Enhancing Robotic Precision in Construction: A Modular Factor Graph-Based Framework for Deflection and Backlash Compensation Using High-Accuracy Accelerometers

Julien Kindle[1,2], Michael Loetscher[2], Andrea Alessandretti[2], Cesar Cadena[1], Marco Hutter[1]

[1]Robotic Systems Lab, ETH Zurich, Switzerland [2]Hilti AG, Schaan, Liechtenstein

Summary

- We propose a method for tightly fusing high-accuracy accelerometer data with joint states and sparse total station measurements to compensate for static deflections in robotic systems with long kinematic chains.
- The approach is based on physics-informed models to combine backlash and deflection effects with accelerometer measurements and utilizes a modular factor graph formulation.
- Experiments on six datasets, recorded with a large-scale construction robot, demonstrate that the proposed method achieves a 50% reduction in positioning error compared to the state-of-the-art Virtual Joint Method (VJM). The datasets have been publicly released[3].

Approach

Two calibrated ADXL355 accelerometers are utilized, one mounted at the robot's base and another at the column tip. To integrate these measurements effectively, both linear deflection and joint backlash parameters are optimized for, constrained by the assumption of linear change across all joints.

With the robot base stationary, the robot is "stationed" by positioning the end-effector at four distinct configurations, simultaneously capturing static measurements from the total station and accelerometers. These measurements, together with the deflection models, are incorporated into a factor graph. This setup enables accurate extrapolation of the end-effector pose with millimeter-level precision without continuous total station measurements.

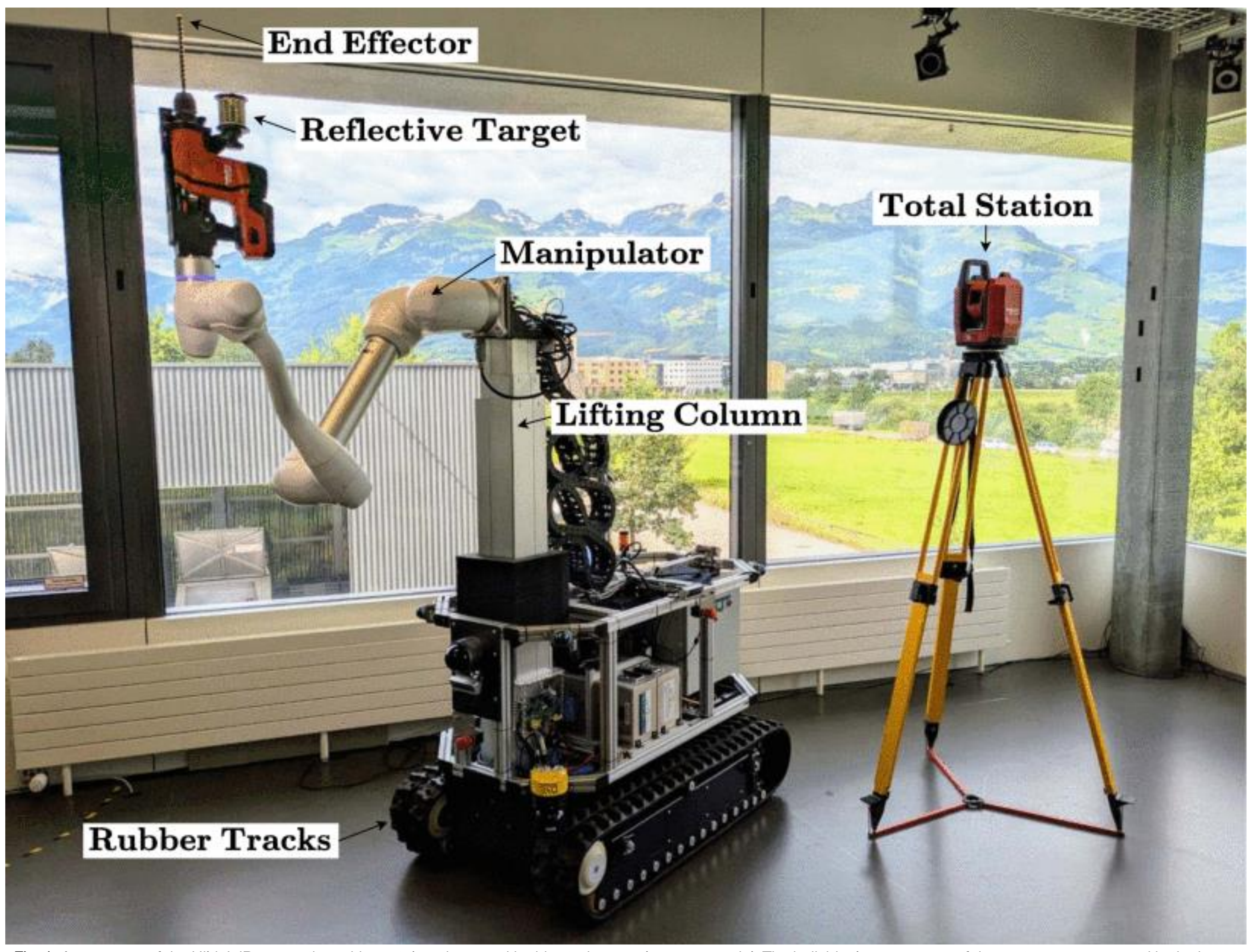

Fig. 1: A prototype of the Hilti JaiBot, together with a total station, used in this study to evaluate our model. The individual components of the system are annotated in the image.

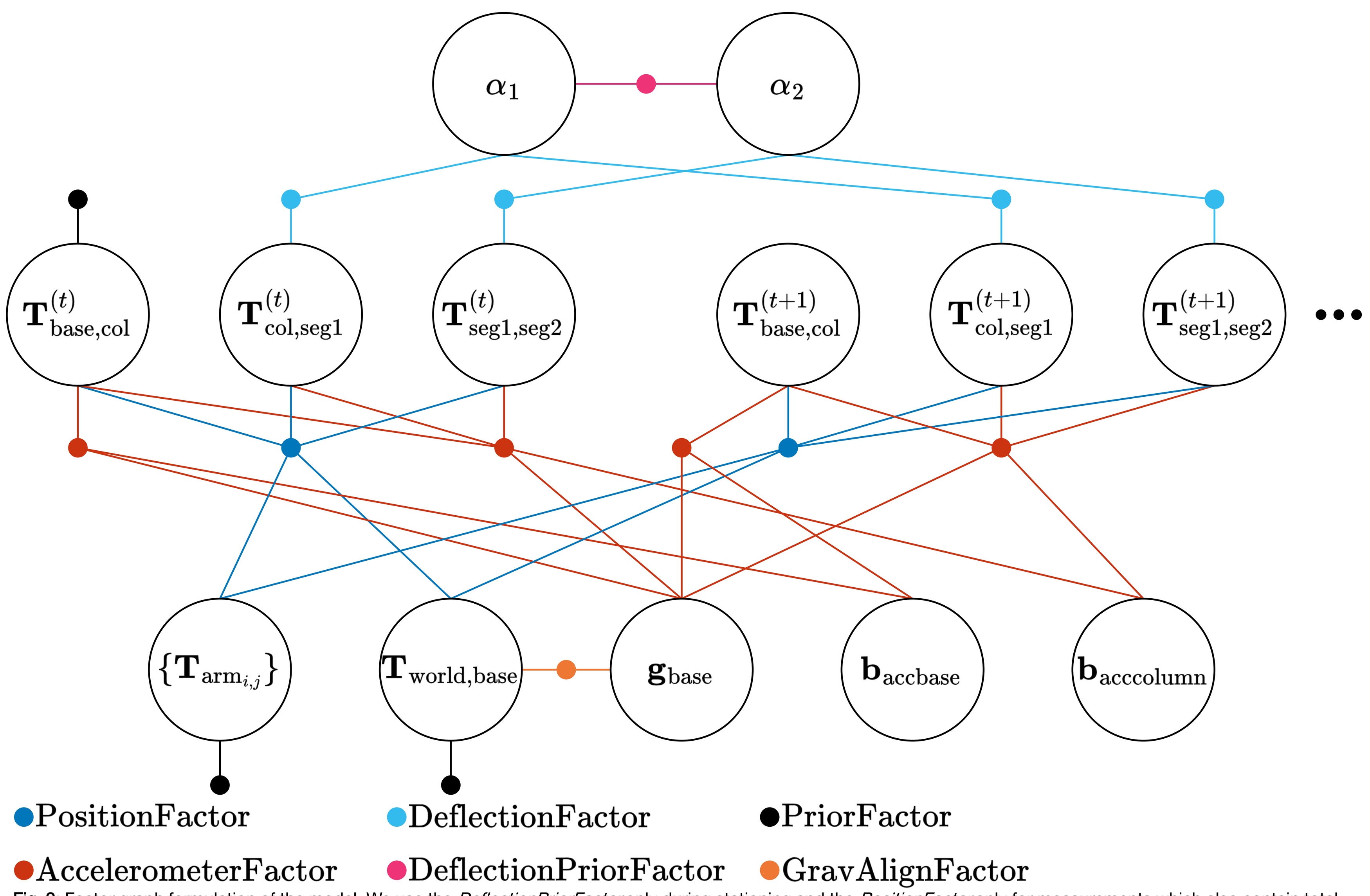

Fig. 2: Factor graph formulation of the model. We use the *DeflectionPriorFactor* only during stationing and the *PositionFactor* only for measurements which also contain total station measurements.

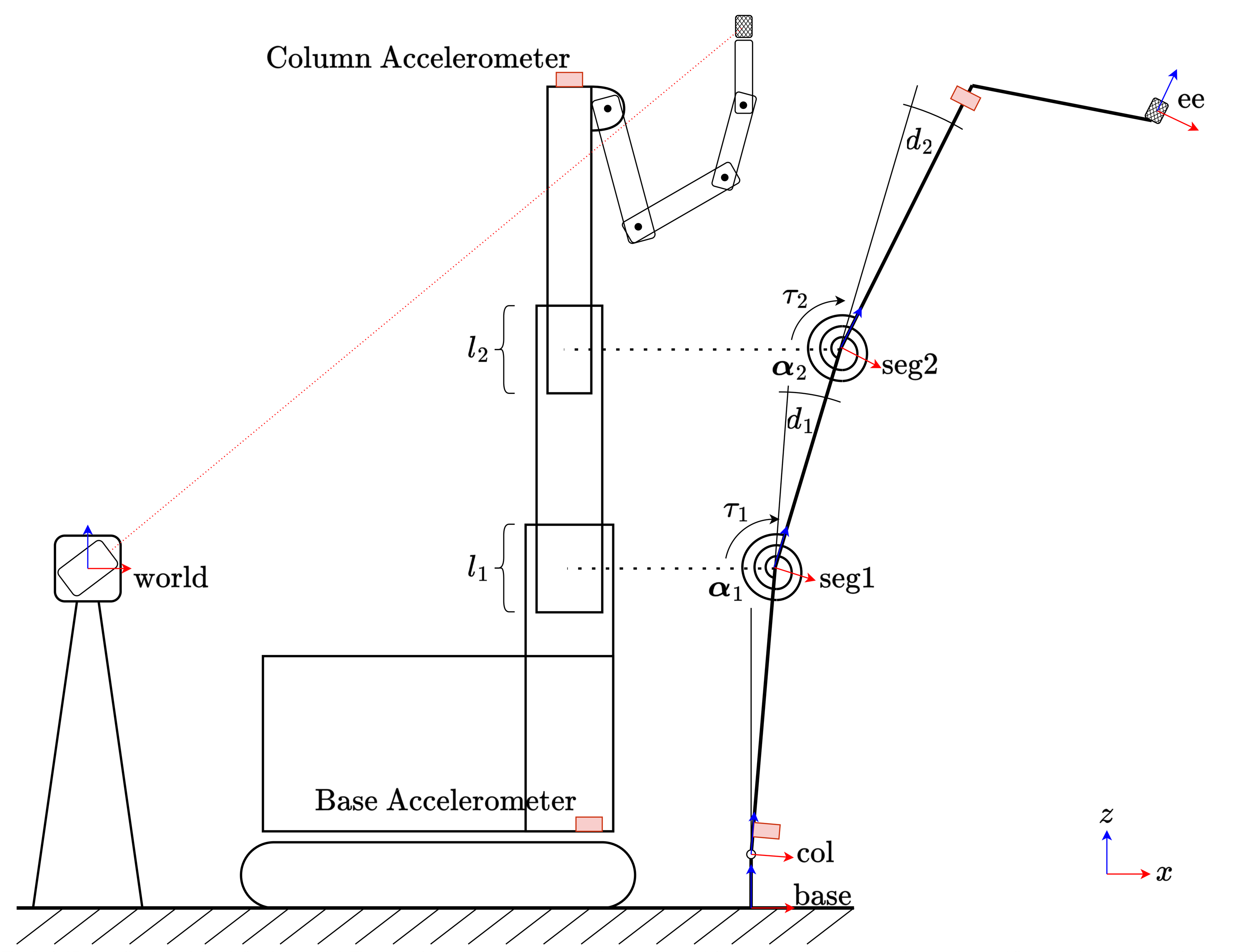

Fig. 3: A 2D visualization of the deflection model. The model is composed of a compliance part modeling the base-environment interaction and linear springs with backlash for each column joint.

PositionFactor Residual

$$\mathbf{r}^{(t)}_{\text{pos}}(\mathbf{T}_{\text{world,base}}, \{\mathbf{T}_{\text{arm}_{i,j}}\}, \{\mathbf{T}^{(t)}_{\text{chain}}\}) = \tilde{\mathbf{m}}^{(t)}_{\text{pos}} - \left[\mathbf{T}_{\text{world,base}} \left(\prod_{\mathbf{T}_{i,j} \in \{\mathbf{T}^{(t)}_{\text{chain}}\}} \mathbf{T}_{i,j}\right) \text{fk}(t, \{\mathbf{T}_{\text{arm}_{i,j}}\})\right]_{\mathbf{t}}$$

DeflectionFactor Residual

$$\mathbf{r}^{(t)}_{\text{defl}}(\mathbf{T}^{(t)}_{\text{parent,child}}, \boldsymbol{\alpha}_r, \boldsymbol{\alpha}_p) = \left[\mathbf{T}^{(t)}_{\text{parent,child}}\right]_{\mathbf{R}} \boxminus \mathbf{R}^{(t)}_{\text{model}}$$

$$\mathbf{R}^{(t)}_{\text{model}} = \mathbf{R}_x(d(\tau^{(t)}_x, l, \boldsymbol{\alpha}_r))\mathbf{R}_y(d(\tau^{(t)}_y, l, \boldsymbol{\alpha}_p))$$

$$d(\tau, l, \boldsymbol{\alpha}) = \frac{\alpha_1}{2l} \arctan(\alpha_2 \tau) + \frac{\alpha_0}{l\tau}$$

AccelerometerFactor Residual

$$\mathbf{r}^{(t)}_{\text{acc}}(\mathbf{g}_{\text{base}}, \mathbf{b}, \{\mathbf{T}^{(t)}_{\text{chain}}\}) = \tilde{\mathbf{m}}^{(t)}_{\text{acc}} - \left(\left[\prod_{\mathbf{T}_{i,j} \in \{\mathbf{T}^{(t)}_{\text{chain}}\}} \mathbf{T}_{i,j}\right]_{\mathbf{R}} \mathbf{g}_{\text{base}} + \mathbf{b}\right)$$

DeflectionPriorFactor Residual

$$\mathbf{r}_{\text{deflprior}}(\boldsymbol{\alpha}_l, \boldsymbol{\alpha}_u) = \begin{bmatrix} \alpha_{l,0}\,\beta_{u,0} - \alpha_{u,0}\,\beta_{l,0} \\ (\alpha_{l,1} - \beta_{l,1}) - (\alpha_{u,1} - \beta_{u,1}) \end{bmatrix}$$

Results

Evaluations on six diverse datasets compare the proposed method against both the conventional VJM and an enhanced variant using only the base accelerometer as a tilt sensor (VJM&BT). By tightly coupling accelerometer data to the deflection model, the 95% xy-plane error threshold is reduced significantly - from 7.0 mm (VJM) and 5.1 mm (VJM&BT) to 3.5 mm. An ablation study indicates that the column-mounted accelerometer is the primary source of information for detecting deflection-induced errors. Additionally, it shows that the base accelerometer has a negative impact on the z-error. This may be due to modeling the ground contact as a point while in fact the tracks behave more like a four-bar linkage.

	Pallet	Orthogonal Wood	Wood Left	Seesaw	Diagonal Wood	Outdoor	Overall
VJM	4.7(11.0)|2.7(4.7)	4.8(9.5)|2.6(4.2)	9.6(14.7)|3.4(4.5)	8.8(13.9)|3.0(4.0)	5.4(10.3)|2.8(4.4)	4.6(7.2)|3.1(5.2)	7.0(14.7)|3.0(5.2)
VJM&BT	4.4(10.0)|**2.7**(4.7)	4.6(9.5)|**2.5**(4.2)	4.3(9.5)|**2.7**(4.2)	6.8(12.6)|2.8(3.8)	4.6(9.1)|2.6(4.3)	4.5(7.3)|**3.0**(5.3)	5.1(12.6)|**2.8**(5.3)
FG (ours)	**3.5**(6.2)|2.9(4.3)	**3.6**(4.6)|2.8(4.4)	**3.3**(4.5)|2.9(3.8)	**3.8**(6.2)|**2.8**(4.2)	**3.0**(5.7)|**2.4**(3.9)	**3.8**(4.9)|3.1(4.9)	**3.5**(6.2)|2.8(4.9)

TABLE II: 95% error threshold and maximum error in the xy-plane and z-axis in millimeters for different configurations and datasets, denoted as $R95_{xy}(max_{xy})$ | $R95_z(max_z)$.

	$R95_{xy}$	max_{xy}	$R95_z$	max_z
Full Model (FG)	3.5	6.2	2.8	4.9
Without Base Accelerometer	4.1	8.1	2.4	4.4
Without Column Accelerometer	5.1	15.9	3.4	5.4
Without Both Accelerometers	6.8	16.9	2.9	5.0

TABLE III: Ablation study of our proposed approach FG on the overall performance. All units in millimeters.

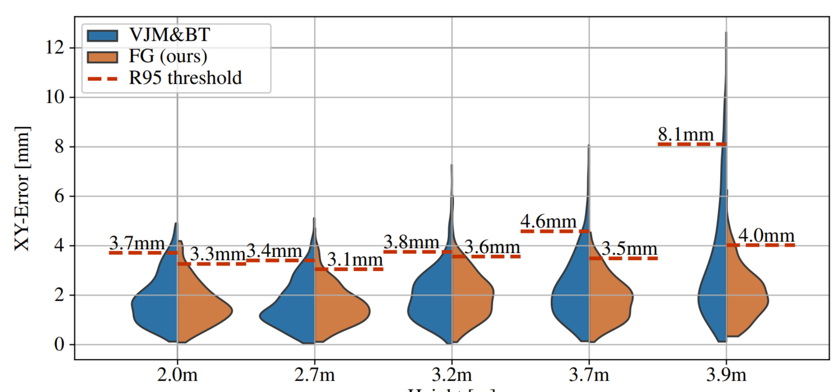

Fig. 7: Histogram of XY-Errors for all individual column heights for our proposed approach FG and the baseline VJM&BT.

[3] Datasets available at: https://github.com/Hilti-Research/construction-robot-stationing-datasets

Paper DOI: **10.1109/LRA.2024.3506276**