

Robot-assisted test stand for calibrating 3-D-printed torque sensors

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Summary: The metrological characterization of 3-D-printed torque sensors currently lacks standardized, automated procedures, which limits the comparability of research results. This contribution introduces a robot-assisted test stand designed for the automated and reproducible calibration of such sensors. The system employs a vertical articulated-arm robot to handle standard weights, effectively eliminating human-induced variability. In this setup, a reference torque sensor serves as the primary traceability standard, whereas the robot-controlled lever-mass system ensures a stable load application. A mathematical model based on the GUM (Guide to the Expression of Uncertainty in Measurement) is implemented to quantify the combined measurement uncertainty. Our analysis shows that the robot's positioning repeatability of 20 µm provides the necessary loading conditions for the reference instrumentation, thereby minimising parasitic forces. Consequently, the overall accuracy is primarily defined by the reference sensor itself. The presented setup enables an automated and traceable characterization of 3-D-printed torque sensors under reproducible conditions.

Keywords: test stand, torque sensor, 3-D printing, additive manufacturing, robot, calibration

Introduction

Measuring torque is essential in technical fields such as drive technology and research [1]. Several sensing principles can be employed for measuring torque, e.g. resistive, capacitive or inductive effects [1]. Currently, strain gauges are frequently employed in torque sensors [1]. However conventional force-torque sensors are typically expensive [2].

3-D printing offers new possibilities for the cost-effective design of application-specific sensors [3]. Various sensing principles can be exploited by creating functional structures using polymers such as PLA and conductive inks. [3]. Numerous publications describe 3-D-printed sensors in which the housings or force-bearing elements are 3-D-printed and then combined with conventional strain gauges or optical detectors as sensor elements [3]. Analysis of the calibration of these sensors reveals that they are often calibrated applying heterogeneous measurement setups involving test weights or reference sensors. Standardised procedures and complete documentation of sensor parameters are lacking in the current state of 3-D-printed torque sensors [3–7]. This hinders the comparability of research results.

This contribution addresses this gap by introducing a robot-assisted test stand for the automated calibration of 3-D-printed torque sensors. Equipped with a robotic arm, the system can apply defined torques and complex movement profiles with a high degree of repeatability. This minimises the impact of manual alignment errors during testing. The test stand allows 3-D-printed prototypes to be characterised under reproducible, automated conditions.

State of the art

Test stands are required for the metrological characterisation of torque sensors in order to determine measurement uncertainties, and ensure traceability to national standards [8]. The current state of the art is examined from two perspectives. Firstly, the measurement setups applied in the development of 3-D-printed torque sensors for calibration are considered. Secondly, established conventional and primary calibration test stands are examined.

Calibration setups for 3-D-printed torque sensors: Palli and Pirozzi [7] developed an optical torque sensor based on a flexible acrylonitrile butadiene styrene (ABS) frame, whose deformation is detected via the positional change of an LED relative to a photodetector. Calibration is performed using cable-guided linear motors with force transducers as a reference.

In [4], Aguilar-Segovia et al. present a 3-D-printed capacitive torque sensor. They employ a test stand with a BLDC motor as an actuator to compensate for the hysteresis and viscosity of thermoplastic polyurethane (TPU) structures employing real-time estimation algorithms. Lee et al. [5] present a capacitive sensor structures based on printed circuit boards, which are calibrated in series with a reference sensor (ATI Nano 25).

Fu et al. [6] employ a system consisting of rotating discs and weights to characterise the static and dynamic properties of sensitive multi-axis sensors made of polyetheretherketone (PEEK). This system enables cross-axis crosstalk to be analysed.

Conventional and primary torque standards:

Conventional torque measurement technology relies either on motor-driven automated test stands or on primary standards that operate according to the dead-weight principle (lever-mass system) [9, 10]. The test stand, presented in [11], at the Physikalisch-Technische Bundesanstalt (PTB) serves as a reference system in the range of small torques up to 1 N·m [11]. The design of this primary standard is based on a horizontal measurement axis with an efficient lever-mass system [11]. The bearing is aerostatic via an air bearing, which reduces residual friction torque to less than 1 µN·m. The system features a weight-changing system that places masses into automated load cages to automate the calibration process. [11]. No vertical articulated-arm robot is used in this process. The counter drive is axially adjustable and protected against overload by a magnetic slip clutch [11]. In order to achieve the target expansion of the relative measurement uncertainty to 0.01%, the lever position is optically monitored and kept in continuous equilibrium via a counter-drive. [11].

A review of the literature on 3-D-printed torque sensors and conventional torque test stands revealed no test stand equipped with a vertical articulated-arm robot for applying test weights to a lever-mass system. This contribution addresses this gap with the aim of eliminating human-made influences on the measurement process through the employment of a robot arm.

Design of the test stand

The test stand comprises several components. Fig. 1 shows the CAD model of the setup. The base is a granite measuring plate. An aluminium slotted plate is mounted on top of this, to which the remaining components are attached. A distinctive feature of the test stand is its deployment of a vertical articulated-arm robot to place standard weights on a defined lever arm during the calibration process. Automating this process with the robotic arm ensures that the standard weights are handled in a reproducible manner without human intervention. This prevents potential errors caused by the operator. The TD110a 10Nm/VA reference sensor (ME-Messsysteme) is employed for measuring the torques that act during the calibration process. The measurement signals from the TD110a 10Nm/VA are processed by the GSV-2MSD-DI measurement amplifier, which is also supplied by ME-Messsysteme. This contribution presents an example of calibrating an inductive, 3-D-printed torque sensor. An LDC1614EVM evaluation board from Texas Instruments is used to process the measurement signals from the sensor. The test stand enables to apply both clockwise and counterclockwise torques to the calibrated sensor. Additionally, the test stand incorporates a temperature sensor via a sepa-

rate microcontroller to monitor temperature during calibration.

System control and software architecture

The test stand is centrally controlled through a PC workstation equipped with ethernet and USB-A interfaces. Communication with the industrial robot is established via an Ethernet/IP connection. The measurement amplifier (GSV-2MSD-DI) and microcontrollers, which acquire temperature data and sensor signals from the test specimen, are connected to the PC via a USB hub. A master software program written in Python serves as the central control unit. This program consists of several subroutines that are sequentially invoked during the calibration process. At the start of a calibration, the user configures the necessary parameters, such as the direction of torque rotation, via a graphical user interface (GUI). The TCP/IP connections to the robot and the measurement amplifier are then initialised. After manually activating the robot's power supply via the GUI, the automated process begins. Hereby, the software for acquiring data from the LDC1614EVM evaluation board is first launched automatically. This is done applying a 'BotModule', which uses image recognition to execute a predefined sequence of interactions to control the manufacturer-specific acquisition software and define the storage path. Next, the robot performs the mechanical calibration cycle, during which standard weights are placed on the lever arm in stages and then removed again. Once the motion sequence is complete, the robot sends a status signal to the master software. Data acquisition then terminates, the measured values are exported in CSV format and the main program closes. The CSV files can then be processed as needed. The system's modular design allows different robot programs to be loaded for specific calibration procedures. In addition to the automated handling of standard weights, this enables endurance tests to be performed, as well as specific measurement tasks for various sensor configurations.

Metrological characterization

The metrological characterisation of the test stand is based on [11]. In this article, Röske present a torque test stand with a lever-mass measurement system. They apply the guide to the expression of uncertainty in measurement (GUM) to evaluate the contributions to measurement uncertainty [11], as is also done in this contribution.

Torque generation: The torque is generated within the test stand based on the definition as the product of the lever arm and the force [11]. Mathematically, this can be expressed as the cross product of the position vector $\vec{r}$, which points from the reference point on the torque axis to the point of force application, and the

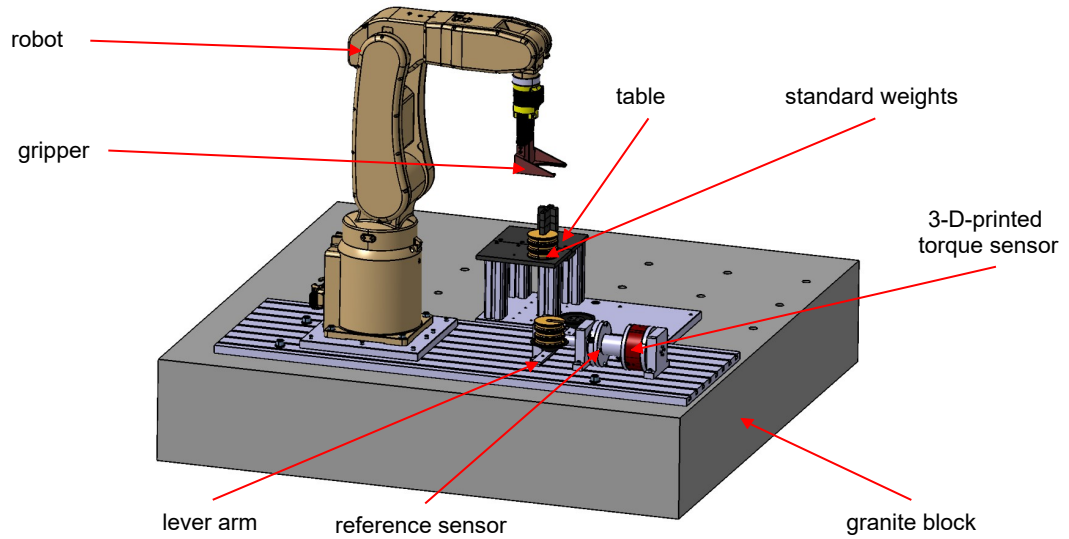


Fig. 1: CAD model of the robot-assisted torque test stand.

force vector $\vec{F}$ [11]:

$$\vec{M} = \vec{r} \times \vec{F}. \quad (1)$$

The sensor's calibration is supported by a lever-mass system that is suspended in several ball bearings. This prevents the applied load from generating an unwanted shear force or bending moment on the axis of rotation. The bearings balance the system's weight and provide the necessary counterforce. This enables the torque to be converted into a force pair and transmitted to the sensor.

Mathematical model: The test stand presented by Röske [11] is a classic lever-type measurement system. The torque applied is primarily determined by the configuration of the lever arm and the test weights. The lever arm and test weights are both traceable quantities and are considered the primary sources of torque and their value for the calibration. Röske [11] describes the mathematical model of his test stand and the generated torque M as follows [11]:

$$M = m \cdot g \cdot l \cdot \left(1 - \frac{\rho_L}{\rho_m}\right) \cdot \cos(\alpha) + \sum_{i=1}^n \Delta M_i \quad (2)$$

In this equation, m represents the total mass of the standard weights and g represents the local gravitational acceleration at the system's location, and l represents the length of the lever arm. The term $(1 - \rho_L/\rho_m)$ corrects for the physically induced air buoyancy, where ρ_L denotes the air density and ρ_m denotes the material density of the masses applied. The angle of inclination of the lever arm relative to the horizontal is denoted by α . Additionally, the term $\sum \Delta M_i$ accounts for up to n different

factors that can influence the total torque [11].

In contrast to the classical lever-mass system described in [11], in which the torque is defined by mechanical parameters, only the reference sensor (TD110a 10Nm/VA) serves as the feedback variable in the robot-assisted test stand. During calibration, the values indicated by the reference sensor are employed. The masses and the lever arm then merely generate the necessary load. The tolerances of the lever arm, reference weights and angle of inclination are no longer directly incorporated into the reference torque calculation. The actual torque is read directly from the reference sensor. As a result, the mathematical model can be significantly simplified:

$$M = M_{ref} + \sum_{i=1}^n \Delta M_i \quad (3)$$

Here, M_{ref} is the value indicated by the reference sensor, and the term $\sum \Delta M_i$ accounts for up to n different factors that can influence the total torque. These include, among other things, the uncertainty of the measurement amplifier and the repeatability of the robot.

Uncertainty Sources

The following section examines the key factors that influence measurement uncertainty of the robot-assisted test stand. Fig. 2 provides an overview of these factors in the form of an ishikawa diagram.

Geometrical characteristics: Alignment errors resulting from the manufacturing tolerances of the individual components, as well as deviations that occur during the assembly of the test stand,

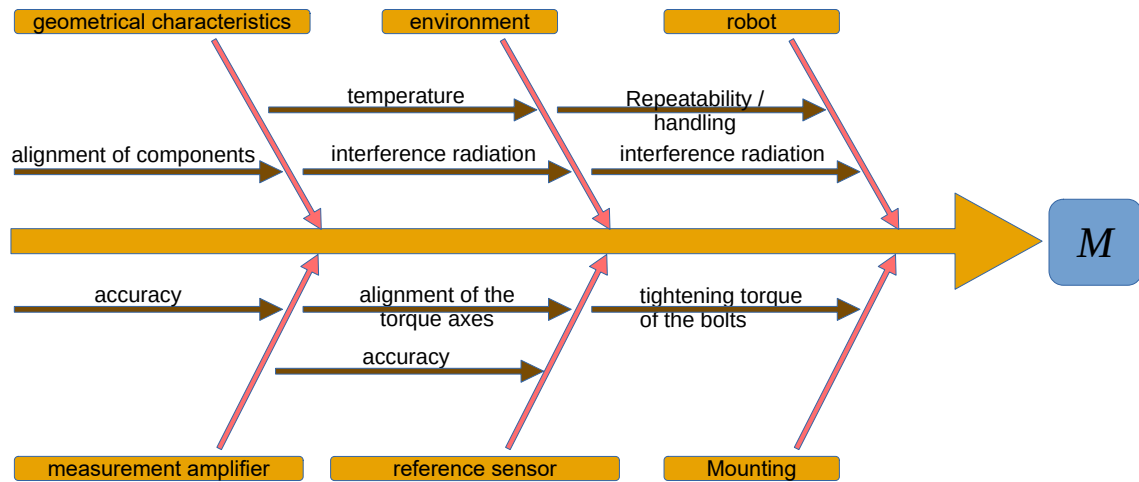


Fig. 2: Ishikawa diagram showing the acting influence factors for the torque.

are referred to here. For instance, the rotational axes are unlikely to be perfectly aligned, resulting in slight discrepancies in the actual torque acting on the sensor. Alignment errors in the rotational axes can also cause parasitic forces and moments.

Environment: The application of physical torque on the test stand is affected by environmental conditions. The primary factor to consider here is temperature. Fluctuations in temperature can cause the metal components of the test stand to expand thermally. Furthermore, temperature affects both the reference sensor and the sensor being calibrated. To minimise measurement uncertainty, ambient temperatures are recorded and incorporated into the mathematical model used to determine the torque.

In addition to temperature, electromagnetic interference fields can affect the measurement. This applies to both the reference sensor and the sensor being calibrated.

Robot: The employment of an industrial robot to automate the calibration process reduces human intervention, allowing standard weights to be placed on the lever arm in a reproducible manner. The robot's repeatability (20 μm [12]) is crucial for positioning the standard weights on the lever arm, since deviations in position lead to variations in the effective length of the lever arm. Additionally, electromagnetic interference from the robot's drives can affect the measurement signal chain. In order to eliminate dynamic effects such as vibrations or acceleration forces, measurements are only taken after a stable static state has been achieved following the placement process.

Reference sensor: The actual torque is measured employing a TD110a 10Nm/VA

torque sensor from ME-Messsysteme as the reference sensor [13]. The accuracy of this sensor is a key factor in the uncertainty assessment of the test stand. In addition, the uncertainty of the measurement amplifier must also be considered.

Mounting: The tightening torque during the installation of the test specimen is a critical factor. This can subject the calibrated sensor to undesirable mechanical stress. Insufficient tightening torque reduces contact stiffness at the connection point. This can lead to micro-movements and nonlinearities in the force flow, resulting in increased hysteresis and reduced repeatability. Conversely, excessive or asymmetrical tightening torque can create parasitic stress states within the sensor structure. These stresses can shift the zero point and impair the sensor's sensitivity by altering the structural stiffness. Furthermore, uneven torque distribution often results in parasitic load components, such as shear forces or bending moments, that disrupt ideal force transmission.

Uncertainty budgets

In order to evaluate the accuracy of the torque measurements, the combined measurement uncertainty is determined in compliance with the GUM. In this setup, the reference torque sensor (TD110a 10Nm/VA) is defined as the primary reference. Therefore, the mathematical model for the reference torque simplifies to (3). According to the law of uncertainty propagation, the combined standard uncertainty $u_c(M)$ is calculated from the standard uncertainties of the individual input quantities $u(x_i)$ and their respective sensitivity coefficients c_i [11, 14]:

$$c_i = \partial M / \partial x_i \quad (4)$$

$$u_c(M) = \sqrt{\sum_{i=1}^n \left(\frac{\partial M}{\partial x_i} \cdot u(x_i) \right)^2} \quad (5)$$

As the uncertainty according to equation (3) is primarily determined by the reference sensor, the contributions of the sensor-related uncertainties are included in the measurement uncertainty budget with equal weighting.

Uncertainty components: The following uncertainty components are considered based on the calibration approach:

- **Reference sensor (u_{ref}):** The uncertainty of the TD110a 10Nm/VA sensor (Class 0.1), including hysteresis and non-linearity. This is the primary source of uncertainty.
- **Measurement amplifier (u_{amp}):** The uncertainty of the measurement amplifier GSV-2.
- **Zero point drift TD110 10a (u_{drift_s}):** Potential drift of the sensor signal before or during the measurement cycle.
- **Zero point drift GSV-2 (u_{drift_a}):** Potential drift of the signal before or during the measurement cycle.
- **Repeatability (u_{rep}):** This component accounts for the variability in measurements, indirectly capturing mechanical influences such as the robot's positioning repeatability, lever arm variations, and angular alignment.

Sensitivity coefficients: All components of measurement uncertainty are equally weighted and are included in the measurement uncertainty budget with a sensitivity coefficient of $c_i = 1$. Other mechanical factors (mass, lever arm, inclination) are no longer treated as direct additive terms in the torque equation. Table 1 summarizes the estimated values and distributions for a nominal torque of 10 N·m. The reason for this is that the accuracy of the reference sensor is specified relative to 10 N·m. The expanded uncertainty is calculated as

$$U = k \cdot u_c(M) \quad (6)$$

with a coverage factor of $k = 2$, providing a confidence level of approximately 95%.

Results

Analysis of the Budget: The metrological analysis reveals that the reference sensor (TD110a 10Nm/VA) is the dominant factor, accounting for the largest share of the uncertainty budget. The systematic errors of the mechanical lever-mass system (e.g. precise lever length or local gravity) do not directly increase the measurement uncertainty of the reference value when the sensor is employed as the reference.

Instead, the industrial robot's precision of 20 μ m ensures reproducible loading conditions. This reduces the "Repeatability" component of the sensor signal to a minimum. The integration

of the robotic system effectively eliminates manual alignment errors and parasitic forces, ensuring that the reference sensor operates under sufficient, axial loading conditions. This result underscores the suitability of the robotic system for automated calibration, as it ensures that the uncertainty is limited by the reference instrumentation rather than the handling process.

Realized test stand: Fig. 3 shows the assembled test stand. The T-slot plate was manufactured by an external contractor. All other metal components, such as bearings, adapters and shafts, were made in the university's metal workshop. During assembly, care was taken to ensure the robot was properly grounded.

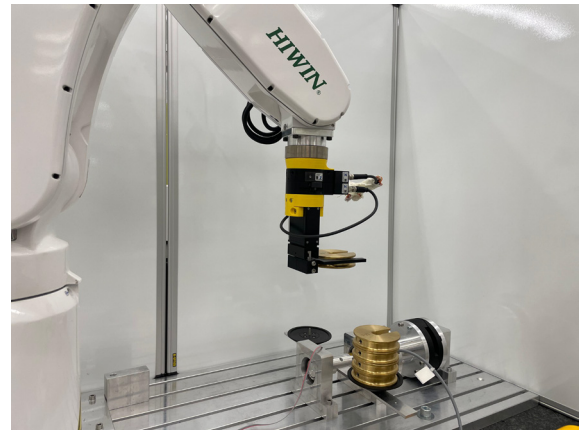


Fig. 3: Photo of the realized test stand.

Measurement: A 3-D-printed inductive torque sensor is used to demonstrate the functionality of the test stand described here. Fig. 4 shows the signals from the 3-D-printed sensor and the reference sensor under stepwise loading. It can be seen that the load can be applied reproducibly employing the test stand. Based on the measured values, the typical parameters of the sensor to be calibrated can be determined.

The next step is to evaluate the test stands' ability to apply consistent and repeatable load levels to the sensor being calibrated. This is achieved by analysing the measured values from the reference sensor across multiple calibration runs and calculating the standard deviation. The load steps are determined automatically and the average value for each level is calculated. This value is then employed as a representative figure for each load step. Clockwise and counterclockwise torque are analysed separately. A total of 24 measurement runs are taken for the test. The results are shown in Table 2. The standard deviations of the load levels are of similar magnitude. The largest standard deviation was observed at level $M_{step} = 2.5$ N·m and

Tab. 1: Measurement uncertainty budget at 10 N·m.

Component x_i	Value x_i	$u(x_i)$	Distribution	Contribution $u_i(M)$
Reference Sensor (TD110a 10Nm/VA)	10 N·m	0.01 N·m	Rectangular	0.00577 N·m
Amplifier Accuracy (GSV-2)	10 N·m	0.005 N·m	Rectangular	0.00289 N·m
Zero Point Drift (Sensor)	-	0.0005 N·m	Rectangular	0.000289 N·m
Zero Point Drift (GSV-2)	-	0.001 N·m	Rectangular	0.000577 N·m
Repeatability (Robot-assisted)	10 N·m	0.002 N·m	Rectangular	0.001155 N·m
Combined $u_c(M)$				0.0066 N·m
Expanded $U(k=2)$				0.0132 N·m

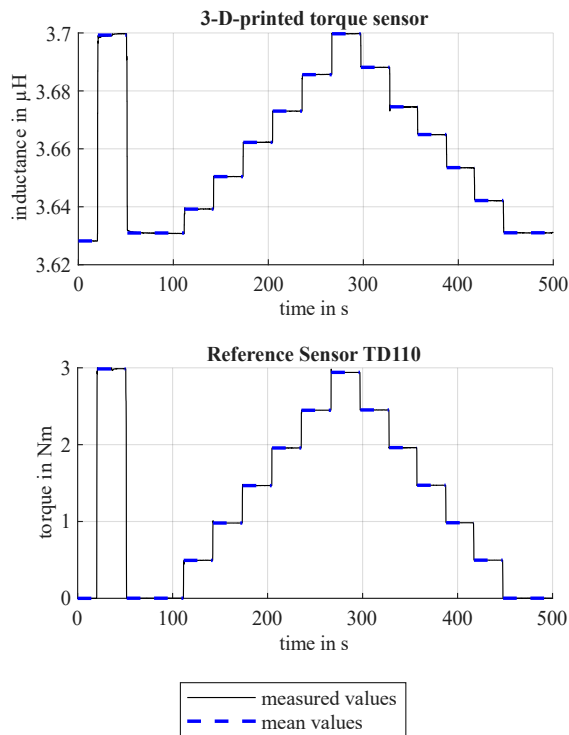


Fig. 4: Measurement values from the reference sensor and the sensor to be calibrated during stepwise loading.

$M_{step} = 2.0 \text{ N·m}$ (clockwise rotation). Overall, the results show that the robot system can be employed to apply load levels reproducibly and perform calibration.

Conclusion

This contribution presents a robot-assisted test stand designed for the automated calibration of 3-D-printed torque sensors. The vertical articulated-arm robot can handle standard weights, effectively eliminating human-induced variability and manual alignment errors. Metrological characterization in accordance with GUM guidelines confirms the system's performance. Defining the reference torque sensor as

Tab. 2: Repeatability of measured values for clockwise and counterclockwise ($n=24$ cycles).

Torque step M_{step} (N·m)	Clockwise		Counterclockwise	
	M_{avg} (N·m)	σ (mN·m)	M_{avg} (N·m)	σ (mN·m)
0.0	-0.01	2.9	0.0	3.0
0.5	-0.51	2.5	0.50	3.2
1.0	-1.03	2.5	0.98	3.3
1.5	-1.54	2.6	1.47	3.3
2.0	-2.06	2.6	1.96	3.4
2.5	-2.58	2.6	2.45	3.5
3.0	-3.10	2.7	2.94	3.5
2.5	-2.58	4.2	2.45	3.2
2.0	-2.06	4.2	1.96	3.2
1.5	-1.54	4.1	1.47	3.2
1.0	-1.03	3.8	0.99	3.4
0.5	-0.52	3.5	0.50	3.3
0.0	-0.01	4.0	0.0	3.3

the primary traceability standard means that the measurement uncertainty is no longer directly influenced by the mechanical tolerances of the lever-mass system. Instead, the robot's positioning repeatability of $20 \mu\text{m}$ ensures that the reference sensor operates under reproducible and sufficient loading conditions, minimizing parasitic forces and off-axis effects. Consequently, the absolute accuracy of the test stand is primarily defined by the accuracy class of the reference sensor (TD110a 10Nm/VA), whereas the robotic handling ensures that this accuracy is reached consistently across all measurement cycles.

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References

- [1] Rainer Schicker and Georg Wegener. *Drehmoment richtig messen*. Hottinger-Baldwin-Messtechnik, Darmstadt, 2002. ISBN: [3000090150](#).
- [2] Max Yiye Cao, Stephen Laws, and Ferdinando Rodriguez y. Baena. Six-Axis Force/Torque Sensors for Robotics Applications: A Review. *IEEE Sensors Journal*, 21(24):27238–27251, 2021. doi: [10.1109/JSEN.2021.3123638](#).
- [3] Lukas Stiglmeier, Thomas M. Wendt, and Stefan J. Rupitsch. 3-D-Printed Torque Sensors: A Review. *IEEE Sensors Journal*, 24(12):18740–18761, 2024. doi: [10.1109/JSEN.2024.3397919](#).
- [4] Jose Eduardo Aguilar-Segovia, Maxime Manzano, Sylvain Guégan, Ronan Le Breton, Alice Farhi-Rivasseau, Sylvain Lefebvre, and Marie Babel. Multi-Material Torque Sensor Embedding One-Shot 3D-Printed Deformable Capacitive Structures. *IEEE Sensors Letters*, 8(9):1–4, 2024. doi: [10.1109/LESENS.2024.3440195](#).
- [5] Dong-Hyuk Lee, Uikyum Kim, Hosang Jung, and Hyouk Ryeol Choi. A Capacitive-Type Novel Six-Axis Force/Torque Sensor for Robotic Applications. *IEEE Sensors Journal*, 16(8):2290–2299, 2016. doi: [10.1109/JSEN.2015.2504267](#).
- [6] Liyue Fu, Aiguo Song, and Dapeng Chen. A Polyetheretherketone Six-Axis Force/Torque Sensor. *IEEE Access*, 7:105391–105401, 2019. doi: [10.1109/ACCESS.2019.2932387](#).
- [7] G. Palli and Salvatore Pirozzi. An Optical Torque Sensor for Robotic Applications. *International Journal of Optomechatronics*, 7(4):263–282, 2013. doi: [10.1080/15599612.2013.879500](#).
- [8] Diedert Peschel and Dirk Röske. Messunsicherheiten bei der Drehmomentmessung. *tm - Technisches Messen*, 72(5):308–317, 2005. doi: [10.1524/teme.72.5.308.64796](#).
- [9] Hans Jörg Fraiss, Lioba Stenner, and Dirk Röske. Development of a New 400 kN m Torque Calibration Machine. pages 1–4, August 30–September 4 2015. Accessed via IMEKO Repository.
- [10] Mikołaj Woźniak and Dirk Röske. Investigation of the Calibration and Measurement Capabilities of the New 5 kN m Torque Calibration Machine at GUM. pages 1–4, August 30–September 4 2015. Accessed via IMEKO Repository.
- [11] Dirk Röske. Metrological Characterization of a 1 Nm Torque Standard Machine at PTB, Germany. *Metrologia*, 51(1):87–96, 2014. doi: [10.1088/0026-1394/51/1/87](#).
- [12] Hiwin GmbH. Montageanleitung RA605-710-SL-A, 08 2001. Dokumentationsnummer: RA605-01/2-DE-2001-MA.
- [13] ME-Meßsysteme GmbH. *Datenblatt TD110a 10Nm/VA*. ME-Meßsysteme GmbH, Hennigsdorf, Deutschland, 05 2026. Dokumentationsnummer: 6480.
- [14] Joint Committee for Guides in Metrology (JCGM). JCGM 100:2008. Evaluation of measurement data – Guide to the expression of uncertainty in measurement. Guide, BIPM, 2008. GUM 1995 with minor corrections; corrected version 2010.