

Uncertainty modeling of refraction effects in non-central camera calibration

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Key words: Photogrammetry; LiDAR-camera multi-sensor system ; camera calibration; ChArUco board; refraction model; uncertainty propagation

SUMMARY

With the rapid adoption of LiDAR-camera multi-sensor system (MSS) in industrial and intelligent perception, accurate calibration of camera intrinsics is critical for reliable sensor fusion and robust scene understanding. Target-based camera calibration with ChArUco board or checkerboard is, however, limited by the quality of corner measurements. In practice these measurements carry uncertainty that propagates through the calibration pipeline and can bias both intrinsics and extrinsics. Moreover, in this work, in order to enable the camera to operate in extreme environments, the camera is enclosed in a protective housing with a front-mounted dome port. The dome port introduces refraction that perturbs ray geometry and invalidates standard pinhole mappings from 3D points to the image plane.

To address these challenges and improve LiDAR-camera sensor fusion, this study incorporates a physically grounded refraction model for an in-air dome-port camera into the imaging model. Uncertainty is explicitly modelled by assigning a covariance matrix to each detected ChArUco corner, and these uncertainties are propagated to the estimated intrinsics, distortion coefficients, extrinsics, and the decentring between the dome port centre and the camera optical centre. The resulting parameter estimates are accompanied by statistically justified covariance matrices, enabling uncertainty-aware residual weighting during optimization. This yields more consistent LiDAR-camera alignment and improves the accuracy of downstream state estimation.

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FIG Congress 2026
The Future We Want - The SDGs and Beyond
Cape Town, South Africa, 24–29 May 2026