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# Decentralized structure-integrated spatial force measurement in machine tools

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ABSTRACT

New manufacturing processes and extended movability of modern machine tools, such as five-axis kinematics or hexapods, increase the demand for in-process measurement of spatial forces and torques in up to 6 degrees of freedom (DoF). The approach proposed in this paper is based on the idea of integrating 6 single-axis force sensors into the machine's structure and converting these sensor forces to spatial forces and torques at the tool centre point (TCP) using a measurement model. This concept is advantageous to costs, ruggedness and available workspace when compared to state-of-the-art 6 DoF force/torque transducers. At the same time, the achievable measuring accuracy is similar and also significantly better than the accuracy of drive current based force evaluation. On the other hand, structure and machine influences have to be addressed by suitable measurement models. This article presents design, parametrization, verification, and characterisation of these measurement models on the example of four integration concepts, two in rigid bar frameworks and two in bar kinematics. Further, experimental results are shown which are classified in comparison to a 6 DoF F/T sensor and drive current based force measurement. Finally, other influences, such as structural design and deformations, as well as the integration of sensors and models into the machine's control software are discussed.



## 1. Introduction

In-process measurement of forces and torques is increasingly required by many manufacturing applications, e. g. process diagnosis and monitoring, quality assurance, or adaptive process control. With the extended movability of modern machine tools, like five-axis kinematics or hexapods, the demand for measuring *spatial* forces and torques in up to 6 degrees of freedom (DoF) is growing.

Usually, a 6 DoF measurement is achieved by the use of commercial 6 DoF force/torque transducers (F/T sensors) mounted close to the tool centre point (TCP) which results in a reduction of usable work space, causes restrictions to the machine's ruggedness, e. g. according to milling chips, cutting fluids and mechanic strains, and also entails high financial costs. Unique, self-developed, mostly strain gauge based, multi-axis force sensors, e. g. integrated into a spindle mounting [1], can keep the workspace reduction to a minimum but increase the system costs even more.

Alternatively, forces and torques are obtained from drive currents, which is very limited in accuracy because of interfering non-linear and stochastic influences from the mechanics between force application and measurement.

Solutions using integrated single-axis force sensors exist for particular applications, such as spindles [2,3] and micrgrippers [4], but they do not combine multiple sensors necessary for spatial measurements.

Very rarely, force sensors are already system integrated, e. g. implicit in a hydraulic hexapod through obligatory pressure sensors in [5], although in this application they are not used for spatial force measurements.

Therefore, a huge potential exists in a direct integration of multiple robust and economic single-axis (1 DoF) force sensors into the machine structure combined with a control-integrated transformation of the measured forces to spatial forces and torques at the TCP.

## 2. Approach

Bar frameworks, as commonly used within lightweight designs and bar kinematics, are particularly suitable for the integration of single-axis sensors. These frames are used for example in hexapod structures (Fig. 1) or for lightweight spindle mountings (Fig. 2).

Four new approaches for structural sensor integration are evaluated (Fig. 1) and compared to two standard solutions:

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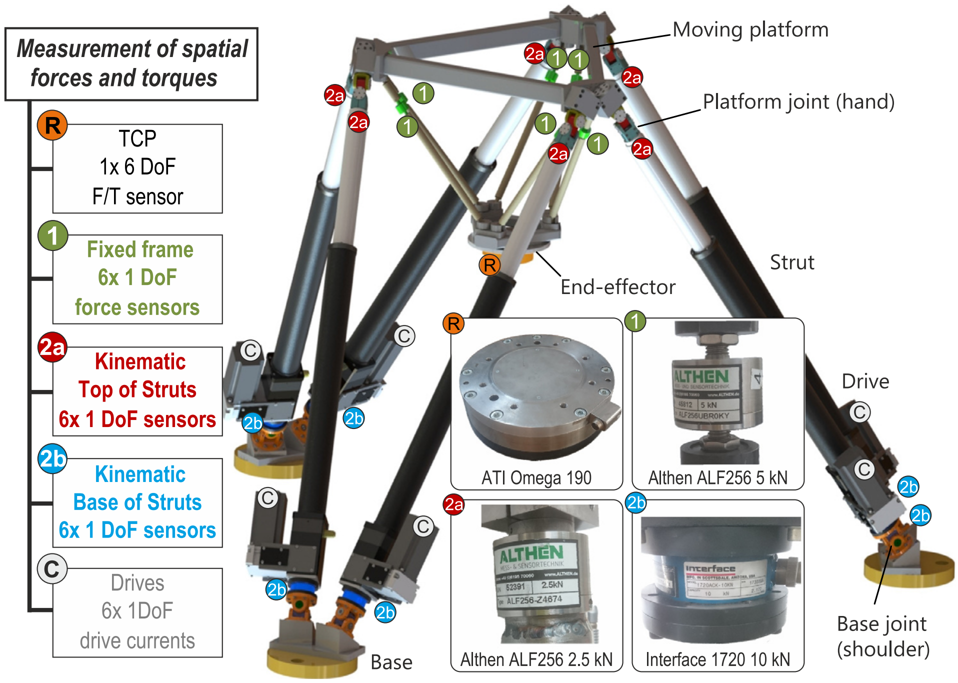


**Fig. 1.** Evaluated positions of force sensor integration.

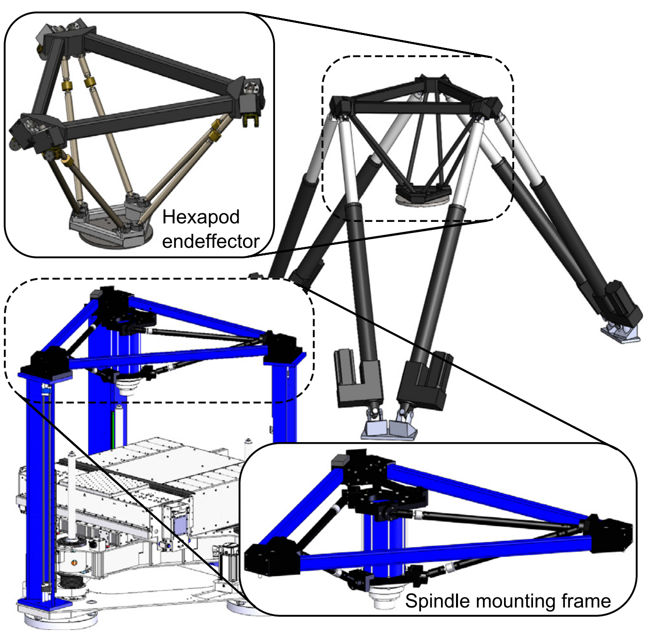


**Fig. 2.** Light-weight rigid bar frameworks in machines, particularly suitable for force sensor integration; above: end-effector of hexapod FELIX (moving), below: spindle mounting frame of experimental machine MAX (not moving)

R F/T sensor with 6 DoF mounted at the TCP (as reference),

1 **Rigid bar framework** with integrated single-axis force sensors, which is
   a **not moving**, like the spindle mounting frame of the experimental machine MAX (Figs. 2 and 3),
   b **moving**, like the end-effector platform of the hexapod FELIX (Figs. 3 and 3),

2 **Bar kinematic** with integrated single-axis sensors at the
   a **top of the struts** of the hexapod MINIHEX (Fig. 3),
   b **base of the struts** of the hexapod FELIX (Fig. 3),

C Drive currents evaluation (for comparison).

Depending on the exact sensor placement, structure and process induced influences are included through a respective measurement model, which contains

- for all approaches: sensor positions and orientations (36 parameters), which are constant for rigid frameworks, and sensor calibration offsets (6 parameters),
- for moving rigid bar frameworks (Section 3): additional framework pose (6 parameters), mass and centre of gravity (4 parameters), and
- for kinematic integration into a hexapod (Section 4): additional 96 parameters for masses and centres of gravity of the 24 additional moving machine parts between sensors and TCP.

## 3. Rigid framework sensor integration

### 3.1. Structural design

For rigid bar frameworks with integrated force sensors (Fig. 2), the measurement quality can be increased by intelligent design of the framework's geometry. Crucial for an appropriate transformation of 1 DoF sensor informations into spatial forces and torques at the TCP is a suitable sensor placement and orientation, to guarantee that all 6 DoF force components of an external load can be detected with a good and comparable sensitivity.

However, in many cases, maximal sensor sensitivity behaves reciprocally to other relevant design criteria, like maximal structural stiffness, minimal mounting space or high overload protection.

In the following, the main coherences to describe force transformation, sensitivity, and stiffness are presented. For detailed information and design variants please refer to [6].

The sensor forces $\underline{\boldsymbol{F}}_{\mathrm{q}} = \left(F_{\mathrm{q}_1}, F_{\mathrm{q}_2}, F_{\mathrm{q}_3}, F_{\mathrm{q}_4}, F_{\mathrm{q}_5}, F_{\mathrm{q}_6}\right)^T$, can be transformed to spatial forces and torques at the end-effector

$$\underline{\boldsymbol{F}}_{\mathrm{x}} = \begin{pmatrix} \boldsymbol{F}_{\mathrm{x}} \\ \boldsymbol{M}_{\mathrm{x}} \end{pmatrix} = \begin{pmatrix} F_{\mathrm{x}} & F_{\mathrm{y}} & F_{\mathrm{z}} & M_{\mathrm{x}} & M_{\mathrm{y}} & M_{\mathrm{z}} \end{pmatrix}^T \tag{1}$$