Development and evaluation of optical needle depth sensor for percutaneous diagnosis and therapies

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ABSTRACT

Current methods of needle insertion during percutaneous CT and MRI guided procedures lack precision in needle depth sensing. The depth of the needle insertion is currently monitored through depth markers drawn on the needle and later confirmed by intra-procedural imaging; until this confirmation, the physicians' judgment that the target is reached is solely based on the depth markers, which are not always clearly visible. We have therefore designed an optical sensing device which provides continuous feedback of needle insertion depth and degree of rotation throughout insertion.

An optical mouse sensor was used in conjunction with a microcontroller board, Arduino Due, to acquire needle position information. The device is designed to be attached to a needle guidance robot developed for MRI-guided prostate biopsy in order to aid the manual insertion. An LCD screen and three LEDs were employed with the Arduino Due to form a hand-held device displaying needle depth and rotation. Accuracy of the device was tested to evaluate the impact of insertion speed and rotation.

Unlike single dimensional needle depth sensing developed by other researchers, this two dimensional sensing device can also detect the rotation around the needle axis. The combination of depth and rotation sensing would be greatly beneficial for the needle steering approaches that require both depth and rotation information. Our preliminary results indicate that this sensing device can be useful in detecting needle motion when using an appropriate speed and range of motion.

Keywords: Needle Depth Measurement, Needle Insertion, Optical Sensor, Image Guidance, Percutaneous Therapy

1. INTRODUCTION

Percutaneous interventions are minimally invasive procedures which can be used for both diagnosis and therapy. This method involves insertion of treatment needles under image-guidance such as ultrasound (US), fluoroscopy, computed tomography (CT) or magnetic resonance imaging (MRI) [1]. Percutaneous interventions are used in a variety of procedures including biopsy, ablation therapy, drainage, and brachytherapy [2]. US is the most commonly used modality to perform percutaneous diagnosis and therapies as it can provide real-time imaging guidance [3]. However, some lesions are not as clear on one imaging modality and may be better visualized on another. Because of this, CT and MRI are often used to provide better visualization [4, 5]. However, unlike US, CT and MRI guidance generally cannot be used continuously throughout needle insertion. Thus, needle insertion cannot be monitored in real-time through image-guidance using CT and MRI [6].

During needle insertion in CT and MRI guided procedures the insertion depth of the needle is monitored through visual inspection of markers drawn on the needle to confirm the desired depth. This provides a view of the insertion depth which may be inaccurate as these markers are not always clearly visible. No other feedback as to the depth of the needle is provided to the physician until after the needle has been inserted at which point the insertion depth is confirmed through scans [6-8]. Current methods of needle insertion during percutaneous diagnosis and therapy using CT and MRI guidance therefore lack an accurate and continuous way to measure needle depth throughout insertion.

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It has been suggested that the lack of precise needle insertion depth readings can be resolved through the use of an optical encoder which can sense the depth of needle insertion [9]. The use of an optical encoder allows the physician to retain control of needle insertion and can cause minimal disruption to workflow of the procedure. While at the same time, such an encoder will allow for feedback of the position of the needle throughout insertion. This feedback should provide more accurate placement of the needle, which can ultimately improve targeting accuracy and minimize procedure time.

Previously, Seidl et al designed an optical device to sense needle insertion depth in one dimension. This device effectively addresses the issue of needle depth measurement and is capable of measuring needle insertion depth with sub-millimeter accuracy [10]. However, we expect that the use of a different optical sensor could allow measurement of not only needle insertion depth but also rotation around the needle axis. If this two dimensional measurement is possible, it will greatly benefit the needle steering approaches proposed by others [11].

In order to provide visualization of needle insertion, we designed an optical needle measurement device using the sensor from an optical computer mouse. We designed our sensing unit so that it is capable of two dimensional measurements, measuring both the needle insertion depth as well as the rotation of the needle throughout insertion. The current device is specifically designed to be attached to the robotic needle guidance system developed by Song et al for MRI-guided prostate biopsy [12]. Our needle depth measurement device can therefore be used to aid in manual insertion of the needle in addition to the robotic guidance of needle insertion position for the percutaneous intervention.

2. METHODS

We designed and fabricated a sensing unit which houses an optical mouse sensor, PAW3512DK. The sensing unit is connected, via a USB cable, to an Arduino Due microcontroller board housed in a custom-made enclosure shown in Figure 1. The microcontroller board is used in order to acquire needle position information from the sensor. The sensing unit has a diameter of 58 mm and a height of 64 mm. The casing of the sensing unit has a 1.3 mm channel through which the needle is inserted; there is a window within the casing allowing the optical sensor to detect needle insertion and rotation. The sensing unit can be mounted on the robotic needle guide device developed by Song et al to aid in MRI-guided prostate biopsy [12].

A handheld display unit was designed to house Arduino Due microcontroller board as well as a 3.2” liquid-crystal display (LCD) screen and an Arduino Uno microcontroller board mounted with an Arduino WiFi shield. The Arduino Due is programmed to indicate the needle depth through a numerical indication as well as a graphical display on the LCD screen. The degree of rotation and the time period of insertion are also numerically indicated on the LCD screen. In order to provide a clear indication that the needle is approaching the target, three different colored LEDs were added: 1) green - to proceed with insertion, 2) blue - the needle is approaching the target, and 3) red - to stop insertion when the target has been reached. Finally, an Arduino WiFi Shield mounted on the Arduino Uno board is connected to the Arduino Due board to wirelessly send information to a computer to continuously record needle insertion and rotation data.

We conducted two sets of experiments to assess the accuracy of needle sensing using the developed sensing unit. The first experiment aimed to assess the accuracy of depth measurement. Three operators performed 10 needle insertions each, a 92 mm insertion using an 18-guage biopsy needle, under two speed conditions: a speed of less than 5 mm/s and a speed between 7 and 11 mm/s. We collected the depth of insertion detected by the device while measuring the actual depth of insertion at each attempt. The discrepancy between measured insertion depth and actual insertion depth were collected for each attempt as measurement error. The average measurement error for the 10 attempts was calculated for each user at each speed. The average of the three users’ measurement error was also calculated for each insertion speed.

The second set of experiments aimed to access the accuracy of the device’s detection of needle rotation. We collected the degree of rotation of the needle detected by the device while measuring the actual degree of rotation at each attempt. Two operators performed needle rotation 10 times at three speeds of rotation: less than 1 s/90 degree rotation (fast), 2 to 3 s/90 degree rotation (medium), and 4 to 6 s/90 degree rotation (slow) for four measured degrees of rotation: 90 degrees, 180 degrees, 270 degrees, and 360 degrees. Discrepancy between the detected degree of needle rotation and actual degree of needle rotation was collected as measurement error for each attempt. The average measurement error for the 10 attempts was calculated for each user at each speed for each of four rotations. The average of the two users' measurement error was also calculated for each of four rotations at each speed.

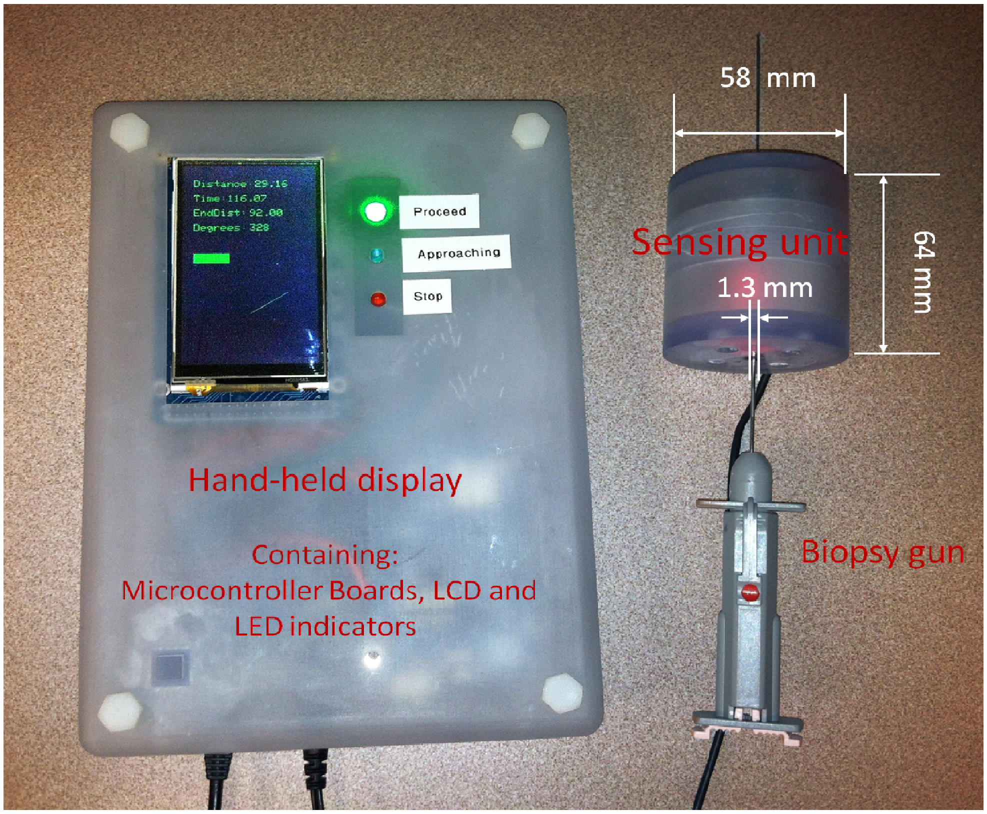

Figure 1. Needle depth measurement device and handheld indicator with LCD display of needle depth and LED lights indicating approach to the target location.

3. RESULTS

Figure 2 shows the result of the first experiment, which tested the accuracy of insertion depth measurement. The result indicated that the speed of insertion has an effect on the ability to properly detect the depth of insertion. As shown in Figure 2, when the needle was inserted 92 mm, the device measured an average depth of 77.26 ± 9.30, 58.68 ±4.39, 87.98 ± 6.43 mm for the three users at the speed of <5 mm /s. The overall average of the three users at this speed was 74.64 ± 14.05 mm. However, at a speed between 7 and 11 mm/s the measurements were more accurate, the average depth measured for the three users was 82.03 ± 1.99, 91.40 ± 0.88, 91.78 ± 1.05 mm respectively, with an overall average of 88.57±3.31 mm.

The average detected rotation by each user at each speed in the second experiment, which tested the accuracy of the device to sense rotation, can be seen in Figure 3. The average detected rotation by the two users when the insertion was turned at a slow speed (4 to 6 s/90°) was 86.75 ± 4.54 degrees for a 90 degree rotation, 113.60 ± 10.49 degrees for a 180 degree rotation, 186.25 ± 16.08 degrees for a 270 degree rotation, and 306.95 ± 8.09 degrees for a 360 degree rotation. When the needle was rotated at a medium speed (2 to 3 s/90°) the device detected an average rotation of 83.55 ± 3.89 degrees for a 90 degree rotation, 151.90 ± 6.39 degrees for a 180 degree rotation, 182.25 ± 7.51 degrees for a 270 degree rotation, and 321.05 ± 14.52 degrees for a 360 degree rotation. When a fast speed (<1 s/ 90°) was used for rotation, the device was able to detect an average rotation of 71.65 ± 6.17 degrees for a 90 degree rotation, 160.95 ±

10.20 degrees for a 180 degree rotation, 208.10 ± 21.78 degrees for a 270 degree rotation, and 328.75 ± 17.76 degrees for a 360 degree rotation.

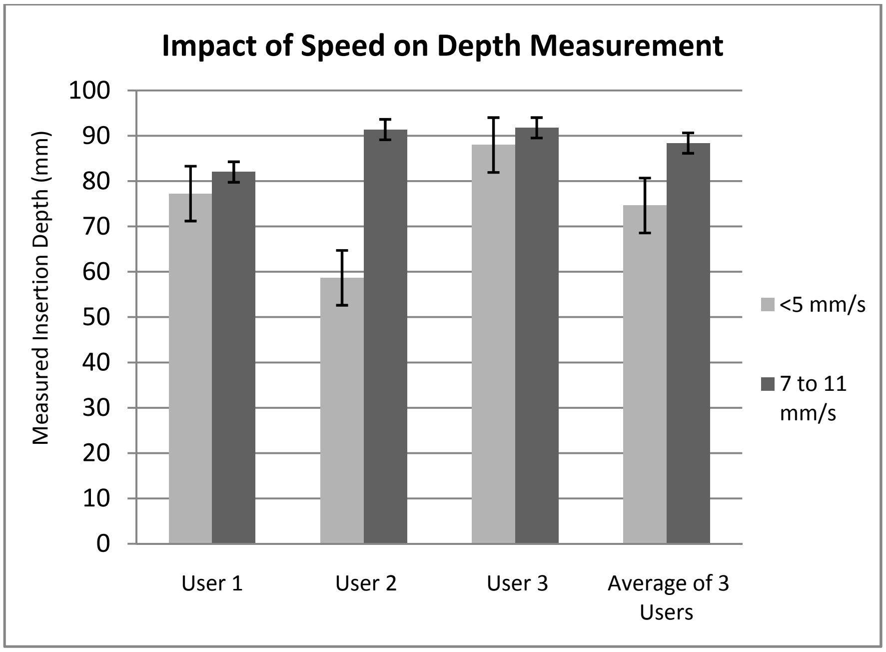

Figure 2. Needle depth measurement at speeds of <5 mm/s and 7 to 11 mm/s for 92 mm insertion. The average measurement for each user can be seen for each insertion speed as well as the average measurement for all 3 users for each speed.

4. DISCUSSION

When performing percutaneous intervention, it is evident that in order to optimally perform a procedure, the lesion must be properly targeted. The use of CT and MRI as guidance for percutaneous intervention can provide an advantage of greater visualization of the target [4, 5]. However, when CT and MRI guidance are used for guidance, imaging cannot be performed during needle insertion and so insertion cannot be monitored in real-time through image-guidance [6]. Some groups have attempted to address this issue through the use of fully robotic needle insertion [13-15]. The use of a robotic manipulator for needle insertion allows the patient to remain within the scanner throughout the procedure and is intended to place the needle at the desired depth. However, this removes control of needle insertion by the physician which may cause problems with patient safety and therefore may not be an ideal solution. Krieger et al suggested that accurate readings of needle insertion depth can be detected through the use of an optical encoder [9]. The use of an optical encoder should allow for detection of needle insertion depth throughout insertion while allowing the physician to retain control of needle insertion and causing minimal interference with workflow.

In order to provide visualization of needle movement throughout insertion, we successfully created a proof-of-concept device using an optical mouse sensor to detect needle insertion depth and rotation. The motivation behind this device is similar to that of Seidl et al in which their group designed an optical device in order to sense needle insertion depth in one dimension [10]. While addressing the same issue, our use of a sensor from an optical mouse is an approach which, to our knowledge, has not been used in previous studies. The use of the optical sensors from a computer mouse was devised to allow us to measure not only the needle insertion depth but rotation of the needle. This two dimensional measurement can be used to be greatly beneficial for needle steering approaches proposed elsewhere [11]. The results of our study give us an indication that this sensor can be useful in detecting needle motion. However, limitations in the accuracy of needle movement detection exist within our results.

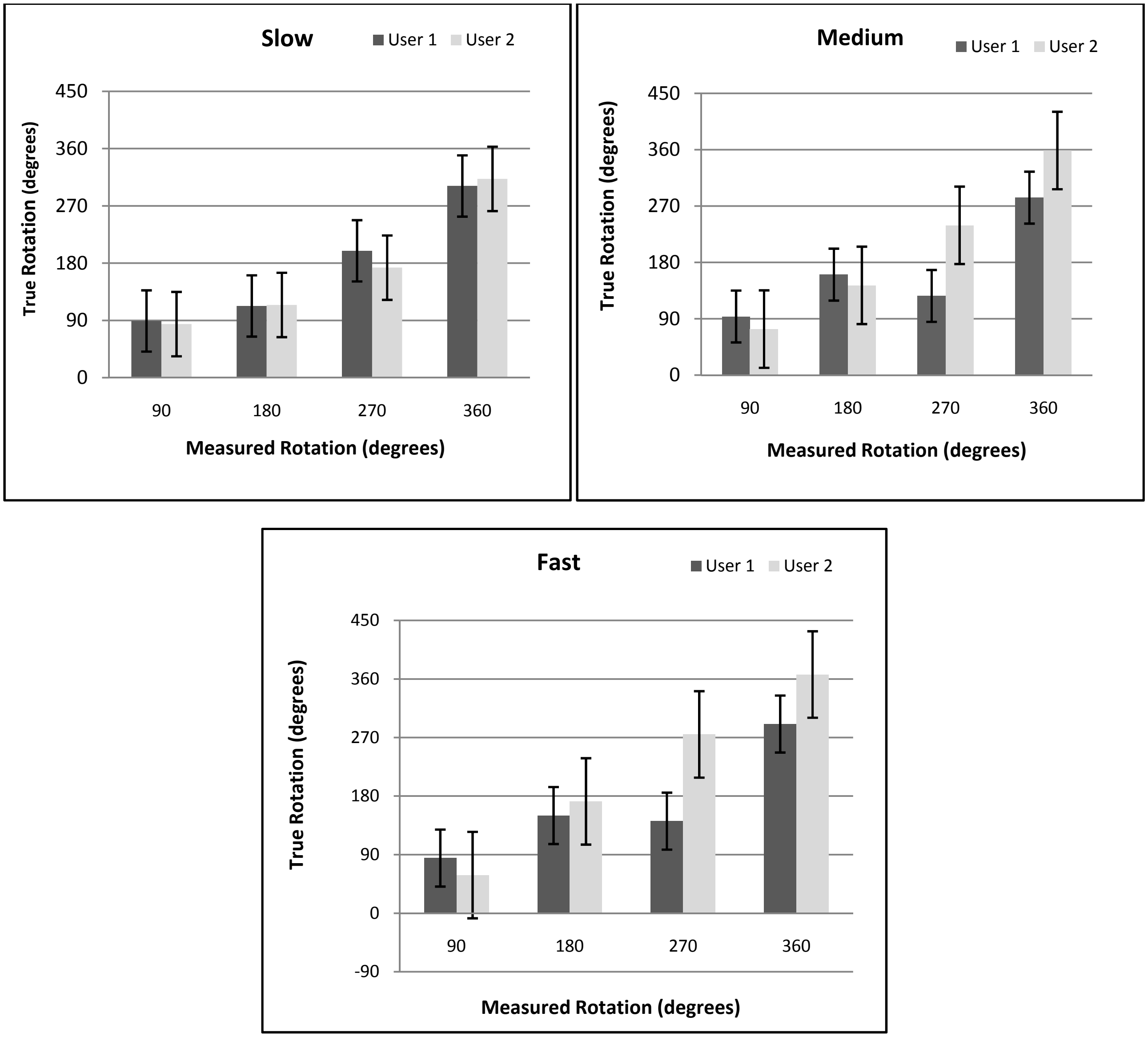

Figure 3. True rotation of needle vs. measured rotation for rotation of 90°, 180°, 270°, and 360°. Accuracy of rotation was tested by two users at three speeds represented by three graphs: 4 to 6 s/90° (slow), 2 to 3 s/90° (medium) and <1s/90° (fast).

As seen in Figure 2, this preliminary study of our device indicates that the use of an optical mouse sensor in order to sense the depth of needle insertion is dependent upon both the speed of needle movement and the skill of the operator. It is evident that using a slower speed of less than 5 mm/s caused less accurate reading of the needle than at the speed of 7 to 11 mm/s. This result is likely due to friction between needle and guiding channel as the users indicated difficulty of smoothly moving the needle at a slower speed. Nevertheless, it is clear that the speed of needle insertion is a factor in the accuracy of our optical sensor. Further, this result indicates that if needle motion is not smooth, the optical sensor provides a less accurate reading. This is a problem which needs to be considered in future generations of the device. Although there was a clear limitation at the slow insertion speed, when the needle was inserted at quicker speed of 7 to 11 mm/s, the device was able to more accurately detect needle insertion depth within an average error within 4mm from the actual insertion depth. This indicates that the use of an optical sensor to detect needle insertion depth would be feasible.

The results of our needle rotation experiment indicate that the ability of the device to detect the rotation of the needle varies in accuracy, which can be seen as high standard deviation in Figure 3. Further, there is a large amount of variability between the results of the two users, indicating that the way the user rotates the needle effects the sensor's detection of rotation. The large changes in the readings could be due to factors such as one user more smoothly rotating the needle resulting in higher accuracy. However, it is evident with both users that there is a high variation within the repetition of each rotation indicating that our sensor may not have consistently accessed rotation speed accurately. Our results indicate that at the fast speed, the average angle detected by our device was most similar to the true rotation angle with the exception of the 90 degree rotation. Rotation at both slow and medium speed resulted in similar average accuracy. However, at all three speeds there was a notable deviation within the results. Since it is an important aspect of our design, the ability to consistently and accurately detect rotation needs to be considered in the next generation of this device.

In both our insertion and rotation experiments, it was evident that the accuracy of the readings of the optical sensor was highly dependent upon user. This result indicates that the variability in the method of insertion among users has a significant effect on the accuracy of the optical sensor. Such an issue could be overcome by using motorized insertion; however, the current device is designed to be used for manual needle insertion. Therefore, such variability would need to be tested by a variety of expert users. If great variability is apparent, this also needs to be considered in the next generation of the device.

A final limitation for our current device is the size of the sensing unit, (58 mm diameter, 64 mm height), shown in Figure 1. The size of the sensing unit is larger than what would be desired for clinical applications, which will likely effect current clinical workflow. Therefore, we will consider ways to make the sensing unit smaller allowing it to have a small effect on the procedure.

Further study of this device would include a test of its ability to accurately sense varied depths of needle insertion and varied types of needles. We could also motorize our tests in order to provide consistent speed of insertion as well as consistent rotation in order to eliminate operator subjectivity in performing needle insertion. Finally, tests by expert users, such as physicians who perform procedures for which they might use this device, would provide valuable feedback for clinical use which needs to be considered in the next generation of our device.

5. CONCLUSION

This preliminary study of our needle insertion measurement device indicates that the use of an optical mouse sensor in order to detect the depth of the needle throughout insertion is feasible. Although there are limitations on quantifying the accuracy that can be attained using our device, within an insertion speed range of 7 to 11 mm/s, the depth of insertion can be detected with a reasonable degree of accuracy i.e., within 4 mm error from actual depth. However, it is clear that at the slower speed of <5 mm/s, the sensing was not consistently as accurate. This is partially due to the needle handling performance of operators to maintain this slow speed of insertion. Also, it indicates a weakness in the ability of this device to accurately detect slower, less smooth insertion. Our results of needle rotation experiment indicate that the ability of the device to detect the rotation of the needle varies in accuracy, having a larger standard deviation. A good amount of deviation in accuracy could be seen between users, implicating that the use of a motorized test would provide more consistent results. However, non-subjective reading is a key requirement of the device, the ability to consistently and accurately detect rotation needs to be considered in the next generation of this device. Overall, we conclude that, through further refinements, two dimensional measurement of needle insertion through an optical sensing will be feasible.

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