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ADVANCED SURFACE SYSTEM FOR CENTRAL VENOUS CATHETER INSERTION TRAINING

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ABSTRACT

An advanced surface for Central Venous Catheterization (CVC) training and evaluation was designed using sensorization techniques, including the use of a hall effect sensor array to measure the insertion depth of a catheter. The sensor array was tested for accuracy in both static and dynamic scenarios, and was found to be sufficiently accurate; measuring position with an accuracy of ±1.1 mm on average. The highest deviations in measured positions were located at the extreme ends of the array where calculations rely on only a single sensor. The maximum deviation in measured position was found to be 3.5 mm. This low-cost system of catheter measurement has the potential to improve feedback and assessment of CVC training.

Keywords: Medical Simulation Training, Sensorization, Catheterization

1. INTRODUCTION

Hospitals have traditionally used the see one, do one, teach one model when training residents to perform Central Venous Catheterization (CVC), an important procedure that occurs over 5 million times a year in the United States [1]. With this model, medical residents are trained by performing procedures on real patients while under supervision. Due to the risk this method involves for patients, many medical centers have expressed a greater interest in simulation methods to allow for repetitive practice and evaluation of procedural steps before the resident performs the procedure in the clinic. Many state of the art simulators have focused training and evaluation on the haptics involved in the procedure, neglecting training on simpler steps and detailed training on the use of the medical instruments involved [2]. Appropriate use of these tools is vital for ensuring sterile technique throughout the procedure which reduces the risk of infection, a complication that is far too common in CVC today [1, 3].

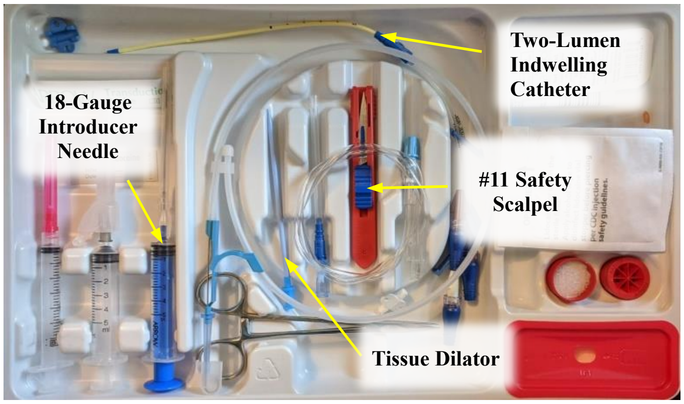

FIGURE 1: CVC INSTRUMENTATION KIT

Sensorization is a modern technique, believed by many to be a driving force for the third industrial revolution, in which multiple sensors are embedded into an object to increase usability and gather information [4]. Sensorization has already led to revolutionary technologies used in daily life by millions around the world, and has the potential to improve medical training as well. In the last 10 years, sensorization has been used to improve methods for rehabilitation, minimally invasive surgery training, and orthopedic navigation [5-7]. To improve the usage training of CVC medical devices, such as those shown in Fig. 1, an advanced testing surface was designed using sensorization to detect and evaluate the use of the instruments used in each step of CVC post needle insertion.

2. MATERIALS AND METHODS

An advanced testing surface, shown in Fig. 2, was designed consisting of a silicone soft tissue simulant surface atop a sensorized needle insertion hole which leads to a sensorized cylindrical vessel. Through the use of a limit switch and two spring loaded push buttons, the device is capable of detecting the insertion and removal of a blunted 18-gauge introducer needle, a tissue dilator, and a blunted #11 safety scalpel: important tools used in performing Central Venous Catheterization, shown in Fig. 1. In addition, the insertion distance of a Two-Lumen Indwelling Catheter is measured using an array of 8 Analog 49E Hall Effect Sensors. The introducer needle and the scalpel were blunted for safety and to prevent damage to the sensors. A 2.5 mm diameter spherical magnet was connected to the catheter to allow for magnetic detection using the hall effect sensors. A microprocessor, Arduino Nano (Sommerville, MA), is used to read and process information from each of the sensors.

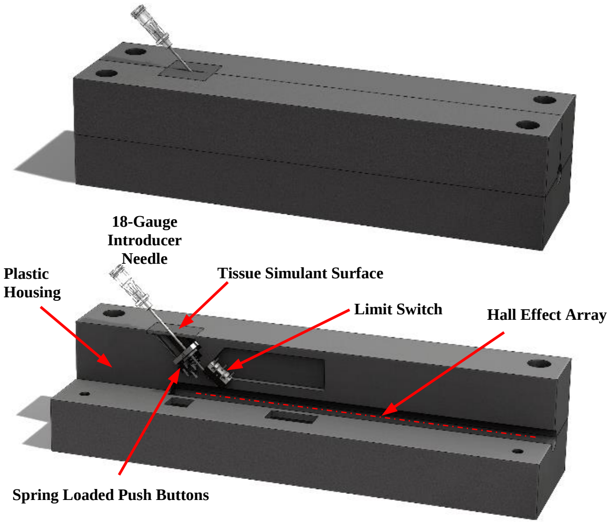

FIGURE 2: ADVANCED TESTING SURFACE

The hall effect sensors are placed with their centers 1 cm apart with the first sensor being 1 cm from the vessel entrance. The distance from the magnet to each sensor is calculated from the measured voltage using the following equation:

$$d = \frac{\ln\left(\frac{V}{A\,R}\right)}{B} \tag{1}$$

where d is the distance, V is the voltage, R is the resolution of the microcontroller, and A and B are experimentally determined constants. A and B were calculated by recording the voltage read by the Arduino Nano in five trials for individual hall effect sensors with the magnet at varying distances from the center of the sensor. A plot of these results can be seen in Fig. 3. Constants A and B for these sensors, with and R^2 value of 0.86, are 104.07 and -0.447 respectively. The maximum distance these sensors can read with a magnet of this size was found to be 15 mm.

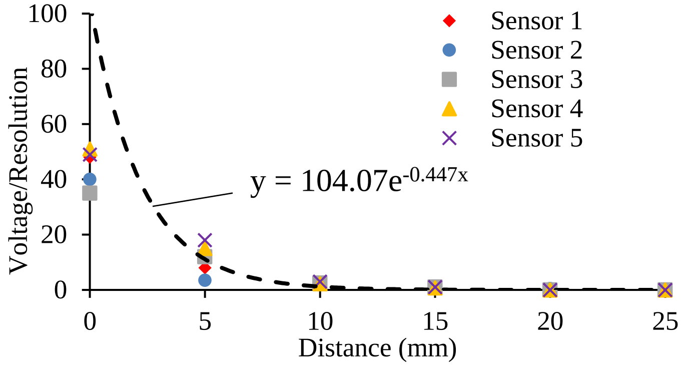

FIGURE 3: HALL EFFECT SENSOR MEASUREMENTS AT VARYING MAGNET DISTANCES

The difference in values from the dashed line and the experimental values at distances close to zero are mitigated by using measurements from multiple sensors as defined in Equation 2. The insertion distance along the cylindrical vessel is calculated by comparing the distances read by consecutive pairs of hall effect sensors in the array. This is accomplished through the following conditional equation:

$$D = \begin{cases} P_1 - d_1 & only\ d_1 > 0 \\ \frac{(P_n - d_n) + (P_{n-1} - d_{n-1})}{2} & d_n, d_{n-1} > 0 \\ P_8 + d_8 & only\ d_8 > 0 \end{cases} \tag{2}$$

where D is the insertion distance, P_n is the position of the nth sensor in the array, and d_n is the distance read by the nth sensor as defined in Equation 1.

The hall effect array was experimentally evaluated using a 12 cm piece of 7.5 mm diameter transparent plastic tubing, which was mounted over a breadboard with 8 hall effect sensors in an array as shown in Fig. 4. Markings were drawn on the catheter every 5 mm starting from the location of the magnet. The experiment was conducted in two tests, one static and one dynamic. In the static test, the catheter was inserted and held in place while 30 measurements were taken at 10 Hz. This was done at 5 mm increments from a position of 0 to 85 mm. In the dynamic test, the catheter was continuously inserted the full 85 mm at a rate of 5 mm/s while measurements were recorded at 10 Hz. Each test was repeated 5 times.

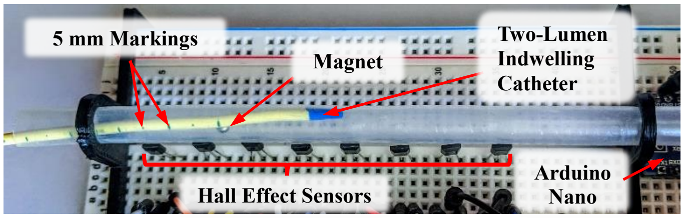

FIGURE 4: EXPERIMENTAL HALL EFFECT ARRAY SETUP

3. RESULTS AND DISCUSSION

The average results from the 5 static tests are shown in Fig. 5. The maximum deviation between the distance measured by the hall effect array and the actual position of the catheter was 3.5 mm, with an average absolute deviation of 1.1 mm. It can be seen in Fig. 5 that the highest inaccuracies occur at the far end of the sensor array. This is expected because the calculations at this position rely on the measurements of only one sensor to calculate distance. Positions under 10 mm are also calculated based upon measurements from a single sensor; however, errors in this position are mitigated by the constraints of Equation 2 which result in distance calculations of zero when the magnet is out of range. Thus, calculation error at the start of the array is significantly lower than at the end. Errors from single sensor-based calculation at the start of the array appear instead at the 10 mm position, which always underestimated the actual position with an average deviation of 1.7 mm.

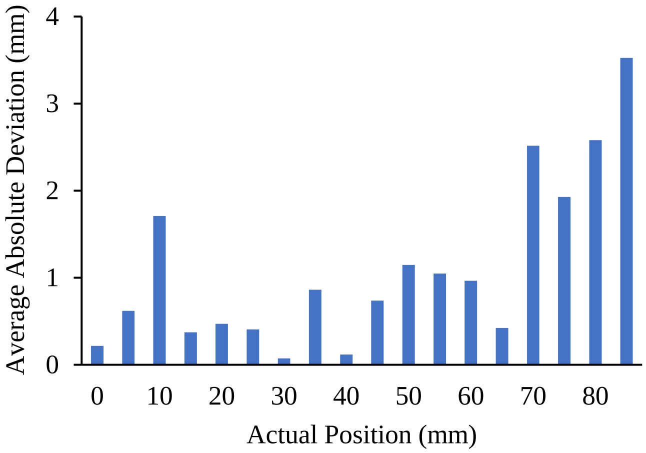

FIGURE 5: DEVIATION OF MEASURMENTS FROM ACTUAL STATIC POSITION

All 5 insertions from the dynamic test, shown in Fig. 6, provided similar results. In each trial, the greatest inaccuracies are found near the end of the array where only one hall effect sensor is detecting the magnet. Similarly, every trial underestimated the position of the catheter as it approached 10 mm. It can be seen however, that the overall trend of each insertion closely follows the actual position of the catheter as it advanced through the tubing.

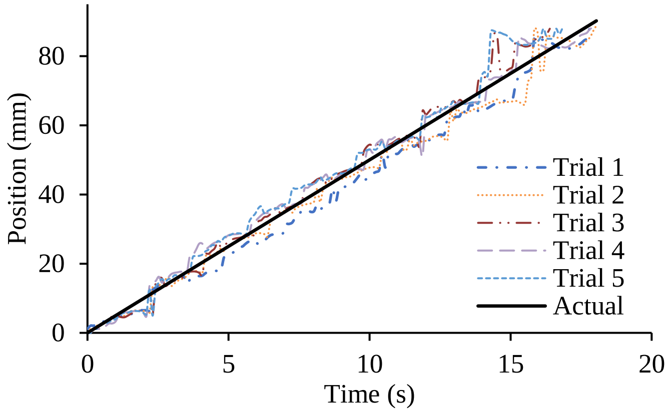

FIGURE 6: DEVIATION OF MEASURMENTS FROM ACTUAL DYNAMIC POSITION

The average speed of each insertion can be found in Table 1. The largest deviation in measured insertion speed at 5 mm/s was an overestimate of 0.36 mm/s, with an overall average measured speed of 5.07 mm/s. Further accuracy could be obtained through the use of more hall effect sensors to ensure that all desired positions are calculated using more than one sensor measurement. Furthermore, longer measuring lengths are possible through the use of longer sensor arrays as the accuracy of measurement was consistent along the central portion of the channel.

Table 1: AVERAGE MEASURED SPEED OF 5 CATHETER INSERTIONS AT 5 MM/S

Insertion	Average Measured Speed
Insertion 1	4.99
Insertion 2	4.92
Insertion 3	5.36
Insertion 4	4.87
Insertion 5	5.22

The results of this experiment indicate that the use of analog 49E hall effect sensors in an array to detect the insertion position of a catheter is appropriately accurate for CVC training purposes. On average, the static position measurements were accurate to ±1.1 mm and the velocity measurements were accurate to 0.16 mm/s. Residents are instructed to place the tip of the catheter in the lower third of the superior vena cava (SVC), which is agreed upon as the ideal position for the tip of a center line catheter [8]. Studies have shown that increases in catheter malfunction rates were statistically significant when the catheter tip was placed further than 4-6 cm superior to the junction between the Superior Vena Cava and the Right Atrium [9]. Due to variations in patient anatomy, and the approximate nature of catheter positioning, the ability to measure position on the mm scale is more than sufficient. Further research is needed to determine the fidelity of the system and the viability of its use as a training device. Future studies will be conducted to test the effectiveness of the device in teaching critical skills to medical residents.

CONCLUSION

A prototype advanced testing surface for CVC procedural training and evaluation, in which an array of hall effect sensors is used to measure catheter insertion distance, was presented. The hall effect sensor array was tested in a two-part experiment and the results were reported. The array was found to be sufficiently accurate under both static and dynamic conditions. The ability to accurately sense catheter position using this system can be used to provide accurate feedback and assessment in CVC simulation training devices.

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