Robotic guidance for percutaneous interventions

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Robotic guidance for percutaneous interventions

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Abstract—A robotic system is being developed by ARC Seibersdorf Research in cooperation with the Departments of Biomedical Engineering and Physics as well as Diagnostic Radiology (both located at the Vienna University Hospital) in order to assist interventional radiologists when they are doing ultrasound (US)- or computed tomography (CT)-guided biopsies. According to the requirements from clinical practice, the complete system is mounted on a mobile platform and uses video I/O as a standardized interface to the various CT and US devices in practical use. During planning of the intervention, the interventionalist can use the US or CT scans acquired before to select the skin entry point as well as the target point. After confirmation of the planning, the robot is moved to the start position using different modes of motion. Finally, the needle is manually inserted by the interventionalist. The complete intervention can be monitored and documented by means of superimposed information of the planned and real biopsy trajectory on the actual CT or US scan. A feasibility study making use of a dedicated custom-made robotic system is aimed to validate the elaborated concept. The paper describes the developed arm and the controller architecture, and gives some first results from a pre-clinical test using a needle-penetrable medical phantom.

Keywords: Image-guided intervention; computer-aided surgery; medical robotics; interventional radiology; biopsy.

1. INTRODUCTION

Image-guided percutaneous biopsies of pathologic tissue are commonly the first step towards therapy in many diseases of structures or organs. However, the value of a diagnostic technique depend on its sensitivity, specificity and accuracy, as well as how its results affect clinical management. Especially for deeply situated target areas, various intra-operative imaging modalities — computer tomography...
(CT), ultra-sonography, fluoroscopy, as well as magnetic resonance imaging (MRI) — are applied largely by radiologists for planning therapy, for guidance of the procedure and for post-procedure follow-up. A freehand biopsy technique, i.e., manual estimation of the skin entry point, as well as of the needle angulation using information from intra-operative imaging, may lead to incorrect needle insertion, and can be cumbersome and time consuming due to the need for permanent re-imaging. In order to increase the accuracy and to support the interventional radiologist to reduce the amount of time often necessary to simply target a lesion, a dedicated custom-made robotic system is being developed by ARC Seibersdorf Research in coorperation with the Departments of Biomedical Engineering and Physics, as well as Diagnostic Radiology (both located at the Vienna University Hospital). The main goal of the system is not only to improve diagnostic accuracy, but also to reduce both the amount of time for the procedure as well as the risk of possible complications while planning an oblique trajectory.

In more detail, the potential advantages will be:

- Improved accuracy and consistent results of biopsy samples.
- Improved visualization and planning of the biopsy trajectory in order to avoid critical structures.
- Improved safety and lower risk of complications.
- Shortening of the interventional procedure.
- Reduced radiation dose for the radiologist and patient during intervention [1].
- Planning of complex (double-) oblique access routes if necessary.
- Reduced treatment costs due to lower morbidity.

The robotic system should serve as an active guidance system. Based on pre-operative imaging and planning, the medical instrument will be positioned (manually or automatically) at the skin entry point. During the intervention, the (optionally blocked) robot kinematic holds the needle guide in a defined position/orientation to the patient’s body. The needle insertion itself will be manually performed by the physician. Using a real-time intra-operative imaging modality like fluoro-CT (CTF) or ultra-sound (US), the intervention can be visualized and adapted to the current situation if needed. The robot serving as the physician’s ‘third hand’ helps to shorten the time associated with searching for the desired insertion point and angulation (especially caused by the limited dexterity while reaching into the CT gantry); it also allows the surgeon to maintain the planned trajectory effortlessly. For the entire system a maximal error (i.e. the distance between needle tip and target) of ±3 mm was defined from the clinical point of view.

Planned clinical applications for this first prototype are biopsies in the abdominal area — intra-operative imaging modalities in use are CTF and B-mode US. The long-term goal is to create a multi-purpose system for a broad range of percutaneous treatments, in any part of the body, using any kind of intra-operative image guidance.
2. METHODS AND SYSTEM COMPONENTS

Other than for existing prototypes (see [2–4]) it was one of the major requirements to combine the system with different imaging systems available in the hospital. Thus, the entire system is mounted on a mobile rack and uses a video signal as a standardized input source. Using the system with different CT scanners as well as with US systems also led to a tailored 7-d.o.f. kinematic structure of the robot system. Delivering of the skin entry point is performed by a 4-d.o.f. gross positioning system. Three linear axes in cartesian configuration together with one additional rotational link for a rough orientation of the needle establish the basic kinematics of the robot system and guide the needle-positioning unit (NPU) to the entry position (see Fig. 1). The final orientation of the needle is done by means of the NPU with its 2 linear d.o.f.s. Another linear d.o.f. with a limited stroke of 50 mm moves the entire NPU to the patient’s skin in a secure approach movement, i.e. with minimized velocity and force. Setting the needle orientation is strictly decoupled from movement of any axis of the gross positioning system. The remote center of motion (‘pivot point’) for angulation of the needle is maintained by the kinematic structure of the NPU in order to achieve the maximum safety during the intervention.

For the NPU, considerable attention was paid to develop a very compact, but precise and dexterous, device. Orientation of the needle is defined via relative motion of two parallel ‘fingers’ connected to each other with spherical joints (see Fig. 2).

The complete system includes the following components:

- Intra-operative imaging device (CT scanner or US imaging system) with a standard video interface.
- Optical tracker system (NDI Polaris) for real-time localisation of (i) the imaging device, (ii) the patient and (iii) the robot base. For redundant localization of the needle position/orientation, the needle positioning unit may be tracked as well.

![Figure 1. Kinematic structure of the gross positioning unit and realized prototype [5].](image-url)
A 4-d.o.f. robotic system for gross positioning (Fig. 1). For the realized robot prototype the three linear axes are driven by DC servo motors; transformation into linear movement is done by ball screw systems. For axis control and kinematics calculations, optical linear encoders are used as an internal sensor system. Rotational axis A4 is direct-driven by a DC-motor + planetary gear combination with an incremental encoder for angle measurement (for details, see Table 1). The resulting working area of the gross positioning system in $x-y-z$ coordinates is $450 \text{ mm} \times 450 \text{ mm} \times 700 \text{ mm}$ ($x$-coordinate corresponds to the cranial-caudal axis; $y$-coordinate in the transversal direction).

A 3-d.o.f. NPU (Fig. 2). For the three linear axes of the NPU (A5–A7), mini-stepper motors are in use. Transformation to linear movement is also done by high-precision ball-screw systems (for details, see Table 1). The combination of the two linear axes A6 and A7 realized in the first prototype of the NPU allows needle angulation of $\pm 15^\circ$.

A specially designed robot control system (Windows 2000-based industrial PC). Axes A1–A4 are controlled by four MIP50 controllers (DC controller unit; 4Q-PWM 60 kHz PID position control; Maxon Motors) connected to the main control system via an RS-485 network. Control of the stepper motors is done with cascaded off-the-shelf controller boards (Swift200; programmable two-axes controller; Cortex Controllers) connected to the PC via an RS-232 interface.

Input device and safety switches.

Medical navigation software ROBUST for definition of the needle trajectory and for monitoring of the intervention (Linux-based industrial PC equipped with video capture card WinTV-PCI-FM 718; Hauppauge). ROBUST has been developed using C++ programming language with Qt-Library (release 1.45) and SUSE-Linux (release 7.1).

It should be mentioned here, that it stands as a requirement to execute interventions also inside the CT gantry which essentially influences the robot kinematics. For the gross positioning unit, the required workspace in addition with the desired absence of singularities recommend the use of a cartesian configuration described in Fig. 1. Linear axes A1 and A2 position the NPU in a plane perpendicular to the CT support.
### Table 1.
Actuating systems and position sensors for robot prototype

<table>
<thead>
<tr>
<th>Axis</th>
<th>Actuating system</th>
<th>Position sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>DC servo motor</td>
<td>optical linear encoder (accuracy ±5 μm, measuring length = 520 mm)</td>
</tr>
<tr>
<td></td>
<td>tooth belt gear $i = 1:1$</td>
<td>micro switches for stroke limitation</td>
</tr>
<tr>
<td></td>
<td>ball screw gear (600 mm stroke)</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>DC servo motor</td>
<td>optical linear encoder (accuracy ±5 μm, measuring length = 520 mm)</td>
</tr>
<tr>
<td></td>
<td>ball screw gear (600 mm stroke)</td>
<td>micro switches for stroke limitation</td>
</tr>
<tr>
<td>A3</td>
<td>DC servo motor</td>
<td>optical linear encoder (accuracy ±5 μm, measuring length = 720 mm)</td>
</tr>
<tr>
<td></td>
<td>tooth belt gear $i = 1.78:1$</td>
<td>micro switches for stroke limitation</td>
</tr>
<tr>
<td></td>
<td>custom made trapezoid screw gear (820 mm stroke, plastic nuts)</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>DC servo motor</td>
<td>digital rotational encoder</td>
</tr>
<tr>
<td></td>
<td>planetary gear $i = 66:1$</td>
<td>micro switches for stroke limitation</td>
</tr>
<tr>
<td>A5</td>
<td>miniature two-phase stepper motor</td>
<td>micro switches for stroke limitation</td>
</tr>
<tr>
<td></td>
<td>planetary gear $i = 14:1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>tooth belt gear $i = 1:1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ball screw gear (40 mm stroke)</td>
<td></td>
</tr>
<tr>
<td>A6</td>
<td>miniature two-phase stepper motor</td>
<td>micro switches for stroke limitation</td>
</tr>
<tr>
<td></td>
<td>planetary gear $i = 3.71:1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>tooth belt gear $i = 1:1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ball screw gear (20 mm stroke)</td>
<td></td>
</tr>
<tr>
<td>A7</td>
<td>miniature two-phase stepper motor</td>
<td>micro switches for stroke limitation</td>
</tr>
<tr>
<td></td>
<td>planetary gear $i = 3.71:1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>tooth belt gear $i = 1:1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ball screw gear (20 mm stroke)</td>
<td></td>
</tr>
</tbody>
</table>

table — movement can be done in single-axis mode or in a coordinated (combined with the appropriate movement of rotational axis A4) circular motion. The linear axis A3 is orientated parallel to the feeding axis of the CT table (i.e. the cranial-caudal axis of the patient) and easily allows positioning of the NPU inside as well outside of the CT gantry.

#### 2.1. NPU

The NPU — the tool of the biopsy robot — is aimed to perform fine orientation of the needle without simultaneous movement of the main axes (A1–A4) of the robot system. As well as keeping the kinematic transformations quite simple, this strictly decoupled movement of the ‘strong’ robot axes for (gross) positioning and subsequent setting of the exact orientation by means of the ‘gentle’ d.o.f.s of the NPU makes a substantial contribution to the operational safety of the robot system. Positioning and orientation stages may be independently enabled/disabled by hardware means. Another safety feature of the NPU includes the kinematic definition of the needle pivot point the during angulation. The fixed lower ‘finger’ of the NPU (see Fig. 2) defines the skin entry point of the needle and maintains this
remote center of movement during the complete intervention in order to avoid skin tensions. Compared to other kinematic configurations (e.g. a 6-d.o.f. articulated robot system), the chosen approach shows no singularities — maintenance of the remote center of motion during needle angulation is absolutely robust against faulty kinematic transformations and controller breakdowns.

The specially designed kinematic structure for the NPU also offers the required dexterity despite the limited size of the device. In order to also support interventions inside the CT gantry, the main extension (310 mm; including fingers) of the NPU was set to the longitudinal axis of the patient support table, whereas the transverse dimensions of the NPU (i.e. width and height) are limited to 100 mm for both directions [6].

For use of the NPU inside the CT gantry, all parts within the scanning area are radiolucent in order not to disturb the X-ray visibility. The NPU fingers are made from carbon fiber composite material; polymer spherical bearings (the prototype NPU uses modified ‘Igubal’ flange-mount bearings from Igus) and the needle guide also do not interfere with the imaging modality. For easy sterilization, the two fingers (together with the bearings) can be disconnected from the NPU by means of a rapid-change bayonet connection.

2.2. Robot control system

A specially designed control system performs and supervises all required movements of the robot system and is the central interface for all particular subsystems, i.e. the medical navigation software, the robot system, the input device as well as the security devices. After receiving input data from the planning station (entry and target point) or from the input device (manual movement for selected axes, coordinated movement, etc.), adequate information for the robot axes controllers is generated and transferred to the subsystems.

Figure 3 shows the general structure of the robot control system and the established signal/information flow. The important components of the control system are:

- The main control system (industrial PC with Windows 2000 operating system, Pentium III CPU 1 GHz, robot control interface developed in Delphi 5.0). With the robot control interface, all system parameters of the axes controller boards (for all 7 d.o.f.s) can be monitored and set. The actual as well as desired position (sent by the medical navigation system ROBUST) are displayed in both coordinate systems, joint coordinates as well as world coordinates (see Fig. 4a). In addition, the system interface allows manual control of the robot system if required. Another feature of the system is the possibility to three-dimensionally (3D) simulate the movement to the desired position in a separate window (simulation written in Open-GL; see Fig. 4b) in order to avoid critical situations (e.g. collision avoidance).
Figure 3. Control system and information flow.
Figure 4. (a) Main control window. (b) Simulation of the desired approach movement.
• Axis control modules (MIP50 servo controller for axes A1–A4 and Swift200 programmable stepper controller system for axes A5–A7), including power stage and digital I/Os.
• Specially designed input device ‘UI’.
• Central logic unit ‘Logic Box’.
• Power supply unit.

The ‘Logic Box’ is responsible for adjustment of the ‘UI’ signals to the signal level of the axes controllers as well as for logic processing of state and/or error signals. User input is transferred from the ‘UI’ to the ‘Logic Box’ which finally generates the required signal pattern for each particular axis controller.

2.2.1. Safety issues. In general, all control tasks mentioned above are distributed between several hardware and software components of the control system in order to achieve maximal safety. To give an example, basic robot movement in single-axis mode can be performed independently from the main control system (e.g. in the course of a system breakdown). For this operating mode user input at the ‘UI’ is transferred to each axis controller by means of discrete logic elements instead of any programmable elements. A system of different security levels embraces this control architecture in order to react to possible error scenarios in an efficient way. Table 2 shows error situations at different urgency levels and describes the reaction implemented in order to bring the system into a secure state.

2.3. Registration and calibration

The core of the system is an optical tracking system (POLARIS; NDI) which measures the 3D position data of all involved system components. The main advantage of an optical system results from its relatively high positional accuracy (for the used POLARIS tracker the accuracy is about 0.35 mm under optimal conditions). Drawbacks are given by the fact that the optical contact between the tools has to be maintained at all times. Another disadvantage lies in the low data acquisition rate (up to 60 Hz under optimal conditions; 20–30 Hz in a realistic scenario) and the relatively high costs.

For each system carrying information, i.e. the patient, the robot base as well as the imaging system (gantry of the CT or US probe), a particular coordinate system is defined. The purpose of registration and calibration is to obtain the relationship between all the coordinate systems involved.

2.3.1. Registration of the robot system. In a first step, the rigid body transformation between the tracker tool attached to the robot base and the internal world coordinate system of the robot must be defined by means of a point-to-point registration process. In general, a 3D translation \( t \) and rotation \( R \) has to be calculated that aligns a set of \( N \) 3D points \( x_i \) with a corresponding set \( y_i, i = 1, 2, \ldots, N \) such that
Table 2.
Possible system errors and resulting system state

<table>
<thead>
<tr>
<th>Possible error</th>
<th>Reaction</th>
<th>System state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inappropriate user input in single-axis motion, e.g. potential collision, etc. → user releases ‘UI’ command button</td>
<td>Signal pattern will be updated by ‘Logic Box’ by means of discrete logic elements → transfer to the axis controllers</td>
<td>Movement stops immediately → actual position will be maintained by the controller system</td>
</tr>
<tr>
<td>Inappropriate user input in coordinated axis motion → user releases ‘UI’ command button</td>
<td>Signal pattern will be prepared by ‘UI’ μController and will be generated and transferred to the axis controller by ‘Logic Box’</td>
<td>Movement stops immediately → actual position will be maintained by the controller system</td>
</tr>
<tr>
<td>Error at ‘UI’ μController, e.g. coordinated motion cannot be stopped → user releases foot switch</td>
<td>Foot-switch signal will be transferred to the ‘enable’ port of all axis controllers (directly, bypassing the ‘UI’)</td>
<td>Movement stops immediately → actual position will be maintained by the controller system</td>
</tr>
<tr>
<td>Error at axis controller module; no reaction to any user input possible → user activates ‘emergency stop’ button</td>
<td>Signal from the ‘emergency button’ transferred to the ‘enable’ port of all axis controllers as well as servo motors are disconnected from the power signal via relays</td>
<td>Movement stops immediately → position control for all axes deactivated → magnetic brake system for axis A1 activated automatically</td>
</tr>
<tr>
<td>Break down of main control system (PC)</td>
<td>No RS-485 communication to axis controllers</td>
<td>Robot can be moved in single-axis mode by means of the ‘UI’; no coordinated motion possible</td>
</tr>
</tbody>
</table>

the distance $d_i$ between corresponding points is minimized in a root-mean-square (r.m.s.) calculation — the resulting minimal r.m.s. distance is commonly called the ‘fiducial registration error’ (FRE). For the registration process of the introduced robot system, each $x_i$ is defined by markers on the robot base with known position in the internal robot coordinate system. The points $y_i$ are represented by the coordinates of these markers measured in the reference frame (DRF) of the optical tracker system. The FRE achieved during the first pre-clinical tests typically is about 0.7–0.9 mm.

2.3.2. Calibration of the US probe. The US probe is used in 3D space with a tracker tool attached in order to record the location and orientation of the scan head each time an image is acquired. By calibration of the US probe, it is now possible to assign a 3D coordinate to a 2D pixel of the scan for each given image. The calibration procedure implemented was originally based on the method described by Detmer et al. [7] (a detailed discussion of the implemented procedure is also given in Ref. [8]). A phantom specially designed for the calibration consists of a frame made of perspex (Fig. 5). Six nylon strings were fixed to the frame and 15 plastic spheres with a diameter of 1.5 mm each were glued onto the strings. The frame is put into
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Figure 5. (a) Phantom used for US calibration. (b) Schematic top view — points $F_1$–$F_5$ are used for point-to-point registration of the frame; each nylon string carries two or three plastic spheres ($s_{i1}, s_{i2}, s_{i3}$) for US probe calibration.
Figure 6. Screenshot of the GUI for US calibration.
a tank made of perspex which is filled with a 5% water-alcohol mixture in order to produce a US velocity comparable to fat tissue.

After point-to-point registration of the frame, a rigid transformation can be calculated by which various selected points in an acquired US scan (Fig. 6) are related to point coordinates in emitter space. Since the sphere’s coordinates are known in both emitter and image space, a 6-d.o.f. transformation can be calculated by using the method of singular value decomposition (SVD). The accuracy of this calibration procedure depends on several factors, but mainly on:

- The technical accuracy of the tracking system, i.e. the accuracy of localizing a point in space.
- Geometrical distortions of the image (especially for US images).
- Thickness of the US slice. The thickness of an US image slice increases in proportion to the distance from the scan head. As a consequence, spheres that appear in an image are assumed to be exactly in the US scan, but they may located some distance off the midplane of the idealized 2D image.

The calibration error for US calibration achieved by the described procedure is typically in the range of 0.7–0.9 mm. The same procedure is now going to be tested for CT calibration (results are not yet available).

3. OPERATION PRINCIPLE

3.1. Planning of the intervention

The developed robotic system will be used as follows. After an optional pre-interventional analysis of the best needle trajectory by means of a re-formatted 3D model, planning and performing of the biopsy takes place by using the medical navigation software ROBUST. After loading the calibration data of the used imaging modality and acquisition of (position coded) scans of the target region, the physician selects the desired skin entry point as well as the target point (the two points mentioned can be, but do not have to be, on the same CT slice). Once these positions are defined, the relevant data (angulation, distance to the target lesion) are calculated and sent to the robot controller via a TCP/IP socket connection. At the GUI of the planning software, the virtual trajectory of the biopsy can be inserted in all CT slices involved in order to verify the intervention.

For US-guided biopsies the procedure is very similar to the one described above, apart from the fact that this imaging modality allows one to scan a lesion from very different positions and angulations. Since the position of the US transducer will be recorded by an optical tracking system, the acquired scans are known in their coordinates of a DRF system (i.e. patient) for later calculation of the robot position. For planning the intervention, skin entry point as well as target point can again be selected by means of the available US scans (see Fig. 7). As for the CT-guided
**Figure 7.** Example of a US-guided biopsy. Acquisition of scans from the target region. Selection of the target point (detail).
procedure, the desired biopsy trajectory will be calculated and displayed in all US scans involved.

3.2. Positioning of the robot and execution of the intervention

During the general set-up procedure, the robot will be roughly positioned to the intervention field in single-axis mode by using the special designed input device ‘UI’. After planning the intervention, the NPU will be moved towards its exact start position by a coordinated motion of the robot kinematic (see Fig. 8a). After blocking (optional) of the gross positioning unit the NPU finally moves to the skin entry point in the proximal direction.

After setting the start position and during the intervention the actual trajectory of the needle guide is being calculated via a standard kinematic transformation based on the internal sensor systems of the robot as well as via the absolute position measurement by the optical tracker. All this information is inserted to the actual CT or US scan at the planning GUI in order to monitor the biopsy process (see Fig. 8b). If there is a need for a correction of the needle angulation, this can be simply executed using the two NPU d.o.f.s A6 and A7, but without any movement of the robot main axes A1–A4.

3.3. Influences of patient/organ movement

Patient motion after insertion of the biopsy needle is recognised as a possible cause of injuries when having the needle blocked by the robot. In general, the patient will be fixed by using a special vacuum device [9] in order to avoid the aforementioned situation as well as to minimize relevant positioning errors. For safety reasons the connection between the needle and NPU is realized by means of an elastic clutch, loosening the trocar once a transverse force beyond a certain extent is applied.

To maintain the desired accuracy despite internal organ motion, two different approaches are under validation. Using the capabilities of real-time intra-operative imaging the intervention is permanently monitored (especially for US-guided biopsies). During intervention planning, the physician defines a maximum error for the target position — if the needle trajectory given by the NPU does not match this area of tolerance, the physician will be prompted to either correct the angulation or stop the procedure. For active compensation of patient and/or organ motion a ‘follow target’ control mode is realized at the robot controller. First tests show a sufficient dynamic behavior from the robot itself — the bottleneck for this control mode is defined by the latency of the optical tracking system and its limited available update rate of 20–30 Hz. Improved algorithms for target tracking are under development by various groups (e.g. Refs [10–12]) and should be implemented on the introduced robot system as soon as they are available.
Figure 8. (a) The robot is commanded to the skin entry point by using the input device ‘UI’. (b) Monitoring of the biopsy process. The GUI of the planning system shows the planned as well as the current needle trajectory including deviation from the planned intervention (all this information is superimposed on the actual CT/US scan).
4. RESULTS FROM A FIRST *IN VITRO* STUDY

For a first *in vitro* study, peas (mean diameter $= 9.4 \pm 0.7$ mm) were embedded within a custom-made gel-phantom as targets. Positional data of the targets were calculated by means of a position-tracked US transducer (scanning head C4-2; US-System HDI-UM 9, Advanced Technology Laboratories) and establishing the base for an intervention plan performed with ROBUST. Once the best trajectory for the biopsy was defined, the target frame for the NPU was calculated and transferred to the robot controller. After calculation of the desired robot coordinates, the robot arm was commanded to the planned insertion point aiming at the center of the target. The NPU provided guidance for a 17-gauge coaxial puncture needle, combined with a 18-gauge long biopsy needle. The needle insertion was performed by the radiologist — an automated biopsy device (Magnum Core high speed; 22-mm excursion) was used for sample harvesting. The distance between the actual needle tract and the center of the target was evaluated in two orthogonal axes using US. To show the efficacy, the length of the harvested biopsy specimen also was evaluated.

The biopsy was successfully performed for all 20 targets with only one needle pass necessary. The mean length of the harvested specimen was $5.5 \pm 1.2$ mm. The average radial distance between the needle tip and the center of the target was $1.9 \pm 1.1$ mm.

5. DISCUSSION

A free-hand biopsy technique may lead to limited accuracy when initially lining up the biopsy needle and staying on course with the planned needle trajectory. Additionally, when the physician releases the needle, the needle can drift or tilt away from the desired path due to gravity, particularly when first starting the insertion [13]. Serving as the interventionalist’s ‘third hand’, a US- and/or CT-based robotic assistant thus can increase the accuracy and the clinical outcome of many types of percutaneous interventions. Other key advantages promised by such a system include the reduction of the radiation dose for the patient and physician as well as lower treatment costs tied to reduced patient morbidity.

From a medical standpoint the introduced robot system has to guide a biopsy needle in a way that the maximal distance between actual needle tip and planned target point is less than $\pm 3$ mm. During development of the system, many different sources of position errors occurred and jeopardized the objective mentioned above.

- Due to the disadvantageous positioning of the tracker tools, the technical accuracy of the optical tracker system is far from the accuracy defined in the data sheet of the tracking system. To reduce this problem, tracking data had to be sampled in order to filter the variations of the measurements and to receive valid information. That of course further reduces the latency and available update rate, which finally cut down the dynamic behavior of the entire system.
Based on the problems mentioned above and inaccuracies for the registration points, robot registration could not receive an exact rigid body transformation between the tracked robot base and the internal world coordinate system of the robot. In combination with unavoidable errors of the kinematic parameters of the robot links (misorientation of the robot links due to manufacturing tolerances, inaccuracies for the link parameters, etc.) this finally leads to calculation errors for the kinematic transformations and to wrong target values for the servo controllers.

The structure of the developed robot system was mainly made from aluminum for later adaption to MR scanners. For the same reasons, polymer bearings were used for all robot joints. Due to the mechanical characteristics of the selected materials, the deflection and torsion of the links and the reduced static and dynamic stability of the robot structure — in combination with the realised reach of the gross positioning unit — also contributed to a faulty kinematic model of the robot and to inaccurate kinematic transformations.

For US-guided biopsies, the increasing thickness of the US slice leads to considerable calibration errors which causes inaccurate transformation from the pixel coordinate of the acquired scan to the 3D position of the target during planning. Another problem connected to the characteristics of US scans lies in the fact that especially small targets that appear in the scan may be located outside of the considered flat US scan, which results in a faulty orientation of the needle guide.

Unfortunately, it is not possible to isolate all the problems mentioned above and to define them quantitatively. Nevertheless, most of those sources of errors could be defused considerably. In particular, the errors caused by the registration error and by the differences between the mathematical description of the robot kinematics and real structure could be reduced by an additional calibration of the robot system. Based on a detailed series of position measurements all over the working area of the robot, a set of calibration algorithms could be developed. Implementation of the corrected kinematic transformations could reduce the spherical error measured at the NPU remote centre of motion to $0.96 \pm 0.56$ mm.

Based on the described calibration methods for the robot and US probe, the designed and realized prototype of the robotic system finally could demonstrate positioning of a biopsy needle with sufficient accuracy in a first *in vitro* study.

6. CONCLUSION AND FUTURE WORK

This paper describes the concept behind a robotic guide for CT- and US-based biopsies. Some details concerning the arm and controller architecture are given.

A first prototype of the robot system as well as of the navigation system have been available since early 2002. The system is currently undergoing several pre-clinical tests using medical phantoms in order to evaluate the concept *per se* and each
component of the system in detail. The main focus is also on the validation of the security measurements in order to provide maximum safety during robot operation. First results indicate that the developed robot system has sufficient accuracy for the procedures under consideration. The developed registration/calibration methods for calculation of the robot base coordinates in the patient coordinate system as well as the calibration of the US probe are suitable for further experiments.

Further development will include: (i) further accuracy studies using a needle-penetrable phantom with targets based on CT and US imaging, (ii) risk analysis and validation of the safety measurements as well as (iii) comparisons of assisted and unassisted methods for accuracy and speed, and (iv) additional cadaver studies. Development of a fully MR-compatible robot prototype also is under preparation.

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