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A Syringe Injection Rate Detector Employing a Dual Hall-Effect Sensor Configuration

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Abstract— **Injection of fluids in the body using needle syringes is a standard clinical practice. The rate of injection can have various pathological effects on the body such as the pain perceived or in case of anesthesia, the amount of akinesia attained. Hence, a training system with a modified syringe employing a simple measurement scheme where a trainee can observe and practice the rate of injection prior to administering on actual human subjects, can be of great value towards reduction of complications in real life situations. In this paper, we develop a system for measurement of syringe injection rate with two Hall-effect sensors. Ring magnets attached to the body of the syringe along with the dual Hall-effect sensor configuration help in determining the position of the piston with respect to the syringe body. The two Hall-sensors are arranged in a differential configuration such that a linear relationship is obtained between the volume of liquid in the syringe (in ml) and the Hall-effect sensor output voltages. A prototype developed validated the measurement scheme. The rate of injection was displayed in real-time with a LabVIEW based Virtual Instrument. The error was within acceptable limits illustrating its efficacy for practical training purposes.**

I. Introduction

Injection and outtake of fluids from the human body using syringes is a routine clinical practice. The rate of injection has been shown to have various physiological and pathological changes in the patient. It has been reported to have profound effects on the quality of anesthetic procedures [1]-[3]. Perception of pain, time taken and amount of akinesia achieved in an anesthetic block have been directly linked to the rate of injection in all major fields of anesthesiology [1]-[8]. Therefore, it is of vital importance to practice safe rate of injection prior to attempting procedures on human subjects.

Training on live patients puts the subject at risk of complications, hence it is not advised. Cadavers fail to produce the pathologies required to identify faulty procedures. Therefore, a training system which can provide real-time indication of the rate of injection can be extremely beneficial in reducing risks involved and in improving the quality of injections administered in real-life procedures. Video based methods employed to calculate rate of injection require direct line of sight between the syringe and the image capture system impairing free movement for the trainee[8]. The magnetostrictive displacement transducer [9] and the magnetic encoder [10] based systems are bulky and are not suited for training purposes. A single Hall-effect sensor based syringe injection rate measurement system of [11] has a non-linear calibration curve, making the determination of syringe piston position cumbersome. The system has an error of 5% in determination of rate of injection.

In this paper, we present a dual Hall-effect sensor and ring magnet based measurement scheme for rate of injection. The specially designed syringe piston houses the two Hall-effect sensors in such a way that they operate in differential mode. The relationship obtained between the Hall-sensor output voltages and the volume of liquid in the syringe is approximately linear. Also, the piston conceals the sensors and associated wires from the view of the trainee thus providing a compact and easily maneuverable syringe for real-time training purposes.

II. Syringe Injection Rate Detector

The syringe employs a specially designed piston as shown in Fig. 1. The body and needle of the syringe comprises of a standard off-the-shelf 5ml disposable syringe and 23G needle. Permanent magnets in the shape of a ring are attached to the body of the syringe inside a magnet holder arrangement. The various parts involved in the system are discussed below.

A. Modified Piston Assembly

The piston of the syringe developed by rapid prototyping technique (3D printing) houses two Honeywell SS49E Hall

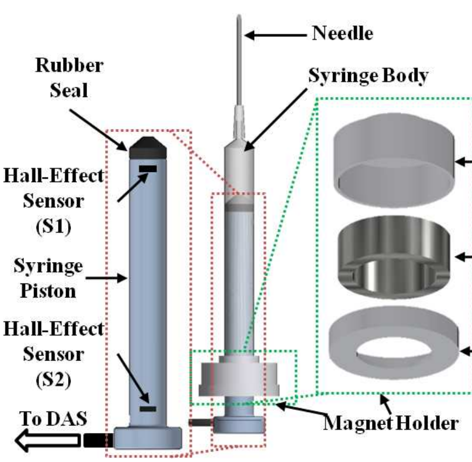

Fig. 1. The various parts of the syringe assembly showing the special piston with dual Hall-effect sensors and magnet holder with ring magnet disassembled from the syringe body.

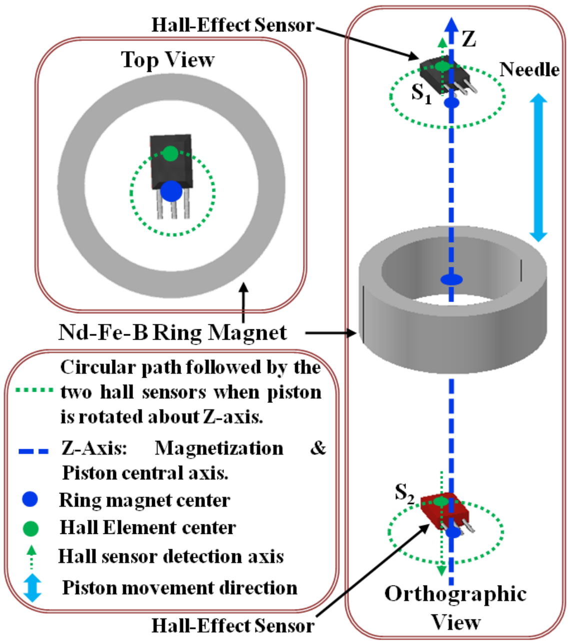

Fig. 2. The dual Hall-effect sensor assembly and the axially magnetized ring magnet. Sensor detection axis is parallel to the central piston movement (Z-axis) showing the circular path followed by the Sensor axis about the Z-axis, when the piston is rotated about Z-axis

effect sensors, $S1$ and $S2$ as illustrated in Fig. 1. The sensors are placed with the detection axis, parallel and non-coincident to the Z-axis as shown in Fig. 2. The Hall-effect detection axis of the two sensors $S1$ and $S2$ are opposite and coincident to each other shown in Fig. 2. Connections from $S1$ and $S2$ are taken out with a 4-core shielded cable from the top of the piston which provides strain relief to the wire and conceals it from the view of the trainee within its translucent body. The other end of the piston, has a rubber seal as usual to prevent liquid leakage. The Hall sensor output voltages V_{S1} and V_{S2} from $S1$ and $S2$ respectively, are then fed to a Data Acquisition System (DAS) which digitizes it for further processing.

The placement of the sensors $S1$ and $S2$ are such that it is on either side of the ring magnet in differential mode (refer Fig. 2). Therefore, when the piston is pushed in the direction of the needle, $S1$ moves away from the magnet while $S2$ moves closer to the magnet by the same distance. Similarly, when the piston is pulled out in the opposite direction, $S2$ moves away from the magnet while $S1$ moves closer to the magnet. For the 5 ml syringe used, the sensors are equidistant from the respective pole faces at the 2.5 ml mark of the syringe. If, d is the maximum distance traveled by the sensors from the respective pole faces and x be the present position of position of $S1$, then the position of $S2$ is given by $d - x$.

B. Magnet Holder

The magnet holder houses three ring-shaped Nd-Fe-B permanent magnets as shown in Fig. 1. The outer diameter, inner diameter and the thickness of each magnet is 25.4 mm, 19.05 mm and 2.38 mm respectively. The surface magnetic flux density of each magnet is 2635 Gauss. The axially magnetized magnets are arranged such that they lie on top of each other with their axes coincident to the central axis of the piston (Z-axis) and the direction of piston movement. The magnet holder is held firmly in place, attached rigidly to syringe body as shown in Fig. 1.

The piston is free to rotate about Z-axis (Fig. 2).The detection axis of the Hall-sensor, which is parallel to the Z-axis, can, therefore, describe a circle around the Z-axis, the radius of which is fixed. As the magnetic field produced by the ring magnet is uniform over this circle, hence, the Hall-effect sensor outputs remain unaffected due to the rotation of the piston about the Z-axis. This allows the trainee to freely rotate the piston as may be required for adjustment of bevel direction.

C. Measurement Scheme

A block diagram of the measurement system is shown in Fig. 3. The Hall-effect sensors are powered by a 5V power supply. The output of the Hall-effect sensors are fed to two channels of a NI ELVIS II prototyping board which digitizes the signals at a rate of 10 kSa/s. As shown in Fig. 2, when the piston is moved along the Z-axis, the magnetic field experienced by $S1$ and $S2$ changes as a function of the distance between the respective sensor and its pole face. This distance is a function of the volume of liquid expelled from the syringe expressed in ml. The digitized sensor outputs are passed through a Butterworth low-pass filter of 3rd Order with cut-off frequency of 10 Hz. Thereafter it is fed to a moving average filter for smoothing and then the channels are split up into the two constituent signals, V_{S1} and V_{S2}, from $S1$ and $S2$ respectively. The two voltages are added together and then offset adjusted to obtain V_A. V_A is approximately a linear function of the piston position with respect to the magnet. And the piston position is a function of the volume of liquid in the syringe. A linear calibration curve maps V_A to the volume of liquid in the syringe (p) in ml. This information is then used to calculate the rate of injection

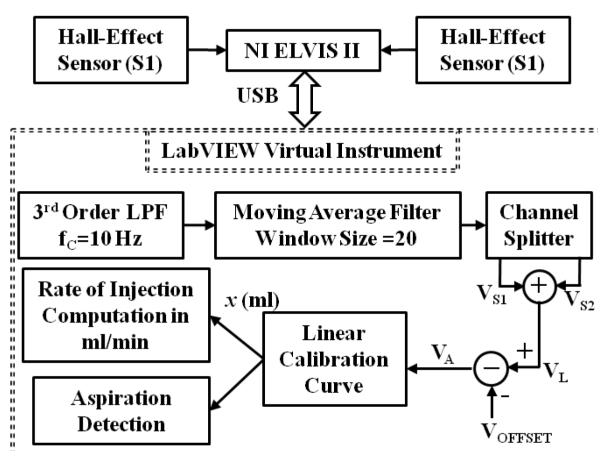

Fig. 3. Block Diagram of the Syringe Injection Rate Detector System

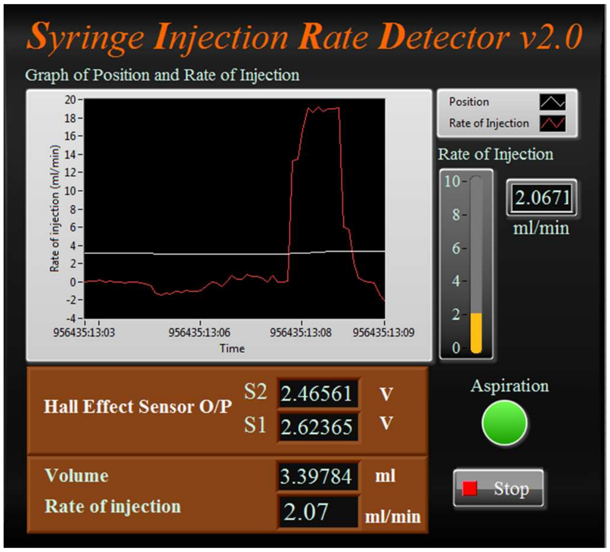

Fig. 4. The front panel of the Virtual Instrument developed showing rate of injection R in ml/min, Hall sensor Voltages, computed position p in ml and aspiration indicators in real-time

in (ml/min) by subtracting subsequent samples of p and dividing it by the time (calculated in minutes) between the two samples. Hence, rate of injection is obtained in ml/min. Aspiration is detected if the rate of injection is negative and exceeds a predefined threshold, V_{ASP}, indicating inflow of fluid into the syringe.

III. Results

A prototype of the system described, was developed and the measurement scheme implemented on a LabVIEW based virtual instrument (VI). The VI front panel is shown in Fig. 4. The output of the two Hall sensors V_{S1} and V_{S2} and calibrated by fitting 4th order polynomials to them as given in (1) and (2) respectively, where, p is the volume of

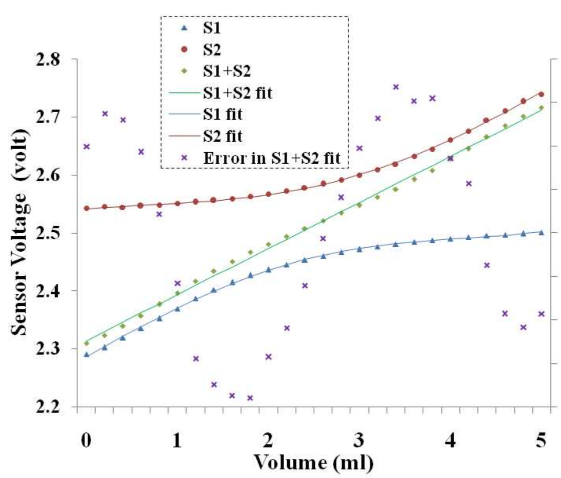

Fig. 5. Measurement curves and polynomial fit for the two Hall-effect sensors output voltages, V_{S1} and V_{S2}. Linear calibration curve fit of V_A obtained by offset adjustment of $V_{S1} + V_{S2}$ is shown. The full scale error distribution in the linear fit of V_A is also plotted.

the liquid in the syringe (or piston position multiplied by the cross-sectional area of the syringe body) in ml, as shown in Fig. 5. The addition of the voltages V_{S1} and V_{S2} after offset correction (refer Fig. 3) results in V_A as shown in Fig. 5. A linear polynomial of (3) is fitted to it, with worst case linearity error less than 0.4% (Fig. 5). This equation is used as the linear calibration curve for mapping V_A to p.

$$V_{S1} = 0.0005194p^4 - 0.005019p^3 + 0.001638p^2 + 0.08663p + 2.286 \quad (1)$$

$$V_{S2} = -0.0003456p^4 + 0.004437p^3 - 0.008212p^2 + 0.01374p + 2.541 \quad (2)$$

$$V_A = 0.07953p + 2.314 \quad (3)$$

It is observed that the coefficients of the nonlinear higher order terms in (1) and (2) are of opposite sign. Hence when (1) and (2) are added, the of higher order terms responsible for the non-linearity in V_{S1} and V_{S2} diminish and can be neglected and the resulting voltage V_A can be approximated with a linear equation in p, given as (3) after offset adjustment.

The worst case error in computation of volume of liquid, p was found to be less than 1.2% of full-scale as shown in Fig. 6. Therefore, the worst case error in calculation of the difference in two samples of p (Δp) would be less than 2.4% of full-scale. Since, the rate of injection (R) is calculated by computing the difference between successive samples of p and then dividing it by the sampling time (t) of the DAS, hence, the worst case error in R will be less than 2.4%, as error in Δt is negligible (50ppm of sampling rate). Fig. 7 shows a graph of the computed volume (p) and the rate of injection(R), obtained from the developed prototype in real-time. It clearly shows that when the computed volume p increases, indicating that the syringe piston has been pulled out, R becomes negative and crosses the V_{ASP} threshold. The aspiration indicator shown in the VI front panel of Fig. 4 is activated.

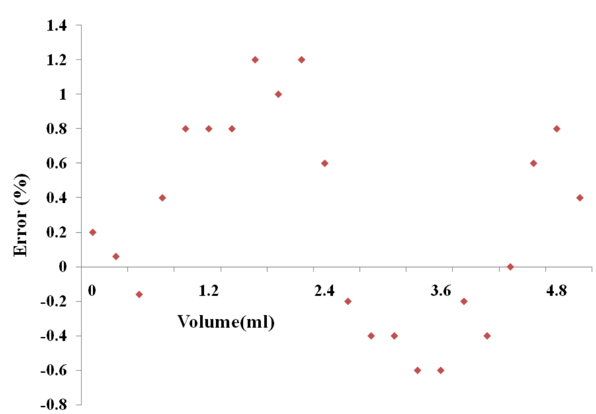

Fig. 6. Full Scale Error plot of the computed volume of liquid, p, obtained from the developed prototype

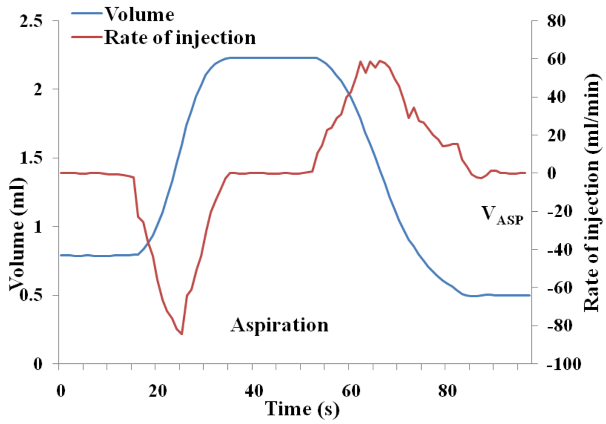

Fig. 7. Graph showing the computed position p and rate of injection R obtained from the prototype developed. Aspiration detection is also indicated when R is negative and exceeds the V_{ASP} threshold

IV. Conclusion

A syringe injection rate detection system based on two Hall-effect sensors in differential mode of operation has been presented. This system will improve training of injection administration procedures. A prototype of the system was built using rapid prototyping techniques. A specially designed piston houses the two Hall-effect sensors. A magnet holder assembly is used to mount ring magnets to the body of a commercially available 5ml syringe. The arrangement of the piston is such that when the piston is moved with respect to the syringe body, one of the Hall-effect sensors move closer to the magnet while the other moves away from it thus producing a differential mode of operation. A linear calibration curve was obtained to map Hall-sensor outputs to the volume of liquid p in the syringe in ml. From tests conducted on the prototype developed, the worst case error in p was found to be less than 1.2% and the error in determination of rate of injection to be less than 2.4%. This is within clinically accepted limits since the rate of injection in practical scenarios rarely exceeds 15 ml/s.

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