Contents lists available at ScienceDirect

Medical Engineering and Physics

ELSEVIER



journal homepage: www.elsevier.com/locate/medengphy

Computed tomography (CT)-compatible remote center of motion needle steering robot: Fusing CT images and electromagnetic sensor data

CrossMark

Navid Shahriari^{a,b,*}, Wout Heerink^a, Tim van Katwijk^b, Edsko Hekman^b, Matthijs Oudkerk^a, Sarthak Misra^{a,b,c}

^a Center for Medical Imaging-North East Netherlands, University of Groningen, University Medical Center Groningen, The Netherlands ^b Department of Biomechanical Engineering, MIRA-Institute for Biomedical Technology and Technical Medicine, University of Twente, Horstring (HR) Z-140, Drienerlolaan 5, Enschede 7522NB, The Netherlands

^c Department of Biomedical Engineering, University of Groningen, University Medical Center Groningen, The Netherlands

ARTICLE INFO

Article history: Received 2 November 2016 Revised 22 March 2017 Accepted 23 April 2017

Keywords: Biopsy Data fusion Fine needle aspiration (FNA) Lung cancer Unscented Kalman filter

ABSTRACT

Lung cancer is the most common cause of cancer-related death, and early detection can reduce the mortality rate. Patients with lung nodules greater than 10 mm usually undergo a computed tomography (CT)guided biopsy. However, aligning the needle with the target is difficult and the needle tends to deflect from a straight path. In this work, we present a CT-compatible robotic system, which can both position the needle at the puncture point and also insert and rotate the needle. The robot has a remote-centerof-motion arm which is achieved through a parallel mechanism. A new needle steering scheme is also developed where CT images are fused with electromagnetic (EM) sensor data using an unscented Kalman filter. The data fusion allows us to steer the needle using the real-time EM tracker data. The robot design and the steering scheme are validated using three experimental cases. Experimental Case I and II evaluate the accuracy and CT-compatibility of the robot arm, respectively. In experimental Case IIII, the needle is steered towards 5 real targets embedded in an anthropomorphic gelatin phantom of the thorax. The mean targeting error for the 5 experiments is 1.78 ± 0.70 mm. The proposed robotic system is shown to be CT-compatible with low targeting error. Small nodule size and large needle diameter are two risk factors that can lead to complications in lung biopsy. Our results suggest that nodules larger than 5 mm in diameter can be targeted using our method which may result in lower complication rate.

© 2017 IPEM. Published by Elsevier Ltd. All rights reserved.

1. Introduction

In the United States and Europe lung cancer screening with low dose computed tomography (CT) is recommended for people at high risk or within clinical trial settings [1,2]. The introduction of lung cancer screening results in an increase of detected nodules. The nodules greater than 10 mm, and small fast-growing nodules would be eligible for clinical work-up, which is often performed with CT-guided lung biopsy. During this procedure the CT system is used to locate the lung nodule and the needle is advanced into the subcutaneous tissue of the chest wall incrementally, and a CT scan is acquired after every needle manipulation. The needle is ad-

http://dx.doi.org/10.1016/j.medengphy.2017.04.009 1350-4533/© 2017 IPEM. Published by Elsevier Ltd. All rights reserved. vanced through the pleura, when it is properly aligned with the nodule. This can either be performed by core needle biopsy (CNB) or by fine needle aspiration (FNA). In CNB a core is cut through the nodule for pathological analysis, while in FNA a smaller needle is used to aspirate cell clusters of the nodule, for cytological analysis. CNB is often reported to result in a higher diagnostic performance, but FNA has a lower complication rate [3,4].

The consequential increase of pleural punctures increases the chance of complications such as pneumothorax and pulmonary hemorrhage [5–7]. Furthermore, the nodule moves due to respiration, which can result in inaccurate biopsy. Therefore, breathing instructions are given to the patient prior to the procedure to minimize the movement. The patient is asked to hold breath in a consistent fashion if the nodule is close to the diaphragm [8].

Flexible FNA needles tend to deflect from their initial path because of their asymmetric tip. This can be used to correct the initial orientation of approach during the insertion of the needle by rotating the needle. This will not only decrease the amount of

^{*} Corresponding author at: Department of Biomechanical Engineering (MIRA-Institute for Biomedical Technology and Technical Medicine), University of Twente, Horstring (HR) Z-140, Drienerlolaan 5, 7522NB Enschede, The Netherland.

E-mail address: n.shahriari@utwente.nl (N. Shahriari).



Fig. 1. The experimental setup and its components: The setup is used for steering a bevel-tipped needle. The needle is steered towards a real target embedded in a gelatin phantom. Computed tomography (CT) images are used to register the target location with respect to the robot reference frame. Electromagnetic (EM) tracker data is fused with CT images in order to perform real-time needle steering. The experimental setup consists of: ① Needle insertion device. ② Remote center of motion robot arm. ③ Anthropomorphic gelatin phantom of the thorax. ④ CT scanner. ⑤ EM tracker. ⑥ Bevel-tipped needle.

needle manipulations, but also create the ability to target even small lung nodules.

1.1. Related work

Different types of needles and robotic setups have been developed to guide the needle towards the targeted lesion. Below we discuss some of these designs, and subsequently present our new design and steering scheme.

1.1.1. Needle steering

Flexible needles can be steered in the body in order to target the lesions accurately. There exist various needle designs such as bevel-tipped (Fig. 1,⑥), pre-bent/curved tip [9,10], concentric tubes [11,12], pre-curved stylet [13], programmable bevel [14], tendonactuated tip [15,16] and active needles [17,18]. Different imaging modalities, such as ultrasound [19], magnetic resonance imaging (MRI) [20] and CT [21], have been used as feedback to control these needles.

Bevel-tipped needles have a simple design and cause minimal tissue damage in comparison with the other needles mentioned above. Bevel-tipped needles deflect naturally while inserted into the body due to the forces exerted to the asymmetric tip [22]. This can be used to control the trajectory of the needle, and plan a feasible safe path to the target. Abayazid et al. developed a three-dimensional (3D) steering algorithm which minimizes the number of rotations, and therefore the tissue damage [10]. The algorithm rotates the needle towards the target when the target approaches the boundaries of the reachable volume.

1.1.2. Needle positioning and needle steering devices

Various robotic setups have been developed over the past two decades for positioning and steering needles. The majority of these robots are positioning devices, meaning that a needle holder is positioned automatically with respect to the target such as in Neorad Simplify (Neorad, Oslo, Norway) and Apriomed SeeStar (Apriomed, Uppsala, Sweden). Maurin et al. developed a 5 degree of freedom (DOF) CT-compatible patient-mounted positioning platform [23,24], and Loser et al. utilized a lockable table-mounted arm which used a parallel remote center of motion mechanism for needle positioning [25]. Stoianovici et al. developed a table-mounted robot (AcuBot) which had actuated translation as well

as an actuated remote center of motion through an parallelogram mechanism [26]. A different approach was done by Tovar-Arriaga et al. where they applied a conventional robot arm on a mobile platform for the task of needle positioning [27]. In all the cases above, the needle insertion was done manually by the clinicians and only rigid needles were considered.

There are also several designs in which the needle insertion is also executed automatically. Seitel et al. developed a patientmounted system (ROBOPSY) which consists of an actuated rotatable arch and a carriage [28]. The robot could only hold and insert a rigid needle, which is not suitable for needle steering applications. Kratchman et al. also developed an actuated arch-based robot to steer a flexible tendon-actuated needle [29]. However, the device was mounted on a passive arm and it is not suitable to be placed in the CT-bore.

The limitation of the aforementioned devices is that none of them is suitable for needle steering. Automatic insertions are done using rigid needles or with large complex devices that are often placed outside the CT-gantry. Furthermore, CT scanners cannot provide real-time images of the patient. Therefore, fusion of real-time needle tracking methods, such as electromagnetic (EM) tracker and ultrasound, to CT images are beneficial.

1.1.3. Multi-sensor data fusion

Data fusion has application in many fields and it is used to combine several sources of measurements to decrease the uncertainty of the resulting information. Data fusion is used in minimally invasive surgical interventions for several imaging modalities and sensors. Ren et. al developed a tracking system that fuses EM and inertial sensors in order to track the position and orientation of surgical instruments in the body [30]. An unscented Kalman filter was used by Lang et al. to fuse EM tracker data with 2D ultrasound images to produce a smooth and accurate 3D reconstruction [31]. Appelbaum et al. developed a system for biopsy of small lesions in which EM tracker data, CT and ultrasound images were fused [32]. A visual feedback was provided to the clinician and the insertion was done manually based on that. Accurate needle steering requires real-time feedback of the needle tip pose, which is a limiting factor in CT-guided interventions. We have proposed fusion of EM tracking data with CT images in order to address this limitation by using the real-time EM tracking data to steer the needle.

1.2. Contributions

In this work, we have proposed and fabricated a novel CTcompatible robot capable of steering a bevel-tipped needle, while the needle pose can be controlled at the insertion point. The robot consists of a needle insertion device (NID) and a parallel remote center of motion (RCM) robot arm. The robot is CT-compatible and mainly made of non-metallic materials to minimize the image artifacts. To the best of our knowledge, this is the first CT-compatible setup which is capable of both positioning and steering a needle. We discussed the design of the NID in previous work [33]. In this paper we present the design of the RCM robot arm, and evaluate the overall system. This new design allow us to steer a flexible needle in a clinically relevant scheme and to study the effect of base-manipulation on steering of bevel-tipped needles. In addition, a data fusion scheme is developed in order to fuse CT images with EM tracking data using an unscented Kalman filter. This scheme benefits from using real-time data of EM tracker for steering, while intermittent CT images can correct EM tracking measurement imperfections.

This paper is organized as follows. Section 2 describes the robot's design and the developed steering scheme. Section 3



Fig. 2. Prototype of computed tomography-compatible needle insertion setup in initial configuration: ① Parallel remote center of motion mechanism. ② Needle insertion device. ③ Worm gear/wheel pair. ④ DC motors. ⑤ Remote center of motion, light blue arrow demonstrates sideways rotation and yellow arrow shows forward/backward rotation of the arm. ⑥ Aluminum oxide fiducials. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

presents the experimental setup, plan, and results. Section 4 concludes our paper and suggest directions for future work.

2. Methods

This section presents the design of a CT-compatible robot, and the registration in CT scanner and EM tracker reference frames. CT images are fused with EM-tracker data to provide needle tip pose as feedback to the steering algorithm.

2.1. Design

We have developed a CT-compatible robot for needle steering application, which can both position and insert a needle. The robot consists of a needle insertion device (NID) and a robotic arm (Fig. 2). We discussed the design and evaluation of the NID in previous work [33]. Here, we present the design of a CT-compatible, 2 degree-of-freedom and remote-center-of-motion (RCM) robotic arm. The NID is attached to the robotic arm as an end-effector. The robot is designed to be used in a CT scanner. Current CT scanners (such as Siemens Somatom Sensation 64 (Siemens AG,Munich, Germany) and Brilliance CT (Philips Healthcare, Best, The Netherlands)) have a gantry opening of about 820 mm. There is approximately 300 mm free space around the abdomen to place the device while a patient is inside the bore.

The arm can rotate the NID around the insertion point, which is the RCM point. This is achieved through a parallel RCM mechanism for the first degree of freedom and a rotating plane for the second degree of freedom. The hinge is mounted at an angle so that the RCM be located exactly on the phantom surface or patient's skin . The range of motion for the forward and backward motion is 50° and 35° , respectively, and 100° for sideways motion (Fig. 2).

The arm is actuated by two Faulhaber 2232U012SR brushed-DC motors (Faulhaber Group, Schnaich, Germany) equipped with a 22E planetary gearbox with a reduction ratio of 28:1 and an IE2-16 two-channel 16 lines per revolution incremental encoder. Each motor drives a worm gear which in turn actuates a worm wheel that is directly attached to their respective hinge. The worm gear/wheel pair are of module 0.5 mm with a lead angle of 2.23 degrees and have a reduction ratio of 50:1. The arm can only be actuated through the worm gear, thus the worm gear/wheel pair acts as a brake when the motors are turned-off. The motors have rated speed of 196 rotations per minute (RPM), and therefore the end-effector speed is rated at 3.9 RPM (23.4 degrees/s). The total gear reduction ratio is 1400:1 resulting in a total resolution of 22400 lines per revolution or 0.016 degrees.

A Raspberry Pi 2 B (Raspberry Pi foundation, Caldecote, United Kingdom) combined with a Gertbot motor controller board (Fen logic limited, Cambridge, United Kingdom) is used to control the robot. The controller uses pulse-width-modulation (PWM) to set the motor speed, and the PWM is calculated using a proportional-integral-derivative (PID) controller.

2.2. Registration

The robot is registered to the CT scanner reference frame using 8 fiducials, which are placed at specific positions on the robot (Fig 2). The fiducials are 5 mm spheres made of Aluminium oxide. The locations of the fiducials are extracted from the CT images using image processing techniques. The absolute rotation and translation of the robot is calculated using a least-squares error method by matching the actual fiducials positions with the CAD model [34]. The needle pose is also measured using the EM tracker, and the measurements are used to register the EM tracker in CT scanner reference frame.

2.3. Computed tomography – electromagnetic data fusion

The EM tracker provides real-time pose of the needle tip, which is advantageous for accurate needle steering. On the other hand, CT images are needed to, first, detect and register the target in the reference frame, and then, to check the actual needle tip during the insertion. Therefore, the needle pose is extracted from the CT images, and the EM tracking data is then fused with the CT data using an unscented Kalman filter (UKF).

UKF is a powerful tool for multi-sensor data fusion [35]. The state estimation is based on the process model, measurement model and measurements, similar to a standard Kalman filter. However, unlike the extended Kalman filter and other Taylor series-based approximation, Jacobian and Hessian matrices are not needed for the unscented transformation [36]. The UKF uses the unscented transformation for nonlinear sampling and propagation of state variables and nonlinear measurements.

The state vector of the tip of the needle is given by

$$\boldsymbol{q} = \begin{bmatrix} p_{t,x}^0 & p_{t,y}^0 & p_{t,z}^0 & \alpha & \beta & \gamma \end{bmatrix}^T \in \mathbb{R}^{6 \times 1},$$
(1)

where $\boldsymbol{p}_t^0 = [p_{t,x}^0 \ p_{t,y}^0 \ p_{t,z}^0]^T \in \mathbb{R}^{3 \times 1}$ is the position of the tip frame (Ψ_t) represented in the CT scanner frame (Ψ_{ct}) . The process model is defined as follows:

$$\boldsymbol{q}_k = f(\boldsymbol{q}_{k-1}, \boldsymbol{u}_k) + \boldsymbol{w}_k, \tag{2}$$

where $\boldsymbol{u}_k \in \mathbb{R}^{2 \times 1}$ is the needle insertion and rotation velocity. The function $f : \mathbb{R}^{7 \times 1} \to \mathbb{R}^{6 \times 1}$ is based on bevel-tipped needle model, and $\boldsymbol{w}_k \in \mathbb{R}^{6 \times 1}$ is the process noise vector. The subscript *k* denotes the discrete time (i.e., $\boldsymbol{q}_k = \boldsymbol{q}(t_k)$). The measurement model is as follows:

$$\boldsymbol{z}_k = h(\boldsymbol{q}_k) + \boldsymbol{v}_k,\tag{3}$$

where the current estimate of state is related to the measurement variable $(\mathbf{z}_k \in \mathbb{R}^{12 \times 1})$ through measurement function $h : \mathbb{R}^{6 \times 1} \to \mathbb{R}^{12 \times 1}$. The measurement noise $(\mathbf{v}_k \in \mathbb{R}^{12 \times 1})$ is assumed to be white Gaussian whose covariance depends on measurement accuracy. EM tracker and CT images provide us with the complete pose of the needle in 3D, and \mathbf{z}_k is the augmented vector of both measurements. UKF fuses all measurements to estimate the states of the system (Eq. (1)). The block-diagram of the system is demonstrated in Fig. 3.



Fig. 3. Block diagram of the experimental setup: a computed tomography (CT) scan is performed pre-operatively and target location is calculated with respect to the needle. The NID pose is measured using electromagnetic (EM) tracking data and also fiducials in CT images, and EM tracker is registered to the CT scanner. The steering is divided into four equal segments based on the insertion length. Real-time EM tracking data is used to steer the bevel-tipped needle. At the end of each segment, a new CT scan is performed and needle tip pose is calculated from CT images using image processing techniques. The needle pose from EM tracker and CT images are fused using an unscented Kalman filter (UKF). The filtered data is used to update the needle steering algorithm. These steps are repeated three times until the needle reaches its final position.



Fig. 4. Reference frames of different components of the experimental setup: the coordinate systems are required to compute the needle tip pose. Computed tomography (CT) scanner reference frame (Ψ_{et}) is at the center of the bore and electromagnetic (EM) tracker reference frame (Ψ_{em}) is located at the center of the planar field generator. The robot and frame Ψ_{em} are registered in CT scanner reference frame (Ψ_{et}) is at the center of the planar field generator. The robot and frame Ψ_{em} are registered in CT scanner reference frame pre-operatively using the fiducials. The frame (Ψ_i) is attached to the needle tip at the initial position. During the experiments the tip of the needle is tracked in real-time using the EM tracker and intermittently using CT images. The data are fused using an unscented Kalman filter. (a) The low-level controller boards. (b) Bevel-tipped needle with a 5 degree of freedom EM sensor represented in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Experiments

This section describes the experiments performed to evaluate the system. The experimental setup and plan are explained below, followed by the results at the end of this section.

3.1. Experimental setup

The experimental setup shown in Fig. 4 is used to validate the design and the proposed steering algorithm. It consists of the NID, controllers, an EM tracker and a CT scanner. The CT scanner used in the experiments is the Siemens Somatom Force (Siemens AG, Munich, Germany). The settings are the defaults used for abdomen scan, which are a tube voltage of 90 KVP, tube current of 234 mAs, pixel spacing of 0.96 mm, slice thickness of 0.5 mm and convolution kernel of Br40d.

A needle with the diameter of 0.55 mm (23.5 gauge) equipped with a 5 DOF EM sensor is used to track the needle tip with the EM tracking system. The needle tip pose is measured 20 times per second using an Aurora v3 EM tracker (Northern Digital Inc., Waterloo, Canada) [37]. The EM tracking system consists of a field generator, a system control unit and a sensor interface unit. The EM tracker measures the 3D position, pitch and yaw angles. According to the manufacturer, the root mean square (RMS) of the position error is 0.7mm and it is 0.20° for the orientations, if the planar field generator is used. The motor encoder is used to measure the roll angle (rotation about needle axis). The assumption is that the torsion about the needle axis will cause only minimal offset between the tip and base angles. The needle steering is performed outside of the CT bore to minimize the interference with the EM tracker.

An anthropomorphic gelatin phantom is used in the experiments. The gelatin phantom is made by mixing 14.9% (by-weight) porcine gelatin powder (Dr. Oetker, Ede, The Netherlands) with 85.1% water. This mixture results in a phantom with a Young's modulus of 35 kPa [38]. The targets are spheres of different sizes made of Play-Doh, which is easily mold-able and gives good contrast on CT.

3.2. Experimental plan

Three experimental cases are used to evaluate the robot design, interference with CT and the proposed steering scheme. The experimental cases are:

Case (I) Hardware tests

The robot is positioned in different poses, which are equally distributed in the work space of the robot. A 6-DOF EM sensor is embedded at the tip of the NID (at the RCM), and the pose of the robot is measured using EM tracker and also CT images. The angular accuracy and the error in RCM are calculated.

Case (II) CT noise analysis

The CT-compatibility of the device is evaluated through noise analysis of CT images. Although signal-to-noise ratio (SNR) is a fundamental concept in noise analysis, it does not characterize the noise completely [39]. Therefore, the noise-power spectrum (NPS) is commonly used for noise analysis of CT images. NPS is the Fourier transform of the autocorrelation function which



Fig. 5. Hardware test results: (a) The desired angle for sideways motion (see Fig. 4) *versus* the actual angle of the robot. (b) The desired angle for forward/backward motion (see Fig. 4) *versus* the actual angle of the robot. (c) Position of the theoretical remote-center-of-motion (RCM) point (in blue) *versus* the actual needle insertion device (NID) tip in different configurations. The color code depicts the absolute error.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

characterizes the noise texture and is computed as

NPS
$$(f_x, f_y) = \frac{1}{N} \sum_{i=1}^{N} \left| \text{DFT}_{2D} \Big[I_i(x, y) - \bar{I}_i \Big] \right|^2 \frac{\Delta_x \Delta_y}{N_x N_y},$$
 (4)

where f_x and f_y are the spatial frequencies in x and y direction (Fig. 4), respectively. DFT_{2D} is the 2D discrete Fourier transform, $I_i(x, y)$ is the signal in *i*th region of interest (ROI), and \bar{I}_i is the mean of $I_i(x, y)$. N is the number of ROIs, and N_x and N_y are number of pixels, and Δ_x and Δ_y are the pixel spacing in x and y direction, respectively.

A homogeneous cylindrical water phantom is used to compute the NPS. CT images are acquired of the water phantom with and without the NID on top of it. Several regions are sampled in the CT images and the Fourier transform is computed for each region. The Fourier transforms are then averaged over all the samples, and the mean 2D NPS is calculated.

Case (III) Steering

Steering experiments are performed in an anthropomorphic phantom by fusing the EM tracker data and the CT images. The EM tracker, target location and the robot are registered in CT scanner reference frame at the beginning of each experiment.

The insertion length is divided into 4 equal segments. The needle is steered using the the real-time feedback from the EM tracker. The steering algorithm is based on the method proposed by Abayazid et al. [10]. The insertion is paused at the end of each segment, and a new CT scan is performed. The needle pose is extracted from the CT images and it is fused with the EM tracker data. This procedure is repeated for three more times until the needle reaches its final position. It is possible to increase the number of steps, which will result in more accurate steering but also more radiation dose.

3.3. Results

In the experimental Case I, each degree of freedom of the robot arm is tested individually. Each set-point is reached 5 times from both directions, in order to evaluate the accuracy and check for any hysteresis effect. Fig. 5a,b show the measured angular positions of the NID *versus* desired set-points. The average angular errors are $0.98 \pm 0.62^{\circ}$ and $0.36 \pm 0.48^{\circ}$ for sideways and forward/backward motion (Fig. 2), respectively. Fig. 5c shows position of the theoretical RCM point *versus* the actual NID tip in different configurations. The RCM error is calculated as the absolute distance between the desired and actual RCM position in 3D space. The mean of RCM error is 4.37 \pm 1.87 mm.



Fig. 6. Computed tomography (CT) noise analysis: The noise power spectrum is computed for a homogeneous cylindrical water phantom. (a) The needle insertion device (NID) is on top of phantom. (b) The phantom is in the CT scanner without the NID. (c,d) The 2D noise power spectrum (NPS) calculated for case (a) and (b), respectively, using 12 ROI shown by dashed-red squares. The artifacts caused by the NID are limited and do not interfere with tracking the needle in the CT images.

The NPS is calculated in the experimental Case II using 12 ROIs. The robot is positioned straight up on top of the water phantom, which is the position that causes the maximum artifact, in order to calculate the NPS for the worst-case scenario. It is shown in Fig. 6a that the robot introduces minimal additional noise to the images and it is visible also in the 2D NPS shown in Fig. 6c,d. The 2D NPS shows that the artifacts correspond to specific spatial frequencies (the bright horizontal area), which depends on the location of the robot with respect to the phantom.

In experimental Case III, the needle is steered towards 5 real targets. The targets are spheres with a radius ranging between 1.98 mm and 8.65 mm and the insertion depth ranging between 55.99 mm and 101.08 mm. The needle is steered towards the

Table 1

Experimental results for Case III: Computed tomography images are fused with electromagnetic tracking data using an unscented Kalman filter. The needle is steered towards 5 real target. The targets are placed at different locations and depths (see also Fig. 7). The error is calculated as the absolute 3D distance between the needle tip and center of the target.

#	Target x(mm)	Target y(mm)	Target z(mm)	Target size(mm)	Error
1	0.22	11.08	81.83	8.65	2.06
2	14.89	-3.88	101.08	1.98	2.37
3	0.96	10.64	89.25	8.15	0.96
4	-3.38	8.54	79.15	5.60	2.43
5	-1.70	5.88	55.99	3.93	1.09
				Mean error	1.78 ± 0.7



Fig. 7. Needle trajectory for experimental Case III: The needle is steered towards 5 real targets in an anthropomorphic gelatin phantom. The targets are placed at different locations with depths varying between 56 mm to 101 mm. The needle trajectory is extracted from the computed tomography images. The trajectory and target location are presented in the reference frame (Ψ_i).

center of the targets and the experiment is evaluated by calculating the absolute distance between the target position and needle tip position in 3D space. The mean targeting error is $1.78 \pm 0.70 \text{ mm}$ (Table 1). The results show an improvement with respect to our recent work, where we demonstrated a targeting error of 1.94 ± 0.63 mm using only CT images for a virtual target [33]. This comparison demonstrates that the proposed data fusion scheme is effective and results in approximately 10% less targeting error. The needle trajectory is shown in Fig. 7 for all 5 experiments.

4. Discussion and future work

In this paper, we have presented a novel CT-compatible robotic setup for steering a bevel-tipped flexible needle. The robot consists of the NID and a 2 DOF remote-center-of-motion arm. The robot arm orients the NID at the needle insertion point and the needle is then steered using the NID. A new steering scheme is also presented where the needle tip pose is tracked using real-time EM tracking data and intermittent CT images. EM and CT data are fused using an unscented Kalman filter every time a new CT scan is performed. The EM tracker and CT scanner are registered preoperatively, and CT images are used to register the target position in the reference frame.

4.1. Discussion

Several experiments are conducted to evaluate the accuracy and the CT compatibility of the robot. The results of the first experimental case show that, in the worst case, the robot arm can have an orientation error of about 2 degrees. The error is small near the zero-configuration (Fig. 2) and it increases as the robot moves towards the extreme configurations, such as fully-extended or fullyretracted arm. In theory, the RCM should be one stationary point, however, this is not the case during the experiments. The main cause of the error in positioning of the robot arm and the RCM point is the backlash in the worm gears and bearings, and also bending of the arms. Due to the relatively long arms of the robot, a small error at the base results in a greater error at the end-effector. However, the error is expected to decreases if the robot parts are fabricated with a higher precision, and long slender parts are replaced by stiffer ones. The noise analysis in the second experimental case demonstrates that the robot adds limited amount of artifacts to the CT images, which do not interfere with tracking the needle in the phantom. In the third experimental case, five steering experiments in an anthropomorphic gelatin phantom of the thorax resulted in a targeting accuracy of 1.78 \pm 0.70 mm. In this study, we assume that the lesion has a spherical shape. The center of a lesion is considered to be the target for the needle steering algorithm. The accuracy of the steering algorithm should be less than the radius of the lesion in order to have a successful biopsy. Therefore, using our new steering scheme, nodules with a minimum diameter of 5 mm can be reached successfully.

4.2. Future work

Although the current study is a step towards bringing needle steering into clinical practice, we believe it can be further improved in future work. The main limitation of the current design is lack of translational motion. Actuated fine 3D translation of the RCM point can help positioning the robot accurately at the insertion point. Biological tissues are inhomogeneous which cause the needle to deflect differently, specially if the needle tries to puncture the chest wall or vessels. Therefore, experiments in cadaver are necessary in order to validate the system for clinical use. Furthermore, physiological movements need to be considered and compensated for in the system. Finally, pre-operative path planning can help in defining the suitable insertion location and initial pose of the needle.

Conflicts of Interest

None.

Ethical approval

Not required.

Acknowledgment

This study was supported by funds from the Samenwerkingsverband Noord-Nederland (SNN) Program (Project RICIBION-Robotic Interventions using CT-Images for Biopsies of Lung Nodules) and University Medical Center Groningen (UMCG).

References

- Moyer VA. Screening for lung cancer: U.S. preventive services task force recommendation statement. Ann Intern Med 2014;160:330–8.
- [2] Kauczor HU, Bonomo L, Gaga M, Nackaerts K, Peled N, Prokop M, et al. ESR/ERS white paper on lung cancer screening. Eur Radiol 2015;25:2519–31.
- [3] Yao X, Gomes M, Tsao M, Allen CJ, Geddie W, Sekhon H. Fine-needle aspiration biopsy versus core-needle biopsy in diagnosing lung cancer: a systematic review. Curr Oncol 2012;19:16–27.
- [4] Heerink WJ, de Bock GH, de Jonge GJ, Groen HJM, Vliegenthart R, Oudkerk M. Complication rates of CT-guided transthoracic lung biopsy: meta-analysis. Eur Radiol 2016:1–11. doi:10.1007/s00330-016-4357-8.
- [5] Yeow KM, Su IH, Pan KT, Tsay PK, Lui KW, Cheung YC, et al. Risk factors of pneumothorax and bleeding: multivariate analysis of 660 CT-guided coaxial cutting needle lung biopsies. Chest 2004;126:748–54.
- [6] Khan MF, Straub R, Moghaddam SR, Maataoui A, Gurung J, Wagner TOF, et al. Variables affecting the risk of pneumothorax and intrapulmonal hemorrhage in CT-guided transthoracic biopsy. Eur Radiol 2008;18:1356–63.
- [7] Ko JP, Shepard JAO, Drucker EA, Aquino SL, Sharma A, Sabloff B, et al. Factors influencing pneumothorax rate at lung biopsy: are dwell time and angle of pleural puncture contributing factors? Radiology 2001;218:491–6.
- [8] Cham MD, Lane ME, Henschke CI, Yankelevitz DF. Lung biopsy: special techniques. Seminars Respir Crit Care Med 2008;29:335–49.
- [9] Webster III RJ, Kim JS, Cowan NJ, Chirikjian GS, Okamura AM. Nonholonomic modeling of needle steering. Int J Robot Res 2006a;25:509–25.
- [10] Abayazid M, Vrooijink GJ, Patil S, Alterovitz R, Misra S. Experimental evaluation of ultrasound-guided 3D needle steering in biological tissue. Int J Comput Assist Radiol Surg 2014;9:931–9.
- [11] Sears P, Dupont P. A steerable needle technology using curved concentric tubes. In: IEEE/RSJ International Conference on Intelligent Robots and Systems; 2006. p. 2850–6.
- [12] Webster III RJ, Okamura AM, Cowan NJ. Toward active cannulas: Miniature snake-like surgical robots. In: IEEE/RSJ International Conference on Intelligent Robots and Systems; 2006b. p. 2857–63.
- [13] Okazawa S, Ebrahimi R, Chuang J, Salcudean SE, Rohling R. Hand-held steerable needle device. IEEE/ASME Trans Mechatronics 2005;10:285–96.
- [14] Ko SY, Rodriguez y Baena F. Toward a miniaturized needle steering system with path planning for obstacle avoidance. IEEE Trans Biomed Eng 2013;60:910–17.
- [15] Roesthuis RJ, van de Berg NJ, van den Dobbelsteen JJ, Misra S. Modeling and steering of a novel actuated-tip needle through a soft-tissue simulant using fiber bragg grating sensors. In: Proceedings of the IEEE International Conference on Robotics and Automation; 2015. p. 2284–9.
- [16] van de Berg NJ, Dankelman J, van den Dobbelsteen JJ. Design of an actively controlled steerable needle with tendon actuation and FBG-based shape sensing. Med Eng Phys 2015;37:617–22.

- [17] Datla NV, Hutapea P. Flexure-based active needle for enhanced steering within soft tissue. ASME J Med Devices 2015;9(4):041005–6.
- [18] Ryu SC, Quek ZF, Koh JS, Renaud P, Black RJ, Moslehi B, et al. Design of an optically controlled MR-compatible active needle. IEEE Trans Robot 2015;31(1):1–11.
- [19] Abayazid M, Moreira P, Shahriari N, Patil S, Alterovitz R, Misra S. Ultrasound-guided three-dimensional needle steering in biological tissue with curved surfaces. Med Eng Phys 2015;37:145–50.
- [20] Su H, Cole GA, Fischer GS. High-field MRI-compatible needle placement robots for prostate interventions: pneumatic and piezoelectric approaches. Adv Robot Virtual Real 2012;26:3–32.
- [21] Zhou Y, Thiruvalluvan K, Krzeminski L, Moore WH, Xu Z, Liang Z. CT-guided robotic needle biopsy of lung nodules with respiratory motion experimental system and preliminary test. Int J Med Robot Comput Assist Surg 2013;9:317–30.
- [22] Misra S, Reed KB, Schafer BW, Ramesh K, Okamura AM. Mechanics of flexible needles robotically steered through soft tissue. Int J Robot Res 2010;29:1640–60.
- [23] Maurin B, Bayle B, Gangloff J, Zanne P, de Mathelin M, Piccin O. A robotized positioning platform guided by computed tomography: practical issues and evaluation. In: Proceedings of the IEEE International Conference on Robotics and Automation; 2006. p. 251–6.
- [24] Maurin B, Bayle B, Piccin O, Gangloff J, d Mathelin M, Doignon C, et al. A patient-mounted robotic platform for CT-scan guided procedures. IEEE Trans Biomed Eng 2008;55:2417–25.
- [25] Loser MH, Navab N. A new robotic system for visually controlled percutaneous interventions under CT fluoroscopy. In: Proceedings of the International Conference on Medical Image Computing and Computer-Assisted Intervention; 2000. p. 887–96.
- [26] Stoianovici D, Cleary K, Patriciu A, Mazilu D, Stanimir A, Craciunoiu N, et al. AcuBot: a robot for radiological interventions. IEEE Trans Robot Autom 2003;19:927–30.
- [27] Tovar-Arriaga S, Tita R, Pedraza-Ortega JC, Gorrostieta E, Kalender WA. Development of a robotic FD-CT-guided navigation system for needle placement-preliminary accuracy tests. Int J Med Robot Comput Assist Surg 2011;7:225–36.
- [28] Seitel A, Walsh CJ, Hanumara NC, Shepard J-A, Slocum AH, Meinzer H-P, et al. Development and evaluation of a new image-based user interface for robot-assisted needle placements with the Robopsy system. SPIE 2009;7261. 72610X-72610X-9
- [29] Kratchman LB, Rahman MM, Saunders JR, Swaney PJ, Webster III RJ. Toward robotic needle steering in lung biopsy: a tendon-actuated approach. SPIE 2011;7964. 796411–796411–8
- [30] Ren H, Rank D, Merdes M, Stallkamp J, Kazanzides P. Multisensor data fusion in an integrated tracking system for endoscopic surgery. IEEE Trans Inf Technol Biomed 2012;16:106–11.
- [31] Lang A, Mousavi P, Fichtinger G, Abolmaesumi P. Fusion of electromagnetic tracking with speckle-tracked 3D freehand ultrasound using an unscented Kalman filter. SPIE 2009;7265. 72651A–72651A–12.
- [32] Appelbaum L, Solbiati L, Sosna J, Nissenbaum Y, Greenbaum N, Goldberg SN. Evaluation of an electromagnetic image-fusion navigation system for biopsy of small lesions: assessment of accuracy in an in vivo swine model. Acad Radiol 2013;20:209–17.
- [33] Shahriari N, Hekman E, Oudkerk M, Misra S. Design and evaluation of a computed tomography (CT)-compatible needle insertion device using an electromagnetic tracking system and CT images. Int J Comput Assist Radiol Surg 2015;10:1845–52.
- [34] Horn BK, Hilden HM, Negahdaripour S. Closed-form solution of absolute orientation using orthonormal matrices. J Opt Soc Am A 1988;5:1127–35.
- [35] Vaccarella A, de Momi E, Enquobahrie A, Ferrigno G. Unscented Kalman filter based sensor fusion for robust optical and electromagnetic tracking in surgical navigation. IEEE Trans Instrum Meas 2013;62:2067–81.
- [36] Julier SJ, Uhlmann JK. Unscented filtering and nonlinear estimation. Proc IEEE 2004;92:401–22.
- [37] Northern Digital Inc. Aurora® electromagnetic tracking system. Available at: http://wwwndigitalcom/medical/auroratechspecsphp, 2012.
- [38] Gefen A, Dilmoney B. Mechanics of the normal woman's breast. Technol Health Care 2007;15:259–71.
- [39] Boone JM, Brink JA, Edyvean S, Huda W, Leitz W, McCollough CH, et al. Radiation dosimetry and image quality assessment in computed tomography. J Int Comm Radiat Units Meas 2012;12:1–164.