Needle Mounted Navigation System for Free Hand Percutaneous Procedures

Diego Dall'Alba, Bogdan Maris et Paolo Fiorini

***Abstract*— In this work we have designed and developed a new navigation system for interventional radiology, implemented in a light and compact device. The system attached to the needle is composed by a small screen that gives hints about the position and the orientation, a controller that commands the screen and interfaces with the computer, and a marker that communicates with a tracking system. By using a real time software the user is guided to move the needle along the desired position and orientation. To the best of our knowledges, this is the first system to have the navigation display integrated directly on the tool. The in-vitro tests we have performed, show how such a system yields a higher precision in the execution of the task and a reduction of the time required to complete the procedure.**

I. Introduction

Clinical practice is increasingly replacing traditional open surgical procedures with minimally invasive techniques. This development results in a transition from direct visual feedback to image-based feedback. Image-guided percutaneous procedures are used for both diagnosis and treatment. The most known diagnostic procedure is biopsy, which is used to collect samples of tissues presumed to be malignant. Therapeutic procedures include tumor ablation based on different technologies such as radiofrequency ablation (RFA), cryoablation (CA) or tumor embolization. These procedures require precise insertion of an elongate instrument, usually referred as ablation probe or simply needle, into the target region. The success of the ablation is constrained by the precise positioning of the needle. Needle based procedures could be subdivided in 3 main steps: localization of the entry point on the patient's skin, orientation toward the target point of the needle and needle insertion. As reported in [1], one of the most underestimated challenges of surgical guidance is the intraoperative display. Different navigation systems have been proposed in literature, based on different tracking technologies or image modalities (see [2], [3] and [4]). All these works prove that the introduction of a navigation system during the procedure improve the performance in the needle insertion task. Anyway, no work addresses the specific problem of providing the navigation information to the user in an intuitive and ergonomic way. The positioning of the needle is still a key issue and most of the time the percutaneous procedure is human based, therefore we propose an integrated navigation system that provides information directly on the tool. The system helps the user to execute the procedure with high accuracy and precision.

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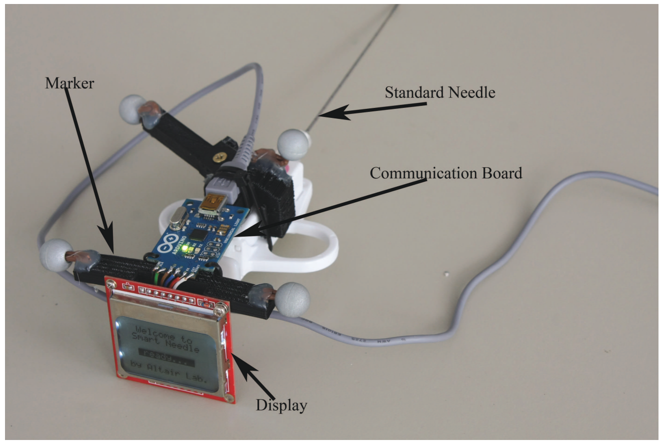

Fig. 1. A standard 18 gauge biopsy needle equipped with the compact navigation system.

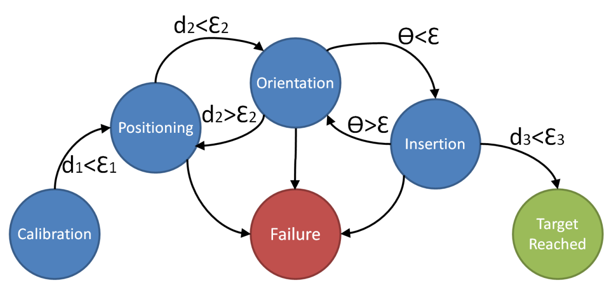

Fig. 2. State machine diagram. The threshold error depends on the current state and on the accuracy of the positioning ($\epsilon_1, \epsilon_2, \epsilon_3$) and orientation ($\epsilon$) to be reached(e.g. $\epsilon_1 < 1mm, \epsilon_2 < 3mm, \epsilon_3 < 4mm$). The on-line value of the target distance is given by the parameters d_1, d_2, d_3 for the positioning and θ for the orientation and is continuously updated on the display by a suitable graphical representation.

II. Materials and Methods

The position and the orientation of the needle are tracked with a passive optical tracking system from NaturalPoint (Corvallis, OR, US) composed by 12 USB infrared (IR) cameras. The precision of the tracking system is less than one millimeter. The proposed navigation system (Fig. 1) is designed to be attached to any type of needle (the first prototype is designed for biopsy needles). This characteristic requires the precise identification of the needle geometry (calibration phase) together with a method to map the navigation information on the display attached to the tool (navigation phase). The purpose of the calibration phase is

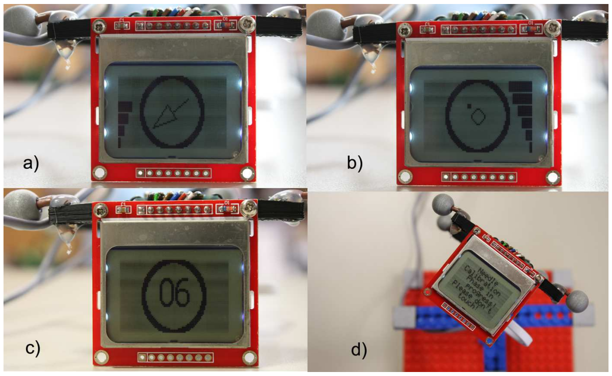

Fig. 3. State machine display a) positioning state. b)orientation state. c) insertion step. d) calibration step.

to identify the rigid transformation that links needle reference system with tracker measurements. This transformation will be used to display the correct information on the screen. The navigation process is modeled as a state machine (see Fig. 2) and to pass from one state to another a threshold is defined depending on the accuracy we want to reach. The first step of the navigation is the positioning of the needle to the entry point. It is advantageous to perform the aligning step after finding the entry point, because the instrument can be pivoted around the contact point between its tip portion and the surface without losing the entry point, which has already been located. When the accurate orientation is found the insertion will take place. For each step of the needle insertion and calibration, different representations are displayed on the screen, as shown in Fig. 3. For more details about the design of the compact navigation system and the calibration method please refer to [5]. The performances of the developed device were tested in-vitro. A polypropylene phantom with a thickness of 2 cm has been chosen for this experiment since it allows the needle to keep the same orientation after insertion. To localize a target point inside the phantom it was used the tip of a second calibrated needle. Five entry positions on the surface of the phantom were fixed. Each of the entry point together with the target point defines an orientation. For each of the 5 entry points positions, the needle insertion was repeated 5 times, for a total of 25 insertions for each user.

III. Results

In the experimental setup no. 1 the needle insertion was performed with the use of a PC monitor placed in front of the user on the same table of the phantom. The 3D information about the tool and the points (entry and target) are represented on the monitor, as in a standard image guided procedure. The experimental setup no. 2 was performed as the setup no. 1 but with the use of the new system that integrates the display applied on the needle. An important measure was the deviation from the desired orientation, once the target point was reached. Since the planning phase defines the safe orientation, we have computed the angle between the planned orientation and the final orientation. The positioning error was measured as the Euclidean distance between the needle tip position and the entry or the target point position, while the orientation error is measured as the dot product between the normalized vector represented by the entry point and target point and the vector representing the orientation of the needle given by the calibration transformation. Six subjects without previous experience have tested the system after the oral explanation of the task. We have compared the results in terms of accuracy in entry and target points localization. In Table I we report the accuracy and precision results of the experiment. We report the entry point localization error (ELE), the target point localization error (TLE) and angular orientation error (AOE). The results of experimental setup 2 show that the mean and STD of the error is lower than in setup 1 for all the errors considered. The use of the proposed system reduces the error (both in the position and in the orientation) and also reduces the influence of the users experience in needle insertion execution. In fact the standard deviation of the data is lower and more stable than in the case without display on the needle. The needle insertion time with the display mounted on the needle is about 40% lower than without the display.

Setup 1 with PC monitor						
	ELE [mm]		TLE [mm]		AOE [degree]	
User	Mean	STD	Mean	STD	Mean	STD
U1	5.114	1.453	4.50	2.542	5.839	1.667
U2	4.006	2.187	5.464	1.410	5.758	1.146
U3	5.081	2.321	4.506	2.187	6.259	2.869
U4	4.136	3.194	5.614	2.739	5.727	2.778
U5	5.147	1.492	4.497	1.665	5.420	1.726
U6	3.876	4.261	5.315	1.765	5.790	1.955
All	4.56	2.485	4.983	2.051	5.799	2.007
Setup 2 with PC monitor and display on the needle						
User	Mean	STD	Mean	STD	Mean	STD
U1	2.79	1.091	3.637	1.121	1.734	1.309
U2	2.703	1.114	3.079	1.677	2.456	1.856
U3	2.697	1.462	2.467	1.578	2.902	1.068
U4	2.727	1.257	3.916	1.988	1.833	1.576
U5	2.916	1.725	2.991	2.091	2.52	1.848
U6	2.627	2.111	3.043	1.26	4.036	0.918
All	2.746	1.46	3.196	1.619	2.58	1.429

TABLE I

Comparison of Error Values in the two experimental setups.

IV. Discussion

This work proposed a new system for an accurate needle placement. We have designed, tested and evaluated the system in an in-vitro experiment. The experiments we have done validate the utility of the tool that can be used in a more complex procedure. The main advantages of the navigation system we have presented are:

- gives the information directly on the tool.
- there is no need for the user to move the eyes from the interventional area.
- improves the accuracy and the precision to reach the desired position and orientation.
- reduces the procedure's time.

In the future works the electronic components will be miniaturized, and also the display should have a higher resolution and a higher refresh rate. The rigid body design will provide more protection to the electronic components. The needle device is being redesigned to take into account cleaning and sterilization requirement imposed by the operation room environment.

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