Tire Deformation Monitoring Sensor for Advanced Driver-Assistance Systems

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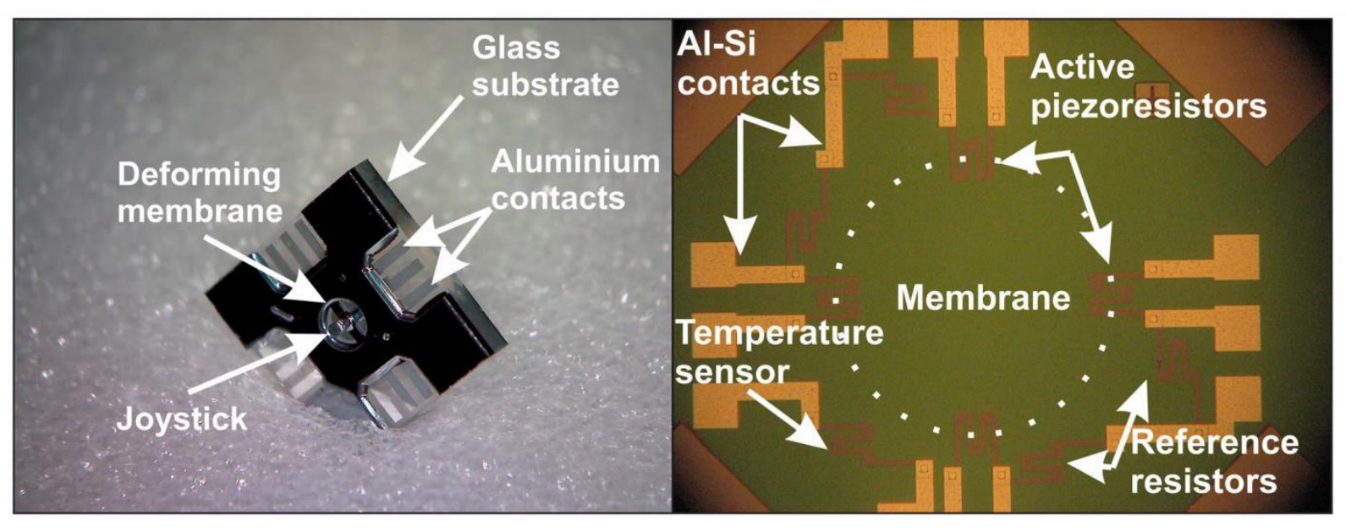
Introduction

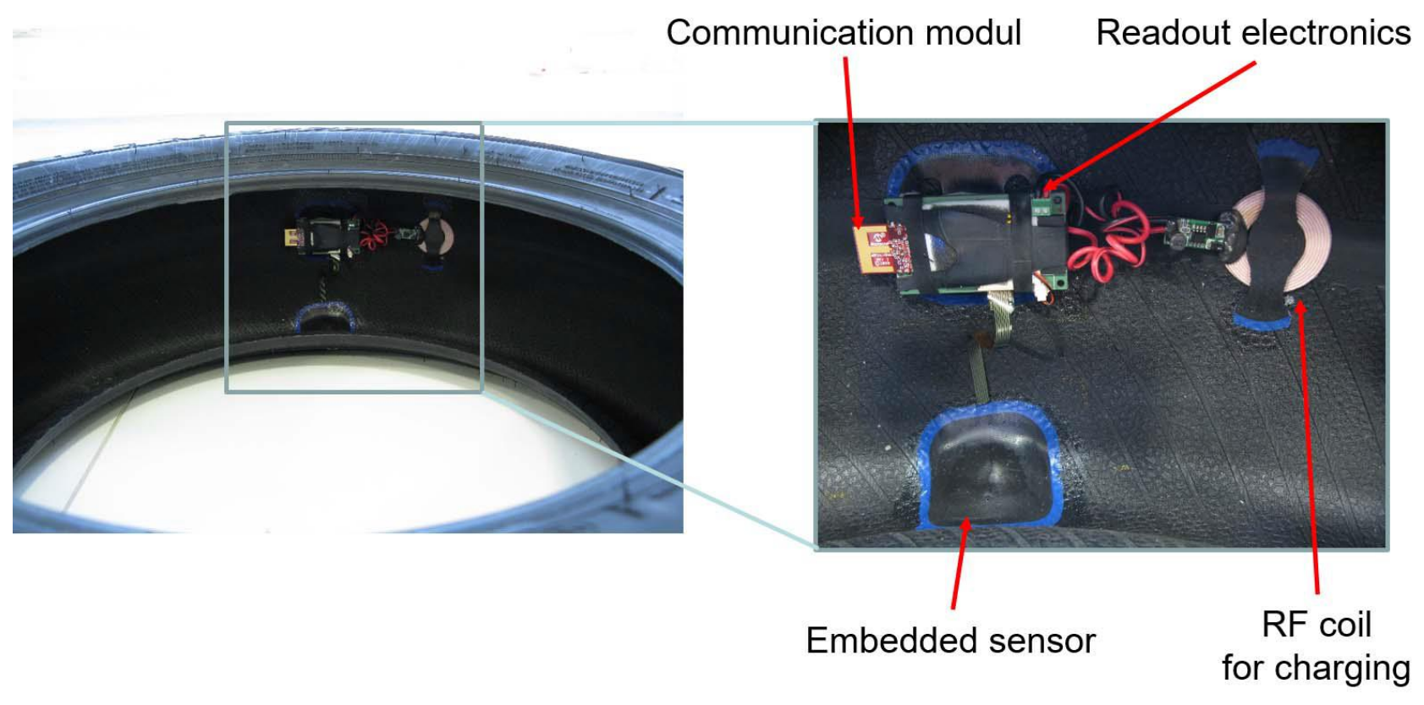
Advanced Driver-Assistance Systems (ADAS), especially in the field of autonomous driving, are gathering more and more information on the move to increase efficiency, reduce emissions, and increase safety. Today, a whole range of sensors are installed at various points in the car to monitor the vehicle movements and the environment. However, the interaction between the tire and the road surface at critical moments, such as a vehicle skidding, can only be detected indirectly through lateral acceleration and turning of the vehicle. Our goal is to collect more direct information on tire traction for each tire individually, using a three-dimensional (3D) piezoresistive force sensor placed on the inner wall of the tire. This allows real-time evaluation of wheel forces, automatic road surface detection, and early detection of skidding events.

Methodology

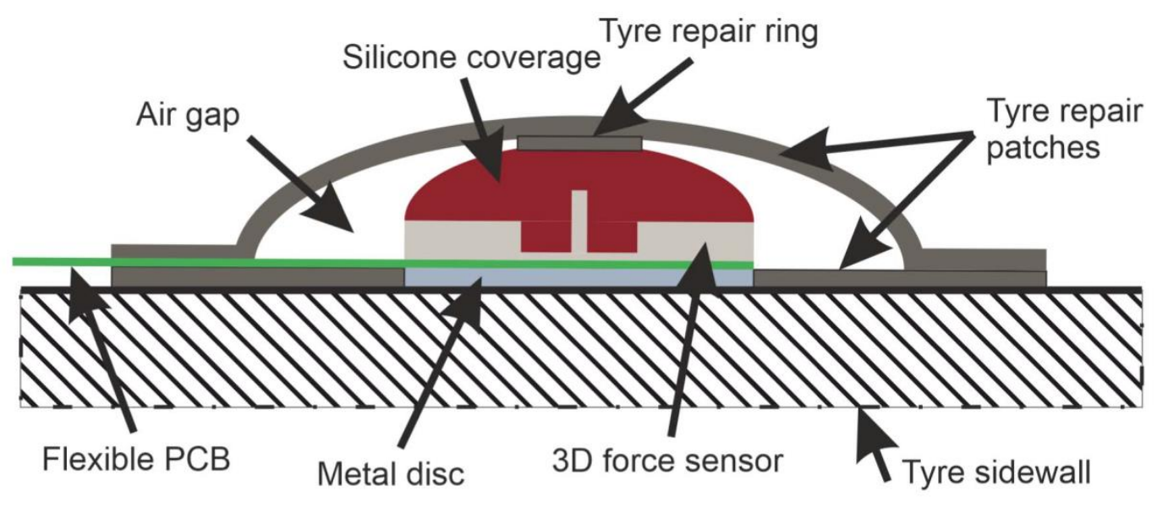
- Used sensor: a 3D piezoresistive MEMS force sensor with 4 strain-sensitive resistors placed around a 3D micromachined Si beam (joystick) on a SOI-based device membrane [1].
- By collecting the 4 voltage-divided signals, all three components of the load force applied on microbeam can be calculated for a bare sensor chip.
- However, in highly deforming environments, such as vehicle tire, protective packaging with high resistance is needed.
- The packaged sensor is placed on the inside of the tire, near the most curved area, to maximize sensitivity.
- The crosstalk between the voltage dividers caused by the packaging requires sophisticated evaluation models.
- In this work, data-driven machine learning algorithm with variable projection layer and adaptive Hermite functions [2] are used for data analysis.



Si-based 3-D force sensor front (left) and back (right)



Components of the integrated tire-deformation monitoring system

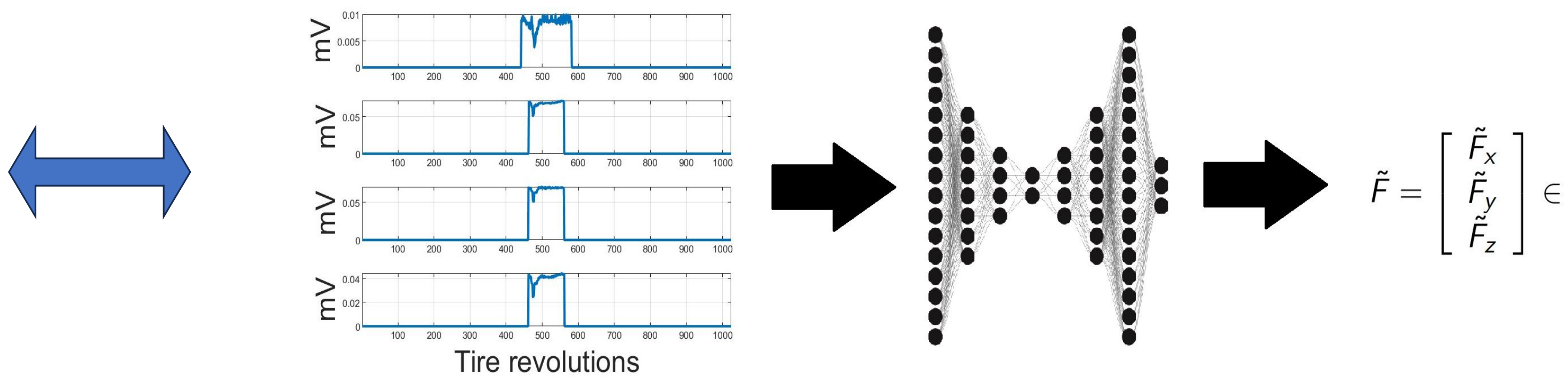


Packaging scheme to protect the embedded sensor while preserving sensitivity

$$F_x = \frac{1}{v_0 \alpha_{ls} \pi_{44}} \left(\Delta V_{right} - \Delta V_{left}\right)$$

$$F_y = \frac{1}{v_0 \alpha_{ls} \pi_{44}} \left(\Delta V_{top} - \Delta V_{bottom}\right)$$

$$F_z = \frac{1}{v_0\, \alpha_{ln} \pi_{44}} \times \left(\frac{\Delta V_{right} + \Delta V_{left} + \Delta V_{top} + \Delta V_{bottom}}{2}\right)$$

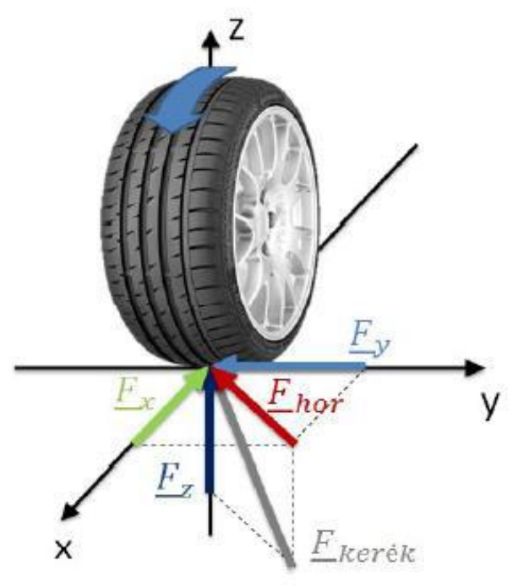


Analytical expressions for bare force sensor chip (left) vs. data-driven machine learning for packaged sensor signals (right)

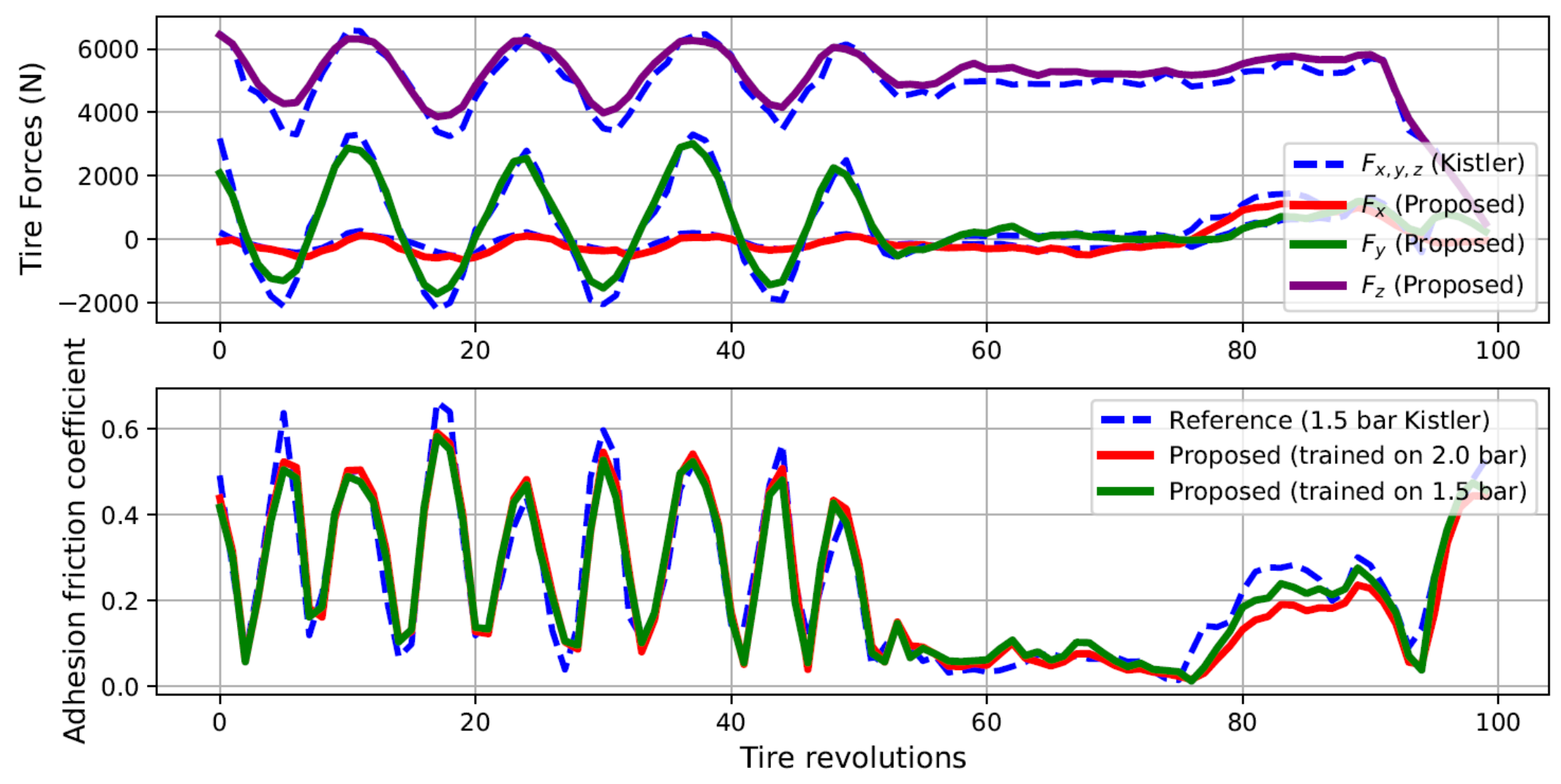
Wheel force estimation

- Aim of the study: to calibrate the tire deformation sensor with a standard wheel force sensor.
- Tests were performed on constant speed (~25 km/h) slalom tracks, straight sections, as well as with accelerations and decelerations using Kistler RoaDyn S625 reference wheel force sensor mounted on a Mercedes-Benz CLA test vehicle.
- Tests were repeated at different tire pressures (p=1.5, 1.8, 2.0, 2.2 bar).
- The collected tire sensor data was first segmented into individual revolutions and then used to train them for the average reference forces for each component separately.
- A second neural network was applied to perform smoothing.
- Adhesion coefficient of friction was also calculated: $\mu = \frac{\sqrt{\bar{F}_x^2+\bar{F}_y^2}}{|\bar{F}_z|}$.

Wheel force reference sensor on the test vehicle



Wheel force components

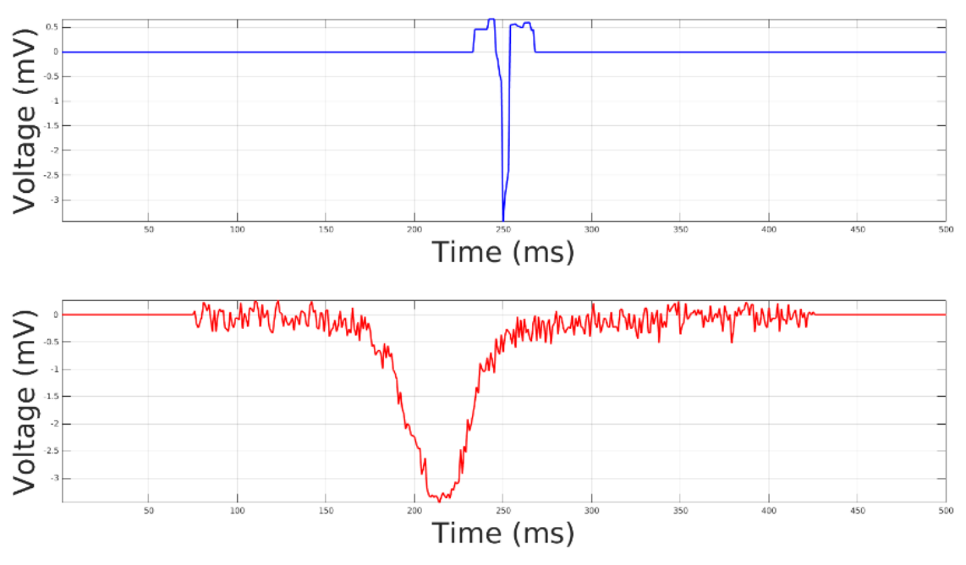


Evaluation of the test sets vs reference force and friction coefficient signals

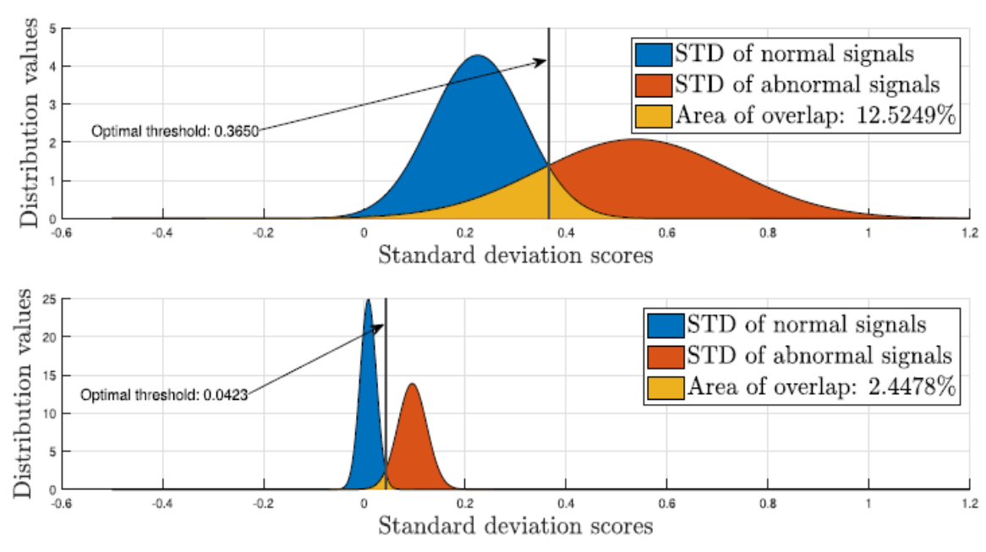
- Despite the limited size of the training set (~2000 revolutions), the algorithm provides a fairly good agreement with the reference values.
- Instead of the wheel forces adhesion friction coefficient (μ) could provide a simple and valuable indicator for ADAS.

Road surface defect detection

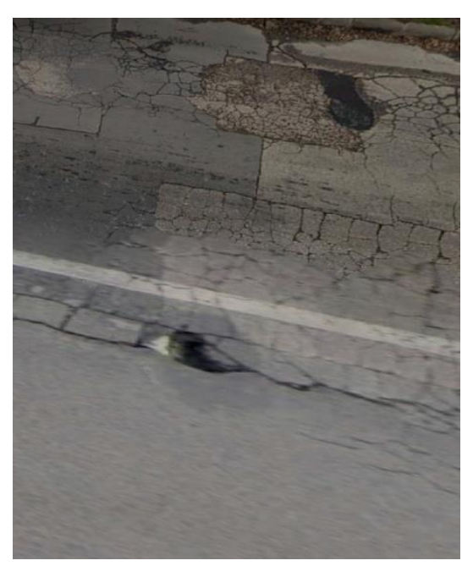
- Aim of the study: tire sensor for automatic detection of road surface anomalies.
- Ground-truth data was collected on two types of roads in Budapest: good-quality road with no visually detectable defects (normal) and poor-quality road with potholes and manhole covers (abnormal) → binary classification.
- Analytic, model-based, and standard data-driven machine learning approaches were compared using a set of 413/103 measurement segments for training/test [3].



Pre-processed tire sensor data from a turn recorded on normal (top) and abnormal (bottom) road



Distribution of standard deviation scores with optimal thresholds before (top) and after (bottom) transformation



Anomalies on the 'abnormal road'

Classifier	Mean Accuracy	Highest	Lowest
Threshold	86.92%	90.38%	79.81%
SVM	93.65%	96.15%	92.31%
Threshold Hermite	93.85%	96.15%	90.38%
FCNN	96.13%	99.02%	94.23%
CNN	96.52%	97.12%	93.20%
VP-NET	**97.68%**	**99.04%**	**96.12%**

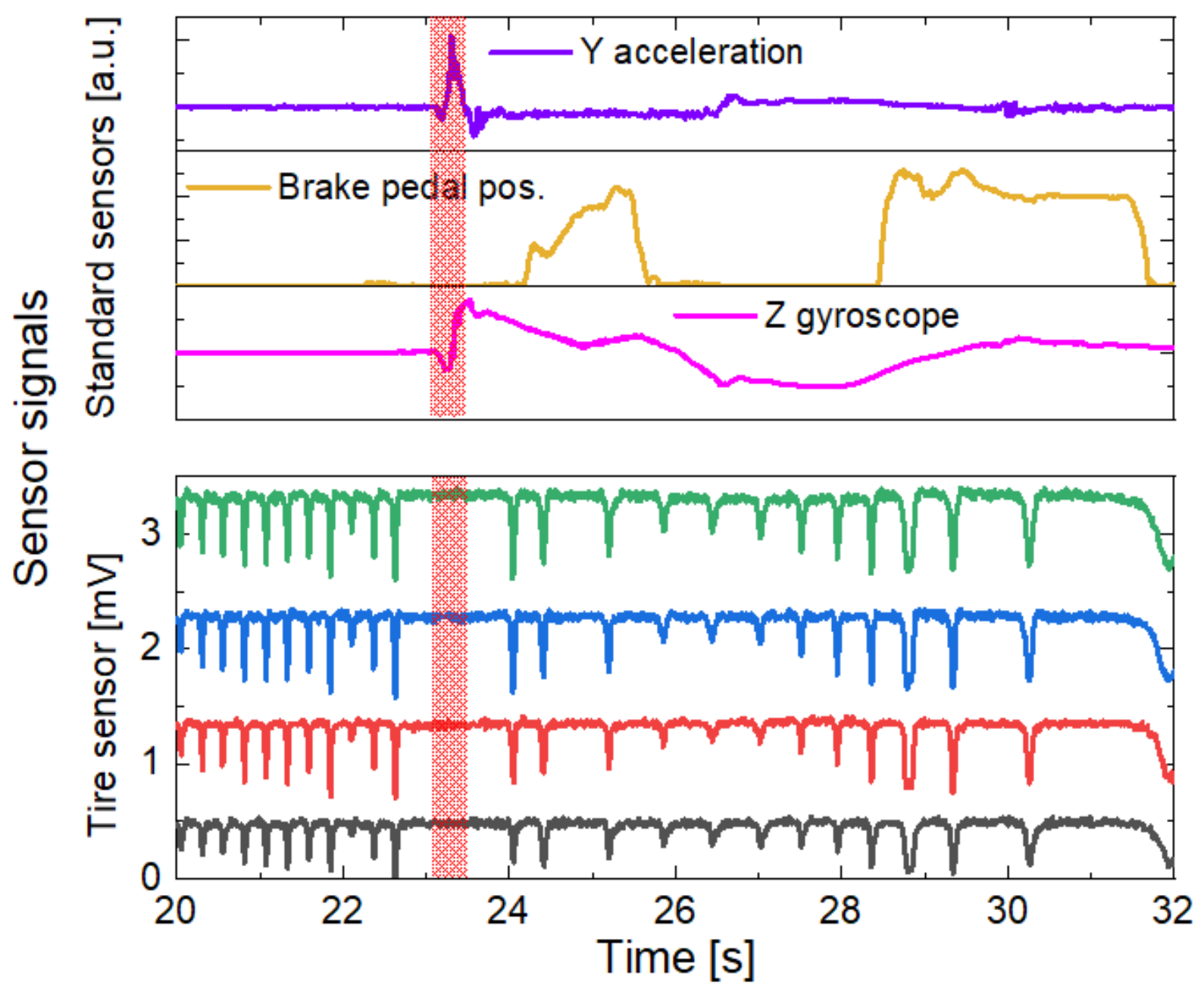
Accuracy of the compared binary classification schemes

- Hermite representation increases the reliability of both analytic and neural-network-based evaluation (Threshold Hermite: ~93.9 % and VP-NET: ~97.7%).
- VP-NET, as a low-demand algorithm, has proven compatibility with low-cost, low-capacity hardware (e.g. STM32 F411RE) enabling real-time detection for standard cars and trucks.

Kick-plate vehicle test

- Aim of the study: demonstrate the capability of the tire deformation monitoring system in the early detection of skidding events.
- Kick-plate vehicle tests were carried out using synchronized signal acquisition from tire sensors and various standard sensors mounted on the test car (Nissan Leaf).

Tire deformation sensor in action



Recorded signals of the standard automotive sensors (upper panel), and of the four half-bridges of the tire sensor. Red region shows the moment of plate excitation.

- Though the detailed evaluation of the signals is still in progress, the characteristic features of the tire sensor signals bodes well for slip detection.

Conclusions

- Direct, real-time monitoring of the road-tire contact condition is feasible with an inexpensive 3D MEMS force sensor.
- Analogous operation proven by the calibration of standard wheel force sensor in use → can replace the expensive wheel force gauge.
- Potential applications of the tire sensor:
  - driver assistance for early warning of skidding
  - load imbalance prediction, e.g. for trucks
  - automatic road surface classification
  - real-time tire condition assessment
- Highly interdisciplinary approach requiring concerted collaboration of sensor system developers, car makers, tire manufacturers, power train and deep learning experts!

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