

Single-filament spatial calibration for robotic ultrasound

J. Osburg^{1*}, R. Bruder¹, A. Kalz² and F. Ernst¹

¹ Institute for Robotics and Cognitive Systems, University of Luebeck, Luebeck, Germany

² Kurt-Semm-Zentrum & Kurt-Semm-Akademie, UKSH, Campus Kiel, Germany

* Corresponding author, email: j.osburg@uni-luebeck.de

Abstract: We present a straightforward spatial calibration method for robotic ultrasound using only a single nylon filament as a geometric reference. By tracking the probe motion and extracting the filament intersection in each 2D ultrasound frame, the rigid transformation between the ultrasound image and the robot end-effector is estimated through a point-to-line optimization. The procedure requires no specialized phantoms and can be performed within minutes, making it well suited for automated robotic ultrasound applications.

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I. Introduction

Ultrasound (US) imaging provides real-time, radiation-free imaging with good soft-tissue contrast, making it well suited for interventional procedures. Integrating US imaging with robotic systems enables controlled and repeatable probe motion, supporting consistent image acquisition and reducing manual workload. To enable correct spatial mapping required for several tasks like 3D US image reconstruction or multimodal image fusion, spatial calibration is needed. Thus, the transformation between the robot's end-effector frame and the coordinate system of the US image can be determined. Spatial calibration is typically done using pre-made phantoms [1, 2] or image-based methods [3], but these approaches often require specialized hardware or complex image processing steps, which increases system complexity. Thus, we propose a single-filament approach, that provides a fast, practical and lightweight alternative for spatial calibration in robotic US.

II. Material and methods

The aim of this method is to find the rigid transformation between the US image coordinate system and the robot's end-effector frame by observing a thin, straight-line target.

II.I. Data acquisition

A twisted nylon thread is fixed between a 3D-printed holder (see Fig. 1A). The holder is placed inside a water bath, which is positioned within the robot workspace. The thread remains straight and stationary throughout the experiment.

The US probe (*Philips XL14-3*) is mounted at the robot end effector using a 3D printed probe holder with known geometry. Firstly, the robot (*KUKA iiwa 14*) is controlled in gravity compensation mode. This enables the probe to be positioned above the filament in hand-guiding mode (see *start pose* in Fig. 2), ensuring that the filament is clearly visible in the US image (see Fig 1B). Subsequently, the

robot moves the probe along roughly 2 cm of the filament while varying its orientation and continuously acquiring US data with corresponding end effector poses.

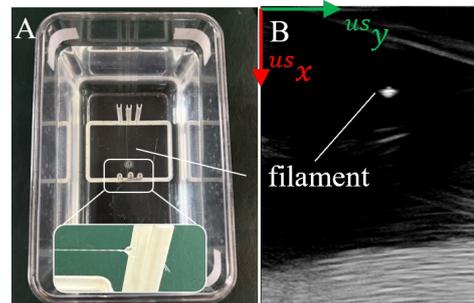


Figure 1: A: Nylon thread passed through a small hole in the holder (fixed with hot glue) and placed in a water tank. B: Exemplary US image showing the filament as the brightest area; gray regions at the bottom are reflection artifacts from the tank.

II.II. Calibration procedure

To determine the position of the filament, the intersection points in the US images must be extracted, represented by the cluster of brightest pixels in the image (see Fig. 1B). This is done by computing a percentile-based intensity threshold (e.g., the 99.5th percentile, determined experimentally) and classifying all pixels exceeding this value as bright candidate regions with respective intensity-weighted centroids as candidate filament positions. Then, a frame-to-frame tracking rule is applied, selecting the candidate located closest to the position in the previous image and within a radius of 10 px. The resulting filament image coordinates are converted to metric units (known image spacing from US station) and embedded into 3D by assigning a fixed depth z , yielding points ${}^{us}x_i = (u_i, v_i, 0)^T$ in US coordinates. For each observation i , the image point is transformed into the robot base frame as:

$${}^b x_i = {}^b R_{ee} ({}^{ee} R_{us} {}^{us} x_i + {}^{ee} t_{us}) + {}^b t_{ee,i}.$$

All transformed points ${}^b x_i$ must lie on the same physical line $L = (P, D)$. With respect to the robot's base frame, $P \in \mathbb{R}^3$ is a point on the filament and $D \in \mathbb{R}^3$ is a unit direction vector, describing the filament's orientation. The orthogonal distance between a point and this line is:

$$\text{dist}({}^b x_i, L) = \|(I - DD^T)({}^b x_i - P)\|.$$

We estimate all unknowns jointly by minimizing the sum of squared perpendicular distances:

$${}^{ee}R_{us}, {}^{ee}t_{us, P, D} \min \sum_i \|(I - DD^T)({}^b x_i - P)\|^2,$$

subject to $\|D\| = 1$ and ${}^{ee}R_{us} \in SO(3)$.

Rotation ${}^{ee}R_{us}$ is parameterized via a 3-vector exponential map (axis-angle), and the line direction D is normalized after each iteration. The optimization is solved with a standard nonlinear least squares solver (Levenberg-Marquardt). We initialize ${}^{ee}R_{us}$ and ${}^{ee}t_{us}$ based on the CAD model of the probe holder, resulting in an estimated transformation from the end effector to the origin of the US image ${}^{ee}T_{us, init}$. Using this initial transformation, all US points are transformed into the base frame, and a PCA line fit provides initial estimates for P and D . The optimization output is the rigid transform ${}^{ee}T_{us}$ as well as the filament line $L = (P, D)$.

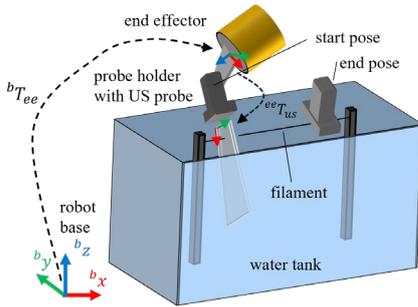


Figure 2: Experimental setup of calibration procedure. An exemplary start and end pose of the US probe are shown.

III. Results and discussion

For evaluation, the accuracy of the calibration procedure was determined by computing the Euclidean point-to-line distances between all reconstructed filament points and the estimated filament line in the robot base frame. This resulted in a mean calibration error of 0.35 mm. In addition, the axis-wise residuals were 0.16 mm for the x-, 0.12 mm for the y- and 0.25 mm for the z-direction. This anisotropy arises because the out-of-plane elevation of the 2D US plane is not directly observed and is only indirectly constrained by probe motion. For a horizontally oriented filament, gravity-related effects such as slight sagging preferentially project into the vertical direction, leading to larger residuals there. Although the metrics capture internal geometric consistency rather than absolute spatial accuracy, it remains suitable for qualitative evaluation. For comparison, the reconstruction of the filament points obtained using the known initial estimate ${}^{ee}T_{us, init}$ resulted in a mean error of 6.3 mm. The calibrated transformation thus strongly improves the alignment of the points along the filament. This can also be seen in Fig. 3A,

where the reconstructed filament points obtained using the optimized transformation ${}^{ee}T_{us}$, align closely along a straight filament line. In contrast, in Fig. 3B the points computed from the initial guess ${}^{ee}T_{us, init}$ exhibit larger deviations.

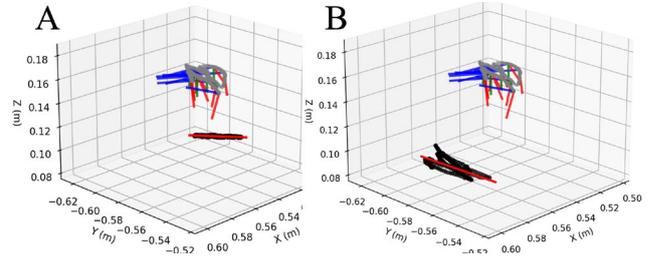


Figure 3: Visualization of US probe path as grey points with respective poses as RGB coordinate frames (red = x-axis, green = y-axis, blue = z-axis). The filament is reconstructed as black points in the base frame. A shows the result for the determined optimized transform ${}^{ee}T_{us}$, while B shows the result with the rough initial estimate ${}^{ee}T_{us, init}$.

A key advantage of the presented method is the very simple phantom design. By estimating the filament line and the transform ${}^{ee}T_{us}$ jointly, the need for complex and usually expensive rigid multi-marker phantoms is eliminated. These special, prefabricated multi-marker phantoms rely on several targets whose relative positions must remain fixed over time. When the material ages, deforms, or dries out, this internal geometry can change, which reduces calibration accuracy. However, a key limitation is the strong dependence on the initial estimate ${}^{ee}T_{us, init}$. Because the optimization is nonlinear and contains multiple local minima, poor initialization can lead to a geometrically valid but incorrect US-to-flange transformation. This issue is especially relevant when different end-effectors or probes are used, as calibration cannot be fully automated. Future work could investigate the use of global optimization approaches or the use of a non-symmetric target (e.g. multiple filaments in different heights), that might improve robustness by reducing ambiguity and dependence on the initial guess. Moreover, alternative filament extraction methods, such as squared-intensity thresholding, should be explored to improve robustness under low-contrast conditions.

IV. Conclusions

The proposed method is simple, low-cost, and easy to reproduce, requiring only a fixed nylon filament and a water bath, and can be completed within minutes, offering strong potential for robotic US applications.

AUTHOR'S STATEMENT

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