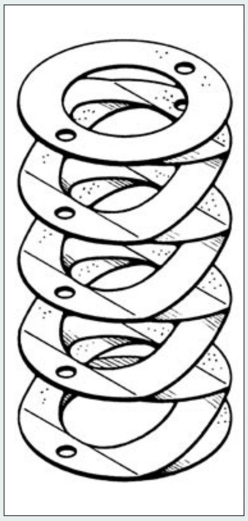


[Photo: Intuitive Surgical Inc.

Modern telemanipulators, such as the Da Vinci by the American firm Intuitive Surgical, use remotely controlled steerable instruments. Such instruments are fairly complex and difficult to miniaturise.

Photo: Intuitive Surgical Inc.

The tools of the robot made by Intuitive Surgical Inc. are fairly complex and require an expensive sterilisation technique.



Dr Ir. Paul Breedveld and Professor Shigeo Hirose of the Tokyo Institute of Technology, invented the Ring Spring consisting of spring steel discs spot-welded together. The Ring Spring has an asymmetrical bending stiffness and a very high torsion stiffness. The holes conduct the wires that control the tip.

First prototype of Breedveld's Endo-Periscope, developed in 1999-2000 during his sabbatical at the Tokyo Institute of Technology.

The endoscope tip can be rotated sideways from –60° to +60° (left), and up and down between 0 and 180° (right).

strings. At one point I was on my way from our coffee machine, which had broken down, to get coffee elsewhere, and the idea hit me of fitting the Endo-Periscope with two normal springs, one inside the other and with a slightly smaller diameter. The annular space between them could then be filled with cables, just like the ring of muscle strings in the squid tentacle. This is going to be the big one, I'm sure. It means that we will no longer need specially designed rings with holes in them, or soldered tubes."

Traffic light

"None of my major inventions were ever conceived in this office of mine," Breedveld adds with a laugh.
"I got the idea that resulted in the Ring Spring when I woke up once at three o'clock in the morning, and the idea for the second prototype suddenly presented itself while I was waiting for the light to change at a pedestrian crossing somewhere in Holland."
He has named his latest invention the Cable Ring Mechanism, and has applied for a worldwide patent on the idea. Since the annular gap is completely filled with cables, they can only move along their own length, so they can no longer slip sideways to the inside of the curve. The second spring holds them in place. By tensioning and relaxing the cables the tip can be curved in any direction.
Although the Cable Ring Mechanism was inspired by a squid tentacle, the mechanism works along slightly different lines. A squid tentacle probably has a whole ring of muscle strings to make it less vulnerable. If one or two of the muscle strings get damaged, the remainder of the ring will still be perfectly capable of moving the tentacle in all directions. The tip with the Cable Ring Mechanism uses the ring of cables to prevent them slipping out of place along the curvature of the spring.
Breedveld again places the prototypes produced so far next to each other. "You can see how each design is slightly thinner than the last, and also how the bending mechanism gradually moved away from the existing mechanism using joints. We started with a special spring with a zigzag structure in one direction, but without any joints. Next we had a special spring that could move both ways, with a double zigzag structure, and now we have two normal springs, one inside the other, with cables filling the gap in between. The funny thing is that the special springs we used made it increasingly difficult to scale down the mechanism, whereas the Cable Ring Mechanism makes it easier, since it takes fewer cables to fill up the gap between the springs. In fact, a diameter of one millimetre would be ideal."

Complexity

According to Breedveld, the complexity of the mechanism has also been considerably reduced.
"The current design uses only standard components: cables, helical springs, washers and tubes. Even the springs can be bought off the shelf in small diameters. This means that the design will be very cheap to produce, a couple of euros for each tip, as opposed to the couple of hundred euros which current tip models cost. This is just what we set out to achieve. What we now have is a disposable tip rather than an expensive tip that has to be sterilised after every use and at great cost.'
The latest prototype was completed last year and measures only five millimetres in diameter, with an internal diameter of two millimetres. Between the two springs run 22 thin steel cables, each only 0.45 millimetre thick. Cable friction is practically a non-issue, and the tip will easily flex through 120 degrees. At the end of the tip the cables have been compressed between two rings.
Breedveld: "Some people who see the Cable Ring Mechanism for the first time wonder why the Ancient Greeks never thought of it, since it looks so simple. As is often the case with good design, with hindsight it appears so simple, but it's a long and winding road getting there."
For continued development of the tip, Breedveld and Jules Scheltes founded DEAM BV, a recent TU Delft spin-off company. DEAM BV, that collaborates with other manufacturing companies to develop instruments, aims to market the tip in 2006.

Instrument control

In a slightly different form a tip using the Cable Ring Mechanism can also be used to remotely control instruments fitted to the end of the tip.
"For this purpose, the assembly no longer needs to be hollow down the centre, as for use in endoscopy," Breedveld says.

"We can dispose with the internal spring, and replace it with a cable that can be moved along the length of the tip to operate an instrument, which can be anything from a pair of pincers, a hook, or a gripper, to an ultrasound instrument. For certain applications it might also be useful to replace a cable in the Cable Ring with a flexible tube or fibre-optics, who knows. In any case, we have covered every angle in a patent."

The researchers at Delft University now have a basic technique that is suitable for an entire range of medical applications. There is no reason why the tip could not be only one millimetre in diameter, which would open up the way for cheap remotely-controlled micro-instruments and catheters.

"Micro-instruments are not a major issue in abdominal surgery, in which a five-millimetre cut is small enough, but I can imagine there being interest from the eye, ear, or brain surgery disciplines."

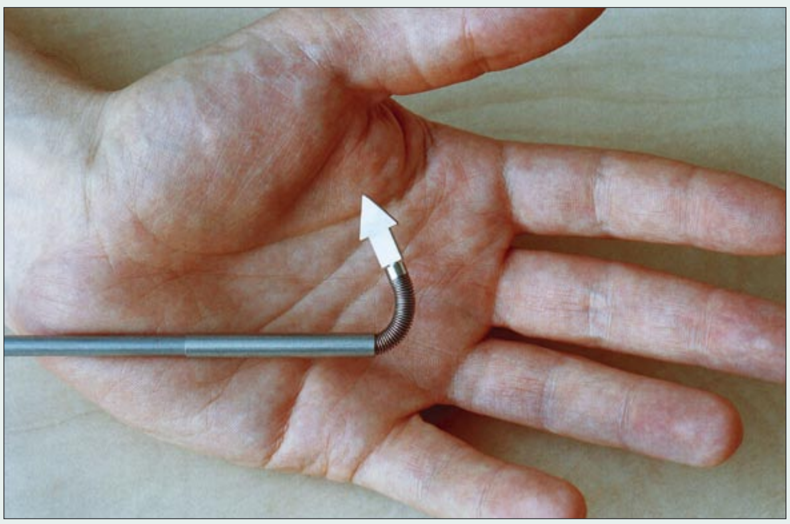
Breedveld can see possible applications in an industrial context in addition to medical applications.

"Internal inspections of complex engines and fuel tanks spring to mind, or being able to fasten screws around corners. This is now being done using rigid endoscopes and instruments, but freely controllable tools can be very efficient. In any case, the industrial market is a lot smaller than the market for medical applications, if only because the sterility of the instrument is not an issue in industrial use, where the tip can be used again and again, whereas for medical use, it would simply become a disposable tip."

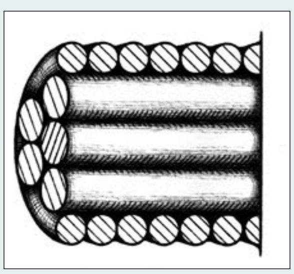
Breedveld already had many contacts among surgeons, but through DEAM BV he has now been in contact with a lot of industrial representatives. In the last few months he has been visited by practically every major medical industry in the world.

"For a number of companies we are now preparing prototypes to their exact specifications," Breedveld explains "and surgeons are already asking us when they will be able to buy a movable tip control system using the Cable Ring Mechanism. According to them, they would really like the system for instrument applications. The complex manoeuvring of small instruments remains a major problem in keyhole surgery, which involves surgeons performing operations through small incisions."

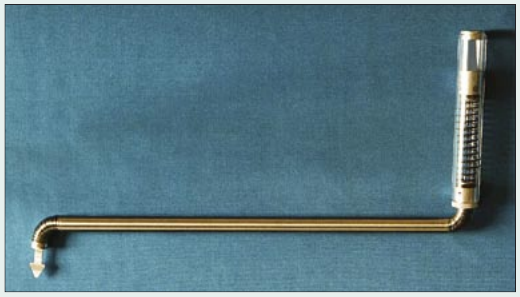
For more information, please contact Dr Ir Paul Breedveld, phone +31 15 278 5232, e-mail p.breedveld@wbmt.tudelft.nl, or Dr Ir. Jules Scheltes, tel. +31 6 150 75341, e-mail jss@deamcorporation.com



The third prototype has an outer diameter of just 5 millimetres. Breedveld is currently working on the next generation endoscope, with a diameter of as little as 1.3 millimetres.

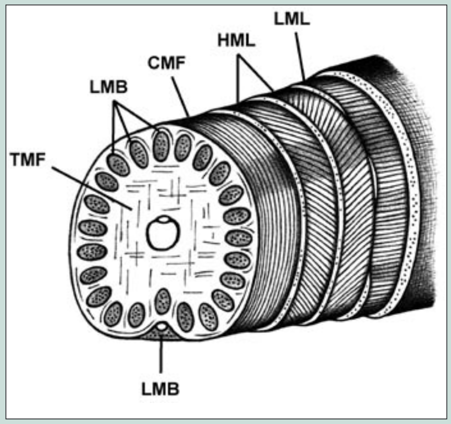


Replacing the inner spring by a cable enables Breedveld to miniaturise a number of steerable instruments and catheters, ready for low-cost mass production.

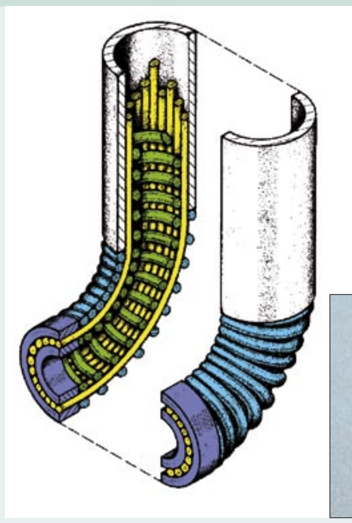


Breedveld's second prototype of the Endo-Periscope, developed in 2001-2002 had a diameter of 12 millimetres. The significant features of this model are the simplified construction of the grip and the parallologram mechanism.

The tip of the second prototype can be steered over 120° in all directions.

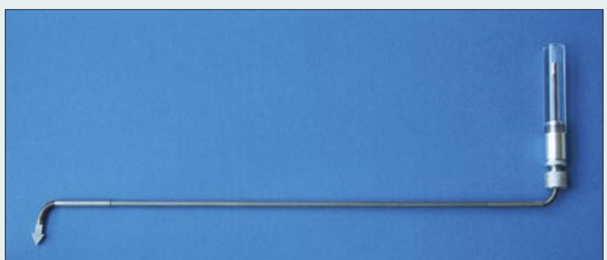


Cross-section of a tentacle of a squid. Belonging to the family of Cephalopods, squids have no hard skeleton for support. Yet they manage to move their tentacles and arms in a great many directions. The tentacle is surrounded by longitudinal and helical muscle layers (LML & HML). The cross-section contains a ring of longitudinal muscle bundles (LMB) enclosed by transverse and circular muscle fibres (TMF & CMF). The tentacle functions as a muscular hydrostat: since the volume of the tentacle remains equal, its stiffness, curvature and length can be changed by the interaction between the longitudinal retractor muscles (LML and LMB) and the circular and transversal extensor muscles (CMF and TMF). The longitudinal muscle bundles (LMB) play a role in retracting as well as bending the tentacle in a certain direction. The ring of muscle bundles inspired Breedveld to create the Cable Ring Mechanism.

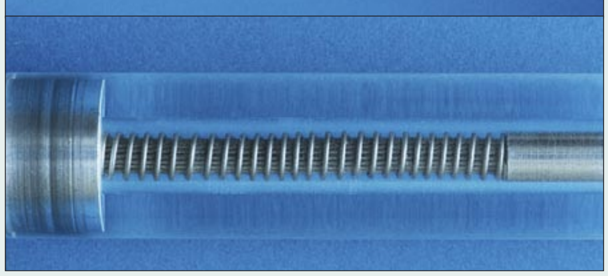


Cross-section of the tip of the recently developed third prototype of the Endo-Periscope, showing the ring of cables, surrounded by two helical springs and fixed at the tip between two rings.

Close-up of a model to test the fixation of the 22 cables between the two rings.



Overall view of the third prototype of the Endo-Periscope.



Close-up of the transparent grip showing the Cable Ring Mechanism.