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ScienceDirect

Procedia Manufacturing 00 (2019) 000–000

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

47th SME North American Manufacturing Research Conference, NAMRC 47, Pennsylvania, USA

Measuring finger engagement during manual assembly operations in automotive assembly

Rishabh Mulesh Vedant, Matthew Krugh*, Laine Mears*

Clemson University International Center for Automotive Research, Greenville, SC, USA

* Corresponding author. Tel.: +1-864-283-7229. *E-mail address:* mkrugh@clemson.edu; mears@clemson.edu

Abstract

Electrical connection defects represent a significant percentage of the defects caused during the automotive assembly process. These defects are usually discovered during the inspection stages of the vehicle. To rework such defects, much time is spent uninstalling and reinstalling components such as instrument panels and carpeting as the connections are covered over during subsequent assembly processes. Human detection of these defects has proven insufficient. This work focuses on finger engagement during manual assembly processes to assist future smart wearable systems in determining human-process interaction state during manual assembly processes. Thus, points of interest are which individual fingers engage with the connector, force exerted, and how it differs among personnel. Pressure sensors were created using a piezoresistive fabric and layered with conductive material to produce a flexible pressure sensor. The piezoresistive fabric changes its resistivity as it is deformed or stretched, and which was calibrated to obtain force values. By utilizing a flexible fabric material, the assembly process was minimally interrupted by limiting interference of a user's tactile feel. A prototype glove pair was developed for testing purposes with sensor placement at each of the five fingertips. Testing was conducted by performing four electrical connections using connectors of a variety of connector sizes.

Keywords: Cyber-human systems; Manual assembly; Assembly assistance; Wearable;

1. Introduction

Electrical connection operations are an important part of the automotive assembly process and is a predominantly manual process. Looking at overall assembly defects, Vineyard and Meredith [1], detailed that roughly 40% of the total defects in manufacturing plants are caused by humans. Rework of these defects can consume significant time when the defects are not caught until a quality gate station and corrected after final assembly during rework. This is due to subsequent assembly processes covering the electrical connections such as trim pieces, seats, and carpet which have to be removed to access which may damage the removed parts. It can be seen that a move to real-time detection and feedback notification structure could have an impact on the final assembly quality if the defect is found and corrected prior to leaving the assembly cell where it was created.

This work is a part of an overall larger work building on human activity recognition which is evaluating human-process interaction recognition using wearable sensors and feedback systems. As with human activity recognition, multiple sensors are being used to provide a higher confidence in the predicted activity. This work focuses on measuring finger interaction while an assembly operation is carried out to provide an understanding of finger engagement during the varied and complex manual assembly process. It can be shown that the fingers used to hold a nut-runner and the fingers used to connect a small electrical connector have different engagement profiles, which fingers are in contact with the workpiece, and understanding this difference in assembly process activities helps to provide a better understanding of which process is being completed.

The measurement of forces during manual assembly tasks required the creation of a reliable force sensing device that fits onto the fingers of the assembly associate. The sensors were attached over a standard nitrile dipped work glove which was used in a local manufacturing plant. The design of the sensors needed to be slim and flexible enough to not cause discomfort in the wearer in addition to allowing for a good tactile feel to carry out dexterous tasks especially with small parts such as small electrical connectors. Thus, a force sensor made up of piezoresistive fabric with conductive fabric electrodes was selected as ideal for the task at hand. As a reliable joining method that could hold the various fabric layers together and adhere to the glove with a strong bond, a heat activated fabric adhesive was selected and utilized to join the various layers of fabric together. Finally, a signal conditioning and amplification circuit for the individual sensors was created to measure the resistance change from the sensors. As the requirements of the application did not require a very precise force measurement force, the overall calibration and repeatability was able to be wider than for force measurement gloves from past literature that sought to measure forces for ergonomic evaluations. Finally, sensor gloves were manufactured, and tests were conducted with human subjects wearing the glove and carrying out electrical connections over a range of connectors.

2. Background

Previous work in sensing human grip strength and object interaction forces exists, such as Koiva *et al*. [2] who designed and tested a machine that could measure forces generated by fingers. Their tests found that average forces exerted by fingers were in the range of 13-16 N and the average thumb forces were around 20 N in value. Lee and Jung [3], [4] studied different tasks like assembling, painting, labeling, fastening, and welding that occurred over a variety of industries by filming worker's hand postures and object properties. They discovered that workers prefer to use a grasp posture (palm is also in contact with object to be picked) when it comes to holding cylindrical pieces while the pick posture (palm not in contact with object) is used for rectangular or sheet type pieces. In an additional work, they defined different types of grasping actions based on the use of different fingers and the palm. They determined that the grasping posture used by the hand depends heavily on the shape, size and orientation of the part to be picked. The primary goals of existing literature are to either measure hand forces or hand posture for ergonomic analysis.

Literature in measuring human grip forces has largely utilized either a MEMS force sensor or piezoresistive fabric/elastomers to measure the forces in situ. Tognetti *et al.* [5] developed a sensor glove that could track hand movements by using conductive elastomer layered onto a work glove. The conductive elastomer shows piezoresistive properties and so can be used similar in method to strain sensors and were placed on the back of the hand. Their objective was to track movements or postures in the hand, not necessarily forces exerted. Sato *et al.* [6] created and tested a sensor glove for measuring hand grip forces. The sensor was made by sewing electrode wire into pressure sensitive conductive rubber and attaching to a leather glove to determine grip force distribution as well as hand position. Wang *et al.* [7] created a sensor with carbon nanotube filled silicon-rubber composite as a piezoresistive material with fringe electrode. This enabled the electrode to not cover the actual sensing area and thereby reducing the overall thickness required. Their experiments found that the electrode could be placed up to 8 mm away from the actual sensing area. Sagisaka *et al.* [8] used flexible printed circuit boards as force sensing elements for the hand. They developed a tactile sensor module that could be designed in the form of thin branched modules. The goal was to ensure mobility of the hand while operating the sensor around joints and skin wrinkles. The glove's inner layer was a sprayed silicone elastomer and outer layer was polyurethane. There were approximately 1000 taxels, individual sensor points in the overall sensor matrix, per hand. There was also work into sensing hand forces using Force Sensing Resistors (FSRs) such as Nikonovas *et al.* [9] who designed and manufactured a force sensing glove which used FSR's attached to a glove. The design was validated by testing a hand swinging a golf club and then comparing it to data collected by the traditional method of putting the sensors on to the object to be gripped (golf club handle). Lee *et al*. [10] developed an FSR glove that could be used for measuring grip forces exerted by the human hand on cylindrical handles varying from 50-75 mm diameter. It was observed that the grip forces for holding a larger diameter part were more than that of a smaller diameter part even though their weights were the same. Conversely, Kalra *et al.* [11] used MEMS force sensors on grip handles in their study. Their research was targeted at understanding the hand-handle interface forces during the operation of a power tool. This research was conducted to test the feasibility of low-cost MEMS sensors in grip force measurement on a vibrating power tool. They concluded that the sensors applied symmetrically around the central axis gave good estimates f forces and that handle vibration had negligible effect on the output sensitivity. Harris [12] designed a force sensor grid by using 2 layers of piezoresistive fabric with conductive thread stitching in a cross pattern such that the intersection of the threads stitched to different layers marks the grid lines.

Similar to FSR, piezoresistive fabric has previously been used to measure hand force such as Atalay *et al.* [13] which created capacitive force sensors that use fabric electrodes with a silicone elastomer as dielectric. These materials are first manufactured as a sheet and then the sheet can be cut into the required shape. Another advantage is that sensors cut from the same piece will have consistent baseline capacitance values. Day *et al.* [14] developed a tactile sensor grid using piezoresistive fabric material as well as fabric electrodes. The design of the array had two pieces of spandex with conductive fabric strips glued on one side using iron-on adhesive. The orientation of strips of the two pieces is perpendicular to each other. The piezoresistive fabric is then inserted in between to complete the sensor. The work was part of efforts to create soft robots with tactile sensing skin. Büscher *et al.* [15] developed a force sensing glove using Eeonyx fabric as piezoresistive material, conductive fabric as electrodes and a spacer mesh to increase the idle resistance. The conductive fabric was etched (conductive material removed) along certain locations to create multiple taxels or tactile pixels. A total of

54 taxels were made on the glove spanning each finger as well as the palm. The taxel matrix was then sewn onto a glove. A thin rubber coating was applied to the glove to protect it as well as provided better tactile feel to the wearer. Thickness of sensor was approximately 1.5 mm. The sensor was used to study how humans perform tasks like grasping and manipulation with the aim to use the understanding to create a skin-like layer for a robotic hand and explore using it as a gaming interface.

Much of the previous works surveyed were for ergonomic or robotics research in measuring grip strength or hand posture. This work intends to build upon the work of previous researchers and extend finger force sensing to human process-interaction recognition by measuring finger engagement during manual assembly tasks with automotive electrical connections being the example in this work.

3. Methodology

For human force sensing, the predominant methods of force measurement can be divided into two categories; MEMS force sensors and piezoresistive fabrics/elastomers. Much literature and commercial systems use either of these two methods. The MEMS sensors were not selected for the final design due to their high thickness which would impede the manual assembly process. Also, the tactile feel of the sensors, whether it be while contacting the fingers inside of the glove or attached to the outer layer of the glove was poor due to the thickness, hardness, and limited flexibility of the MEMs sensor materials. This loss of dexterity is not desirable for the operator of the product during interaction with small and complex assembly components. Touch sensitivity is especially needed in operations where the associate has to reach into a recess or a low visibility area of the vehicle to make a connection. The associate will usually identify the correct connection or module by sense of touch alone. Thus, the piezoresistive fabric was a better choice for a force sensor. The research by Büscher *et al.* [15] was an influencing reference for this work as it used a sensor construction to meet similar requirements in this work. Their research objective and scope of intended data output differed from this work which naturally caused divergence in the final sensing system developed.

Two piezoresistive materials were evaluated based on historical use in literature and what was commercially available and included Velostat, manufactured by Desco Industries and Eeontex piezoresistive fabric by Eeonyx. Velostat is a polyolefin material impregnated with carbon black with a surface resistivity of approximately 31 kohm/sq. cm. Eeontex is a nylon-spandex blend material (72%-28% respectively) with an applied conductive coating. The Eeontex fabric was found to have better resistance range for our application.

A number of different sensor designs were tested with some based on those used in literature. The use and shape of spacers, conductive thread, conductive fabrics and the number of configurations that could be achieved were varied. The sandwich type design with a layer of piezoresistive material between two layers of conductive fabric material was found to provide the most stability in the output signal. The resulting configuration was similar to the design used by Büscher *et al.* [15] but with a reduced number of taxels.

There were three choices to be considered for the electrodes of the system. Conductive thread was rejected as it tended to have varying contact with the fabric as it was stretched and flexed resulting in poor contact and a physical seam that could interfere with tactile feel. Knitted conductive fabric was rejected as it was comparatively thicker than woven fabric but delivered performance quite similar to the thinner woven fabric. Woven conductive fabric was selected for our application as it fulfilled the required conductivity and space consumption needs while also providing a smooth transition from sensor area to non-sensed area improving any noticeable tactile interference from the sensed area.

Joining of the three layers of the sensor was realized using heat activated fabric adhesive. The adhesive is semi-transparent and adds negligible thickness and stiffness to the sensor. It was only applied along the borders to limit interference in the sensing area. Testing a sample sensor manufactured with heat activated adhesive bonding displayed a bond with the required strength and without considerable changes to the piezoresistive properties in the fabrics. It was tested by wearing and making basic hand movements like stretching of fingers and making a fist while measuring the resistivity of the sensor. Epoxy adhesive was trialed but found to seep into the fabric and cause a significant drop in electrical performance of the sensor. Stitching using conductive thread was also found to be not appropriate as the electrodes could contact each other at the stitches thus shorting the circuit.

A size large nitrile coated glove was used as a reference to set the dimensions for the fingertip sensors. The piezoresistive Eeontex layer was deliberately sized larger than the electrode layers to minimize chances of shorting between the conductive fabric layers. To keep the glove as ergonomic as possible, 5mm wide extensions were designed in the electrodes for connecting wires which extended to the palm of the hand. Since the sensor leads are very thin (0.08 mm thickness) and flexible, this reduces interference while performing assembly activities.

The different layers of fabric were cut by CNC laser. This assisted in producing precise and repeatable components and was especially needed for the Eeontex fabric due to the flexibility of the material making it difficult to cut by hand.

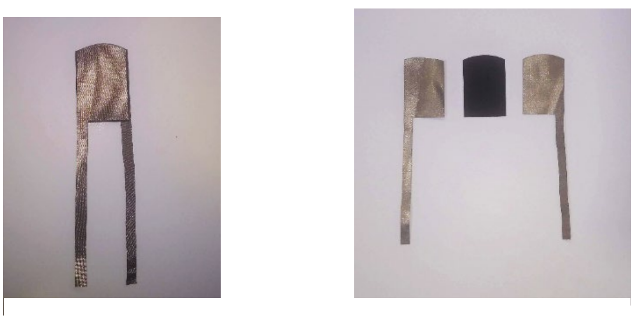

Figure 1. Assembled sensor (left) and layers (right)

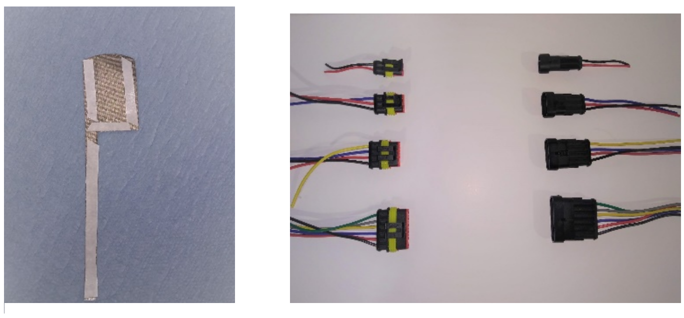

Figure 2. Conductive layer with adhesive (left) and electrical connectors used for testing (right)

4. Testing

To test the force sensing glove a series of electrical connector assemblies was completed with the user assembling four sizes of electrical connectors, characterized in this work by the number of pins; 2-pin, 3-pin, 4-pin and 6-pin with five replications per connector size per user. The male-female connectors chosen for the test were characteristic representatives and were therefore not attached to additional cabling or modules. The sensors were connected to an amplification circuit and a data acquisition unit with a sample rate of 250Hz. A video camera was setup above the test area as a verification for the sensor signals.

The connectors used were single row connectors having a single latch closure with pins, wires, and weather resistance layer to closely resemble common types of automotive connectors. During the testing process, users were given a pair of the instrumented gloves and sat at a table with the connectors presented in front of them. A real-world assembly scenario may also involve ergonomically challenging positions and/or reaching into small spaces to make the connections which will be included in future work as it may alter how the user makes the connection.

5. Results

Figure 3 below shows a normalized output obtained during testing. Each output was normalised from 0-100 with 0 being no voltage and 100 maximum output voltage measured during the test due to inherent differences in the base voltage of each sensor. To determine that a finger was engaged in the activity, the peak and average value of the sensor of the signal should be higher than 20% of the maximum possible signal. The video recording of each test was used to confirm

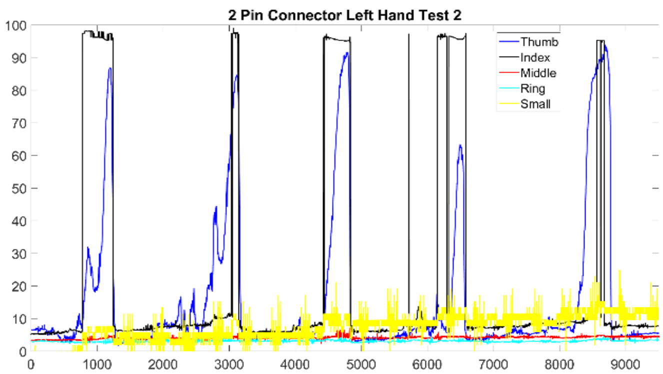

Figure 5. Left hand sensor output

engagement.

An instance where the video recording was very useful was when the data showed the index finger not being engaged in some replications. It was discovered that users would occasionally use the side surface of the index finger to hold and press the connector. This part of the finger was not covered by the force sensor and so did not show any output. Future work will include changing the size and shape of the sensor to measure the actively engaged area during manual assembly processes. From the finger engagement plots, it can

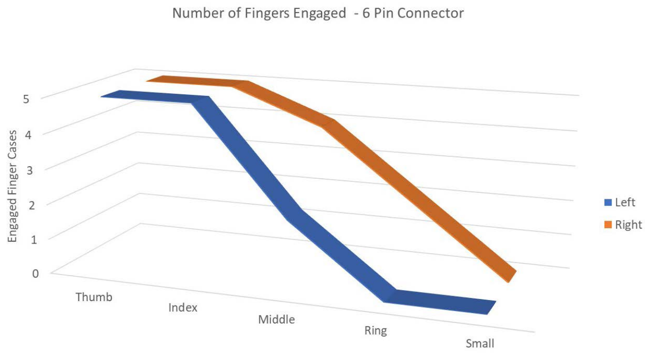

Figure 3. 6-Pin finger engagement by finger

be seen that generally there is an increase in the number of engaged fingers with increase in the size of connector.

Figures 5 and 6 plot the average finger engagement across all subjects and demonstrates the predicted trend of Index finger and Thumb used in all connections tested with subsequent fingers becoming engaged as the connection size increased. It can also be noted that the subsequent fingers of the user's dominant hand became engaged earlier than the subsequent fingers on the non-dominant hand. This can be

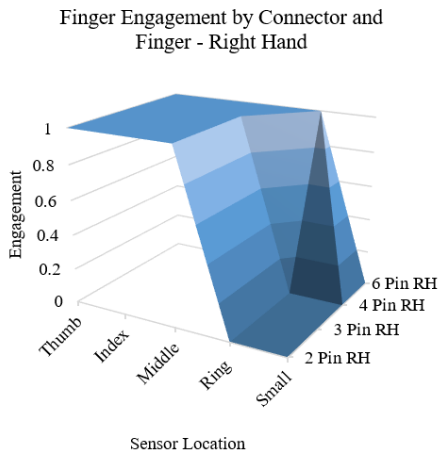

Figure 4. Right hand finger engagement by connector and finger

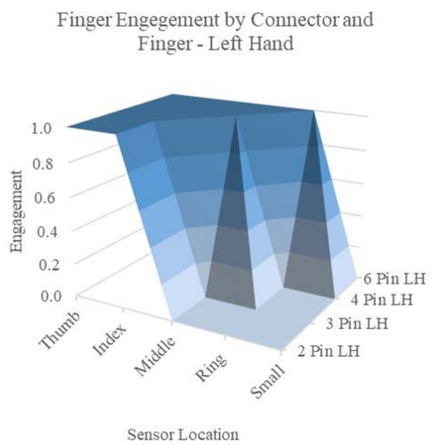

Figure 6. Left hand finger engagement by connector and finger

seen in the finger engagement plots with every user included being a right-hand dominant individual. Future testing will be needed to determine if this relationship switches for left hand dominant individuals as it would affect efforts to create a learning model for the overall goal of human-process interaction recognition. There was minimal involvement of the ring finger during the testing with the finger being engaged only in the 6-pin connector right hand case. It was also noted that there were some instances of false triggering from the ring and small fingers due to the user pressing onto the adjacent finger*,* but the video recording was used to verify that the finger was not actively used, and the signal was rejected. The small finger sensor also displayed some creep during its use which boosted its ratings at the tail end of the test but was ignored as the test video did not display any evidence of engagement.

6. Conclusions

Automotive electrical connections typically provide an aural feedback in the form of a click when the connection has been made successfully. However, on the assembly floor due to loud noises in the background and differences in assembly associates hearing ability, an incomplete click and mishearing of the click are possible causes for defects to occur. These events can create situations in which the operator assumes that they heard a correct engagement feedback which may not have been the case. Thus, looking at the engagement of fingers and especially fingertips will provide a better understanding of the process and in designing a better multi-sensor user feedback device.

This work sought to test a sensor system provide more understanding on automotive assembly associate finger engagement interaction during a manual electrical connector assembly task. From the presented results, it can be seen that as expected, the index finger and thumb were seen to be used very consistently. The middle finger was activated in smaller connectors for the right hand than the left hand which was the non-dominant hand of the users. In a number of instances, it was found from the video that the side surface of the fingertip was used instead of the center. This led to missed finger interactions. There was variation in the peak and average sensor output, but this was not a major complication as the goal of this work was to study finger activation rather than calibrated force levels.

Future work will expand on the sensed area and incorporate the sides of the fingertips to prevent missed engagement and a more effective connection between the sensor and DAQ is required to make a more robust sensor connection that could be used away from a stationary table. A mix of novice and experienced assembly associates is planned to be tested to look at the variation in finger engagement and timing during manual assembly tasks.

Continued testing in expanding the number and types of connections will provide a library of signatures that can be drawn from to better understand the finger engagement of varied automotive assembly tasks and in conjunction with other sensors be used to model a human-process interaction recognition and feedback system to assist users on the factory floor.

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