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Technical Paper

Wearable shear and normal force sensing glove development for real-time feedback on assembly line processes☆

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ABSTRACT

This research aims to develop a force sensing glove worn by workers in manual assembly to measure both shear and normal forces and motion data to evaluate the connections completed and provide real-time feedback to the operator. Many tasks in production assembly are still completed manually due to the intuition needed, complex automation steps, or time constraints. This is largely seen in automotive assembly environments which also creates a greater possibility for error because they consist of predominately human completed operations. These processes include hose and electrical connections which can loosen over time after passing initial quality testing, resulting in costly, time-consuming rework and a diminished brand image. Operator forces and motion data are selected for measurement to ensure processes are completed with the correct approach and ample forces applied while also verifying that all necessary tasks within the takt are completed. Multiple forms of measurement will assist with adapting to operator variability while offering operator accountability and process verification. It was found that operator forces and motion could successfully be captured and analyzed through the developed sensor glove and that the glove offers a robust, durable format that is adequately equipped for use on the physically demanding assembly line.

1. Introduction

This research investigates human shear and normal force measurement through a wearable glove system for real-time feedback of assembly line connection quality. The research is a continuation of the work completed by Kerner *et al.* of a shear sensor development, but the sensor lacked robustness, repeatability, and durability [1]. The wearable system will be implemented in critical production operations that currently utilize a subjective push-pull-push test to determine the veracity of the connections. This verification testing may not indicate an incomplete connection if insufficient force is used or may be forgotten entirely. The investigated connections are ventilation and fuel lines located on the underbody of the vehicles.

Previous research utilized relative movement between a resistive track from a soft potentiometer and an aluminum wiper to measure voltage change under a shear load. The developed sensor could successfully capture the applied shear force under controlled conditions, but it rapidly deteriorated with each test creating more instability due to the aluminum wiper abrading the resistive track. The sensor was unfit for the harsh assembly environment of automotive production due to the geometry of the upper and lower Kapton layers required to achieve a significant relative movement [1].

The objective of this research aims to overcome the design challenges from the previous sensor by developing a new stacked sensor design that captures multiple force and motion signals for an increased confidence of a successful connection detection reducing rework and warranty claims. This includes the creation of a robust sensor application for non-intrusive human shear force measurement. The stacked sensor will augment the operators in their critical role as much of final assembly requires human involvement and dexterity to achieve a level of efficiency and complete complex processes. Manual assembly offers a flexible format that can use reasoning and logic, increasing the potential of what the assembly line worker can determine [2].

The wearable sensing system is developed for use on the assembly line. Therefore, the glove will undergo harsh conditions like fast-paced movements, activation when not measuring for confirmation, and multiple touch points which have the potential to cause damage. Sensor incorporation into the glove remained a vital component to the research

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to ensure that the operators were uninhibited in their movements and did not face discomfort over the course of their shift. This enables the capture of intuitive final assembly operations through sensor signal relationships which require complex movements that cannot yet be automated.

Discussed in the following sections are an overview of where human-integrated technologies are lacking for process confirmation through sensing and robust glove sensing solutions. Next, is a brief examination of human shear force sensing, which is broken down further previous work [1]. Following the background section is the experimental setup and fixture design for determining shear and normal force response. The sensor functional model is then discussed with the stacked sensor development. Then, testing of the stacked sensor glove in the lab and on the assembly line is reviewed with their respective results. Conclusions and future work follows.

2. Background

2.1. Wearable sensing for process confirmation

The topic of Industry 4.0 vs. 5.0 continues to draw varying perspectives and degrees of implementation in today's manufacturing world. An insightful perspective by Xu. *et al.* describes Industry 4.0 as technology-driven and Industry 5.0 as value-driven. Industry 4.0 seeks to develop intuitive technologies, whereas the value-driven initiative of Industry 5.0 utilizes available technologies for improvement [3].

To enable Industry 4.0 approaches, many researchers and companies are exploring the realm of increased sensing capabilities for process monitoring. This varies in application with integration options including sensors on the machine, human, or in the environment. The processes utilize the captured data to ensure the process is being completed correctly, perform predictive maintenance, and inspire a level of accountability through saved data [4]. The value of humans in the workplace has been reinforced in recent years as we near the level of autonomy in manufacturing currently feasible. Thus, humans in the workplace require augmentation to improve working conditions and efficiency [5].

Sensors incorporated onto the human have a growing popularity due to their ability to measure what was previously subjective due to the need for human intuition, the eased workload on the operator, provide critical information for preservation of the operator, and enable a human-machine symbiosis [6–8]. With the changing tides in manufacturing, humans are being recognized as a manufacturing capability that possess the intuitive and flexible nature that creates value over a robotic counterpart [9]. Research conducted by Schönig et al. creates a decentralized production environment that offers control and support to the workers through stored and acquired production data. This allows the workers to access user-specific information and subsidies as desired [10]. The data exchange platforms empowered through wearable process monitoring sensing can be captured through a wide array of devices such as gloves, smartwatches, prosthesis, and more detailed by Muzny et al. [7]. This collection can then be delivered in equally as many ways through most often visual, audible, and tactile feedback loops. Examples of these technologies include wearable scanners such as the ProGlove and Bosch iGlove [11,12]. Another technology is the GM-NASA produced force augmenting glove which amplifies operator gripping capabilities [13]; this is one of the few models that incorporate actuation augmentation together with sensing.

2.2. Force sensing gloves

Throughout manufacturing, humans play a critical role in final assembly, and often times they wear gloves for added protection, comfort, or utility. This offers a seamless opportunity to introduce process monitoring technologies directly on or in the glove that the associates already wear. A handful of products have been released targeting the market of force sensing gloves. Many rely on different operating principles than the glove proposed in this research. Most marketed solutions utilize pressure sensors to measure pressure distribution or activation forces where the glove presented in this paper offers shear and normal force measurement capabilities [14–17,18]. These solutions can provide valuable feedback in a research environment, but they are unfit for the wear and tear introduced by a production environment. This is due to their limited robustness in durability and constrained data processing circuit for general applications.

The Tactilus Technology glove from Sensor Products Inc. can display pressure profiles, but has many invasive sensor leads that interferes with natural human movement [18]. Pressure Profile Systems (PPS) and Novel.de offer full hand pressure measurements, with the addition of normal force measurements with PPS, but they are unfit for manufacturing production because of their high price tag and limited durability [15,17]. The Hoggan Scientific ergoPAK ergoGlove offers a more reasonable price, but only measures normal force and must be within 25 feet of the operating computer [16,19]. Research done by Hammond III et al. on a soft sensor embedded pressure system is minimally invasive and captures motion and tactile data, but is vulnerable to hazards in production (sharp corners, excessive forces) [14]. Research done by Yin et al. investigates what is needed to create a high performing wearable system that presents flexibility and stretchability to connect the user to machines in the environment [20].

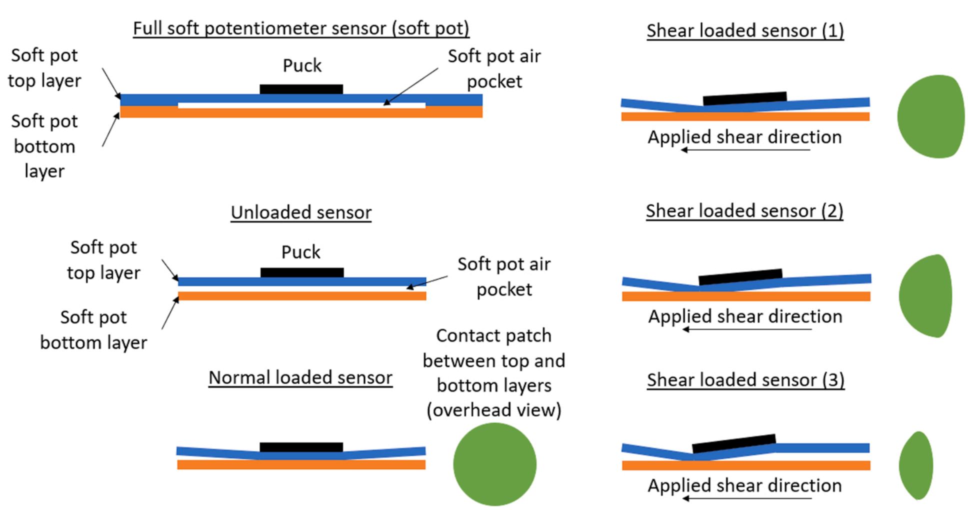

Fig. 1. Changing contact patch under combined normal and shear loading.

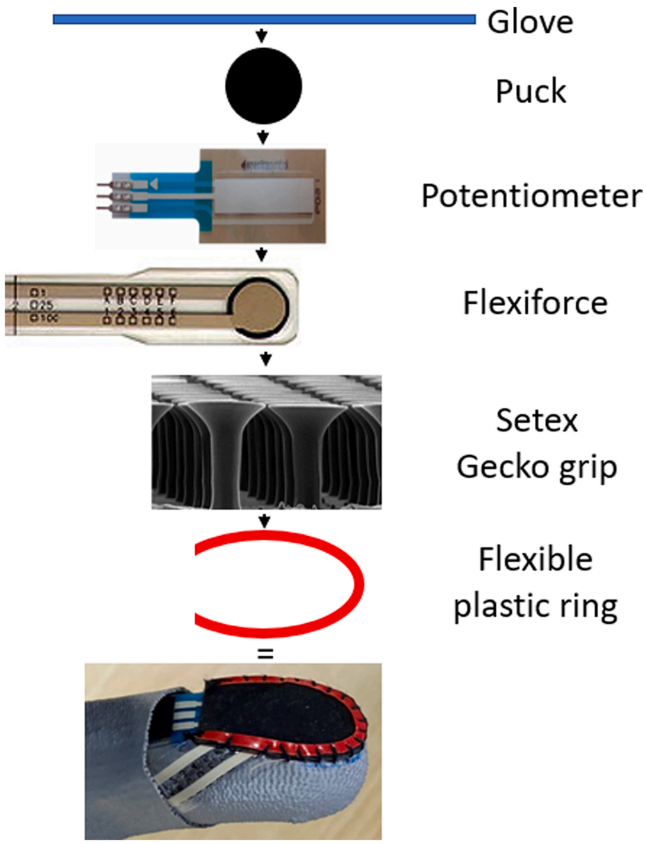

Fig. 2. Stacked sensor element layers and assembled product.

Other force sensing wearables have been proposed for an ergonomic evaluation to ensure the expenditures of workers does not exceed a safe range [21–24]. Weckenborg *at al.* performed an analysis of ergonomic developments aligned with economics in manufacturing. This study shows that recent research endeavors compromise the effectiveness of an assembly line as they improve ergonomic safety for workers [25]. This indicates a need for additional measures to increase quality aligned with safety on an assembly line. This opens opportunities for technologies that can assist with the progression to more automatable processes. Research such as the work completed by Oyekan *et al.* indicate the need for a combined wearable sensing approach with a real-time processing architecture. This will not only ensure workers operate in within ergonomic limits, but the information from the sensors can be leveraged towards automating the process by understanding operator approach and activation [23].

2.3. Human shear force sensing

Marketed solutions and conducted research on shear force sensing is rather limited. This becomes even more apparent when searching for shear force sensing solutions capable of measuring human outputs. Solutions that are presented are bulky, fragile, not flexible, have directional limitations, or have small measurement ranges [26–29,30]. Further exploration into the shear force measurement of humans is discussed in preliminary work for earlier renditions of the wearable sensing system discussed in this research [1].

3. Stacked sensor development

As stated before, earlier design iterations of the sensor utilized relative movement between two layers with an aluminum wiper and piezioresistive track to measure applied shear force [31]. The latest design uses a commercial linear soft potentiometer from Spectra Symbol (SP-L-0012–103–1%-RH) to capture the applied shear force. It operates similar to the old design with a changing contact patch moving along the length of the sensor, but forewent the wiping action with its enclosed design. The authors will refer to this as the shear sensor. The functional method for measuring shear force with the shear sensor operates as shown in Fig. 1. The applied normal force creates a contact patch between the two layers. As shear force is applied, the contact patch location and size vary, changing the resistivity of the sensor. The sensor output is dependent on the starting contact patch. Output under loading beyond the initial activation is repeatable but may yield different values due to the initial starting point on the resistive track.

One characteristic of the shear sensor is its ability to measure both shear and normal force. This created issues of trying to discern the signals to equate them to their shear and normal force components. To counteract this, a Flexiforce normal sensor (a201) was added in line with the shear sensor. This sensor, dubbed the normal force sensor by the authors, reacts only to applied normal force allowing us to filter out the shear component from the shear sensor. An observation from lab and assembly line testing showed that normal force activation varies during connection completion and tends to follow the push-pull-push veracity testing curve. This is due to the human grip naturally increasing as additional shear is applied to prevent slipping. The mutlimodal sensing will increase the confidence of the feedback to assembly line workers regarding the connection status.

To complete the stacked sensor, Geckogrip from Setex Technologies was affixed to the outer layer to protect the sensors and provide improved gripping capabilities under shear loading. The sensor layers and completed stacked sensor are shown in Fig. 2.

The stacked sensor affixed to the glove is shown in Fig. 3. A secondary finger-less glove is placed overtop the sensor glove to protect the sensor leads.

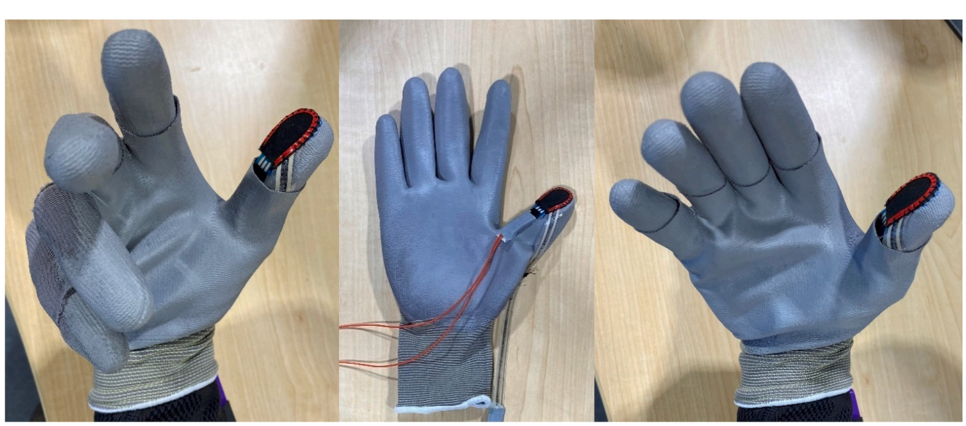

Fig. 3. Stacked sensor affixed to glove for testing.

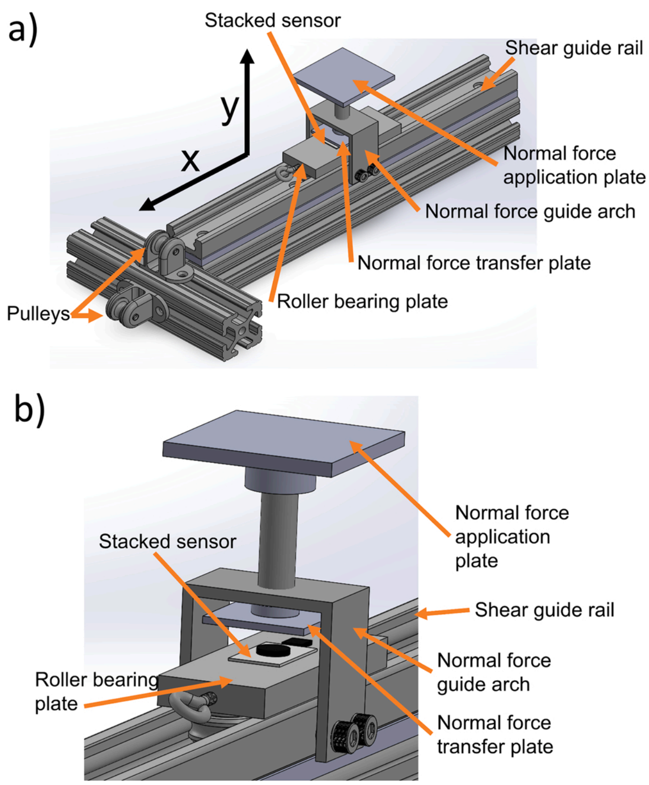

Fig. 4. Shear and normal force isolating fixture.

4. Methodology

4.1. Shear-normal fixture

To be coupled with a robust feedback method, we must first understand how the sensor system reacts under a combined shear and normal loading. This will help to develop best fit curves for production line prediction and calibration measures. The developed fixture isolates the applied forces to allow monitoring of the sensor signal responses. Normal force is applied via weights placed on a platform which is then transferred in the y-direction to a guided unthreaded bolt which sits on the puck of the stacked sensor. At the bottom of the unthreaded bolt is another plate that allows relative movement of the puck while still applying the full normal force. 300FN Kapton material is placed on the underside of the bottom plate and on top of the puck to mitigate error due to friction. The entire fixture is shown in Fig. 4 part a. The stacked sensor is affixed to a guided plate with roller bearings that moves in the x-direction. An eye-bolt connected to the plate holds the cable which runs over the pulleys to apply the shear loading. A closer look at the stacked sensor placement relative to the applied normal force is shown in Fig. 4 part b.

4.2. Experimental setup

The research consists of three experiment types; repeated normal loading (Normal LU), repeated shear loading (Shear LU), and incremental shear loading (Shear Inc). The repeated normal loading was a series of loading and unloading an applied varying normal force to the sensor. The repeated shear loading utilized a constant normal force with the loading and unloading of a varying shear loading. The incremental shear loading maintained a constant normal force and applied additional shear force without unloading of the previous force. This test was run until failure (i.e. the roller bearing slide overcomes normal force from applied shear and slips out from underneath normal loading).

All forces were exerted through weight which were equated into forces. Shear loading was applied in increments of 0.1 kg or 0.981 N. A breakdown of all 70 experiments are shown in Table 1. Each experiment was repeated 5 times.

Table 1
Shear and normal force fixture experiment breakdown.

Experiment	Applied Normal (N)	Applied Shear (N)
Normal LU	9.81	0
	11.77	0
	14.72	0
	16.68	0
	19.62	0
	21.58	0
	24.53	0
	26.49	0
	29.43	0
Shear LU	9.81	0–4.91
	14.72	0–5.89
	19.62	0–7.85
	24.53	0–7.85
Shear Inc	24.53	0–6.87

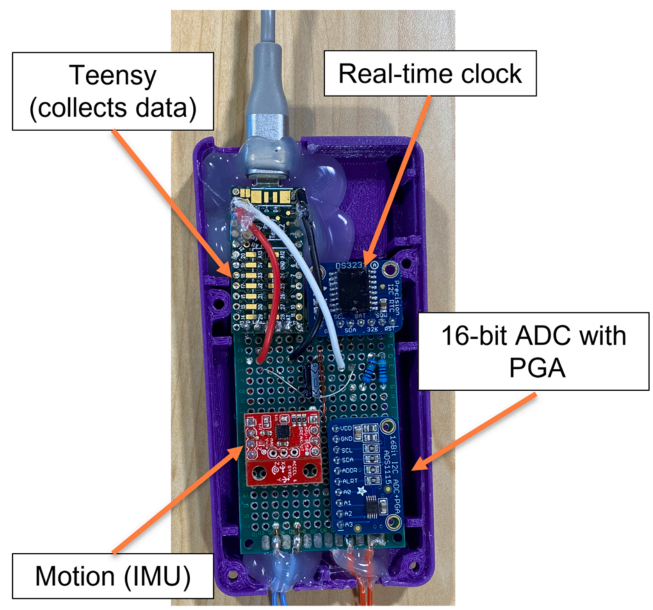

Fig. 5. Wrist module control unit for data collection and motion sensing.

4.3. Stacked sensor control unit

Due to the complexity of the approach, movements, and energy exhibited by each operator, simple force or motion targets do not provide sufficient information for determining connection status. Therefore, the sensor glove is paired with additional sensing capabilities. The control module is a circuit comprised of a Teensy 3.2 board, an accelerometer, a 16-bit ADC, and a Precision RTC. The Teensy board is how the system connects to an outside computer for data collection and saving. This is also where power is drawn to excite the other components in the control module. Data is fed from the shear and normal sensors to the analog inputs of the Teensy board.

The accelerometer provides both acceleration data in x, y, and z and gyroscopic data around those axes. This can be used as a reinforcement for determining when a connection is completed so the real-time feedback can be supplied to the associate. The ADC module was used to amplify the circuit to create a wider working range of both the shear and normal sensor. Without this element, the normal force sensor recorded a narrow range that did not capture the entirety of the connection.

The Precision RTC is a real-time clock that is used to record a timestamp with each data collection point so it can be matched with the data labeling system used on the iPad. The data labeling system was our method of indicating which type of connection was completed at which time. We later parsed through the data and added the respective label to each dataset. The control unit diagram is shown in Fig. 5.

Overall, the control module coupled with the sensor glove recorded voltage changes from the shear and normal force sensors, acceleration in *x*, *y*, and *z*, gyro readings in *x*, *y*, and *z*, and the date and time the measurement took place.

5. Sensor glove testing

5.1. Sensor glove lab testing

Lab captured data was completed by Clemson students. A representation of the assembly line was created in the lab to try and mimic movements, approaches, and grips of the BMW associates. Tests were completed on the insertion force fixture, created in previous research, by multiple students to create a diverse data set [1]. Tests were completed by mating the female end of the connector with the male end attached to the fixture. Initial testing was completed with this stacked sensor glove on the insertion force fixture so the signals from the two sensors could be compared to the expect Mark 10 load cell output.

Lab testing parameters: .

- Sample rate: 200 Hz
- Performed by 3 people
- Single connector pair repeated 30 + times for normal insertion (150 total)
- Single connector pair repeated 5 + time for push-pull-push (25 total)
- 3 connector types tested

5.2. Sensor glove assembly line testing

The line testing was conducted on the assembly line with a BMW associate wearing the sensor glove and corresponding wrist unit. The associate completed their tasks as they normally would, and the Clemson team captured signals while completing the investigated connections along with other processes for later comparison.

Successful connections were captured with the associate using the push-pull-push method across multiple vehicles, with the number of investigated connections per vehicle in the takt ranging from 2 to 3. This does not include the wear the sensor glove endures while completing tasks outside of the investigated connectors. The sensor glove has proven to continue to work after continued use on over 200 vehicles.

In addition to the successful connections measured on the assembly line, the team worked with BMW to inflict purposeful failure in the connections. This was done to capture signals indicating connections that require rework. This is used later for the classification algorithm.

Assembly line testing parameters: .

- Sample rate: 200 Hz
- Performed by 4 assembly line associates
- 264 successful connections captured
- 31 purposeful failure connections captured
- 3 connector types tested

6. Results and analysis

6.1. Functional modeling

Based on the behavior of the stacked sensor in the shear-normal fixture, we expect the stacked sensor in the glove format to follow a similar trend. This being both sensors responding under shear and normal forces exhibiting a linear response. The linearity in the sensor under separate normal and shear loading will create a more friendly

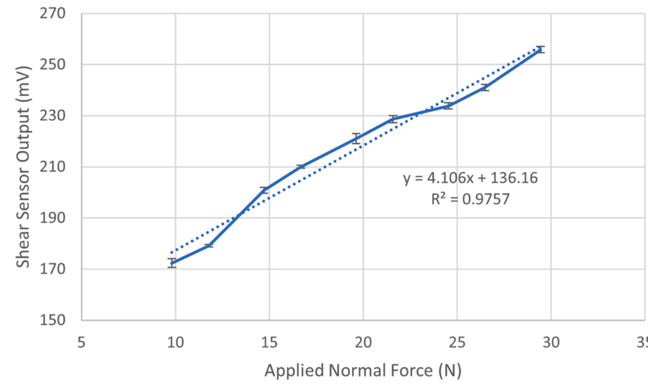

Fig. 6. Shear sensor sensor output under normal loading a) sensor response and b) sensor repeatability.

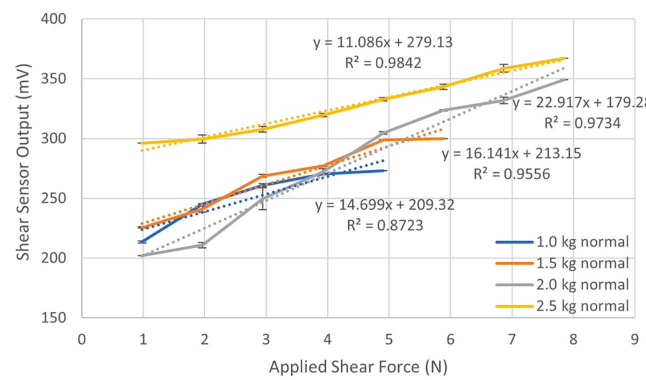

Fig. 7. Shear sensor sensor output under combined shear and normal loading.

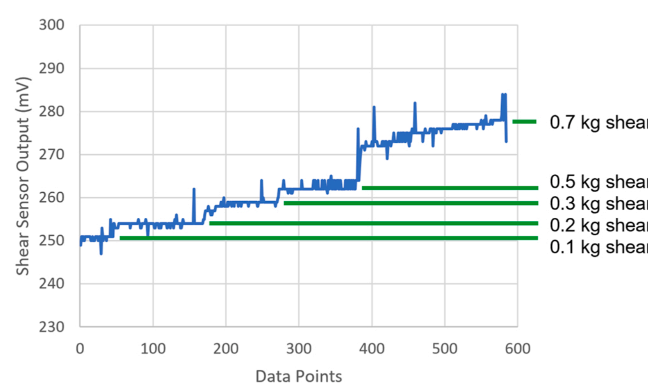

Fig. 8. Shear sensor sensor output under a constant normal load of 2.5 kg and an incremental shear load (Shear Inc).

sensor output for adapting to other processes and/or people. The normal force response in the shear sensor are detailed in Fig. 6 with error bars indicating repeatability.

The graph shown in Fig. 7 gives the sensor outputs of various shear loading under varying normal forces (Shear LU data). Each line indicates a different applied constant normal force. Each data point on the line marks a different experimental shear loading. When the shear force overcomes the applied normal force, causing the roller bearing plate to slip from underneath the normal force application plate, the testing is stopped. All loadings exhibit a relatively linear trend.

As you can see in the graph, the sensor outputs are not always higher with a greater shear force or combination of shear and normal. This is due to the nature of the resistive track in the shear sensor. The resistive track bottom layer makes contact with the silver trace (approximately

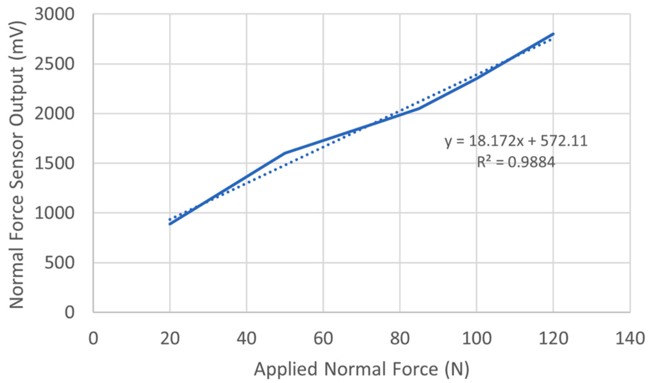

Fig. 9. Normal force sensor linear signal output curve.

zero resistivity) top layer. As the contact patch moves along the track, the resistance, and therefore output voltage, changes. As a result, the force profiles exhibited, which are detailed later in the results section, become the critical component rather than a force target or threshold alone to determine the quality of connections completed on the assembly line. Once activated, the sensor shows an increase in voltage output as shear force is increased as shown in Fig. 8. The green lines indicate the steady-state point of each step in the incremental loading. The additional motion and acceleration sensors will also help to determine the operator approach increasing the confidence of feedback provided to the operator.

The other sensor in the stacked sensor system is the normal force sensor, and the manufacturer claims a linear response under normal loading. This was verified as shown in the sensor output graph of Fig. 9.

6.2. Lab and line testing

After the stacked sensor behavior was determined, the sensor was affixed to the glove with the additional layers and paired with the wrist module control unit. Glove testing began in the lab on an insertion force fixture. In this fixture, the male end of the connector is fixed on a rail system against a load cell which can in turn yield the applied shear force for comparison to the sensor glove output. Additional information on the insertion force fixture is found in previous research [1].

Since the current confirmation method used on the assembly line is a push-pull-push mechanism, the lab testing was broken down as such. Lab testing began with the initial push which we refer to as "normal insertion". A normal insertion indicates that the initial push to complete the connection was made without the subsequent pull-push verification testing. This yields sensor output thresholds for completing each respective connector type. An output from the initial push testing was plotted against the load cell output as shown in Fig. 10. The plot uses load cell output on the abscissa and the shear and normal force sensor outputs on the ordinate axes. This reinforces the previous learning of the linear signals produced by each sensor in the sensor glove. The lower R^2 value for the shear sensor is acceptable because of the variability in the sensor output caused by starting point as discussed in the Stacked Sensor Development section.

Once the thresholds were recorded, testing moved to the full push-pull-push. An example of a push-pull-push type test completed in the lab is shown in part a of Fig. 11. The shear and normal force sensor outputs are again compared to the load cell output. The sensor signals exhibit inflection points for the change in direction of the applied shear force. The inflection point for the initial push to the verification pull-push is highlighted by the green line in the figure. The observed profile including inflection will be utilized in future efforts in the classification algorithm to ensure the entire process is completed by the operator. Testing completed on the assembly line exhibited similar results to the lab testing with additional noise from sensor activation outside of the observed processes. This included other work within the takt and work outside of the takt such as the associate taking a drink of water. For now, the data were manually segmented around the investigated connectors. An example assembly line connection completion is shown in part b of Fig. 11. The initial line testing results yield sufficient information for later evaluation of connection quality.

7. Conclusions

The following conclusions summarize the effects discovered herein: .

- The stacked sensor system is able to capture both shear and normal forces, in excess of 100 N combined loading, from final assembly operators for process verification.
- The shear sensor exhibits a linear response under individual shear and normal loading (average $R^2 = 0.946$ under combined loading).
- Connections completed on the assembly line can be captured and isolated from other items in or outside the takt.
- The sensor system is capable of a repeatable output under various combined loading.
- The sensor glove system offers a robust and durable solution for quality monitoring in a harsh assembly line environment

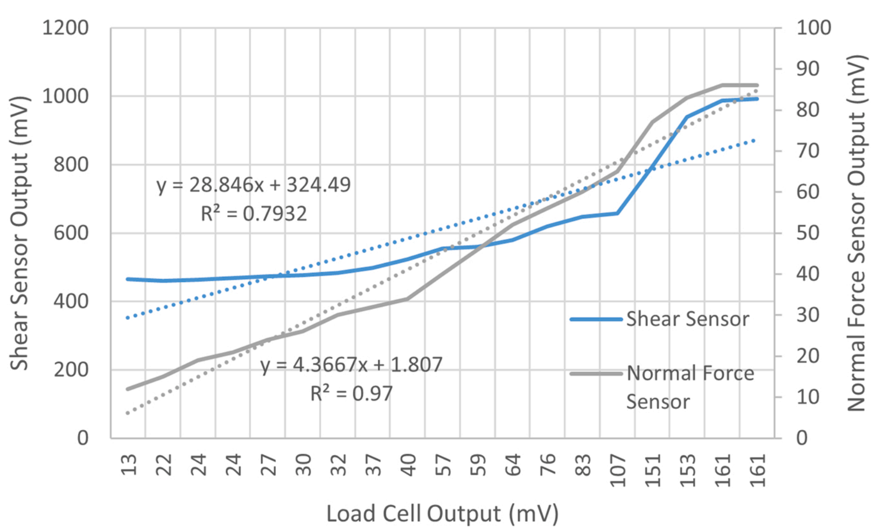

Fig. 10. Lab shear and normal force sensor responses against load cell to show linearity in signals.

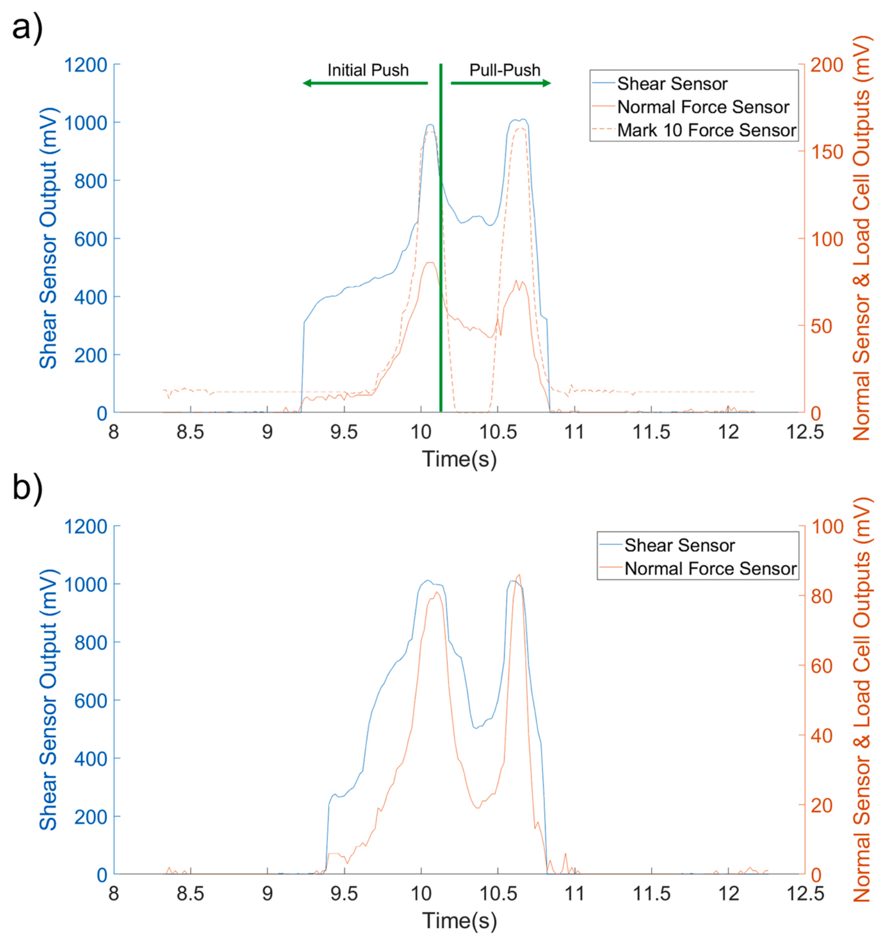

Fig. 11. a) Lab push-pull-push testing sensor outputs against the load cell output b) Assembly line testing sensor outputs.

(maintained functionality for over 200 vehicles of measured processes and additional uncaptured work).

8. Future work

Future directions for the continued progress of the wearable sensing system will focus on algorithm development to automatically segment the data around the connection point and successfully classify connection status. Coupled with this are hardware and circuit improvements which include an internal power supply, an investigation of incorporating additional sensors (such as sound), sensor output noise mitigation, and operator feedback methods. The research team will also run extended line trials with the operators wearing the sensor glove, completing their work as they normally would. This will feed into the classification algorithm to create a larger learning database.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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