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Short Paper

ICG based Augmented-Reality-System for Sentinel Lymph Node Biopsy

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Abstract

In this paper we introduce a novel augmented-reality (AR) system for the sentinel lymph node (SLN) biopsy. The AR system consists of a cubic recording device with integrated stereo near-infrared (NIR) and stereo color cameras, an head mounted display (HMD) for visualizing the SLN information directly into the physicians view and a controlling software application. The labeling of the SLN is achieved using the fluorescent dye indocyanine green (ICG). The dye accumulates in the SLN where it is excited to fluorescence by applying infrared light. The fluorescence is recorded from two directions by the NIR stereo cameras using appropriate filters. Applying the known rigid camera geometry, an ICG depth map can be generated from the camera images, thus creating a live 3D representation of the SLN. The representation is then superimposed to the physicians field of view, by applying a series of coordinate system transformations, that are determined in four separate system calibration steps. To compensate for the head motion, the recording systems is continuously tracked by a single camera on the HMD using fiducial markers. Because the system does not require additional monitors, the physicians attention is kept solely on the operation site. This can potentially decrease the intervention time and render the procedure safer for the patient.

CCS Concepts

• ***Applied computing*** → *Health care information systems;*

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1. Introduction

The sentinel lymph node biopsy (SLNB) has proven to be a standard diagnostic tool for the detection of subclinical lymph node metastases and many other tumors such as malignant melanoma, prostate carcinoma or breast carcinoma. Other diagnostic methods, such as the lymph node sonography or the fine needle aspiration of the sentinel lymph node (SLN) currently provide no comparable sensitivity results [HMB*02, SUM*09]. The current gold standard for the presentation and targeted SLN biopsy is the pre-operative radionuclide lymphoscintigraphy (see Figure 1). It is carried out by applying the Technetium-99m (^{99m}Tc) labelled nanocolloidal albumin, in a two day clinical protocol. Pursuant to §8 StrlSchV (the German Radiation Protection Ordinance) a second day is mandatory, because the radiation exposure for the operating personnel would be above the legally permitted limits. The total injected activity of 80MBq does allow a surgery, at the earliest, one day post injection. However, a potentially bigger problem of ^{99m}Tc is, that it can only be produced in five research reactors worldwide that are approximately 50 years old. In May 2010, the two largest reactors had to be shut down due to age-related wear and tear, which led to a significant shortage of ^{99m}Tc. As a result, a large number of SLNB could not be performed. Since then the shortage of ^{99m}Tc has been reoccurring.

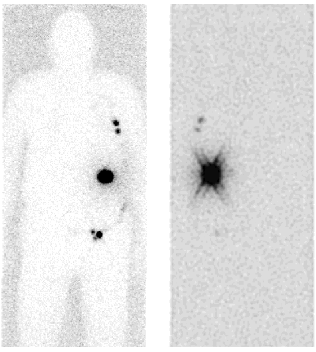

Figure 1: *Visualization of SLN by means of the lymph nodes scintigraphy procedure. Source: https://nuklearmedizin-neubrandenburg.de, accessed 16/06/2018*

There are also additional clinical problems with ^{99m}Tc. In case of rapid lymphatic drainage, as can often be observed in the head

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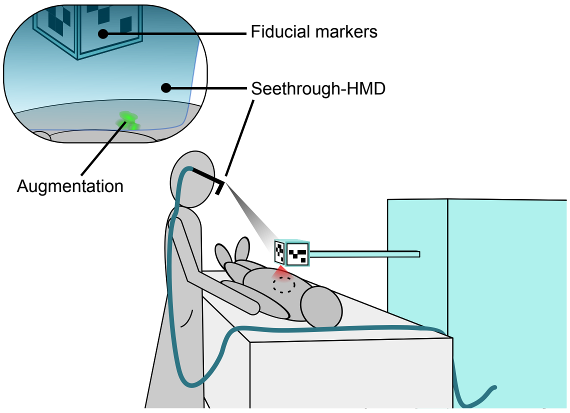

Figure 2: *A schematic of the clinical setup: The cubic recording device with fiducial markers is positioned over the patients labelled SLN. The HMD position is estimated using the HMD camera and the fiducial markers. The recorded ICG information is rendered directly into the physicians line of sight [Ano17].*

and neck region, only count rates of < 100 cps can be measured with a gamma probe on the day of the injection. Since the ^{99m}Tc has only a half-life of 6 hours, the detection of the SLN can be extremely difficult, sometimes even impossible. For these patients non-radioactive labeling techniques must be applied. Methylene blue has so far been used as a non-radioactive dye for SLN labeling. However, methylene blue has an allergenic potency and poses the risk of permanent tattooing [RTG11]. ICG may represent a potent alternative to ^{99m}Tc and methylene blue, as it has a lower allergenic potency and causes significantly less permanent tattoos in the area of the intradermal injection site [HDK*10]. ICG has been used for decades in heart, circulatory and microcirculation diagnostics [MDD*09,USY*08], but also in liver function diagnostics [IFS*09] and ophthalmology [CDQG11]. Several applications of ICG are already mandatory in oncology [PMR*11, SvdSB*12] as well.

Applying commercially available ICG detection solutions the physician must always share his attention between the operation site and an external monitor, where the ICG information is provided. The constant focus shift can among other things lead to distraction of the physician and fatigue. Our system can minimize those potential distractions by providing the desired ICG information directly in the physicians' field of view.

2. The system concept and clinical setup

The concept of the AR system can be seen in Figure 2. The entire system is comprised of three components: the recording device, the AR display and the system software. At the start of SLNB, the cubic recording device is placed over the patients tumor. Next, the fluorescent dye ICG is injected into the immediate tumor vicinity. From there, it flows to the draining SLN via the lymphatic system. The draining process can be visualized, if the lighting conditions are good and the NIR cameras are sensitive enough. The time form injection of the ICG to the start of SLN detection ranges between 10 and 25 minutes [GRH*15], making the use of ICG a real-time surgical intervention that does not require a pre-operation hospitalization of the patient. Since the draining SLN might be located outside the initial field of view of the recording device, a repositioning of the recording device might be required during the draining process. To allow for an easy repositioning, the cubic housing is attached to a long swivel arm and has been outfitted with two handles. After the ICG has reached the SLN, the biopsy can be performed under AR visualization.

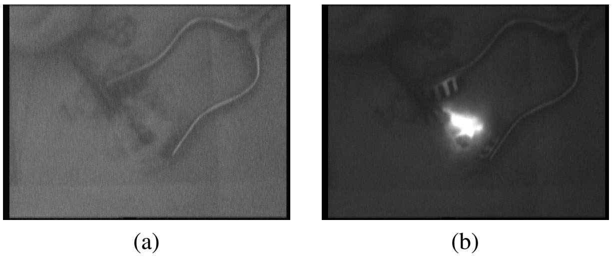
(a) (b)

Figure 3: *Operative view of a SLN labelled with ICG through a NIR camera. In (a) the infrared light source excited the ICG is switched off. In (b) it is switched on.*

The recording system is responsible for the image acquisition. To detect the fluorescence of the excited ICG, the system is equipped with two NIR cameras. Each NIR cameras shares an optical path with an additional color camera. However, the most important part of the recording system are the utilized optical filters. The ICG dye is excited using wavelengths of about 800nm. It absorbs the incoming infrared light and starts to emit a fluorescence signal with a wavelength of 820-830nm (see Figure 3). Only steep edged filters are suited to separate the fluorescence from the present ambient light, so that detection can be achieved. The great benefit of having two different camera types that share the same optical path is, that an easy blending between the NIR and color camera image can be achieved. The resulting NIR overlay of the ICG information can be displayed e.g. on an external monitor to visually enhance the operation site for everyone in the operation to see (see Figure 4). This is how commercially available systems visualize the ICG to the physician. Because we want to visualize the ICG in the view of the physician using an HMD, the two NIR cameras of the recording device are combined to a rigid stereo-camera system. This way it is possible to extract structural and location information about the target SLN. The color cameras can be used further for documentation purposes and other use cases, e.g. the extraction of the body surface. The latter is a planned feature of the system that is currently not available. The recording system is attached to the processing PC using four USB 3.0 cables for the IDS cameras and one USB 2.0 cable for driving all other system components. The cameras are connection to a dedicated USB 3.0 PCI-Express card, to prevent performance issues on the recording side.

The second component of the AR system is the HMD. The HMD is equipped with two projectors that each have a maximum resolution of 1280x1024 pixels. For each projector a semitransparent mirror serves as a display. The HMD can drive each display separately, allowing for monocular or binocular use cases. Between the

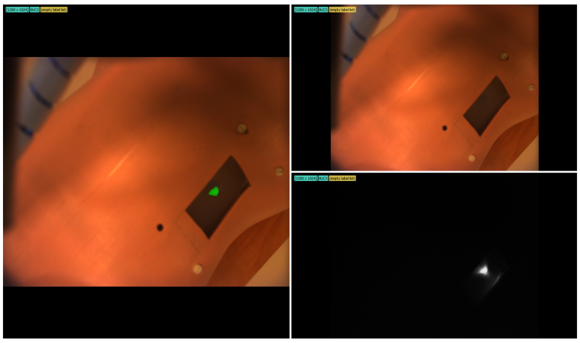

Figure 4: *Visualization of an ICG labelled SLN (left) generated from a set of NIR (bottom right) and color camera (top right) images.*

two display projectors, there is a color camera integrated into the HMD housing. The camera can be used to track objects from the wearers point of view. In the system setup, the camera is used to track the HMD location relative to the recording system by the use of fiducial markers on the surfaces of the cubic recording system. The HMD is attached to the processing PC using HMDI and USB 2.0 cables.

The remaining and third component of the system is the controlling software, which foremost manages the camera connections at the system start and triggers the desired processing modes e.g. 2D or 3D visualization. The software is further used to calibrate all system components, including the cameras, the displays and the eye position of the wearer. It is also used to toggle and manipulate additional components that are integrated into the recording system. For example activate/deactivate a spotlight, select the number of NIR-LEDs that are active during ICG visualization or enable a target cross-hair laser for accurate placement of the recording systems viewing direction.

To generate and visualize the spatial SLN information in the HMD display four calibration steps are required, which are explained in the next section.

3. The system calibration

To achieve the AR visualization of the SLN, all components of the visualization pipeline must be calibrated. The first components that require calibration are the utilized cameras, namely the two NIR cameras, that form a stereo camera system inside the recording device, and the HMD camera. The camera calibration is achieved using a calibration pattern, e.g. a checkerboard with a well-established physical size between the individual checkerboard fields. Each camera must record several images of the calibration pattern with different camera viewing angles. Following the image acquisition, the intrinsic camera parameters can be derived from the image data by solving the Perspective-n-Point problem. There are multiple open source libraries that are capable of performing this intrinsic camera calibration [Bra00, GJnSMCMJ14]. After completion of the intrinsic camera calibration, the focal length, image center, image skew and the distortion coefficients of each camera are known and can be used for different imaging tasks e.g. position estimation or point projection.

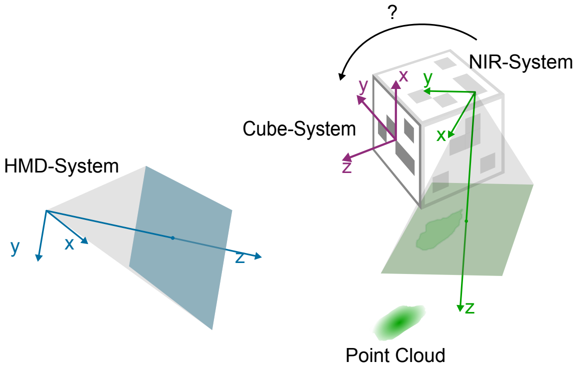

Figure 5: *The unknown transformation between the NIR camera center and the reference system on the cubic housing determined by the fiducial markers coordinate system [Ano17].*

Because we want to determine and visualize the spatial location of the detected ICG information, we additionally require the extrinsic camera parameters of the stereo NIR camera system. The extrinsic camera parameters are the spatial location of the cameras relative to a common frame of reference. For the calculation we select one NIR camera as the reference camera. Its spatial location is the unit matrix. The second cameras extrinsic parameters are defined by a transformation matrix $M = [R|t]$ with the rotation component R and the translation component t relative to the reference camera. The calibration of the stereo camera system is performed analogue to the calibration of a single camera. The only difference is, that all the checkerboard corners must be visible in both NIR camera images at the same time. Given both the intrinsic and extrinsic camera parameters, the systems essential and fundamental matrix can be computed. These matrices are important to generate the ICG depth map and thus the representation of the labelled SLN. The next step for an easy depth map generation is the rectification of the NIR camera images. After the rectification both images reside in a common image plane. The process is used to simplify the problem of finding matching points in both images. These point correspondences are required to generate the depth information from the image data. Additionally, a threshold is applied before the depth map construction to reduce image artifacts and display only the strongest ICG content. For the representation of the lymphatic flow, the threshold must be chosen at a very small value. The threshold can be manipulated on the fly in the systems software application.

Using the intrinsic parameters of the HMD camera, the relative position between it and the recording device T_{Aruco} can be determined from any detected marker on the recording device. Applying this transformation, spatial points can be transformed from the marker reference system to the HMD camera system.

At this point, most of the coordinate system transformation pipeline is known. The final hardware specific transformation miss-

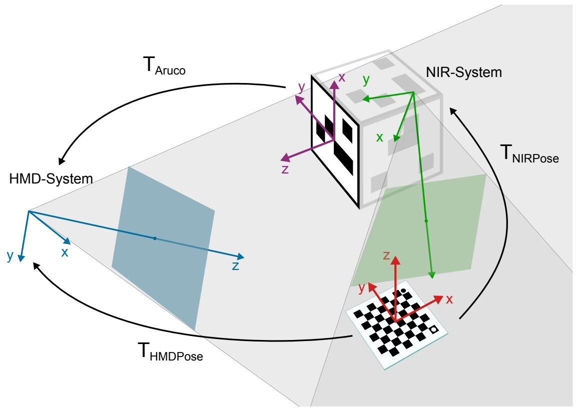

Figure 6: *Schematic of the AR systems visual components, their coordinate systems and the required coordinate system transformations to achieve a correct AR visualization in the HMD [Ano17]*

ing is the unknown transformation $T_{NIRToCube}$, between the stereo NIR camera pairs reference camera and the coordinate system defined by the fiducial markers (see Figure 5). This transformation is required to perform the complete transformation pipeline from the recording system to the HMD. The transformation is unknown, because the precise location of the cameras projection center inside the cubic housing cannot be determined during manufacturing. It's relative location can only be determined by means of a calibration. For the calibration procedure, the HMD camera is again used to simultaneously record the markers on the recording device and a second calibration pattern, e.g. on a table (see Figure 6). At the same time, the calibration pattern must also be seen inside the reference camera of the stereo camera pair. From this configuration, the transformation components T_{Aruco}, $T_{HMDPose}$ and $T_{NIRPose}$ can be determined, which are all required to calculate $T_{NIRToCube}$. The transformation chain is determined by converting the identity transformation to $T_{NIRtoCube} = T_{Aruco}^{-1} * T_{HMDPose} * T_{NIRPose}^{-1} * R_1^T$. The rotation R_1^T must be reversed, because the ICG data is located in the rectified image coordinate system. All calibrations until this point are hardware dependent and can be performed only once. This is because the system is designed rigidly, so no changes should occur during its usage.

The last calibration however is user specific and must be performed each time the HMD is used. With each user, the location of the eyes relative to the HMD displays changes. It even changes for the same user, if the HMD is fastened at a different position than during a previous application. The eye position influences how the SLN representation must be rendered to the displays to achieve a correct alignment with the world space. The last calibration is used to determine the location of the eyes relative to the HMDs camera coordinate system. Currently the single point active alignment method (SPAAM) is used to achieve the eyes to display calibration [TN00]. During the calibration a cross-hair pattern is displayed for each eye. A physical calibration pattern, that can be tracked using the HMD camera, must be aligned with the displayed pattern. Taking images at different depth levels leads to a location of the eyes. As mentioned before, this calibration step must be performed every time the HMD position changes relative to the users eyes. This is a drawback of the AR display method but cannot be circumvented.

Figure 7: *Evaluation of the ICG disparity using a 3.5cm piece of pork meat. A colored disparity profile is given for each of the seven test cuts (bottom) through the labelled meat [Ano17].*

4. Results

Similar to other commercially available devices, the system is able to generate an overlay between the detected ICG inside the SLN and a color camera image (see Figure 4). Furthermore, the system can generate a spatial representation of the SLN by the use of a stereo NIR camera system. Provided that the entire visualization pipeline has been calibrated, a visualization of the SLN representation can be achieved directly in the physicians field of view. As far as we know, no other device is capable of doing so. For the camera calibrations an average back projection error of 0.54 pixels could be achieved for 20 test calibrations. The achievable disparity can be qualitatively assessed using Figure 7. The disparity curve for pork meat phantom is steady and plausible inside the selected threshold boundaries. The visualization of a dummy SLN, simulated by an 5mm infrared LED inside a torso phantom, can be seen in Figure 8. The overlay covers the LEDs emitting surface entirely, which indicates a small calibration error for all calibrations. However, the provided image only represents the rendering of the ICG in a single display. For further evaluation, the system is currently tested in the clinic by the target users (see Figure 9).

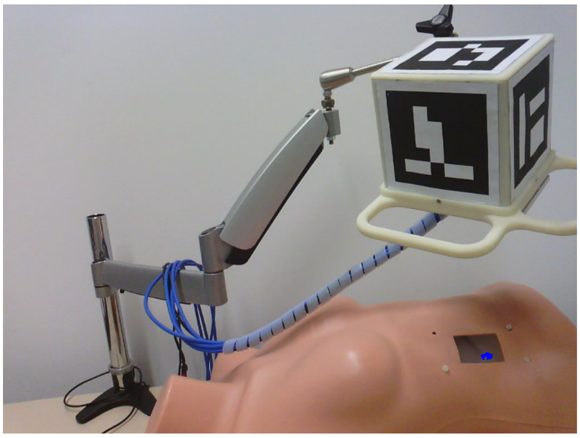

Figure 8: *Visualization of an ICG labelled SLN from the physicians perspective. The image shows the recording system placed over a torso phantom. The SLN is visualized in the torso window as a dense blue point cloud.*

Figure 9: *Live usage of the AR-system in the operation room.*

5. Discussion

A novel AR system for visualizing ICG labelled SLNs has been presented. The system uses a stereo camera system of NIR cameras to reconstruct the location and surface shape of an ICG labelled SLN. The spatial SLN representation can be rendered directly into the view of the physician. This way the physician is not required to shift his attention away from the operation site to e.g. a separate monitor. This potentially allows for a quicker and safer procedure and thus may enhance patient safety. The drawbacks of the AR method are, that the user calibration must be performed frequently and should be optimized further in terms of comfort and handling. The system however has also limitations. Because ICG can only be detected up to 1cm below the skin, some recording positions may not be achieved. Though, the system should not perform worse than the current standard. Occlusions between physician and recording device must however be prevented at all cost, an issue fairly common in most optical tracking systems. Further improvements of the system including coping with deeper SLNs are ongoing research.

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