Rigid 3D calibration in a surgical scenario

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***Abstract*—Autonomy is the next frontier of research in robotic surgery and its aim is to improve the quality of surgical procedures in the next future. One fundamental requirement for autonomy is advanced perception capability through vision sensors. In this paper, we propose a novel calibration technique for a surgical scenario with a da Vinci® Research Kit (dVRK) robot. Camera and robotic arms calibration are necessary to precise position and emulate expert surgeon. The novel calibration technique is tailored for RGB-D cameras. Different tests performed on relevant use cases prove that we significantly improve precision and accuracy with respect to state of the art solutions for similar devices on a surgical-size setups.**

***Index Terms*—Autonomous robotic surgery, calibration, RGB-camera**

I. Introduction

A significant part of current research in Robotic-assisted Minimally Invasive Surgery (R-MIS) is focussing on the development of autonomous systems for the execution of repetitive surgical steps, such as suturing, ablation and microscopic image scanning [1]. Autonomy requires systems with advanced perception, reasoning and motion planning, as highlighted in [2], [3]. However, image-guided interventions require an accurate calibration to map poses of robots, instruments and anatomy to a common reference frame. We propose a novel calibration method for the surgical robotic scenario using the da Vinci® Research Kit (dVRK) and an RGB-D camera. We perform exhaustive experimental validation on relevant use cases for surgery. We separate the calibration of the robotic arms (two Patient-Side Manipulators, PSM1 and PSM2, and an Endoscope Camera Manipulator, ECM) from the hand-eye calibration of the camera. For both calibrations we propose a three-step method with closed-form solution:

1) touching reference points on a custom calibration board with the end-effectors of the surgical robot.
2) recognizing the same reference points with the RGB-D camera.
3) mapping the poses reached by the robotic arms in the first step to the 3D points computed in the second step.

The main advantage of the proposed method is the improved accuracy in a 3D metric space and with our method the camera can be mounted on the moving endoscopic arm of the dVRK, overcoming the limitations of a fixed camera.

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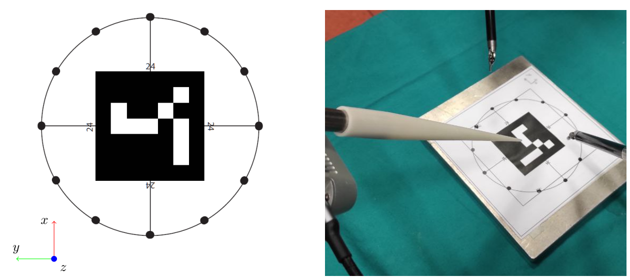
II. The framework

We use a custom calibration board, shown in Figure 1a, with an ArUco marker in the center of a circumference of $50\,\mathrm{mm}$ radius, with several reference dots. We equipped the ECM with a 3D-printed adapter, shown in Figure 1b. The adapter has a smaller tip than the ECM to guarantee precise positioning on the dots on the board.



(a) Calibration pattern (b) ECM adapter

Fig. 1. The calibration components. a) the calibration board with the marker, the coloured axes represents the common reference frame directions b) the adapter for the ECM positioning.

The procedure starts by positioning the calibration board in the robot workspace. We choose a set of reference points P such that each point $p \in P$ is reachable by the three arms and visible from the camera. The points in P must be symmetric with respect to the center of the board to compute the origin of the common reference frame; at least three points are needed to estimate the plane coefficients. The best fitting plane is characterized by the centroid of the point set P, $\mathbf{c}$, and the normal vector $\mathbf{n}$. Their optimal estimations are the solution of the optimisation problem

$$\{\hat{\mathbf{c}}, \hat{\mathbf{n}}\} = \arg\min_{\mathbf{c}, |\mathbf{n}|_2=1} \sum_{i=1}^{n} ((\mathbf{p}_i - \mathbf{c})^T \mathbf{n})^2 \qquad (1)$$

To generate a common reference frame for all the tools, we use tele-operation provided by the dVRK to position the end effector of the PSMs and the ECM on points in P. To this aim, we mount the 3D-printed adapter shown in Figure 1b on the ECM. We touch points with each arm in the same order, then we place the tools above the board to define the plane normal direction.

Afterwards, we proceed with the 3D hand-eye calibration of the camera. We first detect the center of the Aruco marker on the board with respect to the camera frame. Once we get