Robin Heart Force Feedback/Control System Based on INCITE Sensors

– preliminary study

Artykuł recenzowany

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Streszczenie

Przedmiotem pracy jest wykonanie czujnika siły 3D wg technologii MEMs i zastosowanie go jako mikrodżojstika siłowego do sterowania położeniem robota Robin Heart PVA. Ponieważ robot posiada 5 stopni swobody uruchomienie wszystkich możliwości ruchu jest wykonane przez zastosowanie sprzęgła przełączającego obiekt sterowania. Poprzez odpowiednie naciśnięcie czujnika uzyskujemy możliwość sterowania funkcjami tego sferycznego robota (z różną prędkością): pochylenie do przodu lub w bok lub alternatywnie wsuw/wysuw liniowy i obrót narzędzia wokół osi. Wykonano specjalny projekt umieszczenia czujnika w odpowiednim uchwycie mocowanym do narzędzia chirurgicznego. Wykonano odpowiedni system sterowania z nowym czujnikiem i dokonano porównania ze sterowaniem za pomocą klasycznego pilota.

Abstract

The subject aim of the this work is the investigation studying of applicability of 3D MEMS based force micro-sensors made by 3D MEMSmicromachining technology and use it as micro-joystick to control the position of robot Robin Heart PVA. Since the robot moves with 5 degrees of freedom to run utilise all the possibilities of movement is done available by the use of the switching clutch control object. By pressing the in appropriate mode (way) the sensor provides the ability to control the functions of the spherical robot (at different speeds): to lean forward or sideways or alternatively to penetrate or withdrow withdraw and to rotate of the tool axis is possible. The sensor was fastened in its special of the surgical tool. AnApplicability of appropriate control system equipped with a newthis novel sensor was investigated in and a comparison with to the control using the classic remote control methodswas investigated. Preliminary tests of laparoscope integrated force sensors were also investigated accomplished to provide additional on-line information for the surgeron during operation.

INTRODUCTION

The lack of force feedback is one of the main barrier of the progress of the development and widespread application of the robots in surgery, nevertheless to meet these needs of mechatronic tools and surgical robots is a huge challenge for designers, as the requirements of precise measurement, safety and the durability must be accomplished simultaneously.

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According our additional goals **3D contact force detection** will be also demonstrated in minimal invasive surgery (MIS) **as the following functions:**

- **force controlled robotic movement just during the operation,**
- *supporting palpation, patients diagnostic information during the operation,*
- *force feedback, strength measurement in the jaws*

We also plan to create a haptic system to provide feedback to the operator for precise control the robot's tools position and action, and monitor the state of the actual tissue touched by the laparoscope.

High-precision and full ergonomic surgical robot control utilising these force sensors and appropriate software/hardware environment enables Robin Heart robot to enter in the market as one of the most innovative surgical tool – more safe for patients and more comfortable for surgeons. It is important to increase the efficacy of the therapy by means of robots. We expect that the development of these crucial elements and functions of surgery robotic systems could be an opportunity to implement a European robot, which have already been widespread accepted in the medical world. We also hope that this development will create new jobs in the high-tech sector.

SYSTEM DEFINITION

This specific surgery robot development was started from the preliminary characterisation of the tools – tissue reaction (mechanical characteristic, force levels for specific operations, dynamic analysis of tools work) and person – tool and then man – machine contact (kinematic analysis of surgeon motion).

ABBREVIATIONS

MEMS	– **M**icro **E**lectro-**M**echanical **S**ystems
MIS	– **M**inimal **I**nvasive **S**urgery
CVD	– **C**ardio**v**ascular **D**iseases
FEM	– **F**inite **E**lement **M**ethod
DRIE	– **D**eep **R**eactive **I**on **E**tching
SOI	– **S**ilicon **o**n **I**nsulator
PDMS	– polydimethylsiloxane
PCB	– **P**rinted **C**ircuit **B**oard
ADC	– **A**nalogue-**D**igital **C**onverter
I2C	– **I**nter-**I**ntegrated **C**ircuit (Philips Semiconductor – NXP)
CAN	– **C**ontroller **A**rea **N**etwork (Bosch)

The main task of the surgical robot module control is the mapping and analysis the movements of the surgeon operator (position / velocity and possibly other physical parameters) and facilitate arm movement by developing appropriate control signals to the actuators. Additional highly desirable feature of the system is a built-in circuit reverse transfer experience to feel the force / touch the person is handling tools.

Currently, the applicability of MEMS 3D force sensors for controlling the robot movements (force joystick) was demonstrated by design and fabrication of appropriate sensor chips and their integration in the laparoscopic handle.

Additionally we could mention the extended applicability of these microscale sensors as "tactile" receptors integrated into the laparoscope tool and provide additional information to the surgeon about the tool-tissue connection from inside the patient's body as presented in Fig. 1. This feeling can help the operator

- to make immediate correcting actions during the operation – cutting, separation, handle and move tissues,
- to care vascular clamping,
- to tie a knot
- to recognise the type of tissue (pathology, calcification)
- to manipulate between different elements of internal organs without the risk of harming neighbouring tissue,

and

- to sense collision of arms / or tools by automatic robot recognition

An appropriate control systems and test beds has been developed at FRK to evaluate these possibilities. Preliminary tests were accomplished to reveal the possible information can be provided by the force / tactile sensors integrated in the laparoscope head.

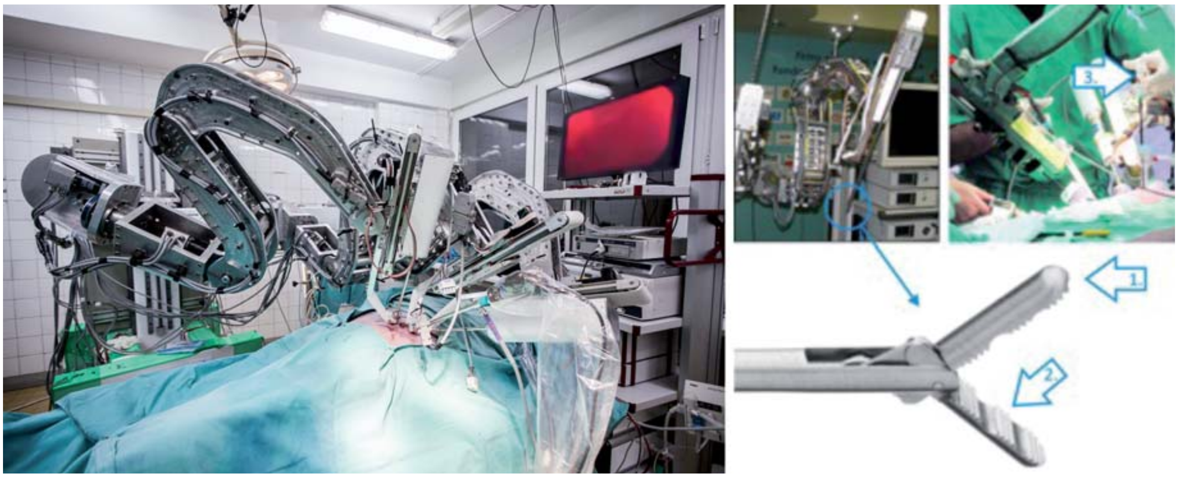


Figure 1. The representation of the proposed applications of the vectorial force sensor in ROBinHEART Minimal Invasive Surgery robot systems

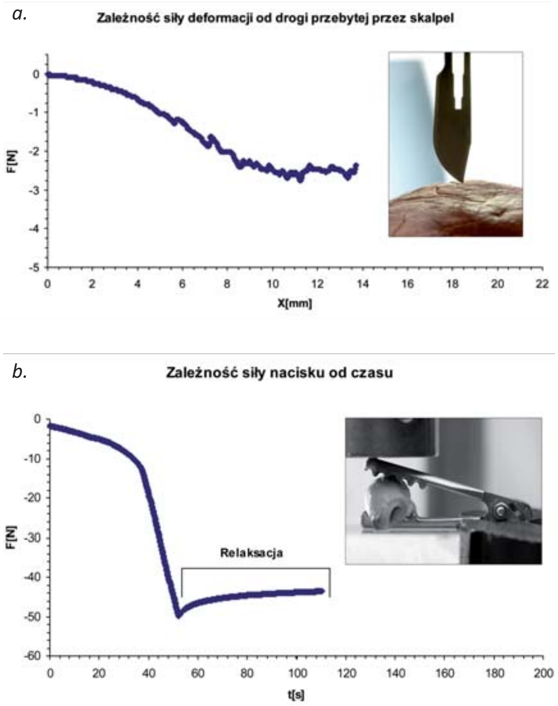


Figure 2. Study of tissue-tools reactions and tools trajectories – first designing phase of surgery robot. Graphs show the applied forces between doctor-blade and skull (a.) and during vessel deformation (b.) in time.

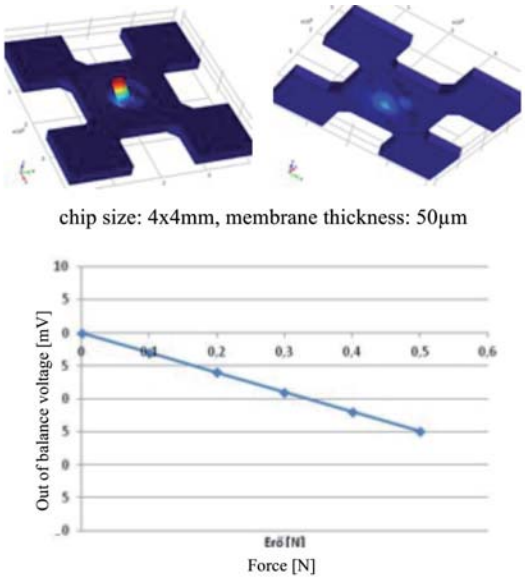


Figure 3. Mechanical and multi-physical modelling of the force sensor structure can predict the functional parameters of the device. Deformation and stress distribution of the embedded piezo-resistors are applicable to deduce the estimated signal vs. applied force function of the force sensor with the applied geometries.

RESULTS

BIOMECHANICAL CONDITIONS IN MIS SURGERY

During the definition phase of functional requirements regarding the MIS robot we analysed the mechanical impacts influenced the applied surgical tools during various activities on tissues. The typical applications are presented in Fig. 2.

As the preliminary results represents, we have to consider lower (0-5 N) force range in case of tactile sensing and tissue recognition, although higher (0-100 N) force range regarding the monitoring grasping of laparoscope tweezers.

SENSORS DESIGN, FABRICATION AND PACKAGING

On the basis of the preliminary results of MEMS sensor fabrication optimised micromachining technology were established for processing force sensor chips on 4” silicon and borosilicate glasses wafers. The features of the proposed MEMS structures are summarised in Table 1.

For determination the precise geometric parameters (membrane thickness, lateral geometry) and the sensitivity of the embedded piezo-resistors, coupled Finite Element Method based modell was

Table 1. Functional and geometric specifications of MEMS based force sensors for MIS applications

0.1.1 Requirement	**0.1.2 Specification**	**0.1.3 …**
0.1.4 Operating force range/direction dependency	0.1.5 0-5N / 3D (tissue recognition) 0.1.6 0-10N / 3D (laparoscope control) 0.1.7 0-100N / 1D (laparoscope tweezers)	0.1.8 The operating range of the specific sensors will be set by the geometric parameters of the structural diaphragm (width, length (or diameter) and thickness).
0.1.9 Transduction principle	0.1.10 piezoresistive readout	0.1.11 Measuring the stress induced signals of the symmetrically arranged four piezoresistors in the deforming membrane.
Geometry **0.1.12 (w x l and** **0.1.13 membrane thickness)**	0.1.14 max. 2x3mm for the tweezers 0.1.15 max. 4x4mm for the laparoscope control 0.1.16 membrane thickness: 20-100µm	0.1.17 The geometry is defined by the 0.1.18 average form factor of the 0.1.19 laparoscopic tools. The membrane parameters are defined with the aid of FEM modelling considering the targeted detection ranges and sensitivities.
0.1.20 Key materials	0.1.21 SOI Si wafer, Borofloat® glass	
0.1.22 Realisation **0.1.23 technology**	key steps: 0.1.24 double side lithography, ion implantation of p+ piezoresistors, DRIE, hybrid wafer bonding,	0.1.25 The process was defined considering the targeted membrane geometry and the required fabrication accuracy.

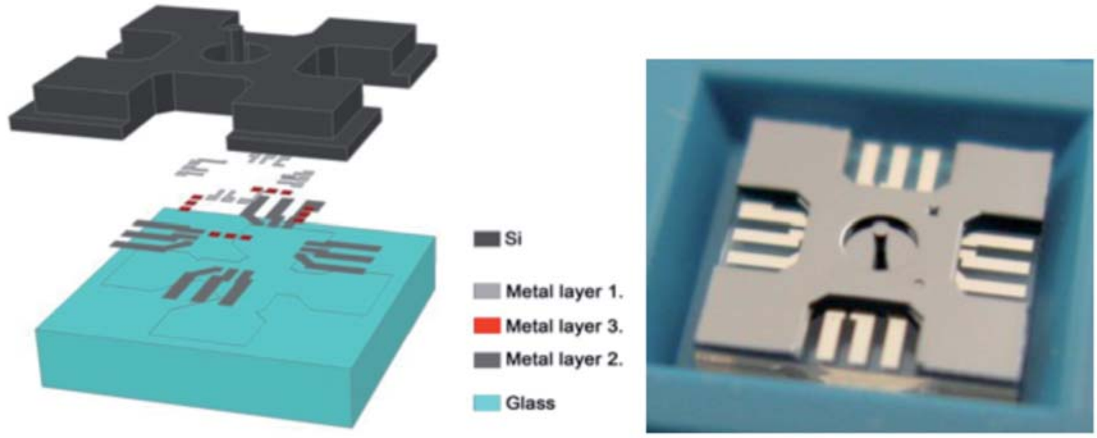


Figure 4. The schematic structure of the 3D force sensor test chip (left) and the manufacture MEMS structure (right).

developed and studied in details. Stress induced deformations and piezoresistive effects as local resistivity change were calculated by Comsol Multiphysics in order to define the output signal of the sensor. The results of the FEM modelling presented in Fig. 3. In case of 900 µm membrane diameter and 50 µm membrane thickness the calculated sensitivity of the sensors is 30 mV/N.

4x4 mm^2 force sensors (with membrane diameter: 900µm and membrane thickness: 50 µm) were manufactured for actuation of the robotic arm and laparoscopic camera and also for preliminary tests to identify appropriate sensing functions in the laparoscope (see Fig. 3).

Membrane thicknesses of 10 and 50 µm provide sensitivities of 170 and 50 mV/N output voltage of the non-covered sensor for perpendicular load. The alternative membrane geometry in combination with the variation of the protecting elastomer thickness enables us to select the most appropriate sensors for the targeted functions. Downscaled force sensors are being developed to further integration in laparoscopic heads of surgery robots, as deposition of biocompatible elastic coating technique is also in process. The known effect of the silicon protecting cover results in serious degradation of sensitivity has to be taken into consideration regarding the definition the properties of the selected material and also its geometric variations.

A special packaging was implemented for the imaging laparoscopic camera control device and for preliminary biomechanical tests. As presented in Fig. 5, the force sensor chip was mounted on a dedicated package and covered by a specially shaped

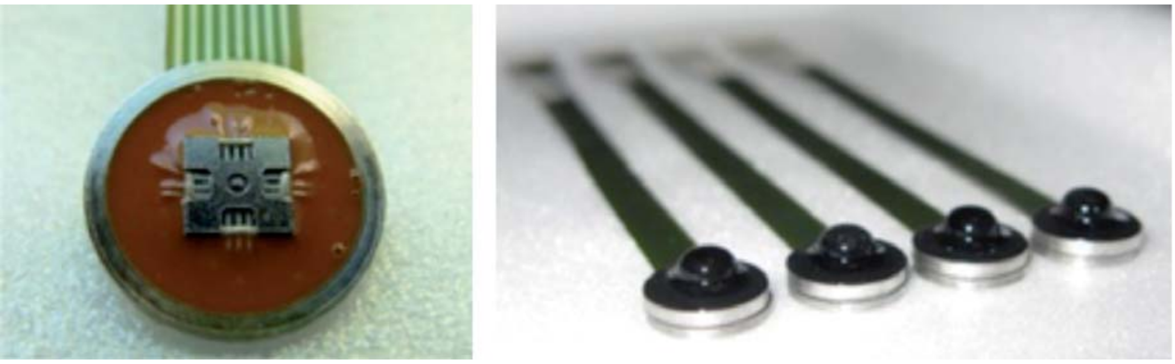


Figure 5. The packaged force sensor for the MIS laparoscopic camera control device mounted on a dedicated flexible PCB and covered by a PDMS cap. The polymer coating is black to eliminate light induced false signals.

flexible polydimethylsiloxane (PDMS) cap. The PDMS cap was coloured to eliminate the photo carrier generation affecting the offset resistance of the integrated piezoresistors.

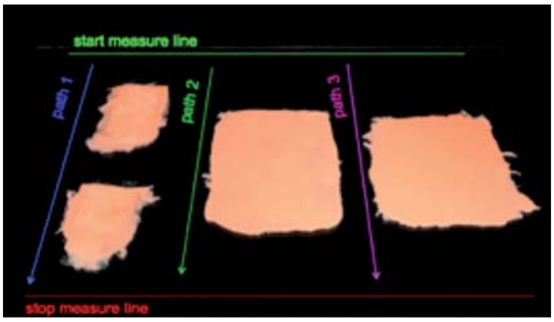
The 3D MEMS force sensor's readout mechanism is based on piezoresistivity changes sensed by division of the reference voltage according to the force applied. The divided voltage signal is than digitalized right at the sensor, the analogue to digital conversion is performed by high-end circuits. The AD converters not only converts the signals related to the force measurement, but temperature sensor signals, which is integrated into the sensor chip also, and the reference voltage level as well. These digitalized data is accessible through I2C protocol bus, however the medical instrument linked to the handle of the surgery robot via CAN-bus communication.

BIOMECHANICAL ANALYSIS OF TISSUES BY APPLICATION OF MEMS FORCE SENSORS

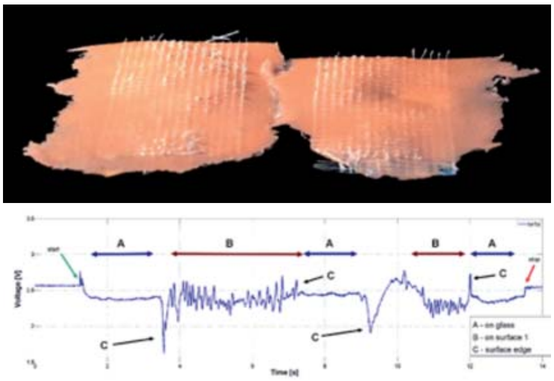
Preliminary force sensing based characterisation of tools-tissue reaction has been performed in FRK Biocybernetics Laboratory. Artificial surfaces with different roughness were tested to identify the accessible information can be revealed from tissue contact measurements. Typical results are shown in the following figures. (Figs. 6.A – 6.D).

Figure 6 clearly presents the applicability of the tactile / force signal for surface roughness recognition of different artificial materials, although the measurement speed could significantly influence the recorded time dependent force graph.

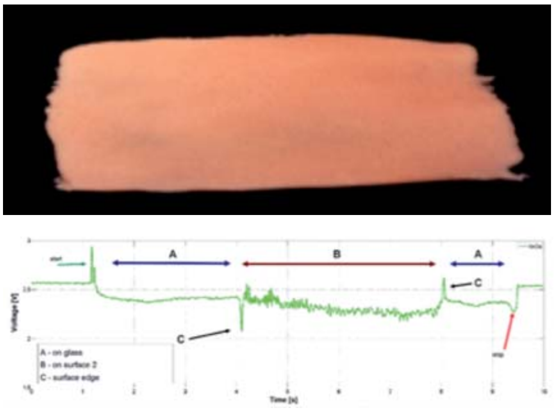
Test were also performed on various surfaces of a pig heart to recognise the mechanical differences between the analysed tissues . Palpable heart surface landmarks can be found by detecting force reaction using equipped by new sensors end of surgical tools. The heart wall is made of 3 layers: epicardium, myocardium and endocardium. Tested tactile sensors allows to recognize the anatomical charac-



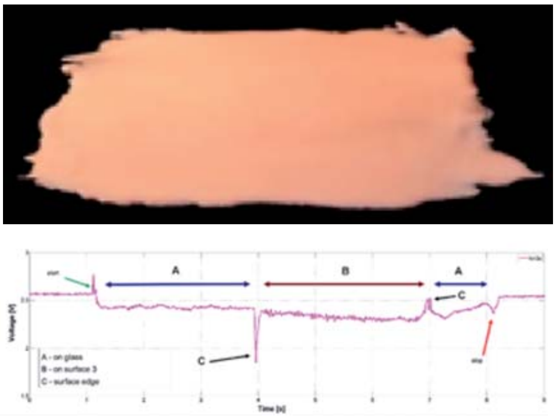
6.A. Measured paths on different surfaces



6.B. Surfaces texture test – path 1



6.C. Surfaces texture test – path 2



6.D. Surfaces texture test – path 3

Figure 6. Sensors were tested to identify various artificial surfaces

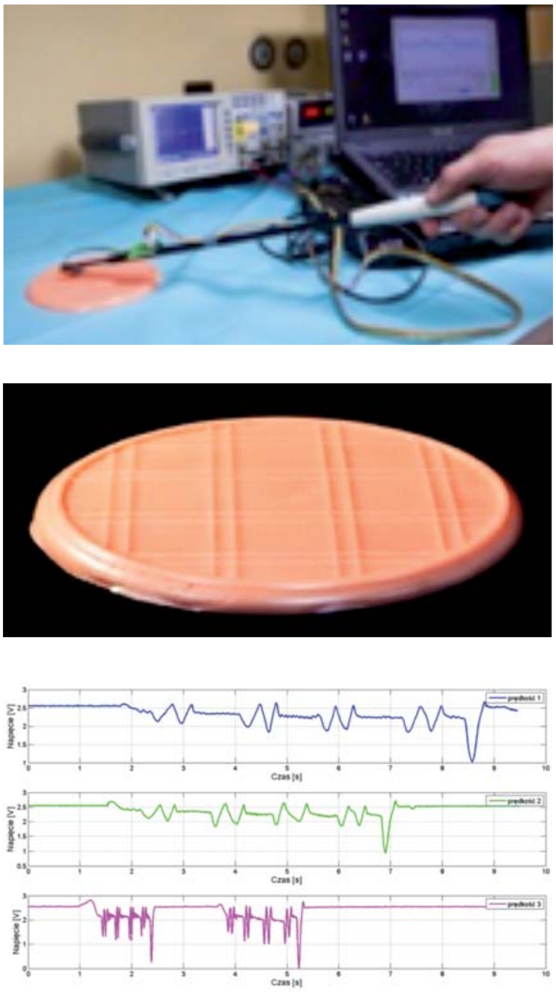


Figure 7. Signal differences when applying various measurement speed over the same sample path

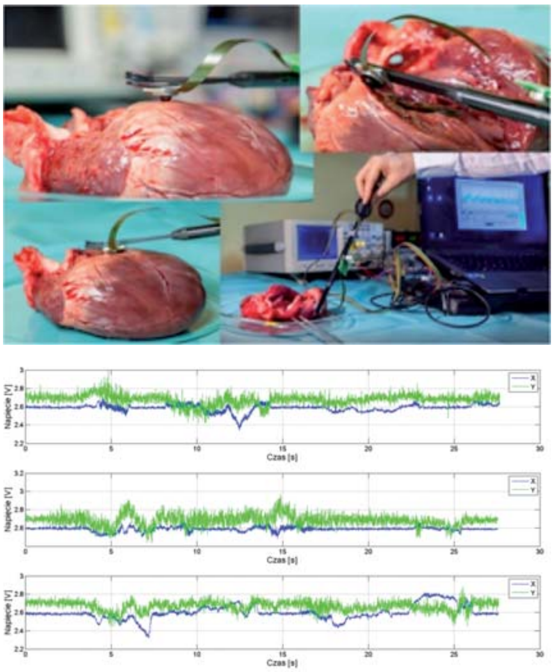


Figure 8. Heart test (pig's heart) – results

teristics of the surface of the heart; right atrium, left atrium, right ventricle, and left ventricle, coronary artery but above all to assess the altered elastic properties of the heart wall as infarction, inflammatory, neoplastic and the location of calcification.

CONTROLLING THE POSITION/MOVEMENTS OF ROBOT

Robot control tests

The preliminary version of the imaging camera control system was constructed in the FRK's Laboratory by integration of the dedicated 4x4 mm^2 3D force sensor chip into the laparoscopic tool, as presented in Fig. 9. Functionality was demonstrated by driving a simple robotic arm dedicated as imaging camera console during minimal invasive surgery robotic interventions.

Conclusion

Actually, our work was focused on the preliminary definition of the biomechanical effects present during surgical operations. According to the results force sensors were designed and manufactured by 3D Silicon micromachining technology. The functionality of the proposed MEMS sensors were simulated by FEM modelling and characterised experimentally. The sensitivity of the manufactured piezoresistive force sensors were measured as 170 and 50 mV/N. The force sensors were assembled on flexible PCB and their application for control controlling Robin Heart Vision camera was proved. Force and tactile

Figure 9. The assembly of the manufactured force sensors onto the endoscopic tools of Robin Heart Vision robot for controlling motion/position/orientation.

measurements were also accomplished on artificial and real animal tissues to evaluate the applicability of the sensors for biomechanical screening during MIS surgery.

As presented in this paper FRK focused on FORCE FEEDBACK & ERGONOMIC CONTROL of surgical Robin Heart robot supported by the MEMS 3D force sensor of MTA EK MFA, visioning the following three applications:

- as a touch sensor in the front part of the tool giving surgeon the opportunity to palpation, evaluation of touch operations in the area of tissue
- as a tool holder sensor giving surgeon the opportunity to assess the range of force of tissue clamp (reducing the risk of destruction), measuring the strength of the manipulation (e.g. measuring the force when engaging in a surgical knot) and forces capture surgical needles or other technical element used during operation
- as a sensor of interface robot control system, operating in force control mode, giving the surgeon a chance to control the position of the endoscopic vision system using a robot Robin Heart Vision during classical operations using laparoscopic tools (mini joystick mounted in the handle tools or mini remote control).

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