Lovis Schwenderling, Christian Hansen*, Florian Heinrich

AR visualization of automated access path planning for percutaneous interventions

Abstract: Minimally invasive interventions, e.g., percutaneous needle interventions, have many advantages compared to traditional surgery. However, they may require complex and time-consuming planning with experience-dependent success. Automated access path planning is faster and more consistent but individual preferences and situational circumstances are not considered. To this end, displaying the path planning results directly on the patient's skin, using projector-based augmented reality (AR), was investigated. A constraint-based path planning was implemented to evaluate the quality of every path, taking into account risk structures and path length. A visualization was developed to display the results on the skin and to allow for path selection. The choice of the path followed by a navigated insertion was evaluated in a pilot study (n=5), considering four levels of the visualization with different amounts of displayed insertion points. Participants stated that they preferred to have multiple potential puncture points displayed. However, the results for the considered variables show only small differences. Overall, it has been shown that projector-based AR visualization of automated access path planning is possible and enables individual, situation-adapted insertion point selection. More research is required to further explore optimal display of paths.

Keywords: Projector-based Augmented Reality, Automated access path planning, Insertion point visualization

https://doi.org/10.1515/cdbme-2021-1011

***Corresponding author: Christian Hansen:** Otto-von-Guericke University Magdeburg and Research Campus STIMULATE, Magdeburg, Germany, e-mail: hansen@isg.cs.uni-magdeburg.de.
1st Author Lovis Schwenderling, 3rd Author Florian Heinrich: Otto-von-Guericke University Magdeburg and Research Campus STIMULATE, Magdeburg, Germany

1 Introduction

Minimally invasive procedures are an alternative to open surgery in many medical specialties, characterized by the avoidance of large wounds. The use of, e.g., laparoscopic or percutaneous interventions can result in faster recovery with reduced pain, shorter hospital stays and a lower likelihood of complications [1]. However, during such procedures the altered visual and haptic feedback is disadvantageous. A lack of direct vision and tactility of the tissue must be compensated by the radiologist, causing their expertise to have a significant influence on the outcome of the intervention [2].

Image-based planning of the access path to a target can reduce the chance of injury to risk structures. In many needle-based interventions, linear access paths are planned. These can be defined based on two points: the target point and an insertion point on the skin [3]. Depending on quality requirements and case complexity, planning often takes a long time and depends heavily on the radiologist's experience [4]. Automated access path planning could be faster and more consistent and is thus a viable alternative [5].

Most approaches for automated access path planning are based on the definition of conditions. *Hard conditions* (HC) comprise requirements that can be described by Boolean values, e.g., risk structures that must be avoided [3]. *Soft conditions* (SC) can be represented by numerical values and thus enable a rating of paths, e.g., the proximity to risk structures [4]. A wide range of implementation approaches exists, including projections [4] and simulations [6]. Approaches without conditions can, for instance, be based on the grey value gradients in the image data [7] or the evaluation of risk values [5] and risk functions [8] assigned to relevant structures.

Usually, insertion points are displayed and investigated on the planning computer. Slice-based approaches integrate the information in the medical image data, showing appropriate paths [4], as well as non-recommended approaches [3]. 3D-model-based displays often show a color-coded visualization of the insertion points on the skin [9] or organ surface [10]. Other approaches visualize access paths directly [11].

A drawback of automated path planning is that individual preferences and conditions in the operating room cannot be taken into account. In addition, transferring the planned insertion point to the operation site can be difficult. Usually this is done using anatomical landmarks or reference objects that are visible in the image slices [12]. The visualization of the selected point directly on the skin using Augmented Reality (AR) has shown promising results in reducing errors during the insertion [13]. This is often implemented in the context of a navigation visualization that provides information on the insertion point as well as the necessary needle position and rotation. However, these approaches require a preconceived plan for the intervention, which renders considering the specific situation in the operation room impossible for the planning.

A visualization that displays several possible insertion points on the skin, from which the most feasible path can be chosen, enables the radiologist to make decisions in the intervention room. To the best of our knowledge, this has not been implemented before. Therefore, an AR-approach was developed that shows a selection of possible paths directly on the skin. Projector-based AR was used to minimize limitations in reality perception and to provide the visualization sterilely. The use of automated path planning enables a rapid assessment of insertion points, allowing a pre-selection to be made for the radiologist to facilitate the decision process.

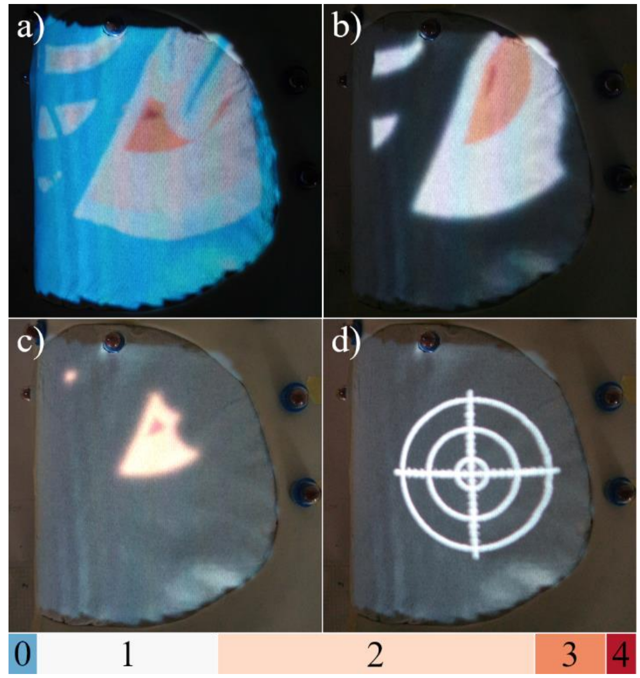

Figure 1: The considered levels of the insertion point visualization (a - d) and the color scale used (below). The numbers on the color scale indicate the associated categories of the path quality value.
a) Mode 1: Visualization of all surface points,
b) Mode 2: Visualization of insertion points in cat. 2-4,
c) Mode 3: Visualization of insertionpoints in cat. 3&4,
d) Mode 4: Visualization of the best insertion point

2 Materials and Methods

An automated path planning and the corresponding insertion point visualization were developed and evaluated in a pilot study. An overview of the implementation and procedure is given in the following.

2.1 Apparatus

Commonly used condition-based automated path planning was implemented. Criteria were selected based on existing literature on condition-based path planning, as mentioned in the introduction. Intervention-specific requirements, such as preferred injection angles [4], were not considered to allow universal use. Two criteria were defined. *Risk structures* could not be punctured (HC). The greater the distance between path and structure, the better (SC). The distance to risk structures was evaluated relative to a maximum distance, above which no further verification took place. This was set to 1 cm, following the maximum distance check used by Heinrich et al. in an intraoperative distance visualization [14]. The maximum *path length* resulted from the measures of the needle used (HC). Shorter paths were rated as better (SC). The evaluation of path length was relative to the longest possible path for each target.

The insertion point evaluation was based on a raycasting strategy, scanning the body surface in a grid pattern from a freely selectable target. With 3D models of internal organs, bones, cartilages, and blood vessels, selected from an anatomical database [15], all HC were applied by checking whether the skin was visible (obstruction check) and reachable (distance check) for the ray. For each resulting insertion point, SC were applied and an associated path quality value between zero (low quality) and one (high quality) was determined and saved along with the associated texture coordinates.

The path quality value of the possible puncture points was displayed directly on the body surface. A divergent color scale was used (see Figure 1). The blue-red gradient is a temperature analogy, where blue (cold) represents the non-valid puncture points, and the different shades of red (warm) display the path quality value. The darker the shade of red, the better the associated point.

For visualization, the path quality value was divided into five categories to allow for good differentiation between safer and less safe insertion points. Category 0 contained all non-valid paths. Category 1 (path quality value: 0 – 0.25) included the most unsafe insertion points, e.g., paths in direct proximity

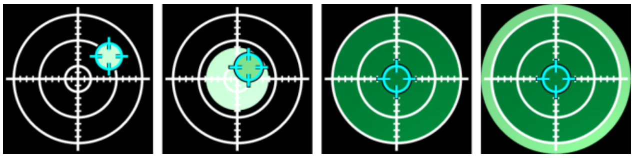

Figure 2: The direct navigation visualization used for the guided needle insertion. Needle orientation was represented by the smaller, blue circle, insertion depth by the filling of the white crosshairs. The first three images show a gradual improvement with the third image as the desired target position. The fourth image indicates that the needle has been inserted too far. Taken from [16].

to risk structures. Category 2 (0.25 – 0.7) consisted of points that are neither particularly safe nor unsafe. Category 3 (0.7 – 0.9) and Category 4 (0.9 – 1) included safe points, whereby the further subdivision enabled a distinction of particularly safe paths. A segment of the color scale was assigned for each category, representing the corresponding paths (see Figure 1). Based on the categorization, the visualization could be used with different levels of information. Here, the number of puncture points shown decreased from the first mode (all categories are shown, see Figure 1a) to the last mode (only the best point is displayed, see Figure 1d). The visualization was implemented as a vertex and fragment shader, using the saved texture coordinate for each determined insertion path. Based on the corresponding path quality values, the surface was colored according to the color scale (see Figure 1). For the last mode, this step was omitted. The application was implemented in the game engine Unity (Unity Technologies, USA).

The insertion point visualization was combined with a needle navigation that guides the user from the selected point to the target (see Figure 2). For this purpose, the navigation aid was always placed at the contact point between the needle and the body surface. For the last mode, the crosshairs were placed at the texture coordinates of the best path quality value.

The visualization was projected onto the surface of a torso phantom that allowed for needle insertions in a foam area. Internal structures differed in the density of the material. A multi-projector system of three projectors (Barco F22WU-XGA, Barco GmbH, Germany) was used to reduce occlusion due to the shadow cast by the user and create a brighter visualization that is less dependent on ambient light. A photogrammetric scan of the surface within a world coordinate system was performed, based on which the projectors were calibrated (ProjectionTools, domeprojections.com GmbH, Germany). The surface scan was used to calculate the insertion point visualization and the path navigation. The position and rotation of the needle used for insertion were determined using optical infrared tracking (fusionTrack 500, Atracsys LLC, Switzerland), with registration to the world coordinate system.

2.2 Evaluation

A within-subject design study was conducted to evaluate the visualization and its levels in the context of path selection and needle insertion. Participants were asked to insert a needle into a torso phantom multiple times for each mode. This involved first selecting a path based on the visualization shown, and then the navigated needle insertion.

Five dependent variables were considered. For the *Accuracy*, the final distance between needle tip and target structure was measured as the Euclidean distance between the virtual objects of the navigation application. The *Task completion time* needed for path selection and needle insertion was clocked. To evaluate the selected path itself, the *Path quality value* of the chosen point was regarded. Lastly, after each task, the participants were asked to rate their subjective *Confidence in path selection* and *Confidence in needle insertion* on a 6-point Likert scale with verbal anchors ”very confident”, ”confident”, ”rather confident”, ”rather unconfident”, ”unconfident” and ”very unconfident”.

First, informed consent and demographic information was collected for each participant. Subsequently, the visualization and task were explained in the context of a training session. Participants were asked to familiarize themselves with the setup and were able to perform test insertions. In the course of the study, three trials were performed for each level of the visualization. The order of modes was randomized. Each trial included a selection of an insertion point and subsequent needle insertion, using the navigation aid displayed (see Figure 2). When participants were satisfied with the needle placement, the study director terminated the trial on a verbal signal and asked about subjective *Confidences for path selection* and *needle insertion*. Individual punctures were repeated if recognition of the needle was no longer possible due to tracking problems. After completion of all punctures, a final interview with the participants was conducted.

3 Results

Five individuals (3 female, 2 male) participated in the study, with an age range of 19 - 28 years (median: 26 years). The participants had a background in medical technology and/ or computer science. Due to the pandemic COVID-19 situation, only research fellows from the institute were invited. The results of the evaluation are shown in Figure 3.

All results show only small differences between the variables and high variance. This may be caused by the small sample size. In the case of the insertion parameters, the tracking problems encountered may also be a reason.

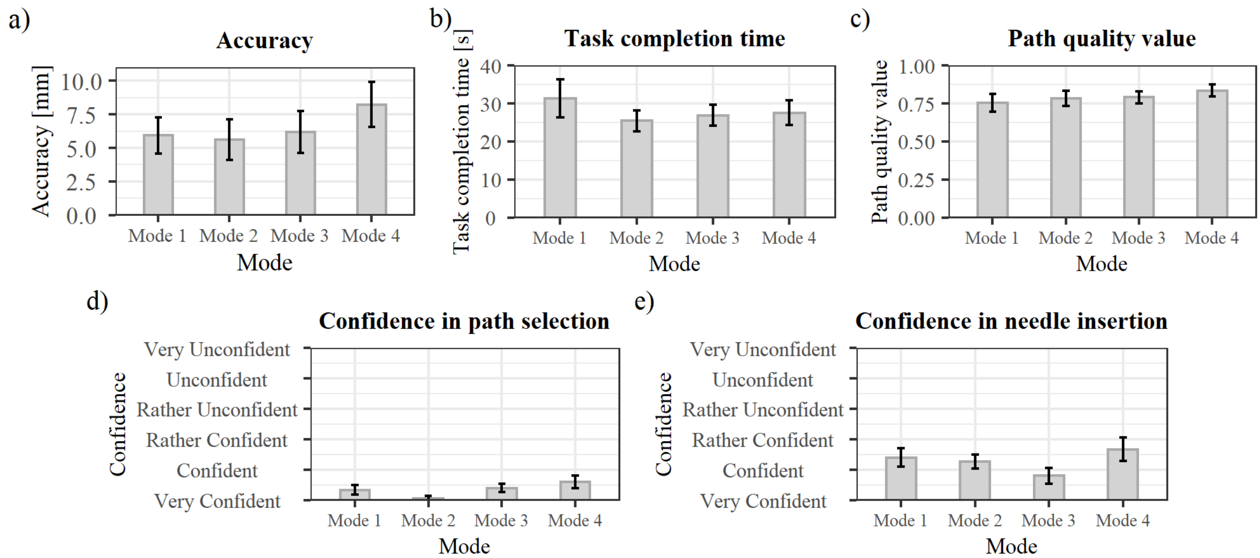

Figure 3: Overview of the effects of the visualization levels on a) *Accuracy*, b) *Task completion time*, c) *Path quality value,* d) subjective *Confidence in path selection*, e) subjective *Confidence in needle insertion.* Error bars represent standard error.

On average, subjects took longer to complete the task when all items were displayed and were fastest when items in the top three categories were displayed. Too many displayed insertion points could be distracting; too few paths presented provided less contextual information and consequentially increased uncertainty. This was explicitly stated during the final interview and is also indicated by the *Confidence in path selection*, which was lower for modes with fewer displayed paths.

In the evaluation of subjective *Confidence for the needle insertion*, displaying the three top categories performed best. However, participants stated that they predominantly evaluated the tracking problems encountered. The results for *Accuracy* show a similar distribution. Since the navigation always ensures guidance from the selected insertion point to the target, no *Accuracy* differences were expected. Existing inconsistencies can result from non-ideal insertion positions, which could not be changed for the last mode, displaying only the best point, resulting in a difficult-to-perform procedure.

The highest *Path quality value* was obtained for the last mode (displaying only the best point). This results from the fact that other levels do not allow a differentiation of the best point due to a discrete display of the categories. Overall, all participants indicated that they relied heavily on the visualization and preferred to select insertion points from the best category, resulting in the high *Path quality values* for all levels.

4 Discussion

During the execution of the study, it was noticeable that the participants blindly trusted the visualization. This may be due to the lack of information available. First, the participants had no anatomical knowledge or experience with interventions, thus hindering the decision making. While no medical background or experience with similar interventions is required to use the visualization, it is necessary to critically evaluate the information shown and decide on an optimal path. However, in the context of this work, due to the pandemic COVID-19 situation, no individuals with appropriate qualifications could be invited. Further evaluations should be conducted with participants who are part of the target group. In general, participants did not know the target location. In part, this also resulted from the aforementioned aspect: due to the lack of background knowledge of the participants, an interpretation of medical image data was not possible. When placing the needle on the surface, no indication of the target position was presented before the display of the navigation visualization. However, knowledge of the inner structures was needed by the participants to evaluate the visualization. In further studies, it should be investigated whether a representation of the target position or internal structures in general can facilitate the decision making. Besides the combination with medical image data, an addition of a target visualization to the AR insertion point display could be considered. To this end, other AR modalities could also be taken into account.

During insertion, line-of-sight tracking problems depending on the needle rotation and insertion point position occurred for all subjects. This concerned all insertion-related variables (*Accuracy*, *Task completion time* and *Confidence in needle insertion*). It is possible that inaccurate tracking influenced effects on the previously mentioned variables. In further studies, line-of-sight problems should be avoided, e.g. by better camera placements or the choice of a different tracking method.

When dividing the visualization into the different levels, only the best point was shown for the version with the least paths displayed. This was chosen based on existing AR navigation visualizations, which usually show only one pre-planned path. In the context of the levels, however, a display of the entire best category would also have been possible. This way, a better comparability of the path quality values could have been achieved, since a differentiation of the best value would not have been possible at any level. An alternative to allowing comparison of the path quality value for all levels as considered in this work, is to use a continuous color scale. This would allow the identification of the best point even when several paths are displayed.

5 Conclusion

In this work, an AR visualization of puncture points directly on the skin was presented. The basis was an automated path planning, which determined possible puncture paths based on surrounding risk structures and the distance to the skin. Different levels of the visualization were investigated, displaying varying amounts of insertion paths. Results of the pilot study indicated that the visualization of multiple insertion points has advantages over displaying only one access path. The AR visualization enables adaptation of automated path planning to individual and situational preferences in the intervention room. However, further research is required to optimize the visualization and evaluate the implemented planning approach. A representation of the internal structures should be considered in order to allow a differentiated use of the puncture point visualization. Subsequently, an evaluation of the application with radiologists in a clinical context is required. Comparisons to conventional planning approaches as well as navigated interventions should be performed.

Author Statement

Research funding: This work was funded by the German Research Foundation (HA 7819/1-2).
Conflict of interest: Authors state no conflict of interest.
Informed consent: Informed consent has been obtained from all individuals included in this study.

References

[1] Roumm AR, Pizzi L, Goldfarb NI, Cohn H. Minimally invasive: minimally reimbursed? An examination of six laparoscopic surgical procedures. *Surg Innov*. 2005:261-287.
[2] Stassen HG, Dankelman J, Grimbergen KA, Meijer DW. Man-machine aspects of minimally invasive surgery. *Annu Rev Control*. 2001:111-122.
[3] Schumann C, Bieberstein J, Braunewell S, Niethammer M, Peitgen H-O. Visualization support for the planning of hepatic needle placement. *Int J Comput Assist Radiol Surg*. 2012:191-197.
[4] Schumann C, Bieberstein J, Trumm C, et al. Fast automatic path proposal computation for hepatic needle placement. In: *Medical Imaging 2010: Visualization, Image-Guided Procedures, and Modeling*. ; 2010:76251J.
[5] Shamir RR, Joskowicz L, Antiga L, Foroni RI, Shoshan Y. Trajectory planning method for reduced patient risk in image-guided neurosurgery: concept and preliminary results. In: *Medical Imaging 2010: Visualization, Image-Guided Procedures, and Modeling*. ; 2010:76250I.
[6] Baegert C, Villard C, Schreck P, Soler L, Gangi A. Trajectory optimization for the planning of percutaneous radiofrequency ablation of hepatic tumors. *Comput Aided Surg*. 2007:82-90.
[7] Vogelbacher C, Bauer MHA, Kappus C, Freisleben B, Nimsky C. Computerassistierte Trajektorienplanung für tiefe Hirnsimulation und Stereoelektroenzephalographie. In: *CURAC*. ; 2013:239-243.
[8] Vaillant M, Davatzikos C, Taylor RH, Bryan RN. A path-planning algorithm for image-guided neurosurgery. In: *CVRMed-MRCAS'97*. ; 1997:467-476.
[9] Seitel A, Engel M, Sommer CM, et al. Computer-assisted trajectory planning for percutaneous needle insertions. *Med Phys*. 2011:3246-3259.
[10] Essert C, Haegelen C, Lalys F, Abadie A, Jannin P. Automatic computation of electrode trajectories for deep brain stimulation: a hybrid symbolic and numerical approach. *Int J Comput Assist Radiol Surg*. 2012;(4):517-532.
[11] Khlebnikov R, Kainz B, Muehl J, Schmalstieg D. Crepuscular rays for tumor accessibility planning. *IEEE Trans Vis Comput Graph*. 2011:2163-2172.
[12] Arnolli MM, Hanumara NC, Franken M, Brouwer DM, Broeders IAMJ. An overview of systems for CT-and MRI-guided percutaneous needle placement in the thorax and abdomen. *Int J Med Robot Comput Assist Surg*. 2015;11(4):458-475.
[13] Mewes A, Heinrich F, Kägebein U, Hensen B, Wacker F, Hansen C. Projector-based augmented reality system for interventional visualization inside MRI scanners. *Int J Med Robot Comput Assist Surg*. 2019:e1950.
[14] Heinrich F, Schmidt G, Jungmann F, Hansen C. Augmented Reality Visualisation Concepts to Support Intraoperative Distance Estimation. In: *25th ACM Symposium on Virtual Reality Software and Technology*. VRST '19. Association for Computing Machinery; 2019.
[15] Mitsuhashi N, Fujieda K, Tamura T, Kawamoto S, Takagi T, Okubo K. BodyParts3D: 3D structure database for anatomical concepts. *Nucleic Acids Res*. 2009;37:D782--D785.
[16] Heinrich F, Joeres F, Lawonn K, Hansen C. Comparison of Projective Augmented Reality Concepts to Support Medical Needle Insertion. *IEEE Trans Vis Comput Graph*. 2019;25(6):2157-2167.