Cooperative Robotic Gamma Imaging: Enhancing US-guided Needle Biopsy*

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Abstract. Sentinel lymph node (sLN) biopsy mostly requires an invasive surgical intervention to remove sLNs under radioguidance. We present an alternative method where live ultrasound is combined with live robotic gamma imaging to provide real-time anatomical and nuclear guidance of punch biopsies. The robotic arm holding a gamma camera is equipped with a system for inside-out tracking to directly retrieve the relative position of the US transducer with respect to itself. Based on this, the system cooperatively positions the gamma camera parallel to the US imaging plane selected by the physician for real-time multi-modal visualization. We validate the feasibility of this approach with a dedicated gelatine/agar biopsy phantom and show that lymph nodes separated by at least 10 mm can be distinguished.

1 Introduction

The concept of multi-modal imaging is well established in the domain of nuclear medicine, where SPECT/CT, PET/CT, and PET/MR all combine functional with anatomical information. As such, the combination of these modalities is mostly limited to whole-body systems, with notable exceptions being the ClearPEM-Sonic [1] and endoTOFPET-US [2] projects for organ-specific PET and ultrasound (US) imaging. A procedure likely to benefit from a combination of functional and anatomical data is the sentinel lymph node (sLN) biopsy for breast cancer patients, where a radiotracer or colored dye is injected close to the cancer and its spread through the lymphatic system is monitored to identify the first series of nodes that are biopsied for histological assessment. The presence of cancer cells is a key element in staging the disease.

Classic radio-guided surgery uses a 1D gamma probe or a 2D gamma camera to identify radioactive-positive lymph nodes in open surgery [3]. Since these techniques provide functional information only, open surgery is required for the

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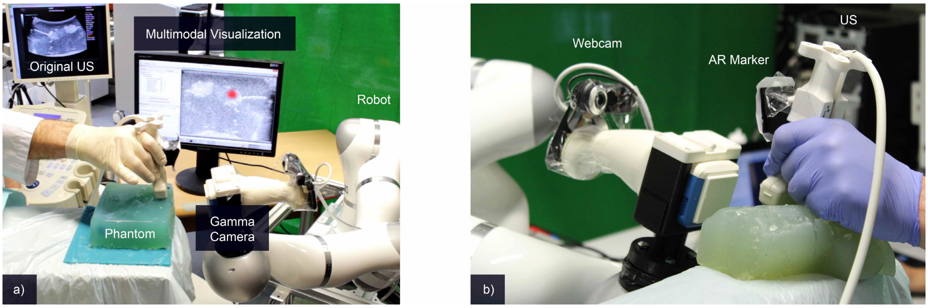

Fig. 1. a) View of the full setup and b) close-up of the multimodal image acquisition.

removal of sLNs. The possibility of punch biopsy under multi-modal guidance was recently introduced by combining freehand SPECT with 3D compounded ultrasound [4] and extended to thyroid imaging [5]. The current approach, whilst allowing for a combination of nuclear and anatomical information, suffers from having to conduct two subsequent acquisitions. This not only extends the procedure, but further does not provide any correction of anatomical deformations during the US scan or a real-time update of the information in the case of a displacement of the tissues of interest. Finally, they rely on external tracking systems, hampered either by the limited accuracy of electromagnetic tracking or the requirement for a line of sight between the tracked devices and an external optical tracking system respectively.

In this work we suggest a novel approach where the sLN punch biopsy can be performed by a single physician under the assistance of a cooperative robotic arm holding the gamma camera. The arm is equipped with a camera system for inside-out tracking, based on the detection of a 2D-marker as suggested by [6]. Using this tracking approach, the robotic arm cooperatively follows the US transducer during the intervention, where the gamma camera is positioned in a way to provide real-time 2D/2D gamma information and ultrasound images to guide the biopsy needle. While the idea of collaborative robotics has been introduced in the medical environment for telemanipulated systems [7] or laparoscopic camera placement [8], this paper introduces the combination of a light-weight robotic arm with camera-in-hand visual servoing in the context of a combination of functional and anatomical information.

2 Materials and Methods

2.1 Setup

The key element of our setup, as shown in Fig. 1, is a LBR 4+ (KUKA, Germany) light-weight robotic arm. A custom-designed 3D-printed mount attached to the tip of the robot arm is used in order to support both a CrystalCam (Crystal Photonics, Germany) gamma camera as well as a QuickCam Pro 9000 (Logitech, Switzerland) wide angle video camera. Ultrasound imaging is provided by an UltraSonix RP US system (Ultrasonix, MA, USA) with a curvilinear probe (model C5/60). The camera detects the position and orientation of a 2D ArUco marker [6] which is rigidly attached to the ultrasound transducer. We further use an infrared optical tracking system (Polaris Vicra, Northern Digital Inc., Ontario, Canada) during the calibration procedure. A standard punch biopsy needle (HistoCore 250 mm, BIP GmbH, Germany) was used in the experiments.

The system consists of two major software components. The first one is a collection of concurrent processes dedicated to tracking and robot control, while the main purpose of the second is visualization. The only communication between them regards the position of the gamma camera with respect to the US probe, expressed as a 6DoF transform, which is necessary in order to correctly merge the images received from both devices.

2.2 Tracking and Robot Control

Our setup is based on the ROS framework [9], and in particular we leveraged the TF library[1] to maintain a global knowledge of the current position of the individual objects of interest in space. Most notably, this includes the robot, the gamma camera and the US probe.

We make use of a wide-angle camera as tracking device in order to retrieve the relative position of the US probe with respect to the gamma camera, and in turn to the robotic arm. This is achieved through the tracking of an AR marker attached to the probe, which provides the transform ${}^{webcam}_{marker}T$. As the main interest lies in the pose of the tip of the gamma camera with respect to the tip of the US probe, two more transforms are necessary to constitute the calibration of the system: i) a transform from the AR marker to the tip of the US probe defined as a reference frame in the middle of the scanning surface, with the x axis pointing along the probe and z pointing out of the scanning plane, and ii) a transform from the camera to the tip of the gamma camera defined as the center of the sensor, with x pointing to the gamma camera handle and z pointing inside the sensor. This convention minimizes the rotational component between the two tip reference frames.

Calibration. The system requires a one-time calibration in order to find the relative position of the components (robot hand-gamma camera-webcam, AR marker-tip of US probe).

The transformation between the RGB data and gamma camera tip is composed of two individual calibrations with respect to the robot end effector, c.f. Fig. 2a

$$ {}^{webcam}_{gamma}T = {}^{webcam}_{ee}T \ {}^{ee}_{gamma}T, \tag{1} $$

where *gamma* is the gamma tip, *ee* is the robot end effector and *webcam* is the camera reference frame. The transformation ${}^{webcam}_{ee}T$ is found with a procedure based on the Tsai-Lenz algorithm [10] in the eye-on-hand variant, with the

[1] `http://wiki.ros.org/tf`

implementation provided by the ViSP library [11]. In this regard, the robot is moved to several poses such that the camera can observe the AR marker and the ArUco [6] tracking library can estimate the transform from the camera to the marker for each position. The resulting series of corresponding transforms are used as input for the calibration algorithm in order to compute the transform between the camera and the robotic arm end effector.

Next, we retrieve the transform ${}^{ee}_{gamma}T$ using a NDI tracking device and a dedicated instrument that replaces the gamma camera collimator. The transformation between the tracking system and the basis of the robot is found with the eye-on-base variant of the aforementioned Tsai-Lenz algorithm, which requires a marker attached to the robot end effector. Then, the transformation between the calibration tool and the end effector is computed as

$$ {}^{ee}_{gamma}T = {}^{ee}_{tool}T = {}^{ee}_{base}T \; {}^{base}_{NDI}T \; {}^{NDI}_{tool}T, \tag{2} $$

where *base* is the robot base, *NDI* the NDI tracking device, and *tool* the calibration tool reference frame which by definition coincides with the *gamma* reference frame that is the objective of the calibration procedure.

Finally, the calibration of the US tip, *i.e.* the transform ${}^{marker}_{us}T$ from the AR marker to the desired reference frame is retrieved through an analogous procedure. After calibrating the NDI to the robot, an NDI pointer tool is positioned on the tip of the probe. The final transform is then computed from the following transform chain:

$$ {}^{marker}_{us}T = {}^{marker}_{pointer}T = {}^{marker}_{webcam}T \; {}^{webcam}_{ee}T \; {}^{ee}_{base}T \; {}^{base}_{NDI}T \; {}^{NDI}_{pointer}T \tag{3} $$

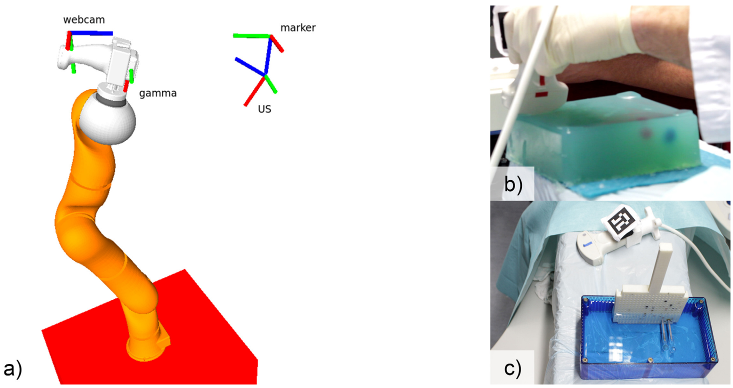

Fig. 2. a) Overview of the reference frames. b) and c) respectively show the gelatine/agar and the plastic sphere phantom.

2.3 Cooperative Path Planning

A static transform is added to the scene in order to represent the desired position of the gamma camera tip with respect to the ultrasound tip. To do so, the gamma frame is placed at a distance of 10 cm and 2 cm in the z and x directions, in order to align the top of the gamma camera and US images and keep a comfortable distance to the patient. The planning software consists of a control loop that runs in a dedicated process, which brings the gamma camera tip in position (0,0,0) with respect to the target reference frame in order to obtain the desired motion:

```
while not shutdown do
    wait for tracking data;
    compute trajectory;
    if success then
        execute trajectory;
        sleep 0.1 seconds;
    end
end
```

Algorithm 1. Robot control loop

Thereby, the sleeping step has a normalization effect and avoids robot vibration and controller overload. The robot movement happens at considerably slow speed (240 mm/s) for various reasons, first of all safety. Furthermore, a slow speed prevents the robot from overshooting the movement in one direction, which would cause the marker to exit the camera image and the tracking to get interrupted. Moreover, a slower movement is also reassuring for both the user and operator. As a safety measure, movement is interrupted when tracking is lost; furthermore, complete trajectory planning is performed at every iteration in order to avoid problems at singular positions or joint limits.

2.4 Image Visualization

The visualization is implemented as a pipeline for the CAMPVis framework [12]. This includes modules to connect to the gamma camera, an OpenIGTLink client receiving images from the US device, and a client for the transformation between the two images, respectively. The US acquisition module provides a live streaming of the US rays, while the gamma camera transmits single events being only visible by integrating them in time for each pixel individually. Hence, the intensity at a given pixel is represented as the number of events that have been observed in the last period of time and is thresholded in order to exclude single random events. In order to resemble the probabilistic nature of the gamma information, pixel information is blurred before visualization using a Gaussian window and alpha blending. For live fusion of US and gamma information, the latter is projected into the US plane along the normal represented by the gamma tip z axis. Thereby, the translation and the varying spatial resolutions are taken into account in order to create a geometrically correct image, resulting in a labeled US image, where radiation is blended in red.

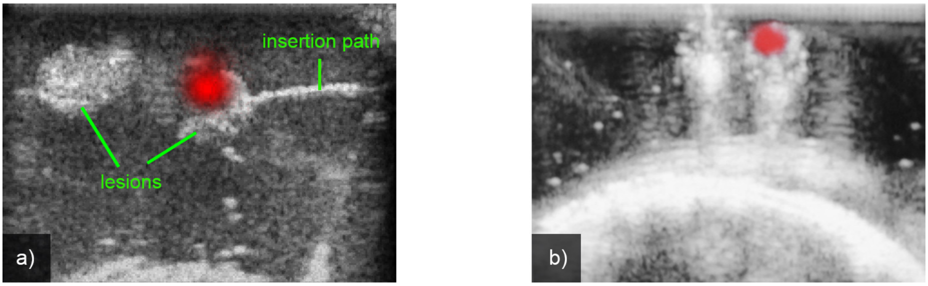

Fig. 3. Multimodal nuclear and US visualization of a) two lesions in the gelatine/Agar phantom and b) two spheres in the accuracy phantom.

3 Experimental Validation

Biopsy Phantom. We evaluate the suitability of the proposed system under two aspects. A first experiment shows the qualitative benefit of the system for a physician performing a sentinel lymph node biospy, provided that it is possible to correctly identify radioactive lymph nodes with this technique. To do so, we use gelatine and agar phantoms for multimodal SPECT (Fig. 2b), CT and US imaging that can be biopsied, following the procedure proposed by [13]. The lymph nodes are mimicked by a mix of 12 weight percent (wt%) of gelatine and 8 wt% of agar, while the surrounding tissue is made of 4 wt% and 1.5 wt% of Agar. 1 MBq of ^{99m}Tc is added to some of the lymph nodes and both, hot and cold nodes are inserted at an average depth of 2 cm into the tissue mimicking material and visually distinguished by blue and red food coloring.

The procedure starts by guiding the gamma camera towards the phantom. In this sense, a medical expert holds the ultrasound transducer into the field of view of the camera mounted on the robot. The ArUco marker is then recognized and the gamma camera follows the US. In the following, a scan for lymph nodes is performed, where the fusion of SPECT and ultrasound helps the examiner to localize the two radioactive nodes within the phantom. If a radioactive-positive target is found, a biopsy is performed under US guidance.

Fig. 3a shows a typical visualization of the combined nuclear and US information for two adjacent nodes. The radioactive-positive lesion is clearly identified. The insertion path of the biopsy needle is also clearly visible. A biopsy study was conducted on 4 lesions, two of which were radioactively labelled. The biopsies confirmed that all lesions were correctly identified in the multi-modal images.

Accuracy. A second experiment evaluates the minimum distance between two nodules, one of which being radioactive-positive, to be distinguished from the other. As shown in Fig. 2c, two plastic spheres with a diameter of 9 mm are filled with 0.5 MBq of ^{99m}Tc each and mounted rigidly on two bars on an evaluation board, where it is possible to change the distance between their centers in steps of 10 mm. The board is set up in a box of water such that the spheres are positioned 3 cm away from the edge of the box and the spheres are covered by

2 cm of water. The ultrasound probe is immersed into the water in order to scan the spheres. The augmented images are visually evaluated to estimate the minimal distance allowing for a clear identification of the radioactive-positive sphere. Fig. 3b shows the multimodal image acquired with the hot and cold spheres adjacent to each other, at a distance of 10 mm between their centers. The hot sphere can be clearly identified.

Marker Tracking Accuracy. As a side experiment we evaluated the precision of the marker tracking application. A marker was fixed to a surface and kept in the field of view of the camera while moving the robot arm. We compared the motion as detected from the marker tracker and the robot controller, and the standard deviation between the two resulted to be 1.7 mm. We deemed the accuracy as appropriate to the needs of the particular clinical application.

4 Discussion

The first part of the experimental validation shows that our approach allows for a clear identification of radioactive-positive nodules, as they can be successfully differentiated from cold nodules in a dedicated multi-modal phantom. The outcome of the biopsy, where every nodule was correctly targeted, confirms that this system can be used to guide a punch biopsy needle. The second experiment shows that even closely located nodules can be distinguished. The system proved to be stable to allow for a full scan of the region of interest to detect and identify nodules and to perform the biopsy during intervention. The robotic arm followed the ultrasound device at a stable distance, providing for an intuitive handling and constant image quality.

On the contrary of [5] and [4], the presented solution provides real-time simultaneous multi-modal nuclear and US imaging, without requiring for consecutive imaging and the need to correct for deformations due to the US acquisition. The use of the camera-in-hand inside-out tracking voids the necessity for an external optical tracking system, relieving the operator from having to pay attention to not obstructing the line of sight. Moreover, the workflow is extremely similar to a standard US-guided punch biopsy, which is familiar to many physicians. On the other side, however, our system does not provide 3D volumetric imaging, consequently requiring the physician to take acquisitions from different directions to be able to distinguish nodes that would be hidden in one particular 2D view. Although using a lightweight robot might seem like an exaggeration at this stage of the development, our system opens the way to further developments on the path of collaborative robotics in the medical environment. In particular, the inclusion of an external RGBD monitoring would provide for live collision avoidance while voice control of the robot would facilitate additional interaction with the robot. Finally, a clinical study will be required in order to evaluate the full feasibility and potential of such an approach.

5 Conclusion

This paper presents the first prototype for cooperative robotic gamma imaging to enhance US-guided needle biopsy and offers a real-time imaging solution that could contribute to reducing the number of open sentinel lymph node resections. It introduces the use of camera-in-hand visual servoing for multi-modal medical image acquisition and opens the way for further developments in this domain.

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