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Development and evaluation of a new image-based user interface for robot-assisted needle placements with the Robopsy system

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ABSTRACT

The main challenges of Computed Tomography (CT)-guided organ puncture are the mental registration of the medical imaging data with the patient anatomy, required when planning a trajectory, and the subsequent precise insertion of a needle along it. An interventional telerobotic system, such as Robopsy, enables precise needle insertion, however, in order to minimize procedure time and number of CT scans, this system should be driven by an interface that is directly integrated with the medical imaging data. In this study we have developed and evaluated such an interface that provides the user with a point-and-click functionality for specifying the desired trajectory, segmenting the needle and automatically calculating the insertion parameters (angles and depth). In order to highlight the advantages of such an interface, we compared robotic-assisted targeting using the old interface (non-image-based) where the path planning was performed on the CT console and transferred manually to the interface with the targeting procedure using the new interface (image-based). We found that the mean procedure time (n=5) was 22 ± 5 min (non-image-based) and 19 ± 1 min (image-based) with a mean number of CT scans of 6 ± 1 (non-image-based) and 5 ± 1 (image-based). Although the targeting experiments were performed in gelatin with homogenous properties our results indicate that an image-based interface can reduce procedure time as well as number of CT scans for percutaneous needle biopsies.

Keywords: Medical Robotics, Image-Guided Therapy, Graphical User Interface

1. PURPOSE

Minimally invasive interventions such as biopsies or ablation therapies often require precise insertion of needle-shaped instruments into soft tissue organs such as the liver and lung.¹⁻⁵ Figure 1 shows the workflow for Computed Tomography (CT)-guided needle biopsies of the lung. Due to the iterative nature of the procedure, many CT scans are needed to succeed in placing the needle precisely into the lesion. The main challenges of conventional CT-guided organ punctures are the mental registration of the medical imaging data with the patient anatomy required when planning a trajectory, and the subsequent precise insertion of a needle along it. One way to address these issues is to use an interventional robotic device which assists inserting the biopsy needle. Cleary et al.⁶ and Pott et al.⁷ give an overview on such systems. Current research focusses on robotic systems for percutaneous needle insertions.⁸⁻¹⁴ Walsh et al.¹⁵ introduced a lightweight medical robot device Robopsy, prototyped using parts made by stereo lithography which enables remote stabilization, orientation and insertion of a needle into the human body (e.g. the lung) based on a user defined trajectory. For controlling the robot, the compound needle insertion angles (in-plane and off-plane) and the insertion depth must be extracted from the CT image. Although the initial version of the user interface of the Robopsy system provided some visual feedback and enabled the procedure to be performed remotely, it was not integrated with the medical imaging data. Thus, it was necessary to perform the path planning on the CT console where the resulting insertion

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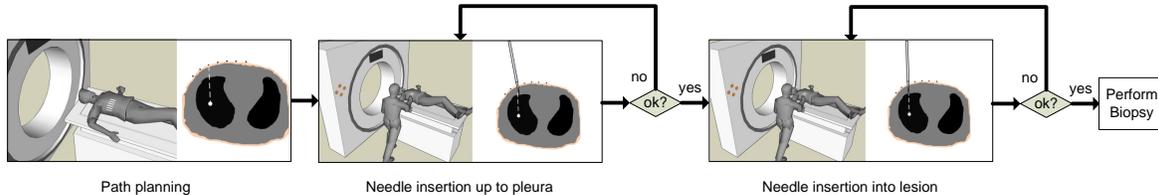


Figure 1. Workflow of a needle biopsy in the lung. First, the trajectory is planned with the help of a radio-opaque grid affixed to the skin of the patient. The gantry of the CT scanner may be tilted in order to visualize the planned needle path in a single CT slice. Next, the desired needle angles and depth from the skin entry point to the target are measured from the CT console, and the needle is incrementally inserted, while taking control CT scans and adjusting the trajectory accordingly until the pleura is reached. A deliberate puncture of the pleura is then performed with minor corrections made if absolutely necessary until the needle is in the lesion. A control CT scan confirms the position of the needle again before the biopsy is taken.

parameters (angles and depth) were determined manually and entered into the robot interface. Limitations of this approach are that path planning in the cranial-caudal direction is not possible or difficult to perform and the resulting planned path cannot be visualized across multiple CT slices.

The aim of this work was to develop a new image-based user interface for the Robopsy system, which allows for intuitive, accurate and fast control of the robot. In this paper, we compare the non-image-based Robopsy approach with the image-based Robopsy approach with respect to time and the number of CT scans required. Data from a retrospective study of clinically performed lung biopsies are also presented for comparison to determine the potential benefit of such an image-based interface.

2. MATERIALS AND METHODS

2.1 Robopsy system

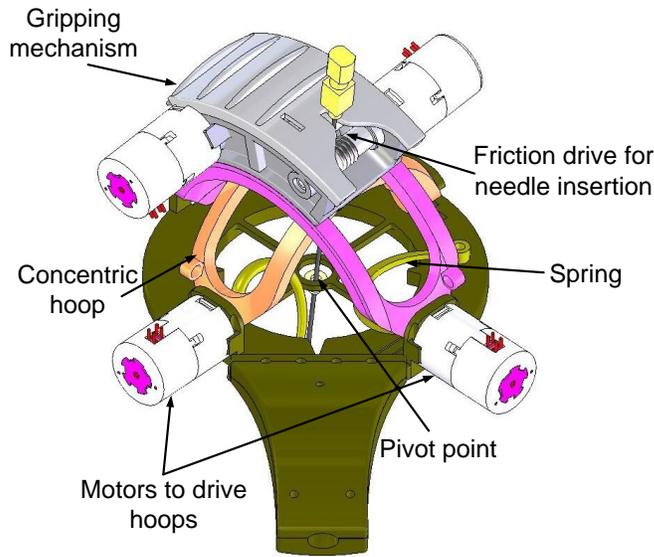
The Robopsy system¹⁵ enables automated needle insertion towards a target within the body (e.g. the lung). The prototype consists primarily of radiolucent plastic parts, moved by four micro motors controlled by a standard electronic control board (cf. Figure 2). The device shown is a prototype made using silicon-molded plastic parts, and clearances on the order of 1 mm are present between the plastic parts. In a production molded device, the clearances would be sub mm.

Once the needle is gripped, two concentric hoops enable the rotation of the needle around a point close to the skin surface (pivot point). The needle is gripped between two rubber rollers (one of them is actuated) that act as a friction drive for needle insertion. The passive roller is mounted on a rack that is driven by a pinion to grip the needle (cf. Figure 2a). The device is affixed to the patient inside the CT room and is connected to a control box that handles commands sent from a remote computer. Thus, the physician is able to remotely control the robot and therefore needle orientation and insertion from outside the CT room.

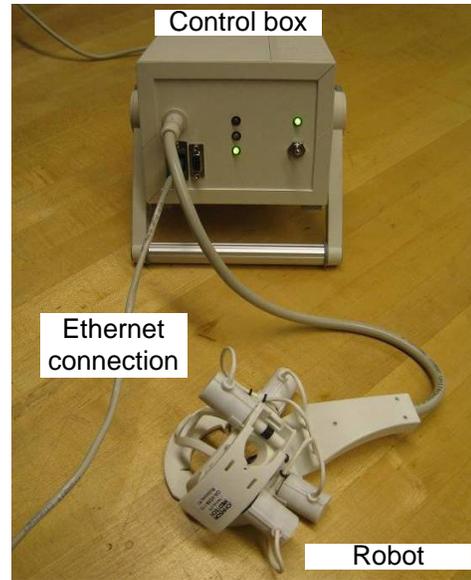
The following paragraphs describe the two different types of user interfaces for the Robopsy system. Both interfaces can be used for a robot driven lung biopsy by slightly modifying the clinical workflow shown in Figure 1. When the path is planned and an entry point is marked on the skin, the robot is placed with its pivot point (cf. Figure 2a) at this entry point. To achieve the transformation from the CT coordinate system to the robot coordinate system, the robot must be registered in the CT images.

2.1.1 Non-image-based robot control

As mentioned before, the initial Robopsy user interface is a non-image-based control console for the robot where angles and depth can be manually entered in order to control the robot (Figure 3a). As there is no medical image integration, the interface can only be used in combination with the console of the CT scanner where the trajectory planning and the determination of insertion angles and depth are performed before being manually transferred to the interface. However, the functionality available from the CT scanner is limited, making the measurement of angles in the cranio-caudal direction difficult, thus restricting the planned path and the needle to be visible in the same CT slice. In order to achieve this, the gantry of the scanner is tilted and often multiple scans at various different angles are required.



(a)



(b)

Figure 2. Robopsy telerobotic tool for percutaneous interventions: (a) Solid model of the robot with two concentric hoops for needle orientation, a rack and pinion for needle gripping and a friction drive for needle insertion. (b) Prototype Robopsy system with robot and control box for processing commands sent to the device

2.1.2 Image-based robot control

The new image-based interface was developed within the open-source cross-platform library “The Medical Imaging Interaction Toolkit” (MITK)¹⁶ and provides direct integration of the medical imaging data with the robotic system. The user can define the path by clicking on the skin entry point and the target point within the lesion on the medical images of the patient. Currently, the needle is manually registered in the image by marking its tip position and a point close to its end. This registration will be replaced by an improved (semi-)automatic method. The corresponding insertion angles and the depth are determined automatically from the given path and needle vectors. The needle and the path are not restricted to lie in the same CT slice for this interface as all calculations are made on three-dimensional image data and not in the individual two dimensional slices, allowing any desired path to be shown graphically.

2.2 Evaluation

For evaluating the developed image-based interface we performed a direct comparison with the old non-imaged based interface (Section 2.2.1). In addition, we qualitatively compared these results with the results of a retrospective study to highlight the potential benefits of such an image-based interface for the clinical procedure (Section 2.2.2).

2.2.1 Comparison of interfaces

The evaluation of both the non-image-based and the imaged based interface was performed with targeting experiments in a custom designed phantom. The parameters used for comparison for these experiments were the times and the number of CT scans for the individual sub-tasks of the procedure.

The phantom consisted of a box filled with ballistic gelatin (Vyse Gelatin Company, Schiller Park, IL, USA) which has a consistency similar to human tissue and is used for ordnance testing (cf. Walsh et al.¹⁵). Two separate sets of five targets arranged in a semicircle were cast on each side into the phantom at a depth of 75 mm from the (planar) surface. Targeting using the non-image-based robotic system was performed with the five targets on one side of the phantom, and the targeting using the image-based system was performed on the other

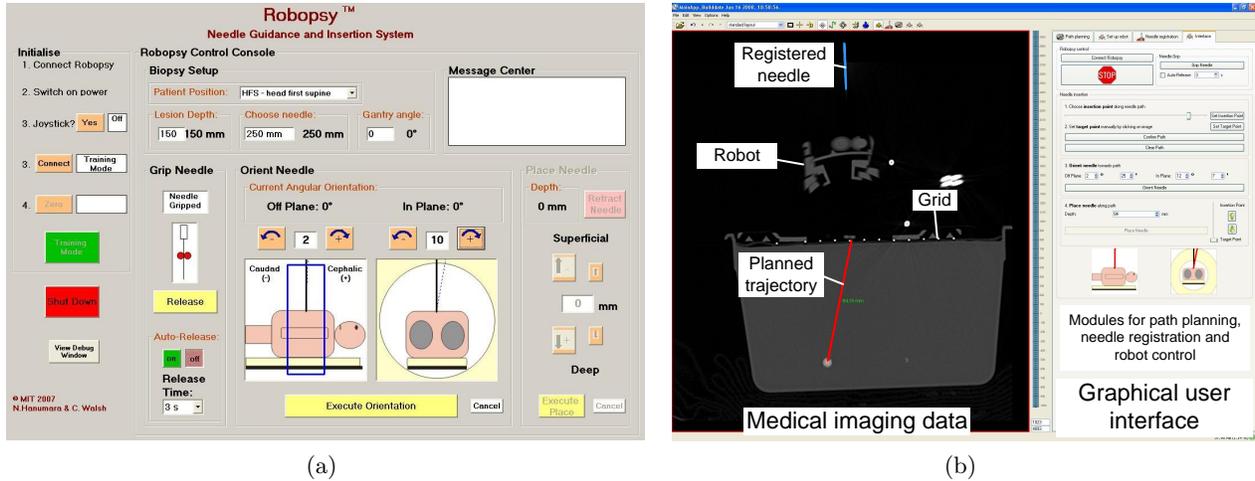


Figure 3. Interfaces to control the robotic device: (a) Current interface without image integration. (b) New image-based interface with integrated medical imaging data.

side. Four wooden sticks were arranged parallel and inserted just below the surface to imitate the ribs of the human body. Figure 4 shows the phantom and the experimental setup. All experiments were performed using a triple bevel needle with a diameter of 1.3 mm (18 gauge) to avoid deflection and bending of the needle.

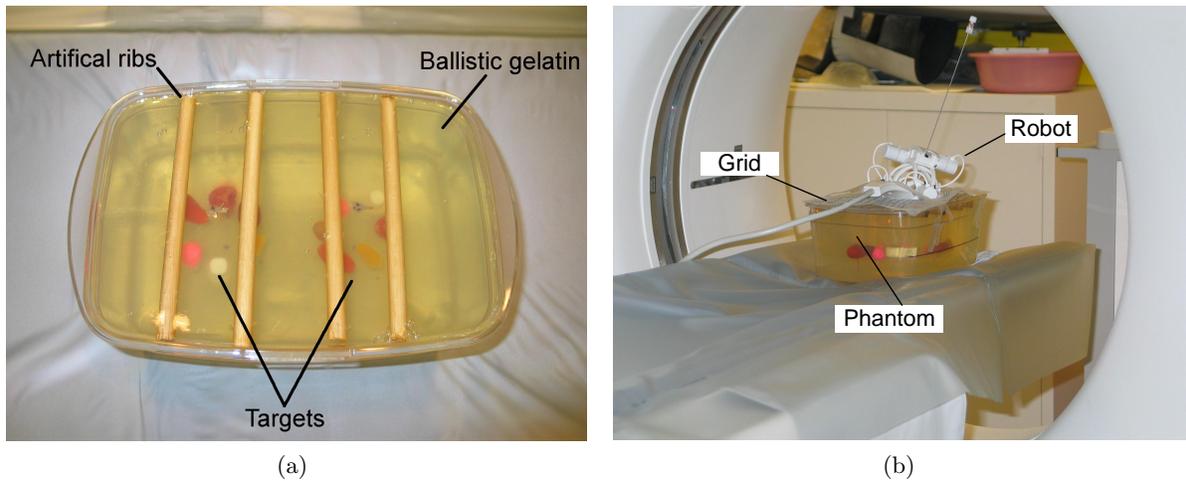


Figure 4. (a) Custom designed phantom comprising 2×5 targets and artificial ribs. (b) Setup during the experiments.

A workflow of both experiments consisted of three main steps that were divided into multiple sub-steps as shown in Table 1:

1. Preparation of phantom and scanner

A radio-opaque grid was placed onto the phantom, and the scanning range of the CT scanner (GE Light-speed H16) was determined via a localizer scan.

2. Path planning and robot placement

With the help of the grid, the trajectory was planned, and the robot was placed onto the phantom. For paths in the cranio-caudal direction, the non-image-based interface required the gantry to be tilted so as to visualize both the path and the needle in one CT slice. In order to achieve this, it was often necessary for the user to scan multiple times at different angles. The image-based interface required the robot to be

placed parallel to the x-z-plane of the scanner with its handle pointing out of the scanner bore, to be able to specify the transformation from image to robot coordinates (cf. Figure 4b). An automated registration of the robot is expected to be included in the next version of the interface.

3. Needle placement

The needle was aligned with the planned path and then inserted towards the target.

In this study, steps 1 and 2 were only performed once as it can be assumed that times for preparation and path planning/robot placement are similar for each target in the static phantom (except for the gantry tilt).

2.2.2 Comparison to conventional needle insertion

In addition a retrospective study of 46 clinically performed lung biopsy cases was analysed to extract the average time, number of CT scans and number of gantry tilts performed. This data was then compared to the results of the phantom experiments to highlight the potential benefits of the telerobotic system driven by an image-based user interface.

3. RESULTS

Figure 5 summarizes the results of the comparison of the image-based and the non-image-based controlled robot. The mean procedure time for targeting one lesion following the described workflow was 21 ± 5 minutes with the non-image-based controlled robot and 19 ± 1 minutes with the use of the image-based controlled robot (n=5). This corresponds to a reduction of the overall procedure time of 11%. The total number of CT scans taken was 6 ± 1 and 5 ± 1 respectively.

The preparation step could be performed with almost equal times (2:25 compared to 2:37 minutes). The path planning took approximately three minutes longer for the non-image-based method (12:04 compared to 8:40 minutes) with the required tilting of the gantry in the non-image-based interface causing most of the difference (8:15±3:06 minutes). For the image-based interface only one CT scan was necessary for the path planning step while approximately two scans were required for the non-image-based system. The needle placement could be performed in a similar time with both interfaces (7:39±2:58 non-image based compared to 8:29±1:20 image-based). For a detailed description of all results of this comparison, the reader is referred to Table 1.

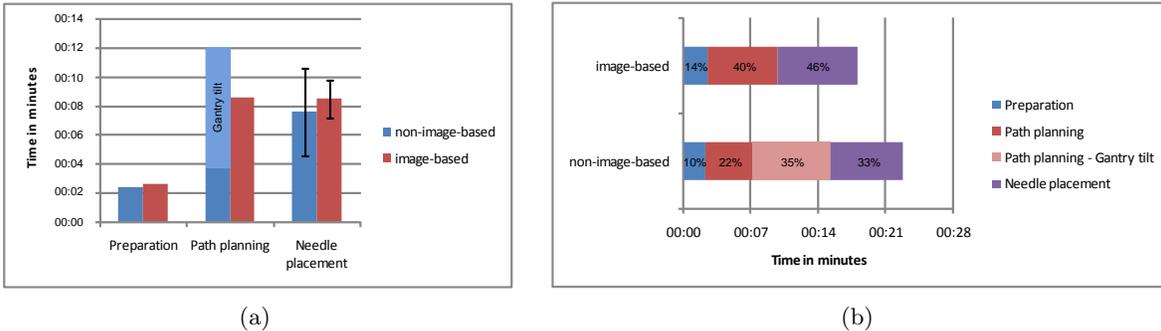


Figure 5. (a) Averaged time needed for the different steps of the workflow. The standard deviation is only shown for the needle placement, because the other steps were not performed for all lesions. (b) Total time needed for the whole procedure and percentages for the different steps.

Table 2 shows the results of the retrospective study (cf. section 2.2.2) of conventional lung biopsies (n=46) where lesion size varied from 0.7 - 5.2 cm. In the table, the conventional workflow is split into a planning and a needle placement step. The planning step can be compared with the path planning step for the robot controlled needle insertions (cf. Table 1). On average, planning took about 15 ± 6 minutes (range: 5 - 33) and 4 ± 2 (range: 1 - 11) CT scans and needle placement could be performed in 30 ± 13 minutes (range: 12 - 73) while taking 14 ± 5 CT scans (range: 6 - 28). 3 ± 3 (range: 0 - 11) gantry tilts were needed to succeed in placing the needle during the procedure.

non-image-based	t in minutes	# trials	image-based	t in minutes	# trials
Preparation	2:25		Preparation	2:37	
Place Grid	0:18	1	Place Grid	0:17	1
Prepare Scanner	1:02	1	Prepare Scanner	1:20	1
Scan Localizer	0:31	1	Scan Localizer	0:30	1
Mark scan region	0:34	1	Mark scan region	0:30	1
Path planning^a	12:04±4:34		Path planning	8:40±0:11	
CT with Grid	0:33	1	CT with Grid	0:30	1
			Load CT Images	0:36	1
Gantry tilt	8:15±3:06		Gantry tilt		
Determine angles	4:04±2:21	1.4±1.1			
Tilt gantry	0:32±0:20				
Control CT ^b	0:22±0:03				
Plan trajectory	1:45	1	Plan trajectory	3:20	1
Mark entry point	0:35	1	Mark entry point	1:18	1
Place robot	1:50	1	Place robot	1:30	1
Zero robot	0:15	1	Zero robot	0:15	1
Grip needle	0:05	1	Grip needle	0:05	1
Planning CT ^c	0:25±0:04	1	Planning CT	0:33±0:11	1
Needle placement	7:39±2:58		Needle placement	8:29±1:20	
			Load CT Images	0:26±0:05	3.0±1.0
Determine angles	1:15±0:49	3.6±1.1	<i>Determine angles</i>	2:02±0:38	2.4 ± 0.5
			Register needle	0:49±0:19	2.4 ± 0.5
			Re-plan path	1:13±0:35	
			Compute angles	0:00±0:00	
Place needle	0:21±0:16	3.6 ± 1.1	Place needle	0:10±0:10	3.0 ± 1.0
Control CT	0:31±0:11	3.6 ± 1.1	Control CT	0:32±0:07	3.0 ± 1.0
Total Time	21:42±5:34			19:13±1:20	
Number of CTs	6.0±1.2			5.0±1.0	

^aAs some steps of the workflow for path planning were only performed once the average was obtained from the same times for each lesion for these steps.

^bNeedle placement was performed directly after the gantry tilt without taking an intermediate control CT scan for two gantry tilt trials

^cThe planning CT was acquired for each lesion to be targeted. The time is therefore averaged over all lesions.

Table 1. Comparison of the two Robopsy interfaces (image-based, non-image-based) regarding the time t and the number of trials for the single step of the workflow. The times given for the individual steps of gantry tilt and needle placement are averaged over the single trials and all lesions. The total values of gantry tilt and needle placement are given averaged over the total values for the lesions. The steps for preparation and robot placement were only performed once before n=5 lesions are targeted with each method.

4. DISCUSSION

In this paper we have compared two different kinds of user interfaces with respect to procedure time and number of CT scans required for controlling the telerobotic system Robopsy. Targeting experiments in a custom developed static phantom were performed with a non-image-based interface and an image-based interface. According to our results the overall procedure time could be reduced by approximately 11% with the new, image-based interface. The gantry tilt for path planning which made up 35% of the total time for the non-image-based interface could be avoided with the image-based interface and therefore had the biggest influence on the reduction of time.

In addition, a retrospective study of 46 lung biopsy cases was analyzed to determine the potential benefits of a robotic system driven by an image-based user interface for percutaneous needle insertions. The results show

Conventional biopsy	time [min]	# of scans	# of gantry tilts
Planning	15±6	4.0 ± 2.4	2.9 ± 2.7
Needle placement	30±13	14.4 ± 5.3	

Table 2. Main steps of a conventional lung biopsy. Mean times, mean number of CT scans and mean number of gantry tilts \pm standard deviation were achieved from a retrospective study lung biopsy cases (n=46). The planning step can be compared with the steps preparation, path planning and gantry tilt of the workflow shown in Table 1.

that in current clinical practice a significantly larger number of CT scans (and associated procedure time) is required compared to the simulated biopsy procedure performed on the static gelatin phantom in this study. Even though the time for a gantry tilt was not recorded for this data, the duration of the planning step could be reduced by approximately 30% (13 minutes) if we assume that the time needed for one gantry tilt can be approximated with the value from the phantom experiments (4.7 ± 2.3 min) and the total time for all gantry tilts can be estimated from this value and the number of gantry tilts performed (2.9 ± 2.7).

The time for the path planning could be reduced drastically with the image-based method, as there was no gantry tilt required. Also, it has to be mentioned that the other sub-steps of the path planning were only performed once and all 5 lesions were targeted from the point the robot was initially placed. Thus, the user had no chance to become accustomed with the new interface as these steps were only performed once and there was no training period before. The needle placement steps showed a similar duration for both interfaces with the image-based interface being slightly slower. This is because the imaging data had to be transferred to the image-based interface each time a CT scan was taken and further, the needle currently has to be segmented manually. However, we found that the number of CT scans needed for needle placement was slightly lower for the image-based interface. The biggest benefit of the image-based interface can therefore be seen in the fact that there was no need to make sure that the path and the needle have to be visualized in the same CT slice and that no gantry tilt is needed since all calculations were made on the three-dimensional imaging data. Although not a direct comparison, our results indicate that, compared to the clinical method investigated in the retrospective study, successful targeting of lesions can be performed using a telerobotic system controlled by an image-based interface with a much reduced number of CT scans and procedure time. The simulated ribs in our phantom did provide a challenge in planning for our user, but clinically a radiologist would have a significantly harder time planning as it is critical to avoid ribs, vessels and other anatomic features. We thus expect the ability to measure angles precisely and visualize paths over multiple slices to be significant in terms of making the procedure more accurate and faster.

Despite our promising results, we recognize that our evaluation did not completely represent the clinical procedure. The user performing the experiments was not a trained radiologist but one of the designers of the robotic device. He did, however attend dozens of clinically performed percutaneous lung biopsies. As such, the presented results may not be representative of exact time values. Nonetheless they show the ability to improve and simplify the controllability of a robot through image integration into the user interface. Also, as there was no training period, our user did not have the chance to become familiar with the interfaces so that the time required for sub-steps like trajectory planning or angle determination could possibly have been further reduced. Furthermore, the robot placement and path planning workflow was not conducted for every single lesion due to time constraints and so the results for these first steps may also not have been truly representative. We recognize that the challenge of accurately placing the needle in our phantom is easier because there is no motion (e.g. due to respiration) and the material properties are homogeneous (minimizing unwanted deflection of the needle). Nonetheless, the very significant reduction in the number of scans we found compared to the clinical procedure demonstrates the potential for the device to improve the procedure in the more challenging clinical environment.

As the experiments for this paper were performed with the first version of this image-based interface there is still plenty of room for improvement in terms of functionality and usability. The localization of the robot in the medical imaging data, and therefore getting the transformation from the image coordinate system to the robot coordinate system is currently performed manually by placing the robot in a special way as described in section 2.2. A more sophisticated registration method would improve the accuracy of the whole system and eliminate the need to place the device in a particular orientation. An automated localization of the needle in the image

will also enhance and speed up the calculations of angles and depth. Moreover the robotic device used for these experiments was rapid prototyped and a production system would have tighter part tolerances. We expect all of these improvements to both the interface and the robot hardware to enable the duration and radiation exposure for these procedures to be further reduced.

In conclusion, image integration into the robotic needle placement system Robopsy is shown to improve the procedure by reducing both the time and the number of CT scans required and enables the telerobotic system to integrate seamlessly with how the procedure is performed today. A major advantage of the image-based interface is, that measurements can be performed directly on the three-dimensional medical imaging data and transferred directly to the robotic device. Furthermore, the ability to plan and visualize paths in three dimensions eliminates the need for tilting the gantry.

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REFERENCES

- [1] Abolhassani, N., Patel, R., and Moallem, M., “Needle insertion into soft tissue: A survey,” *Med. Eng. Phys.* **29**, 413–431 (May 2007).
- [2] Weisbrod, G. L., “Transthoracic needle biopsy,” *World J. Surg.* **17**, 705–711 (November 1993).
- [3] Manhire, A., Charig, M., Clelland, C., Gleeson, F., Miller, R., Moss, H., Pointon, K., Richardson, C., Sawicka, E., and S., B. T., “Guidelines for radiologically guided lung biopsy,” *Thorax* **58**, 920–936 (Nov 2003).
- [4] Ohno, Y., Hatabu, H., Takenaka, D., Higashino, T., Watanabe, H., Ohbayashi, C., and Sugimura, K., “CT-Guided Transthoracic Needle Aspiration Biopsy of Small (≤ 20 mm) Solitary Pulmonary Nodules,” *AJR Am. J. Roentgenol.* **180**, 1665–1669 (October 2003).
- [5] Wallace, M. J., Krishnamurthy, S., Broemling, L. D., Gupta, S., Ahrar, K., Morello, F. A., and Hicks, M. E., “CT-guided Percutaneous Fine-Needle Aspiration Biopsy of Small (≤ 1 cm) Pulmonary Lesions,” *Radiology* **225**, 823–828 (December 2002).
- [6] Cleary, K., Melzer, A., Watson, V., Kronreif, G., and Stoianovici, D., “Interventional robotic systems: Applications and technology state-of-the-art,” *Minim. Invasive Ther. Allied. Technol.* **15**(2), 101–113 (2006).
- [7] Pott, P. P., Scharf, H.-P., and Schwarz, M. L. R., “Today’s state of the art in surgical robotics,” *Comput. Aided Surg.* **10**, 101–132 (March 2005).
- [8] Maurin, B., Bayle, B., Piccin, O., Gangloff, J., de Mathelin, M., Doignon, C., Zanne, P., and Gangi, A., “A patient-mounted robotic platform for CT-scan guided procedures,” *IEEE Trans Biomed Eng.* **55**(10), 2417–25 (2008).
- [9] Patriciu, A., Awad, M., Solomon, S., Choti, M., Mazilu, D., Kavoussi, L., and Stoianovici, D., “Robotic Assisted Radio-Frequency Ablation of Liver Tumors - Randomized Patient Study,” in [*Medical Image Computing and Computer-Assisted Intervention (MICCAI)*], 526–533, Springer (2005).
- [10] Taillant, E., Avila-Vilchis, J.-C., Allegrini, C., Bricault, I., and Cinquin, P., “CT and MR Compatible Light Puncture Robot: Architectural Design and First Experiments,” in [*Proc. 2004 Int. Soc. and Conf. Series on Medical Image Computing and Computer-Assisted Intervention*], 145–154 (2004).
- [11] Kim, D., Kobayashi, E., Dohi, T., and Sakuma, I., “A New, Compact MR-Compatible Surgical Manipulator for Minimally Invasive Liver Surgery,” in [*Medical Image Computing and Computer-Assisted Intervention MICCAI 2002*], (2002).

- [12] Stoianovici, D., Cleary, K., Patriciu, A., Mazilu, D., Stanimir, A., Craciunoiu, N., Watson, V., and Kavoussi, L., "Acubot: a robot for radiological interventions," *IEEE Transactions on Robotics and Automation* **19**(5), 927 – 930 (2003).
- [13] Kettenbach, J., Kronreif, G., Figl, M., Frst, M., Birkfellner, W., Hanel, R., and Bergmann, H., "Robot-assisted biopsy using ultrasound guidance: initial results from in vitro tests," *Eur Radiol* **15**(4), 765–771 (2005).
- [14] Su, L. M., Jarrett, D. S. T. W., Patriciu, A., Roberts, W. W., Cadeddu, J. A., Ramakumar, S., Solomon, S. B., and Kavoussi, L. R., "Robotic percutaneous access to the kidney: comparison with standard manual access," *J Endourol.* **16**(7), 471–475 (2002).
- [15] Walsh, C. J., Hanumara, N. C., Slocum, A. H., Shepard, J.-A., and Gupta, R., "A Patient-Mounted, Telerobotic Tool for CT-Guided Percutaneous Interventions," *J. Med. Devices* **2**, 011007 (10 pages) (March 2008).
- [16] Wolf, I., Vetter, M., Wegner, I., Böttger, T., Nolden, M., Schöbinger, M., Hastenteufel, M., Kunert, T., and Meinzer, H.-P., "The Medical Imaging Interaction Toolkit," *Med. Image Anal.* **9**, 594–604 (December 2005).