euspen's 22nd International Conference & Exhibition, Geneva, CH, May/June 2022
www.euspen.eu

A novel design of soft tool manipulator for hard-to-reach zone machining by micro-EDM

Long Ye[1,2,*], Sam Peerlinck[1,2,*], Alexis Van Merris[1], Jun Qian[1,2], Benjamin Gorissen[1,2] and Dominiek Reynaerts[1,2,#]

[1]*Manufacturing Processes and Systems (MaPS), Department of Mechanical Engineering, KU Leuven, Leuven, Belgium.*
[2]*Members Flanders Make, Leuven, Belgium*

** Joint first authors*
 # Corresponding author: dominiek.reynaerts@kuleuven.be

Abstract
Machining of complex features on hard-to-reach zones, e.g. internal spaces, is difficult by conventional mechanical machining techniques. The challenge comes from two common facts: the small space restricts tool engagement and thus its contact with part surface; the large cutting force exerted on the slender cutting tool results frequently in a deformed or broken tool. To tackle this challenge, an innovative tool clamping method is proposed as a proof-and-concept inspired by a chip-on-tip endoscope, where a camera is held by a slender, flexible tube, reaching tissue inside the body. Similarly, a pneumatic bending actuator is designed and implemented to be capable of carrying a tool electrode, which is used for a force-free machining, i.e. micro electrical discharge machining (µEDM). An elastic inflatable actuator tailored for this application is designed, fabricated and validated to provide a proof of the proposed concept. The fabricated micro-actuators are experimentally studied to assess their performance implementing the texturing on a vertical plate and shows its great potential as tool guider in restricted processing space.

Micro-EDM, surface texturing, micro ceramic injection moulding, soft robotic manipulation

1. Introduction

Hard-to-reach zone machining, e.g. internal space structuring [1] and curved hole creation [2,3], has always been a challenge for a conventional machine tool. In general, the conventional tool holder must have a stiff but complex (often geometrically large) structure in order to resist deformation caused by large cutting force acting on it. This prevents these machining processes from being used in some applications. A concrete example is the texturing of the inner surface of bearing outer rings, or creating artificial defects at the root of a gear tooth. The rigid coupling used in conventional machining, however, is not necessary in a force-free machining, e.g. micro-electrical discharge machining (µEDM) or electrochemical machining, enabling a potential for more flexible approaches. For instance, Ishida et al. [2] proposed a novel structure consisting of an electrode head, a helical compression spring and a fixture, on top of which three wires were fastened through different pulleys. This structure enables a curved trajectory of the electrode in the case of maching a curved hole in the metal mold. Similarly,Okada et al. [3] proposed a suspended ball electrode for curved hole EDM drilling. The ball electrode was connected with the EDM head by a foil, which was covered by the insulated thin resin film. Through tilting the workpiece, holes with different bending angles can be achieved. Albeit flexible in reaching space, these designs have either difficulty in implementation or limation in control, and thus have not received much industrial attraction. This paper proposes a cost-effective, easy-to-implement and simple-to-control design concept for µEDM tool holding based on pneumatic bending actuator.

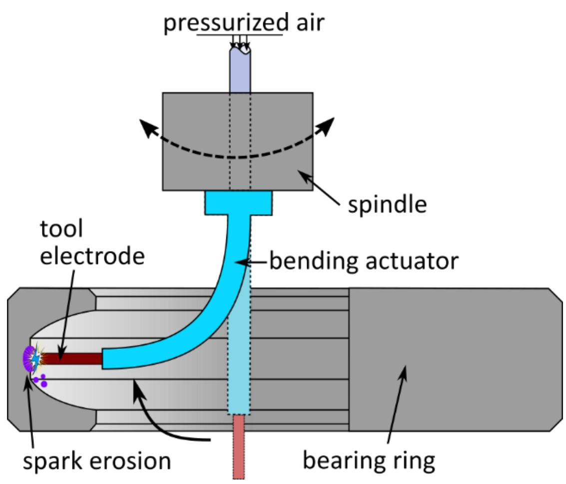

Figure 1. The concept of soft tool manipulator based on a pneumatic bending actuator for µEDM micro-texturing purpose.

Soft robotics is an emerging research field investigating compliant structures for varying applications. A typical example is the design of a multigait soft walker [7], inspired by invertebrate animals such as worms. Unlike its rigid counterpart, the soft robotics often relies on the the structural deformation to achieve sophisticated motions in all degrees of freedom. Meanwhile, the use of soft materials not only simplifies its geometrical design but also results in a low stiffness upon the soft robotic components [8]. The low stiffness makes them suitable for unpredictable environments and inherently safe for human interaction [4], but seems to exclude them from precision machining contexts. In force-free machining however, the potential miniaturization due to the absence of joints and linkages, large attainable deformations and cost effective nature of soft bending actuators, could offer a solution for changing the tool tip orientation. An example of such pneumatic bending microactuator is used as an endoscope end-effector for changing the field-of-view of a miniature camera [5]. In a similar fashion, we propose to manipulate the µEDM tool tip with a soft pneumatic bending microactuator, as schematically shown in figure 1. The tool tip is able to reach in a limited space and engage with the inner wall surface from a controlled angle. This motion flexibility is provided with a soft bending actuator that works on a pneumatic principle. The manipulator can be easily integrated into a machine tool spindle and perform micro-texturing tasks in extreme conditions.

This paper describes the design and fabrication of a larger scale prototype for a soft tool manipulator, and a first experimental validation of the assembly.

2. Soft tool manipulator

The soft tool manipulator is composed of a pneumatic bending actuator, fitted with a clamping system holding the tool electrode and providing a wire connection for the conductive path.

2.1. Bending actuator design and fabrication

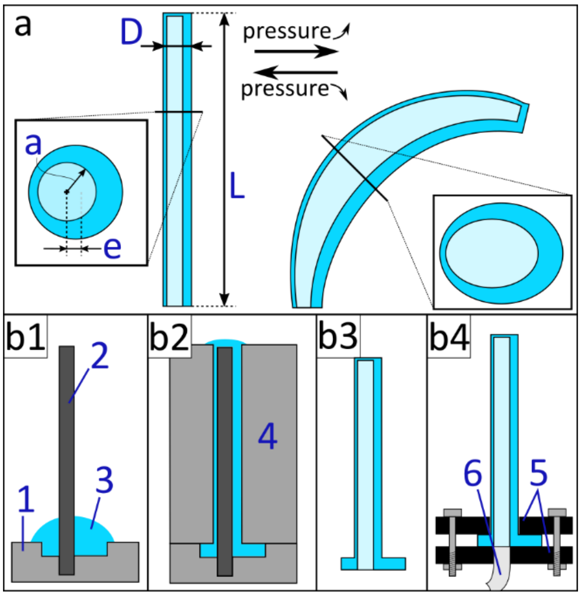

Figure 2. The working principle, including some key dimensions of a pneumatic actuator (a) and different steps in the fabrication process (b) of the proposed bending actuator with (1) the bottom half of the mold, (2) an eccentrically placed rod, (3) the liquid rubber poured into the mold, (4) the top half of the mold, (5) PMMA clamping plates and (6) pneumatic pressure supply tube.

In order to attain high bending angles and to enable miniaturization, a high aspect ratio monolithic pneumatic bending actuator is proposed [6]. As depicted in figure 2a, the actuator consists of a slender cylinder with an internal, eccentrically positioned void. This geometric asymmetry across the actuator's section causes the structure to bend towards the stiffer side upon inflation. The actuator morphology is mainly determined by four dimensions: its length L, diameter D, internal void radius a and eccentricity e. The concrete dimensions for the initial prototype considered in this paper are derived using analytical and numerical models of the structure, from Gorissen et al. [6], and a full 3D FEM analysis is performed to corroborate the expected bending behaviour. The resulting dimensions of the upscaled prototype are displayed in table 1.

Table 1. Dimensions of the bending actuator prototype corresponding to parameters in figure 2.

Dimension	Value [mm]
L	42
D	4
a	1.45
e	0.28

To facilitate later miniaturization of the soft tool manipulator, the pneumatic bending actuator is fabricated using monolithic out-of-plane high aspect ratio molding. In contrast to many different processes for manufacturing of pneumatic actuators, this method uses one-step molding, eliminating the need for manually closing the inflatable void. As depicted in figure 2b1, a 3D-printed bottom mold half with an eccentrically positioned precision rod is filled with *polydimethylsiloxane* (PDMS, Sylgard 184), mixed in a 1:10 ratio with a curing agent and degassed in vacuum. Next, the top mold half is placed onto the mold, positioned using dowel pins and tightened with a screw. The excess liquid PDMS is pushed out through the opening in the mold, as indicated in figure 2b2, and cured for 24h. After curing, the overflow PDMS is removed, the mold opened and the eccentric precision rod extracted, yielding the finished actuator. Finally, to apply pressure onto the void, a pneumatic supply line is added.

2.2. Assembly of soft tool manipulator

The assembly of the soft tool manipulator is schematically illustrated in figure 3. Considering that µEDM is an electric technique where the tool electrode and workepiece should be connected to two polarities of a pulse power supply (PPS), a metal cup made of tungsten carbide (WC) is employed making an electric conduction between the tool electrode and a single core copper wire (BS EN13602). The wire is threaded through the metal cup and its one end is soldered on the cup side while the other end is bonded with the PPS. The tool electrode is squeezed through a small hole on the cover before it is tightly fitted into the drilled hole on the metal cup. In this easy way, the tool electrode has a solid contact with the wire and remains stable during bending actions. Since tool wear is inevitable in EDM, the tool needs to be replaced regularly. This easy fitting scenario makes it convenient for a regular tool replacement. In addition, the fitting hole in the metal cup can be drilled with a varying size with respect to tool electrodes in different diameters. After wrapping up the metal cup, the cover, which is also made of PDMS, is cured around the bending actuator. It is worth noting that the wire has a non-neglectable impact on the bending actuator. This is because in the current design, the wire is left outside the actuator and its tension, though very small, can thus be exerted on the actuator. This issue can be tackled either by an optimized wiring method, e.g. wire connection through the inside of the actuator, or by FEM simulation that is able to quantify and compensate this factor.

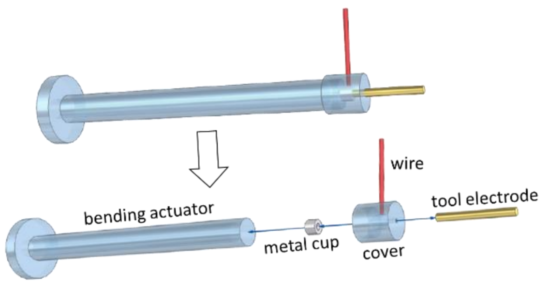

Figure 3. The assembly process for the soft tool manipulator.

2.3. Validation of bending actuator

Several prototypes of the pneumatic bending actuator have been fabricated and tested. The relation between the applied pressure and the attained bending angle is crucial to predict the tool-tip orientation. A first experimental validation has been performed to investigate the repeatability of this relation.

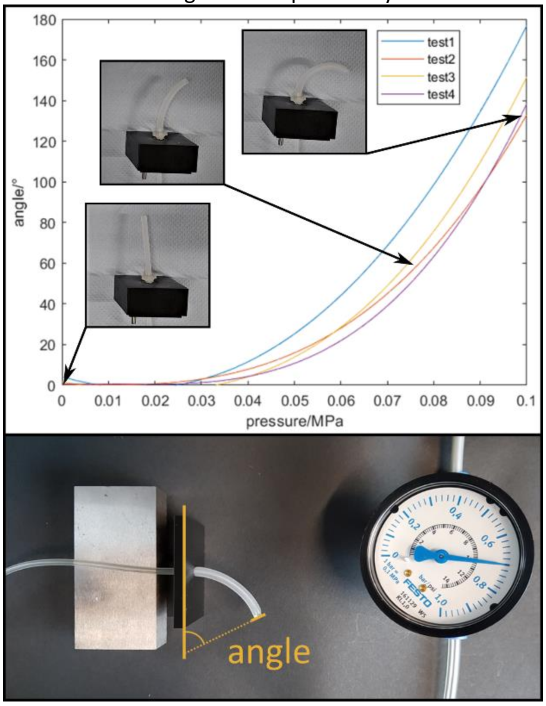

Figure 4. The bending angle measurement setup (left) and results (right) showing a spread in attained bending angle.

Four pneumatic bending actuators of identical design are manufactured in the 3D-printed mold. A pneumatic connection is foreseen for each and they are connected to a pressure supply. An analog manometer is used to monitor the air pressure imposed on the actuators and a clamp fixates them. Figure 4 displays this setup. A pressure sweep is performed and images of the bending deformation are recorded. This enables, via image processing, the relation between the imposed pressure and the attained bending angle to established. This procedure is repeated four times. The resulting graph in figure 4 indicates a large bending deformation, sufficient for EDM-tool manipulation. Between the actuators however, a significant spread in the attained bending angles is observed. This indicates an uncertainty between the pressure and deformation, and is mostly due to inaccuracies in the fabrication process, as the positioning of the excentric rods inside the 3D-printed molds is not sufficiently precise. To increase the repeatability of the deformation, more precise molds are required.

Moreover, to have a highly accurate position control of the electrode tool tip, further development is needed. This will basically consist of implementing a feedback system. In a first phase, this can consist of a camera-based feedback, with real-time tracking of the tool and actuator. In a lab environment this enables a basic position control, but is severely limited by the accuracy of the optical system and has limited practical use. Another possible strategy is to use a model based control strategy aided by different sensors, estimating the state of the soft tool manipulator in real time.

3. Micro-texturing validation experiment

The assembled soft manipulator is validated on a commercial µEDM machine (Sarix® SX-100-HPM) by a micro-texturing experiment. The experimental set-up is shown in figure 5. A metal plate (Ti-6Al-4V) is vertically placed mimicking an internally restricted space. The soft manipulator is attached to a drilling collet which is screwed onto the machine spindle. In this way, the actuator can be controlled up and down to find its texturing position. In addition, an auxiliary hollow electrode is inserted into the collet and connected to the inlet of the soft manipulator. It can supply pressurized air to the actuator, sufficiently sealing the eccentric void. After tuning the input pressure, the actuator holding the tool electrode can reach a normal direction to the plate surface. It is noted this design of soft manipulator targets a surface texturing application. Therefore, the nominal tool electrode (WC, diameter of 0.8 mm) is grinded to 0.1 mm expecting generation of a micro-dimple on the plate surface. The electrical parameters set for the grinding and texturing experiments are listed in table 2. The pulse energy (0.3 mJ) for grinding is large while the energy for texturing is small (8 uJ). The flushing (HEDMA® 111) is supplied from the lateral side covering the erosion area. To reduce the tool deflection caused by the flushing, the dielectric flow rate is tuned to be very slow (0.1 l/min). The produced micro-dimple is characterized by an optical 3D profiler (Sensofar® S Neox) with an objective of 50x.

The measurement result showing the surface topography and cross-sectional profile is presented in figure 6. A micro-dimple with around 150 um in diameter and 15 um in depth can be observed. This observation confirms the machining capability with the proposed soft manipulator in the restricted space. However, the diameter of the micro-dimple seems to be much larger than the grinded tool size, though a lateral sparking gap around 5 um is considered. This could be attributed to the tool deflection caused by the slow flow rate or the small impulsive strike from the discharge process. Indeed, a small disturbance of the position of the tool can be noticed, and a short circuit occurs when the tool is attracted to the workpiece. This phenomenon could be due to electrostatic attraction and needs to be further investigated. In addition, some deposited debris can be observed around the dimple edge. This is due to insufficient flushing when the dielectric flow rate is set extremely slow. As a validation experiment, the initial result demonstrates the potential of our proposed concept that uses a soft gripper to guide the tool in a hard-to-reach space for a texturing purpose. However, improvements are still required to decrease the manipulator's sensitivity to external loading. We observe that the deformation of the pneumatic actuator is influenced by the stiff electric connection, the flowing dielectric and the presumable electrostatic attraction force.

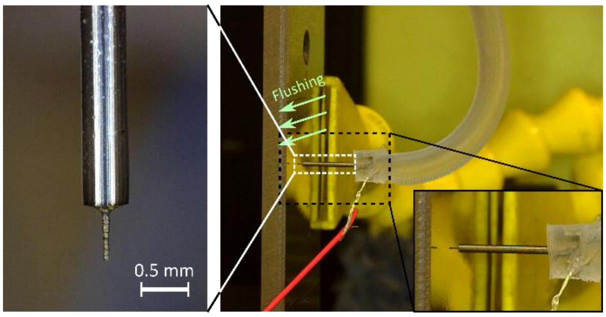

Figure 5. The validation experiment using the soft bending actuator.

Table 2 Electrical parameters used in electrode grinding and texturing

Electrical parameters	Unit	Values	
		Texturing	Grinding
Polarity		-	+
Pulse-on width	us	1	5
Pulse frequency	kHz	150	120
Current	index	100	60
Open voltage	volts	80	130
Adjustment gain*	index	20	80
Servo voltage	volts	72	75
Energy regime	index	100	365
Regulation scheme	index	00-00	02-01

*adjustment gain is a representative of servo control reaction. The higher the regulation gain, the more quickly the system response to variations but this leads to more unstable behaviour of the system.

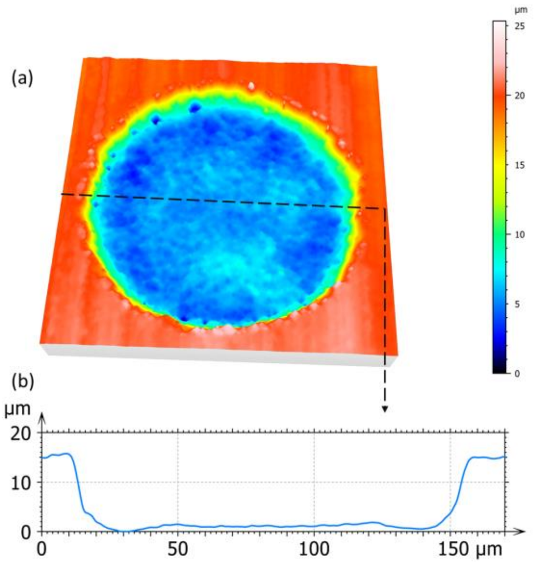

Figure 6. The texturing results, (a) Surface topography and (b) cross-sectional profile of a produced micro-dimple, as a demonstration of the developed soft manipulator. .

4. Conclusions and outlook

This paper proposes a soft robotics-based solution for the problem of tool-tip orientation in some hard-to-reach zone µEDM applications. A tool is connected to the tip of a pneumatic bending actuator displaying a high range of motion. A prototype bending actuator is fabricated using monolithic micromolding, an electrode is fixed to the tip, and a machining step is performed, creating a micro-dimple on a surface parallel with the spindle axis. These results already prove the proposed concept, but are still far from perfect. Firstly, the tool deflection caused by the flow of dielectric or the small impulsive strike from the discharge process needs to be countered. This will be done by increasing the stiffness of the manipulator in the machining position, without affecting its range of motion, through design, material selection or actuation method. Secondly, the accuracy of the fabrication process needs to be increased, as to improve the repeatability of the tool positioning. Thirdly, the prototype actuator should be miniaturized to better fit the envisaged µEDM applications. Finally, the pressure control of the actuator should be integrated with the position control of the EDM machine, so that precise positioning of the electrode tip is possible. This will require a thorough characterization of the soft tool manipulator, under a wide range of circumstances. This will improve the proof-of-concept to automatically texture a surface by implementing a feedforward control strategy based on both FEM models and real-life experiments.

To further expand the practical use of the presented method, a feedback system is envisaged. This could consist of an optical system, with limited practical use, or by developing a digital twin of the soft tool manipulator. Based on sensory input from the machining environment, the current state of the assembly can be estimated and adapted accordingly.

The presented method of using a soft actuator for manipulation of an EDM electrode is a first step in integrating soft robotics in machining processes, and might eventually lead to the ability to texture surfaces on work pieces that have been impossible to reach.

Acknowledgements

This research is supported by the fund for Scientific Research-Flanders (FWO).

References

[1] Inaba Y, Li S, Yamaguchi A, Okada A. Fundamental Study on Internal Space Forming by EDM. *Procedia CIRP*. 2020 Jan 1;95:215-9.

[2] Uchiyama M, Shibazaki T. Development of an electromachining method for machining curved holes. *Journal of materials processing technology*. 2004 Jun 10;149(1-3):453-9.

[3] Okada A, Yamaguchi A, Ota K. Improvement of curved hole EDM drilling performance using suspended ball electrode by workpiece vibration. *CIRP Annals*. 2017 Jan 1;66(1):189-92.

[4] B. Gorissen, D. Reynaerts, S. Konishi, K. Yoshida, J. Kim, M. De Volder, “Elastic Inflatable Actuators for Soft Robotic Applications”, *Advanced Materials*, vol. 29: 43, 2017.

[5] B. Gorissen, M. De Volder, D. Reynaerts, “Chip-on-tip endoscope incorporating a soft robotic pneumatic bending microactuator”, *Biomedical microdevices*, vol. 20: 73, 2018.

[6] B. Gorissen, W. Vincentie, F. Al-Bender, D. Reynaerts, and M. De Volder, “ Modeling and bonding-free fabrication of flexible fluidic microactuators with a bending motion”, *J. Micromech. Microeng.*, vol. 23, no. 4, 2013.

[7] Shepherd RF, Ilievski F, et al. Multigait soft robot. *Proceedings of the national academy of sciences*. 2011 Dec 20; 108(51):20400-3.

[8] Wei Y, Chen Y, et al. A novel, variable stiffness robotic gripper based on integrated soft actuating and particle jamming. *Soft Robotics*. 2016 Sep 1; 3(3):134-43.