Quantitative Assessment of Sensor Accuracy for Estimating Vertical Deflection in Telescopic Robotic Rails

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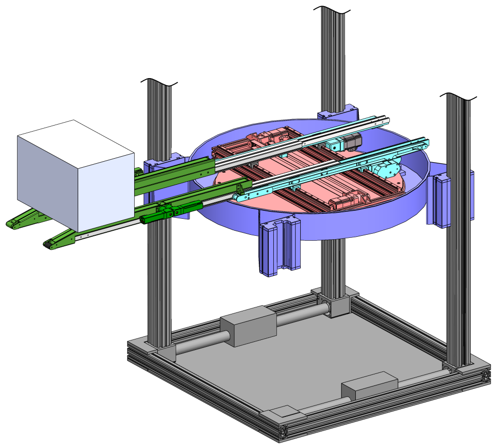

Digital twins of mechanical systems are increasingly establishing themselves as a key technology in industrial automation, particularly in the context of Industry 4.0 [1]. The continuously mapping of the system behavior into the extended dynamic description within a virtual environment opens up opportunities for state monitoring, performance optimization, fault prediction and the implementation as well as validation of advanced control strategies [2]. In the domain of robotics employing telescopic rails for extended reach in automated picking operations, the practical realization of such digital representations critically depends on accurately predicting load-induced deflections. Achieving this requires not only high-fidelity structural models, but also the correct identification of system parameters and a continuous supply of measurement data that provides accurate real-time information on vertical displacement in order to maintain grasp accuracy, avoid prolonged cycle times, and prevent failures [3]. Despite this critical role, deflection sensing in industrial contexts is still frequently overlooked or reduced to coarse approximations, which do not provide the data quality needed to support high-fidelity digital twins.

To address this gap, we present a quantitative assessment of sensor systems for estimating vertical deflection in telescopic robotic rails under varying operational loads and different rail extensions. Four sensing modalities are investigated, spanning a broad spectrum of performance and cost: a high-precision laser Doppler vibrometer [4], a Bosch laser distometer [5], a low-cost MPU6050 inertial measurement unit (IMU) and the integrated accelerometer-gyroscope system of an iPhone 14. Each sensor system is systematically evaluated in terms of measurement precision, absolute accuracy, noise robustness and practical deployability within industrial environments. Since inertial sensors such as the iPhone and the MPU6050 provide angular rather than displacement data, their signals are interpreted through an extended state observer that integrates angular velocity and acceleration according to an equivalent Bernoulli-Euler beam representation of the telescopic rail.

In addition to this analytical observer-based approach, an alternative model derived directly from CAD geometry and validated via finite element simulations is implemented, allowing us to cross-check the suitability of model-driven transformations.

Experimental trials are conducted on a roller-gripper robotic picking platform under representative payload conditions. Each sensor modality is benchmarked against the laser Doppler vibrometer, serving as the reference standard, and their performance is compared with respect to bias, noise characteristics, and responsiveness to different payloads. The results reveal distinct trade-offs between achievable accuracy, integration effort, and cost: while the laser Doppler vibrometer delivers sub-millimeter precision, its line-of-sight requirement limits deployability. Conversely, the MPU-based sensing, despite lower absolute accuracy, offers surprising robustness, establishing itself as a viable low-cost fallback for moderate-precision tasks. By systematically analyzing these sensing solutions within a unified mechanical and estimation framework, the study demonstrates that reliable vertical deflection monitoring need not be confined to high-end laboratory instruments, but can instead be realized through an appropriate combination of model-based estimation and cost-effective sensing, ultimately paving the way for more resilient and adaptive automation in industrial robotics.

Literatur

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