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Wearable shear force-sensing for augmenting manual hose connections in an automotive assembly

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Abstract

In automotive assembly, hose interfaces for engine and cooling applications are critical safety connections as they carry fluids that are essential to keep the engine running and can be flammable. Incomplete hose connections might loosen in operation resulting in fluid leakage and potential field warranty claims. The current quality control in manual assembly for such connections is a push-pull-push procedure (push to lock, pull to check, push to reseat) that relies on manual verification by the operator, which is a subjective evaluation of the connection quality. This research aims to convert this subjective evaluation of successful hose connection into an objective measure through a wearable shear force sensor that measures the operator-induced shear force during the assembly operation. This system could not only reduce assembly defects but also help in reducing the assembly rework time.

Keywords: Wearable force sensing; Shear force sensor; Automotive assembly; Hose connections

1. Introduction

Although automotive assembly is moving towards increased automation, manual assembly by the human workforce remains an integral part of the process due to the complexity and variations involved in a modern vehicle. It is a general misconception that artificial intelligence in an assembly plant removes the worker from the loop. Instead, the reality is that they are augmenting the worker/process by increasing the process quality and improving the standard of the work [1].

Hose connections in the automotive assembly are commonly performed manually due to adaptability and flexibility that is required for the process [2]. Manual process are subject to human errors which significantly contribute to the overall defects [3]. As a result, there is an increased risk of incomplete connection. Further, due to flawed inspection methods, these incomplete connections end up as a defect. In the current evaluation method, the operator making the connection relies only on a push-pull-push procedure (push to lock, pull to check, push to reseat) to verify a successful connection. This is a subjective process where the operator makes a judgment based on their perception of feedback and visual observations. Further, there is also a potential for these hose connections to be present in a location that offer limited visibility or lesser accessibility for the operator making the connection. This can result in a higher likelihood of an undetectable mistake occurring.

Thus, a method to obtain objective information on the connection success through measuring operator-induced forces while making these connections is desired. Though some commercial glove solutions measure force, they are generally intended for lighter applications and lack the robustness that is warranted for a factory floor application. Furthermore, there are no commercial glove solutions that measure the shear component of the force applied by a human hand.

2. Literature Review

Force sensing has been carried out for decades with commercialized force sensors like transducers and load cells.

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Platt *et al*. [4] have done previous research work to employ small strain gauge-based load cells in fingertips to measure contact force in prosthetic hands. However, a drawback to using these load cells in hand applications has been the size constraints and loss of tactile feedback with these hard sensors.

A soft sensor is needed for the wearable application that could measure force without hindering the interacting surfaces. One such soft sensor is the force-sensing resistor (FSR), a conductive polymer material that changes its resistance based on the force/pressure/stress. Since its invention in 1977, it has been commercially used and has also been tested in wearable applications. For instance, Nokonovas *et al*. [5] tested by placing several FSR on the fingers and palm to measure forces during several daily tasks such as lifting saucepans, driving a vehicle, and hitting a golf ball. However, due to the sensor's stiff nature, the placement of these sensors is restricted to a specific location on hand.

Several researchers have used sensors made of flexible piezoresistive materials like polyester or polyimide to customize force-sensing resistors to solve this problem. Klara *et al*. [6] used a low-cost thin-film, which is flexible and trimmable resistive sensors for hand-handle interface forces measurements. Büscher *et al*. [7] developed a tactile data glove using Eeontex (piezoresistive fabric by Eeonyx, USA) combined with conductive fabric as electrodes to study human manual intelligence. Similarly, Krugh *et al*. [8] have used Velostat (Desco Industries, USA), a piezoresistive material embedded inside layers of woven conductive fabric on a glove, to assess an operator's finger engagement making electronic connections in automotive production. However, these piezoresistive fabric sensors' performance is known to be relatively low. Prete *et al*. [9] found a 15% repeatability error in a test performed with a machine that had a controlled load. However, through conditioning circuit, electrode configuration, and techniques like Period Averaging proposed by Giovanelli *et al*. [10], one can limit the uncertainty issues.

A significant challenge with force sensing of hose connections is to sense shear force along with normal force. Due to the combination of design, process, and human factors, the connections under study require significant shear force along with normal force from the operator making the connection. All the technologies that were discussed until now only have the capability to measure normal force. The detection of a shear force poses more challenges than the normal force due to difficulties in parametrizing a material response against shear force. As a result, the commercial availability of shear force sensors is less than that of normal force sensors.

Notably, much previous research on wearable shear force sensors prototypes was developed for more controlled settings and cannot be used in an industrial facility's harsh environment. Even the prototypes that are built to withstand such an environment have robustness and longevity as a concern. For example, a sheet-type shear force sensor was developed by Toyama *et al*. [11] used Kapton as a basal layer on which electrode materials were deposited. However, they had a liquid electrolyte in their prototype that separated the two Kapton layers, which are prone to leakage under factory use. Another novel method was proposed by Tomo *et al*. [12], using a three-axis hall effect-based skin sensor for measuring shear force for robotic interactions. However, due to the use of viscoelastic material like silicone, hysteresis was observed. Further, having several sensors in hand introduced crosstalk between sensors in close proximity.

Many researchers interested in wearable shear force sensors have also tried to explore the capacitive approach. It is the most common technique used in robotic tactile sensing. Polymer-based materials, such as polydimethylsiloxane (PDMS) in Lee *et al*. [13], are used as the substrates for flexible sensors or flexible arrays on which multiple electrode pairs are positioned. With the shear force application, the air gap between these electrodes varies between electrode pairs, which are then used to quantify the shear force. However, the conditioning circuit becomes complicated, and the sensor is subject to noise due to connecting cables. Although capacitance sensors proved interesting as research, they do not suit our application scenario due to the highly sensitive nature of capacitive sensors for temperature changes, humidity, and unexpected collisions with the working environment [14].

An area of interest that is less explored in the wearable shear force sensor is the resistive technique. The underlying principle here is the transduction of force variations into resistance changes. Interest in resistive tactile sensors has recently been increasing due to the simplicity of the readout circuit and its device's design [14]. Due to their substantially lower cost and flexibility, the resistive sensing systems are an attractive choice for hand force measurements in industrial work conditions. The main advantage of these sensors is their low cost when compared to a capacitive sensor [6]. This work aims to build a low-cost, flexible, rugged, and wearable shear force sensor by exploring resistance techniques.

3. Methodology

The initial approach was to start with a simple sensor concept that would validate the theoretical operation and provide insight and experience into the construction process. Hence, an electrode offset technique was first tested to function as a Go/No-go output. This model's learnings were then used to implement a variable resistance prototype that gave a continuous output.

3.1 Go/No-go Prototype

The basic principle is to have two electrodes with a set offset distance, as shown in Fig. 1(a), that are adhered to two layers of materials that could move independently under shear force. The first challenge was to select a material that could be used for our sensor layers. Polyamide film, Kapton, was identified owing to its unique combination of mechanical and electrical properties that withstand extreme temperature, vibration, and demanding environments. Electrodes were made with low-cost conductive materials like aluminum and copper foil. The setup of the electrode pattern is as shown in Fig. 1(b). Two L-shaped electrodes, one adhered to the top and the other to the bottom Kapton layers, are set up with a controlled inter-electrode distance. The layers stick together with a line of adhesive on the edges. When a shear force is applied, the Kapton layers move independently, allowing the electrodes to make contact and close the circuit. Until the target force is reached, there will be no signal from the sensor, and once the target force has been met, there will be a signal output due to the electrodes coming in contact

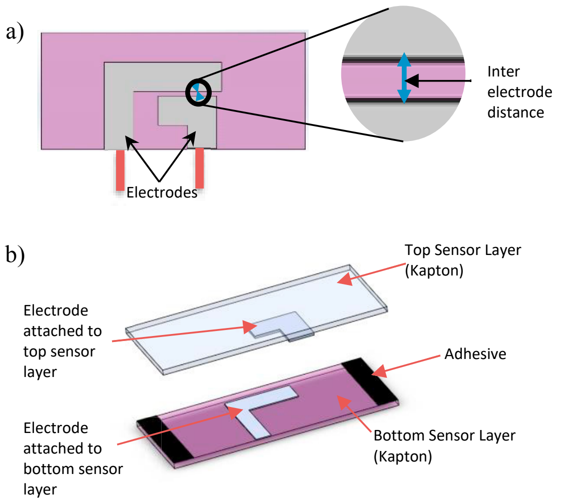

Fig. 1. (a) Go/No-go Sensor layout; (b) Sensor layer stack up.

The Go/No-go prototype's operational limitation was that it could only detect whether a specific activation force was achieved. It does not quantify the applied force at all instances. Hence, to achieve a continuous force measure, a variable resistance prototype was explored.

3.2 Variable Resistance method

The basal layer of the sensor and other variables relating to sensor configuration was retained from the Go/No-go sensor. The bottom electrode was replaced with a highly resistive material to act as a resistive track. As shown in Fig. 2, the top electrode design was modified to act as a wiper that would move along the resistive track under shear force.

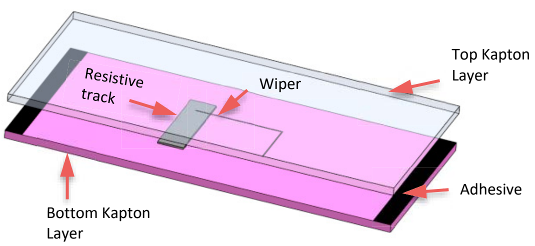

Fig. 2. Variable resistance sensor layout.

With the wiper moving along the track, the resistance in the circuit increases as the current has to now travel a greater distance as shown in Fig. 3. The resistance change from the wiper movement will be used to identify the shear force applied on the sensor.

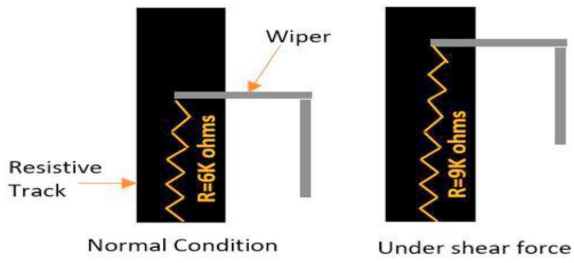

Fig. 3. Variable resistance sensor working principle.

Linear soft pots are commercially available variable potentiometers that are widely used as position sensors in CNC machines and medical devices. They typically have multiple thin layers (collector, spacer, and resistive track) stacked on top of each other. As the wiper design had to be customized and the resolution needed was higher for our application, we only used the bottom resistive track layer from it. Resistive tracks from different commercial potentiometers were tested for the resolution and linearity of the resistance values. The resistive track from the Spectra symbol (SP-L-0012-103-1%-RH) had the highest resistance per unit length (25K ohms/12.5 mm) and good linearity (+1%). The resistive track from the commercial soft potentiometer was removed and adhered to our bottom Kapton layer as shown in Fig. 4(a). The conductive material (Al foil) from the Go/No-go prototype was retained with the required design modification to use them as a wiper as shown in Fig. 4(b).

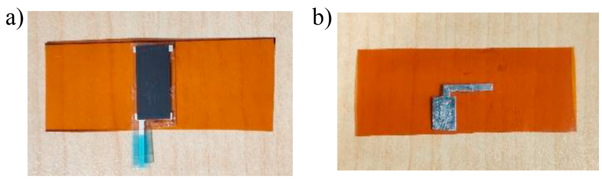

Fig. 4. (a) Resistive track on bottom Kapton layer; (b) Al foil wiper on top Kapton layer.

4. Testing

The shear force fixture shown in Fig. 5(a) was designed to test and calibrate the prototype. The fixture design was based on the testing apparatus developed by Shigeru *et al.* [11] for testing a sheet type sensor output under shear load. The fixture was built with a rail on which a block can slide. As seen in Fig 5(b), the sensor's top layer is adhered to this block, and the bottom layer is entirely fixed on the rail. The movable block has a hook where a string is attached. Known weights can be attached to the string so that this gravitational force is converted to shear force acting on the movable block through a pulley system.

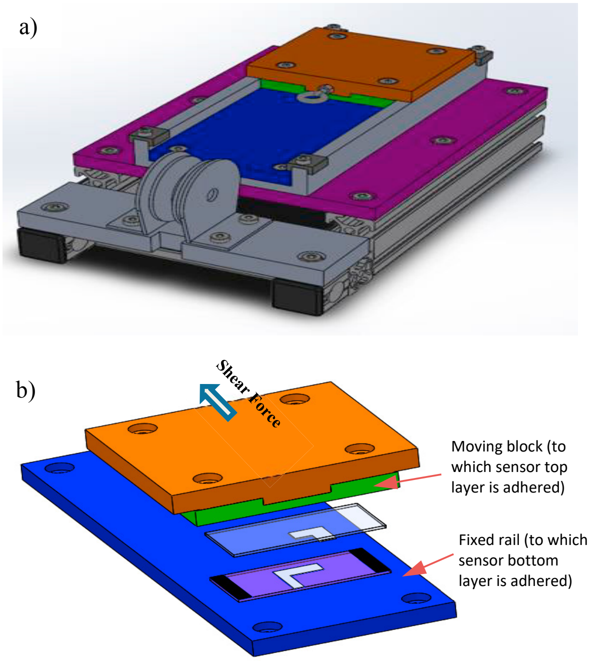

Fig. 5. (a) Shear force testing fixture; (b) Sensor set up in the fixture.

A pull rod-type displacement sensor was used to dynamically measure the displacement of the movable block. The displacement sensor was verified using a Mitutoyo Vernier caliper(500-151-20). For mounting the displacement sensor, an extension to the fixture was designed and integrated into the existing system, as shown in Fig. 6.

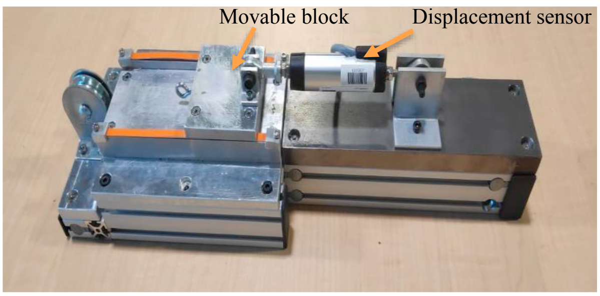

Fig. 6. Displacement sensor added for enabling dynamic measurement.

Different variables present in the prototype design, which could impact the sensor behavior under shear force, were identified. As listed in Table 1, for material, different classes of Kapton: HN(basic), FN(coated with Teflon), FPC(improved adhesion) and Teflon were tested as the material properties like elasticity dictate the displacement achievable. The sensor layer thickness was also explored by testing variations in layer thickness from 1.5 mil (0.0015 in) to 5 mil (0.0050 in) as these dictate the sensor's durability. Tests to study the impact of the size/aspect ratio of the sensor layout were also done. Two main types of adhesive were tested: fixed and flexible. For the adhering technique between the sensor top layer and fixture, the adhesive can either be applied on the complete sensor top area or only on a circular area in the center.

Table 1. Parameters of the sensor architecture.

Parameters	Variations
Material	Kapton HN, Kapton FN, Kapton FPC, Teflon
Thickness	1.5 mil, 2 mil, 3 mil, 5 mil
Size/Aspect ratio	45x20 mm, 20x45 mm, 45x45 mm
Adhesive	Fixed (Cemedine AX-039), Flexible (MG chem epoxy-8332, Ply bond 25LV)
Adhering Technique (Sensor top layer-Fixture)	Adhesive on Complete sensor top area, Only a circular area (variability in dia=5/7.5/10 mm)
Adhering Technique (Sensor top layer-Sensor bottom layer)	Adhere 2 sides parallel to shear force, 2 sides perpendicular to shear force, All 4 sides. Along with variability in the distance between adhesives
Inter electrode distance	Varying the distance between electrodes from 0.1mm to 1mm

Similarly, for the adhering technique between the sensor top layer and sensor bottom layer, as shown in Fig. 7, the adhesive can be applied on two sides that are parallel to shear force or two sides perpendicular to shear force or all four sides. Once again, there is variation possible here as well with respect to the distance between adhesives lines. These adhesive parameters dictate the relative movement between the two layers.

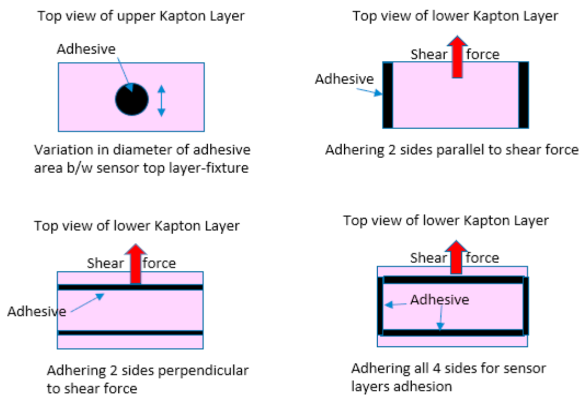

Fig. 7. Adhering Technique parameters in the sensor architecture.

Suitable combinations of the sensor variables were tested to understand each parameter's influence on force vs. displacement profile, activation force, and activation time. For instance, to understand the influence of material, all other parameters, including thickness, size, and adhesive variables, were kept constant while the material was varied. A similar procedure was followed for all the critical variables listed in Table 1. Three prototypes were tested for each type. To obtain the sensor's load-bearing capability, weights were loaded in an incremental manner until the sensor de-bonded. Displacements were measured for each force value using an Arduino Uno that measured the displacement sensor at 490 Hz. The analog output was calibrated to obtain displacement values.

The Go/No-go prototype's activation force was identified using a digital output from the sensor that powers an LED. The corresponding activation time (time between weight addition and LED output) was manually observed using stopwatches. Tests were also carried out to study the repeatability in the activation force that can be achieved from a single prototype. Twenty tests were performed with a Two min interval between each test to replicate the application scenario. Weights were unloaded entirely and then loaded back incrementally for each test to obtain the force-displacement profile and identify the prototype's activation force. Further tests were also done to study the activation time variation for a single prototype under repeatable tests. As we know the activation force from our previous experiment, the prototype was loaded directly to its activation force instead of the incremental loading done previously.

To mimic the actual hose assembly and to parametrize the force applied while making a hose connection, an insertion force fixture, as shown in Fig. 8(a), was used that measures the force acting on the connector. The insertion force fixture had the male end (connector) of our connection fixed on one end to which the female end (hose) can be manually connected. The fixture's fixed end had a Mark-10 series 5i force indicator and series MR01-100 transducer that measured forces of 0.5 N to 10 kN in a dynamic manner while making the hose connection. Fig. 8(b), shows the sensor adhered to a glove gripping the hose before the operator completes the connection in the insertion force fixture. The resistance values of our variable resistance sensor were compared against the insertion force fixture sensor readings.

a)

b)

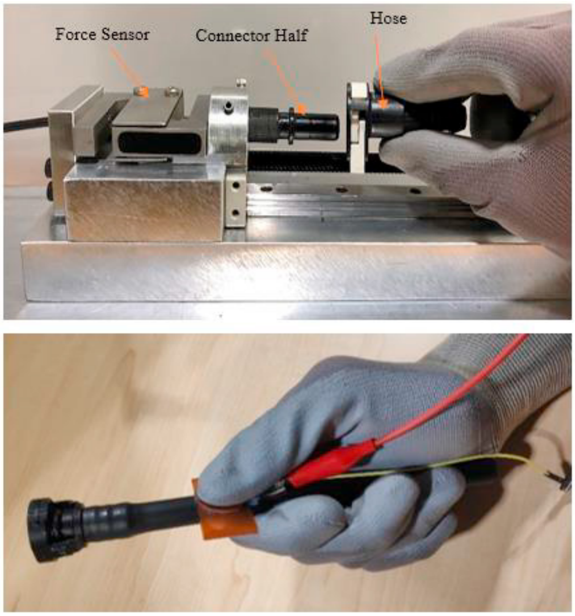

Fig. 8. (a) Insertion force fixture setup; (b) Shear force sensor attached to the thumb of the operator glove.

5. Results

As the testing evolved, the results helped eliminate few options and understand the tradeoffs between specific parameters. We were able to identify the right combination of parameters that our prototype needs for a given force range through these results. The impact and constraints of each variable are to be analyzed to understand the prototype parameters. As seen in Fig. 9, through variation in these sensor parameters, a more comprehensive force range (1N-120N) was achievable. Variation in displacement vs. force across materials was as expected from the material elasticity data properties. Teflon did not suit the target force, and the Kapton HN type had overall superior properties. The 5-mil thickness prototype had the highest load-bearing capability but had very low displacement. The 1.5-mil thickness prototype had the highest displacement possible but with very low load-bearing capability. The 3-mil thickness was selected to optimize both the characteristics. As the aspect ratio was increased, the available displacement also increased but as a tradeoff to maximum load. Flexible type adhesives gave variable displacement for a force input. The displacement increases with an increase in force application time, which is not desirable. The sensor inner layers adhesion technique had the highest impact on the variation of max force & displacement. Adhering two parallel sides for the sensor inner layer adhesion method resulted in increased displacement achievable. With an increase in sensor top layer to fixture adhesion area, the maximum displacement achievable decreased and max load bearable (without de-bonding) increased.

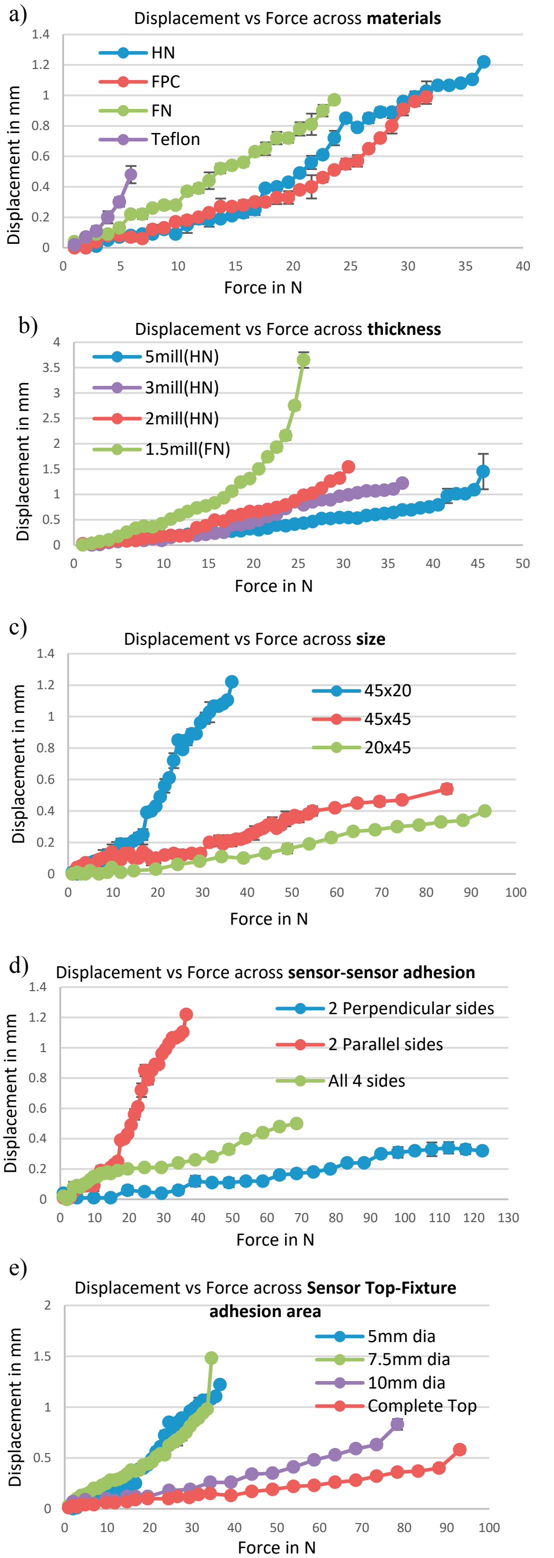

Fig.9. Characterizing the layered material response against known loading conditions for variation in sensor parameters: (a) material; (b) thickness; (c) size; (d) sensor layer adhesion; (e) sensor-fixture adhesion.

Evaluating these sensor parameters enabled to standardize the sensor configuration for a required force and displacement range. This also ensures that the activation force variation will only be controlled by the inter-electrode distance (gap) set between the two electrodes. To corroborate this, six prototypes were made with the configuration shown in Table 2, with variation in inter-electrode distances. As seen in Fig. 10, we observed an increasing trend with the activation force as we increased the inter-electrode distance.

Table 2. Standard Prototype Parameters.

Parameter	Standard
Material	Kapton HN
Thickness	3mil
Size	45x20mm
Adhesive	Cemedine Ax-039
Sensor top-fixture adhesion area	5mm dia circle
Sensor top-Sensor bottom adhesion method	2 Parallel sides

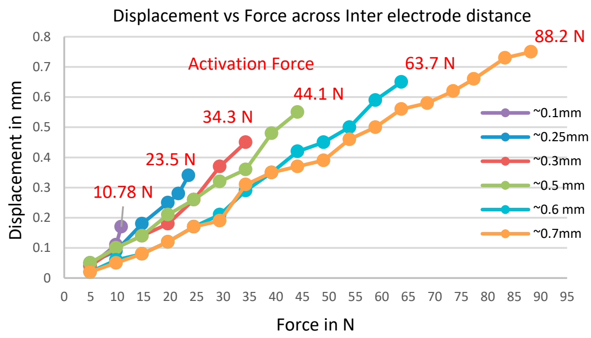

Fig. 10. Variation in activation force across inter-electrode distance.

In repeatability tests, it was observed that the activation force had a consistency of 95% (19 out of the 20 tests). As seen from Fig. 11, there was no trend observed, showing an increase or decrease in activation force due to elastic hysteresis or fatigue.

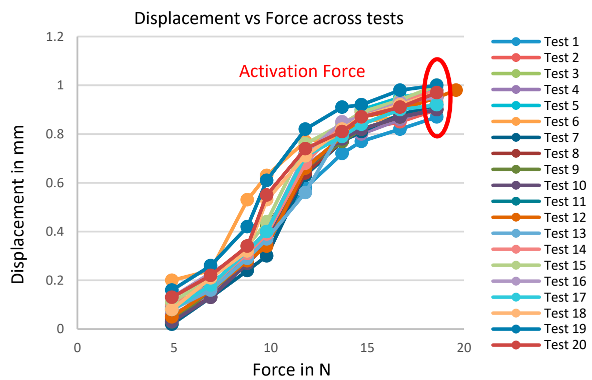

Fig. 11. Go/No-go sensor activation force repeatability tests.

In testing the variation in activation time, the average time for activation over 22 tests came out to be less than a second with a standard deviation of 0.79. As seen in Fig. 12, there were few outliers, which could be noise in the measurement as these were recorded manually.

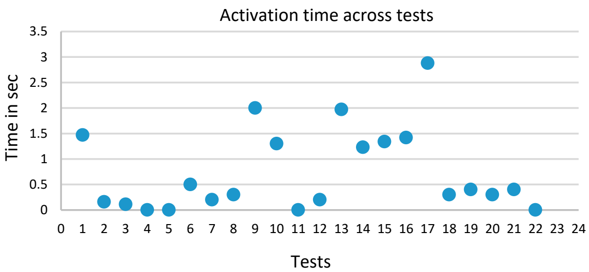

Fig. 12. Activation Time when loaded directly to activation force.

As seen in Fig. 13, the profile of the resistance value obtained from our variable resistance sensor while making a hose connection was able to represent the force profile obtained from the insertion force fixture. Before the operator made the connection, the resistance value was relatively constant, depicting that there was no shear load on the sensor. Only slight fluctuations are observed at this stage, which could be noise due to the operator's unsteady gripping of the hose connector. As seen in the figure, the peaks of both profiles when plotted against time occurred at the same time instant depicting the increase in our sensor's resistance value as the shear force moved the wiper along the resistive track. As the connection is completed, the operator releases his grip, causing a momentary discontinuity between the track and wiper that makes the sensors' resistance value fall below the steady-state seen before the connection.

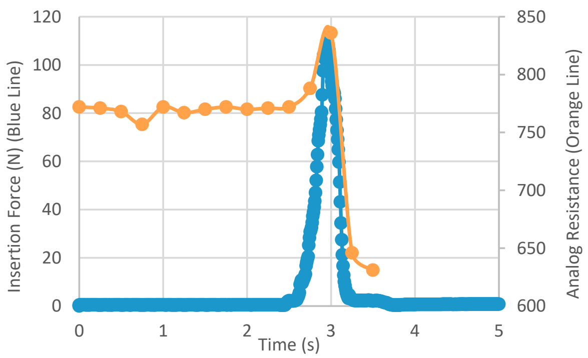

Fig. 13. Sensor resistance output and corresponding Insertion force profiles for a hose connection.

6. Conclusion

The Go/No-go sensor is set up such that a digital output from the sensor will be used to switch ON a feedback system like LED when the sensor experiences a force above the target reference force value that is required for a good connection. This feedback will only communicate whether the connection was good or bad based on the inter-electrode distance set for a reference force value. The force sensor replaces the subjective evaluation method with an objective measure that increases the potential to reduce the number of defects, improving the hose connections' overall quality. The sensor could enable a reduction in the process time as well as operator effort by eliminating the need for the pull and push steps in the current push-pull-push mechanism for a hose connection. Further, the instant feedback from the sensor could help the assembly operator avoid any potential injuries from having to apply an excess force than required for a successful connection. While the Go/No-go sensor's digital feedback is enough to identify a successful connection, having analog feedback from the variable resistance sensor with continuous force values will be better as it quantifies the applied force throughout a connection. The data obtained by this method will not only allow instant data-driven decisions on assembly operation but will also enable data storage for future analytics, ensuring continuous process improvement in the production process.

7. Future Work

Although our tests yielded positive results in the limited environment in which it was tested, this system should be tested by an operator in an automotive assembly line to understand the effectiveness of this device since there are many unaccounted factors like operator training, the comfort while working and the increased complexity in an actual assembly line. For instance, the effectiveness of analog feedback from the variable resistance sensor needs to be compared against the ease of interpreting the digital feedback from the Go/No-go sensor by an operator.

The resistance readings from the handmade variable resistance senor had slight variations in the values, as shown in Fig. 14(a), even when there was no longitudinal wiper movement. This was due to lateral variation (along the wiper) in normal force point contact between wiper and track. Hence, it is desirable to have only a point contact between the wiper and track than a line contact. Such a design requirement calls for an insulation cover on top of the conductive wiper, as shown in Fig. 14(b), leaving only the wiper's tip to be exposed. This, in addition to the need for robustness, motivates direct printing of conductive and insulation layers on the flexible Kapton sheets.

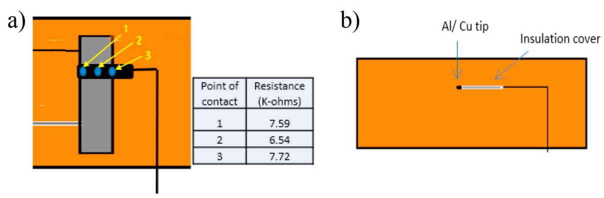

Fig. 14. (a) Variation in resistance across the width of the track; (b) Design for printing the wiper on top Kapton sheet.

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