

Multidimensional Force Estimation in Laparoscopic Instruments with a CMOS-Based Force Sensor Chip

Thorsten Hehn¹, Bernd Folkmer¹, Rachid Nouna¹, Stephan Knappmann¹, Wolfgang Kunert², Steffen Axt², Jens Rolinger³, Achim Brodbeck³, Oliver Amft^{1,4}

¹ Hahn-Schickard, Wilhelm-Schickard-Straße 10, 78052 Villingen-Schwenningen, Germany

² Universitätsklinikum Tübingen, Chirurgische Technologie & Training (CTT), Waldhörnlestraße 22, 72072 Tübingen, Germany

³ Erbe Elektromedizin GmbH, Waldhörnlestraße 17, 72072 Tübingen, Germany

⁴ Albert-Ludwigs-Universität Freiburg, Institut für Informatik, Intelligente Eingebettete Systeme (IES), Georges-Köhler-Allee 304, 79110 Freiburg, Germany
Thorsten.Hehn@Hahn-Schickard.de

Summary:

Minimally invasive surgery lacks haptic feedback, limiting the surgeon's ability to assess tissue interaction forces. This work presents a miniaturized CMOS-based multisensor chip integrated in laparoscopic instruments for multidimensional force sensing. Finite element modeling was used to optimize sensor placement. Machine learning models reconstruct axial, lateral, and gripping forces from 32 sensors per chip. A Random Forest model reached near-perfect accuracy between 0.0001 N and 0.0048 N. Results demonstrate the feasibility of compact, high-precision force sensing in smart surgical instruments.

Keywords: force sensing, CMOS sensor, laparoscopic instruments, machine learning, multidimensional force estimation

Background, Motivation and Objective

Minimally invasive surgical procedures including laparoscopy have significantly improved patient outcomes by reducing trauma and recovery time. However, the instruments currently used in laparoscopy limit the surgeon's tactile perception, as interaction forces between instrument and tissue are strongly attenuated [1]. The loss of haptic feedback can lead to surgical errors and unintentional tissue damage [2].

Existing approaches can be broadly classified into direct sensor integration and indirect estimation methods. Indirect approaches are easier to integrate but generally less accurate [2]. Micro-electro-mechanical systems (MEMS) are particularly promising for direct force sensing due to their small size and integrability. However, existing solutions (e. g. [3]) often lack full system integration or remain limited in practical applicability.

The objective of this work is to develop a compact and integrated sensing system capable of reconstructing multidimensional interaction forces in laparoscopic instruments with high precision. The approach combines a CMOS-based multisensor chip, model-based sensor integration, and data-driven force estimation algorithms, as illustrated in Figure 1.

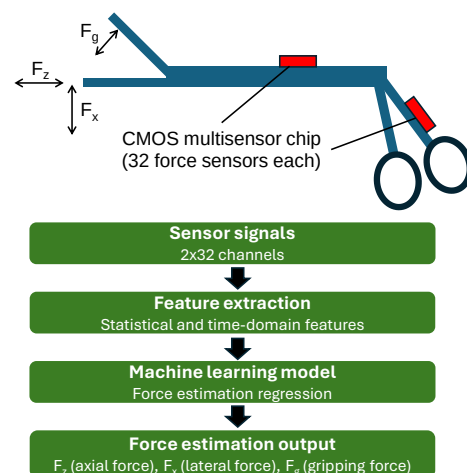


Figure 1: Concept of the proposed force sensing system for laparoscopic instruments: CMOS multisensor chips combined with machine learning for multidimensional force reconstruction.

Force Measurement Concept and System Integration

At the core of the system is a miniaturized CMOS multisensor chip comprising 32 spatially distributed sensors within a footprint of 2.0 x 2.5 mm² and a thickness of 0.3 mm, including readout electronics providing a digital output signal [4]. The chip measures local mechanical stress based on the piezoresistive effect; thus, the force

sensor chip can resolve deformations of the instrument in different axes.

The sensor chip was integrated into a laparoscopic instrument from Erbe Elektromedizin GmbH. The sensors were mounted and electrically connected using flexible interconnects. The sensor was placed at the shaft to capture tool-center-point forces and at the handle to capture gripping forces. Due to the instrument's complex mechanical structure, the resulting signals are nonlinear, requiring advanced modeling for force reconstruction.

Finite element modeling was used to identify optimal sensor placement within the laparoscopic instrument, aiming at a distinct and interpretable stress distribution across the sensor surface. The simulations consider nonlinear effects including contact, friction, and deformation during the opening and closing of the instrument.

Force Estimation Methods

Force estimation was formulated as a supervised regression problem. The input features include 32 sensor values, statistical features (standard deviation and variance), temperature, shaft rotation, and lever arm geometry (45 features in total).

Four regression models were evaluated: Linear, Ridge, Lasso, and Random Forest, each using an 80/20 train-test split including five-fold cross-validation. Feature normalization was applied for the linear models, while the Random Forest model was trained on raw data.

The dataset was acquired using dedicated test setups, where defined axial, lateral, and gripping forces were applied to the instrument. Reference forces were generated using calibrated weights and force sensors, while the corresponding multisensor signals were recorded simultaneously. Both static and dynamic load cases were considered to capture a wide range of operating conditions.

Temperature effects were explicitly investigated, as thermal expansion differences between sensor and instrument introduce measurement drift. Models with and without temperature as an input feature were compared to assess its impact.

Results and Discussion

All evaluated models were capable of reconstructing force components from the sensor data. However, clear differences in performance were observed. The Random Forest model achieved the highest accuracy when including temperature as an input feature, with coefficients of determination of up to $R^2 \approx 1.000$ and mean absolute errors (MAE) of 0.0001 N for lateral force, 0.0027 N for axial force and 0.0048 N for

gripping force (see Figure 2). Linear models also showed strong performance with R^2 values above 0.96, but with higher estimation errors.

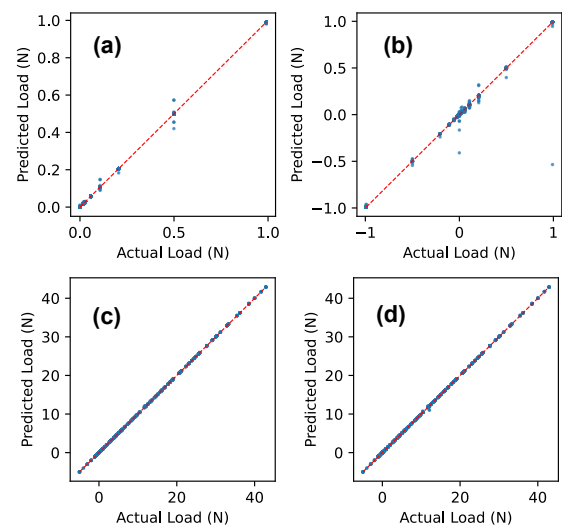


Figure 2: Comparison between measured and predicted load values for Random Forest model. (a) shows lateral force, (b) axial force, (c) and (d) gripping force. Whereas (a) to (c) use the temperature feature, (d) ignores the temperature.

The investigation of temperature influence revealed that linear models only marginally benefit from the inclusion of temperature as an input feature. In contrast, the Random Forest model clearly benefits from temperature as additional feature: As an example, the gripping force MAE can be reduced from 0.0081 N without temperature feature (see Figure 2d) to 0.0048 N with temperature feature (see Figure 2c).

The proposed approach can reliably estimate axial, lateral, and gripping forces despite complex mechanical coupling within the instrument. Our results demonstrate the effectiveness of combining spatially resolved sensing with data-driven modeling.

Conclusions and Acknowledgment

The results demonstrate that the presented multisensor force chip is well suited for measuring mechanical loads in laparoscopic instruments with millinewton accuracy.

The Random Forest model provides maximum accuracy. Our results suggest that it is feasible to use force sensing in laparoscopic instruments to provide real-time force feedback and thus improve surgical safety for both manual and robotic surgery.

The authors thank the Ministry of Economic Affairs, Labour and Tourism of Baden-Württemberg for funding the project "Intelligente Chirurgische Instrumente (InXI)" under grant number BW8_1387/01.

References

- [1] J. Miller *et al.*, "Impact of haptic feedback on applied intracorporeal forces using a novel surgical robotic system-a randomized cross-over study with novices in an experimental setup," *Surg Endosc*, vol. 35, no. 7, pp. 3554–3563, 2021, doi: 10.1007/s00464-020-07818-8.
- [2] W. Wang, J. Wang, Y. Luo, X. Wang, and H. Song, "A Survey on Force Sensing Techniques in Robot-Assisted Minimally Invasive Surgery," *IEEE transactions on haptics*, vol. 16, no. 4, pp. 702–718, 2023, doi: 10.1109/TOH.2023.3329172.
- [3] A. Nakai, K. Kuwana, K. Saito, T. Dohi, A. Kumagai, and I. Shimoyama, "MEMS 6-axis force-torque sensor attached to the tip of grasping forceps for identification of tumor in thoracoscopic surgery," in *2017 IEEE 30th International Conference on Micro Electro Mechanical Systems (MEMS)*, Las Vegas, NV, USA, Jan. 2017 - Jan. 2017, pp. 546–548.
- [4] M. Kuhl *et al.*, "A wireless stress mapping system for orthodontic brackets using CMOS integrated sensors," *IEEE Journal of Solid-State Circuits*, vol. 48, no. 9, pp. 2191–2202, 2013.