SELF-PROPELLING AND STEEERABLE

The design of a self-propelling, steerable needle was inspired by a wasp's ovipositor, a thin, flexible needle-like structure used for laying eggs into larvae hidden inside fruit or wood. The needle's potential medical applications include localised therapeutic drug delivery and tissue sample removal (biopsy). The instrument consists of three or more wires that are moved back and forth inside tissue sequentially. Through friction, a net pulling motion of the tissue towards the actuation unit is generated, resulting in the instrument moving forward inside the tissue. Different sequences of wire actuation can achieve either straight or curved trajectories.

The Delft-based Bio-Inspired Technology (BITE) research group works on the development of innovative technical systems and instruments for minimally invasive surgery and other medical interventions, drawing inspiration from extraordinary biological mechanisms. The group collaborates with academic hospitals, biology groups, veterinary hospitals and companies, and has already brought products to the clinic. BITE output includes surgical knives, tissue puncturing devices, and steerable needles and instruments.

One example is the LaproFlex steerable laparoscopic instrument with ergonomic axial handle, which is now being marketed by spin-off company DEAM (Figure 1). In 2019, the first operation (gynaecological) was performed using the instrument. The technology behind the instrument was already described in *Mikroniek* in 2007 [1]. The LaproFlex has a flexible tip, enabled by an ingenious steering system based on the anatomy of an octopus' tentacle, the so-called cable ring mechanism, which ensures that scissors or a grasper, for example, can be steered in any direction.

Wasp needle-like structure

More recent research on steerable instruments [1] was inspired by the wasp ovipositor, a needle-like structure used by the female parasitoid wasp to drill into wood or fruit and deposit eggs inside living hosts such as larvae. The WASP project was started in 2015, funded by the Netherlands Organization for Scientific Research (NWO), as part of the iMIT programme aimed at developing interactive multi-interventional tools.

The WASP project was focused on medical needles that have to reach their target deep inside a patient's body with high precision. This requires a flexible, steerable needle that can follow complex curved trajectories through complex solid organs while avoiding sensitive structures, such as blood vessels, located along the trajectory between the insertion point and the target site.

AUTHOR'S NOTE

This article was based on an interview with Paul Breedveld, professor of Minimally Invasive Surgery & Bio-Inspired Technology and chair of the Bio-Inspired Technology (BITE) research group in the department of Biomechanical Engineering at Delft University of Technology (NL), and on publications from his group, in particular the Ph.D. thesis by Marta Scali [1].

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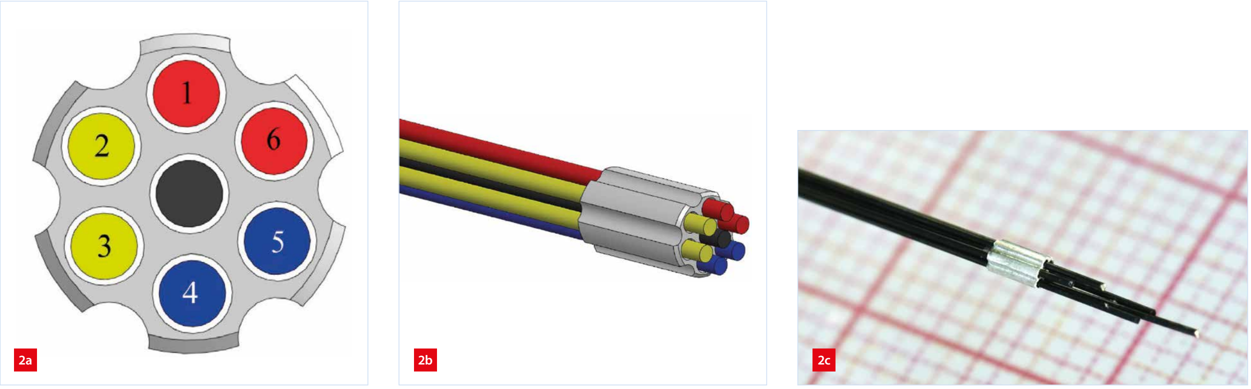
The LaproFlex steerable laparoscopic instrument.
(a) Concept of the patented cable ring mechanism, shown in cross-section as two halves that have been pulled apart for clarity [2].
(b) Commercial version marketed by DEAM, which developed the ergonomic axial handle.



First design of an ovipositor-inspired needle.
(a) Cross-section of the flower-shaped ring, with a central hole to which the central wire is glued and six peripheral holes through which the six other wires can slide back and forth.
(b) Initial position of the wires.
(c) Prototype, showing the tip of the needle with the ring, and some of the wires moved forward.

The wasp's ovipositor is a needle-like structure composed of three longitudinal, interlocking segments that can be actuated individually and independently of each other by musculature that is located in the abdomen of the insect. The propagation of the ovipositor through a substrate is achieved by a push-pull mechanism, in which one of the elements is pushed while the other two are pulled. In this way, the wasp steers the ovipositor along curved trajectories inside different substrates without a need for rotatory motion or global axial push. Inspired by the anatomy and the steering mechanism of this needle-like structure, the aim was to develop an ultra-thin, self-propelled, steerable needle.

Design

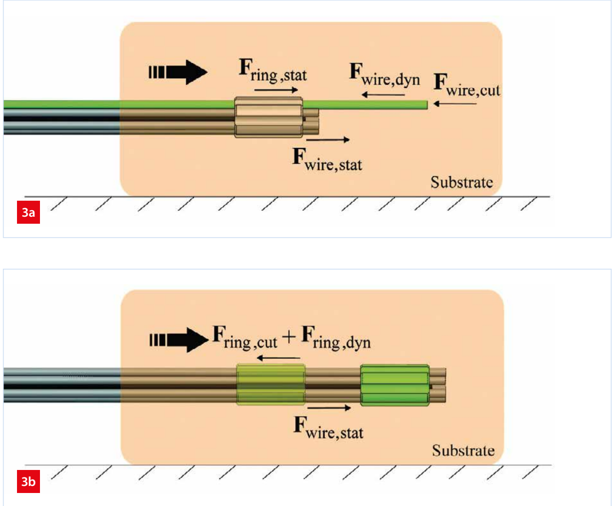
In the first design ([3], the second item), superelastic nickel NiTi wires were used for the segments. Interlocking these turned out to be challenging. In a wasp, the ovipositor segments are interlocked by a jigsaw-puzzle-like structure, which allows them to slide along each other and thus avoid separation. Miniaturisation of such a complex interlocking mechanism was not feasible from a manufacturing perspective.

Therefore, the designers took a step away from nature and decided instead to interlock the wires externally, using a ring with holes through which the wires are fed (Figure 2). The ring was given a flower shape to reduce resistance during propulsion through the substrate. The ring has a central hole to which the central wire is glued and six peripheral holes through which the six other wires can slide back and forth. The first prototype had a diameter of 1.2 mm at the tip and 0.75 mm along the body, while the NiTi wires were 0.25 mm in diameter and 160 mm long, and the flower-shaped ring was 2.0 mm long.

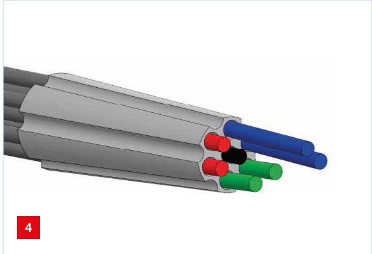
Forward motion

Each proximal end of the six movable wires is connected to a miniature stepper motor, in which a leadscrew-slider mechanism converts rotational motion into linear motion. The needle is moved forward through the substrate firstly by pushing the six wires one by one (or two by two), followed by pulling on all six wires simultaneously, which advances the interlocking ring and the central wire into the substrate.

Figure 3 shows the forces acting on the needle during the forward motion. In the first phase, the sum of the dynamic friction force ($F_{\text{wire,dyn}}$) and the cutting force ($F_{\text{wire,cut}}$) on the wire(s) moving forward should be smaller than (or equal to) the static friction force on the stationary wires and the interlocking ring ($F_{\text{wire,stat}}$ and $F_{\text{ring,stat}}$, respectively). In the second phase, the ring moves forward if the cutting and the dynamic friction forces on the advancing interlocking ring ($F_{\text{ring,cut}}$ and $F_{\text{ring,dyn}}$, respectively) are smaller than (or equal to) the static friction force between the wires and the substrate ($F_{\text{wire,stat}}$).



Schematic representation of the two-phase forward motion mechanism of a needle with six peripheral wires and one central wire. The thick arrow represents the motion of the wires and the ring. See text for further explanation.
(a) First, one wire is pushed forward at a time (green).
(b) After all six peripheral wires have been moved forward one by one, they are pulled back simultaneously, resulting in advancement of the ring and the central wire inside the substrate.



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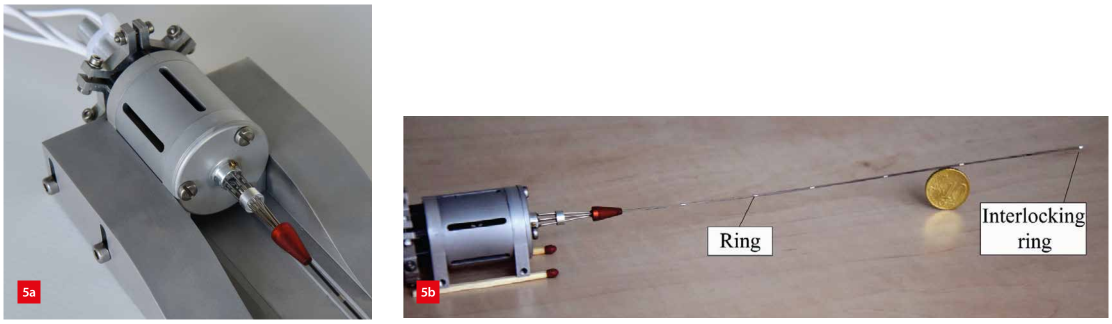
Steering of the needle is facilitated by specific actuation schemes and the use of a conical interlocking ring. The blue and green wires have been given an offset with respect to the red wires. Then all the wires are moved over the same stroke consecutively, thus maintaining the bevel offset required for steering.



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Experimental set-up.
(a) Close-up of the wires emerging from the actuation unit, which contains seven miniature stepper motors.
(b) The actuation unit mounted on an aluminium platform and the gelatine phantom on the cart that can move along a duct.

Steering

A bevel at the needle tip can help to achieve steering. Each needle wire has a flat tip, but bevel asymmetry can be created at the needle tip as a whole. This is done by inducing a bevel offset between pairs of adjacent needle wires. In this way, various bevel angles can be created and steering can be achieved by specific actuation schemes for the individual wires/wire pairs (Figure 4). The steering effect is further enhanced by the use of a conical interlocking ring. This was introduced to counter the observed phenomenon of bifurcation: the effect that wires tend to separate from each other during operation, thus limiting steerability.

Experiments

An experimental set-up (Figure 5) was built consisting of an actuation unit mounted on an aluminium platform, which was provided with a duct to guide a lightweight aluminium cart mounted to four passive (i.e., not driven) wheels in order to move along a straight path with low friction. The cart was used to carry a tissue-mimicking gelatine phantom, in which the needle was to be inserted. The wires were moved back and forth sequentially inside the phantom, generating a net pulling motion of the phantom towards the actuation unit, and resulting in the needle moving forward inside the phantom. Different sequences of wire actuation were used to achieve both straight, curved and S-shaped trajectories. A camera positioned above the cart took photos of the initial insertion and final position of the needle during the experiments (Figure 6).

Conclusion

The ovipositor-inspired needle is the world's thinnest self-propelled, steerable needle. In following prototypes, further

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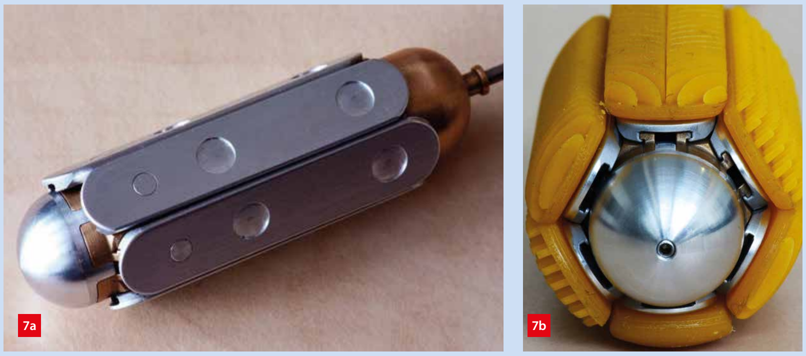
Image of the final position of a needle after insertion. The deflection shows that steering, i.e. deviation from a straight course, could be achieved.

Follow-up

Another project involved the design of a self-propelling device ([3], the first item) for locomotion through the large intestine (colon). This device (Figure 7) contains a miniature electric motor connected to a cylindrical cam. Six sliders are placed around the cam and move forward and backwards following a path defined by the cam. In each step, one slider moves forward while the others remain stationary relative to the environment, generating a smooth, continuous motion at approximately 1/6 of the speed of a moving slider; see the video [V1]. The mechanism allows for a simple, robust construction that can be miniaturised easily.

Experiments were carried out with various flexible 3D-printed structures attached to the outer surface of each slider to generate direction-dependent friction to further enhance grip. Tests in plastic tubes showed fast, fluent self-propelled motion; see the video [V2].

From April this year, a new project funded by NWO has been running, in which needle technology is being developed for prostate interventions under MRI guidance; this is a collaboration with the AUMC in Amsterdam (NL).



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Ovipositor-inspired design of a self-propelling device.
(a) The device has six sliders on its perimeter. One slider at a time moves forward while the others remain stationary relative to the environment, generating a smooth, continuous motion.
(b) Experiments were carried out with various flexible 3D-printed structures attached to the outer surface of each slider to generate direction-dependent friction to further enhance grip.

miniaturisation of the needle to diameters below 0.5 mm was realised. The novel bio-inspired steering and propulsion mechanism enables the design of extremely long and thin needles that can be used to reach targets deep inside the body without a risk of buckling and with the possibility of correcting the trajectory.

When the central wire is removed, a hollow needle is created [4]. This can be used for the transportation of substances, applying the same motion mechanism in a reverse manner, i.e. not needle with respect to external substrate, but internal substance with respect to needle.

Steering, however, has remained a challenge, because the needle exhibits torque. The thinner the needle, and hence the individual wires, the lower the torsional stiffness. Sensors in the needle tip will be required for real-time control of steering. As glass fibres have already been used as 'wires', the fibre Bragg grating sensing principle is a likely candidate. In this way, high-tech photonics will meet bio-inspired design.

REFERENCES

[1] Scali M. (2020), "Self-Propelling Needles – From Biological Inspiration to Percutaneous Interventions", Ph.D. thesis, Delft University of Technology, 2020, ISBN 978-94-6366-282-6, (*repository.tudelft.nl*).
[2] Breedveld, P., "Biologisch geïnspireerde medische techniek – Stuurmechanisme voor sleutelgatoperaties", *Mikroniek*, vol. 47 (4), pp. 14-18, 2007.
[3] *www.bitegroup.nl/self-propelled-devices*
[4] Sakes, A., Steeg, I. van de, Kater, E.P. de, Posthoorn, P., Scali, M., and Breedveld, P., "Development of a novel wasp-inspired friction-based tissue transportation device", *Frontiers in Bioengineering and Biotechnology*, 8:575007, 2020.

VIDEO

[V1] *www.bitegroup.nl/wp-content/uploads/2020/07/Ovipositor-Device_IMG_9725.m4v*

[V2] *www.bitegroup.nl/wp-content/uploads/2020/07/Ovipositor-Device_IMG_9839.m4v*