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MECHANICS-DRIVEN CALIBRATION OF DEPTH CAMERAS FOR 3D MOTION CAPTURE

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Introduction. Consumer-grade depth cameras (e.g., Microsoft Azure Kinect, Intel RealSense) provide affordable 3d tracking, but they suffer from systematic depth distortions, particularly near edges and at longer ranges. Inaccurate depth results in errors in biomechanical measurements (joint angles, segment lengths), compromising both clinical gait analysis and ergonomic assessments. We can derive a physics-informed correction model that generalizes across the camera's workspace by utilizing a simple, controlled mechanical rig with known geometry.

Problem Statement

1. Geometric distortion: Depth error often varies nonlinearly with distance, incident angle, and pixel location.
2. Existing calibration: Standard chessboard or sphere-based calibrations correct intrinsic parameters but do not address per-pixel depth bias under real-world motion.
3. Goal: Develop a calibration procedure that uses known rigid-body motions to fit a corrective mapping $d_t = f(d_m, u, v)$, where $(u, v)$are image coordinates.

Proposed Approach

Mechanical calibration rig: A precision bar of length L-end markers tracked optically (e.g., reflective spheres). The bar is rotated through a set of known angles and translated along known axes.
Data collection: Record synchronized depth frames and marker positions from a motion-capture system (ground truth).
Error modeling: For each pixel along the bar's projection, compute measured depth Fit a basis-function model:

$d_t = a_0 + a_1 d_m + a_2 u d_m + a_3 v d_m + a_4 d^2{}_m + \cdots$, where coefficients a_i capture spatially varying depth bias.

We seek a mapping $d_t = f(d_m, u, v)$, where d_m is measured depth in meters, u, v are pixel coordinates, d_t is true depth in meters, obtained from motion-capture ground truth [2]. To obtain mapping we use multivariate polynomialof total degree p[1]. For example, with $p = 2$ we include all terms

$\{1, d_m, u, v, d^2{}_m, u^2, v^2, d_m u, d_m v, uv\}$. In general, the number of basis functions is $\frac{(p+3)!}{3!p!}$. For each calibration frame and for each pixel along the known bar projection we get one sample$(d_m^{(i)}, u^i, v^i)$ with true depth $d_t^{(i)}$. To normalize depths, we subtract the mean divide by the working range span Δd. Now in design matrix X, each row i contains $X_{i,j} = \phi_j(d_m^{(i)}, u^{(i)}, v^i)$, where ϕ_i is monomial [3].
To find coefficient vector $a = [a_o, a_{1,\dots}]^T$, we use the least squares method $min_a||Xa - d_t||^2$. We use ridge regressionto prevent overfitting-especially at higher p, we add a penalty$min_a||Xa - d_t||^2 - \lambda||a||^2$. λ is chosen via leave-one-out or k-fold cross-validation on calibration set.

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КАЛІБРУВАННЯ КАМЕРГЛИБИНИ НА ОСНОВІ МЕХАНІКИ ДЛЯ ТРИВИМІРНОГО ЗАХОПЛЕННЯ РУХУ

Камериглибини споживчого рівня (наприклад, Microsoft Azure Kinect, IntelRealSense) забезпечують доступне 3D-відстеження, але страждають від систематичних спотворень глибини, особливо біля країв кадру та на великих відстанях. Неправильне визначення глибини призводить до помилок у біомеханічних вимірюваннях (кутів суглобів, довжин сегментів), що погіршує як клінічний аналіз ходи, так і ергономічні оцінки. Використовуючи простий контрольований механічний стенд із відомою геометрією, можна побудувати фізично обґрунтовану модель корекції, яка коректує спотворення по всьому робочому простору камери.