Design and Performance of a Haptic Data Acquisition Glove

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Abstract

The design and adaptation of a haptic data glove based on the Tekscan grip sensor 4255N is introduced in this paper with detailed discussion on sensor selection, implementation, and calibration issues. The gloves are used in experiments to measure human to human haptic interaction. Data analysis methods and initial results are illustrated. Evaluation results show that the pressure sensor based glove can provide force estimations for applications where force measurement accuracy is not strictly required. The glove is also capable of measuring high spatial resolution force distribution at a fast sampling rate.

1. Introduction

Haptic stimuli are perceived by human beings via various internal sensors. In the prospective of sensory channels, haptic perception can be divided into tactile perception and kinesthetic perception, corresponding to cutaneous sense and kinesthetic convey, respectively [14].

Human hands consist of a much more sophisticated haptic sensor structure than any devices the latest sensing technology can provide. The sensing devices developed so far are only capable of measuring a subset of the haptic information perceived by a person, and only with compromised resolution or dynamic range [2].

This paper reports the work of building a haptic sensing glove to measure the force distribution of the human hand. The glove is intended to provide a localized force map between the hand and the object of the environment. The glove is then used to measure interchanged force in human to human handshakes. Evaluation results show that the device can provide a high resolution (320 sensor cells, 6.25 cells per sq-cm), wide dynamic range (up to 200 Kilopascal on each sensor cell) force distribution at a high update rate (up to 120 measurements per second). The sensors have flexible mounting positions for specific applications.

A short overview of the up-to-date tactile sensing technology is given in the Chapter 2, followed by the design and implementation of the gloves in Chapter 3. The handshake experiments, the data processing and the evaluation of the glove are discussed in Chapter 4, followed by the conclusions and future work in Chapter 5.

2. A brief overview of tactile sensing technology

2.1. Tactile sensing device

The sense of touch consists of cutaneous (tactile) perception and kinesthetic sense. The former is received by the receptors in the skin and the tissue underneath, about the stimulation on the surface of the human body; while the latter by the rest parts of the body about the static and dynamic gestures. Haptic perception is the combination of the two senses which includes the most cases of perception we encounter in our daily lives [14].

In presence research, in order to enable a participant to realistically explore and interact with the haptic enhanced virtual environment, it is critical for the engineers who are building the environment to have the information of what is the correct amount of haptic stimuli to apply to the participant. A realistic feeling in comparison with the physical world can then be perceived. Therefore, study on the human behaviour in a haptic prospective is necessary.

Developing devices to measure such quantities is a research line of nearly half a century, matching well with the findings in psychology and physiology. Researchers approach the goal from two distinctive directions: the kinesthetic information is acquired mainly from the joint of the device that the participant holds on to, while tactile information from the measuring mechanisms mounted on the contact surface. A detailed review can be found in [6].

2.2. Pressure sensing technology

Here only the contact pressure between two solid objects is considered. The physical basis of electrically measuring pressure is the piezoelectric feature of certain materials. The electrical feature such as capacity or resistance of the material in contact varies with the exerted pressure under certain rules. Using a read-out circuit, this variation can be transformed into a varying voltage or current signal, and thus sampled into digital computer compatible forms. Since the discovery of the piezoresistivity of semiconductors in the 1950s, a variety of semiconductor-based pressure sensors have been produced meeting the requirements of specific tasks [4, 9, 15]. Recently as the developing of the integrated circuit industry, micro-machined pressure sensors have been developed. Integrated onto a printed circuit board (PCB), the new pressure sensor has marginally higher density. Multi-direction measurements are now possible as well as the distribution of force across the contact area [1, 12].

Another trend of pressure sensing is the flexible pressure sensitive material. It is used to provide an indicator of contact, rather than in accurate measuring devices, in research areas such as manufacturing, human machine interface, and robotics. The material can be shaped into various forms from thin lines to large surfaces to cover the area of concern, so that the output of the measure circuit changes when the area is applied with a detectable pressure. The simple setup and low cost make it possible to cover a large area with such devices. Robots with sensitive skin knowing which part they are being touched have already been developed [5, 7, 18].

2.3. Force sensing technology

Similarly to pressure sensing, force sensors are also based on the piezoelectric materials mentioned above. However, since the piezoelectric material is sensitive to the pressure applied to its surface, well controlled contact area becomes the key factor in force measurement.

One common approach is to build a pressure sensor into a mechanism such that the force to be measured is applied to a button higher than the base and hence transmitted to the sensing surface by the button with a fixed area. The pressure measurement can then be multiplied with this fixed area and results in the force applied. This is the basic idea of a one dimensional load cell [16]. By controlling the contact area, a pressure sensor can be used to give force estimations [2]. For multi-direction load cells, the force along each axis is measured by the differential signal from one set of piezoelectric materials. One load cell consisting of several sets is capable of measuring multi-axis forces both translational and rotational. An example can be found in [21].

Another approach is by ensuring the sensing area larger than the contact area, so that the pressure can be read out from the pressure sensor while measuring the contact area by other methods such as a video camera. The force can be calculated from the two measurements afterwards. Some new approaches even estimate force directly from video image with a pre-trained decision model [17].

A critical point of pressure and force sensing of solid contact is that the sensor should have minimum effects to the original shape and deformation features of the surface; otherwise the measured contact is different from the original. Moreover, for pressure sensing, the sensitive area should be smaller than the contact area, so that the sensor gets fully engaged and gathers the most possible information from the contact. However, for force sensing, it is important that the contact area is not larger than the sensitive area, so that no force is distributed outside of the sensitive region and thus can not be detected by the sensor. Therefore the pressure sensors suffer from modest accuracy when used as force sensors, since the location of pressing yields a significant difference in the results. Load cells see much better performances in this aspect, but the housing makes them impossible for wearable devices which are getting more and more popular in presence related researches. However, as the increasing of sensor density, the sensor size is getting much smaller than the contact area so the force can be estimated at a better accuracy by the summation of the force values on each sensor cell [20].

3. Glove design and implementation

3.1. Preliminary work

3.1.1. Technical requirements. The gloves are used in measuring haptic information of human-environment interaction. The design guideline is to provide reliable, accurate measurements in a high frame rate while not affecting the process being measured. Therefore the evaluation criteria are as follows:

- Robust construction, invariant to temperature, good linearity and low hysteresis, good repeatability;
- High dynamic range, high sensor spatial resolution, provides force distributions of the whole hand;
- Low sensor response time, high system update rate;
- Flexible and wearable design.

The NASA/DARPA Robonaut hand employs the QTC [15] pressure sensor after trying the FSR approach [3]. The FSR glove gives indications of contact while the QTC providing force value when plastic beats are used as force concentrators.

Similarly for the tailored sensing skin from the 90’s [9, 10], the contact area needs to be defined when force values are concerned. For the multi-direction tactile sensor developed recently [1, 12], the dynamic range is yet to be improved until they can be implemented in grip force measurement.

In [2] a very similar glove was built using force sensing resistor (FSR) and evaluated with results similar to the above criteria. The FSR sensor is therefore taken as a starting point.

3.1.2. The FSR prototype. A typical single FSR sensor consists of a polymer film sensing area varying in size and a flat extended cable for the signal read out, as shown in Figure 1. A prototype of the pressure sensing glove is made using 4 FSR sensors with 0.5inch (12.7mm) diameter from Interlink [8] as shown in Figure 1.

In [2] the FSR sensors at the fingertips were covered with metal plates to control the contact area. However, here the mounting of metal plates makes the fingertip no longer flexible and thus reduce the realistic feeling of haptic exploration. Moreover, in a pretest of using metal plates in contact area control, it is observed that due to the elasticity of the FSR sensor, the applied force is not evenly distributed throughout the sensor surface even when a metal plate is placed on top of the sensor. The test results tally with the sensor specification that unevenly distributed pressure results in inaccurate measurement. For the same force applied to the center and the edge of the plate which is placed within the sensitive region of one sensor, up to 80% measurement drops are observed.

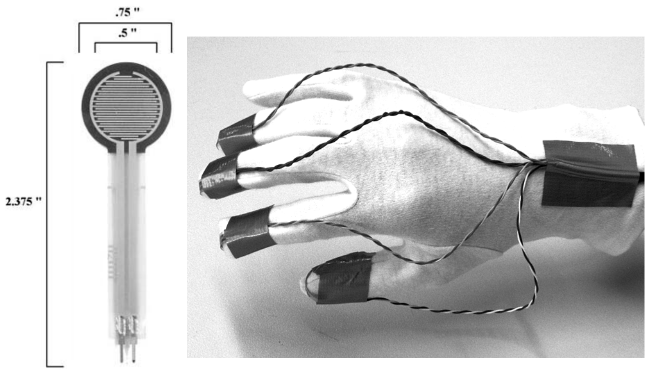

Figure 1 Left: Interlink FSR sensor, right: FSR glove prototype.

Another issue is sensor bending. When the sensor is mounted onto a deformable base such as a glove, the sensing area may be bended even without an intended external force applied. In this case, a non-zero output different from sensor noise can be measured.

It is very difficult to increase the spatial density of the sensors due to the wiring problem. Stacking cables reduce the flexibility and cause even less accurate measurements.

The evaluation of FSR sensor can be found in [2] for which reasons it can be suitable for the situations where cost and simplicity are more concerned than accuracy. However other solutions are considered since the FSR technology does not match the specifications requirements proposed in 3.1.1.

3.2. Tekscan Flexiforce sensor

The Flexiforce sensors from Tekscan [19] are FSR sensors with improved repeatability and linearity. The manufacturer offers a special setup 4255N for measuring grip force. The sensors 4255N has 20 sensing blocks with size 20mm by 20mm, consisting of 16 sensors with size 2mm by 2mm on each block (or 6.25 sensors / sq-cm). The cables are also built into the setup and can be connected to a single interface (named “cuff unit”) and further to the data acquisition card in the computer. The thin film design of 0.15mm thickness provides the user with high flexibility while the sensor itself maintains a dynamic range of up to 200 Kilopascal (30PSI). Figure 2 shows the 4255N sensor from original package [20].

Although Flexiforce sensor is FSR based, the high density and high coverage rate of the sensor help solving the problem of force applied to the edge of the sensitive region. With the densely placed sensor, not only the force exerted to the entire contact area but also the force distribution can be measured.

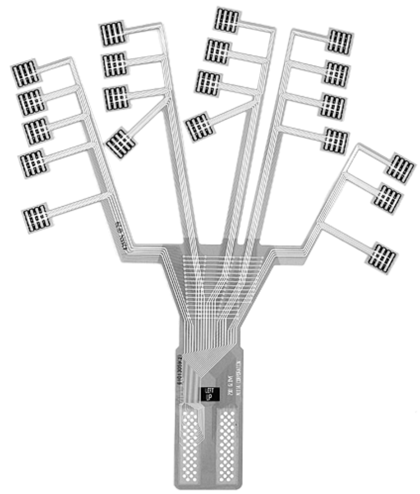

Figure 2 Tekscan 4255N grip sensor.

3.3. Tactile Sensing Glove 1

3.3.1. Design and setup of TSG1. Based on the Tekscan 4255N sensor, a first pair (two right handed) of sensing gloves are built and due to a later adapted version the first version is named the Tactile Sensing Glove 1 (TSG1).

TSG1 fits for the right hand with an artificial leather glove to provide better durability than the cotton glove and the surface is much easier to attach tapes. Double-sided tape is put between the sensing blocks and the glove to ensure firm and consistent connection between them so that the pressure applied to the sensor is less possibly affected by glove elasticity. Stretchable plastic tape is put on top of sensors for protection. Figure 3 shows the sensor positions on TSG1 before covered with protection tape.

Figure 3 TSG1 sensor position.

3.3.2. Performance of TSG1. TSG1 is built following the manufacturer recommended setup of sensor 4255N: 3 sensor blocks on each finger and 5 on the palm. The sensing blocks cover the contact area in most grasping tasks. The dense sensor cells on each block can measure the force distribution during the contact. The update rate of the system is up to 120Hz and the measured data can be stored in ASCII format for post processing. The right hand setup can be transferred into left by copying and mirroring the sensor onto a left handed glove using an identical sensor and reverse the way of inserting the sensor into the cuff unit.

The following problems were addressed:

- The cable of the sensor is easily bended in practice, resulting in the failure of the entire sensor block connected to it.
- The bending problem is observed, resulting from the tension force generated from the glove worn by a large hand that causes unintended tension without external contact.
- Calibration is unreliable for a wearable device like TSG1, details in Section 4.2.
- The force estimation from the pressure data is inaccurate, details in Section 4.3.

The sensor bending problem was proved to be a tension problem when a large hand wears a normal size glove. In adapted design TSG2, encountering bending became rare. The cable bending problem was also solved when building TSG2 by attaching supporting frames to the cables. Experiments and results are shown in Chapter 4.

In general, TSG1 is a fast, sensitive, flexible while reliable device for tactile measuring. It gives high spatial resolution pressure distribution measures of main parts of the hand in grasping task in a high frame rate. The measured data is stored in a convenient and analysis-friendly way. However, calibration and force estimation problems may reduce the accuracy of the results.

3.4. Tactile Sensing Glove 2

Based on the analysis of the handshake measurements using TSG1, changes are made to the glove by adjusting the area where the sensors are mounted. The resulting new version of the glove is called the Tactile Sensing Glove 2 (TSG2).

TSG2 uses the same sensor 4255N from Tekscan. It is rather a specialized glove for measuring human to human handshake force exchange. Comparing with TSG1, the main improvements of TSG2 are:

- The sensors are now more concentrated in the area of hand concerned with the particular application of handshaking.
- Support frames are attached to the cables to avoid bending.

As Figure 4 shows, 9 sensor blocks are mounted at the lower (small finger) part of the hand, while 8 at the upper (thumb) part which are the two parts that are passively being gripped during a human to human handshake. The other 3 blocks are mounted on each link of the index finger to measure the active gripping force exerted to the handshaking partner. The sensor blocks are closely aligned so that the sensors can measure the pressure distribution concerned in the handshake process and therefore provide us with more information on the interaction force during the process.

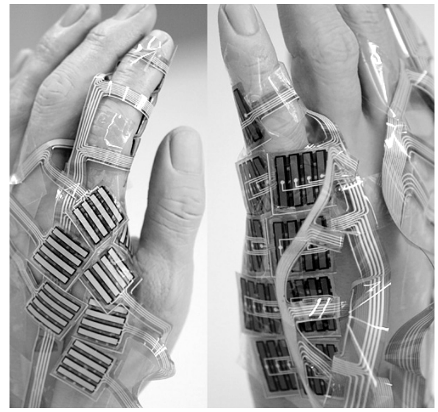

Figure 4 Sensing block position for TSG2 (on a dummy rubber hand), the thumb side on the left and the small finger side on the right.

The same artificial leather gloves are used as bases and the entire sensor is covered with tapes.

As the sensor is designed for mounting on the palm side, all cables are fixed for that setup. Changing mounting position results in an uneven configuration of cables. Moreover, aiming for measuring handshake, the cables must not obstruct the natural contacts of the hands of the handshaking partners, which further constrain the cable wiring. Some cables must be turned over to fit the mounting position. To protect the cables from being bended, supporting frames are used to provide rigid bases for the cables to avoid sharp bends. Two gloves are made following different methods of attaching supporting frames, one as an exoskeleton and the other as short sections. The participants for the handshake experiments provided comments showing that short section frames feels more natural. Figure 5 shows from left to right the original leather glove, the TSG2 design 1 with exoskeleton supporting frame, and the TSG2 design 2 with short section frames.

Figure 5 Base glove, TSG2 design 1, TSG2 design 2.

After employing the supporting frame, the cables are better protected and less easily bended. During the first experiment of 300 handshakes, 2 sensors were worn out, while in the second experiment of 900 handshakes the two TSG2s remained fully functional from the beginning to the end.

TSG2 suffers from the similar calibration and force estimation problems as TSG1. Detailed discussions are given in Chapter 4.

The successful adaptation from TSG1 to TSG2 shows that the design of TSG glove can be generalized. Provided that the region of the hand of concern is known, the TSG can be further adapted to fit other specific tasks with proper methods, such as supporting frames, to protect the bending cables.

4. Measuring handshakes with TSG gloves

The TSG gloves are used to measure force distribution and temporal information in human to human handshake experiments aiming to create realistic handshake in multi-modality virtual environment. A brief introduction of the experiment setup and the methods and initial results of haptic data analysis as well as the improvements of TSG itself are given in this paper. The other aspects of the handshake experiments are not covered.

4.1. Handshake experiments

In order to create a virtual handshake that feels realistic to the human participants, certain behavioral principles are necessary so that they can be followed by the robot as a handshake interface. The data recorded from human to human experiments provide the information of how humans perform in a handshake. The haptic and position information recorded from the experiments are then used to generate models and principles for the handshake robot.

Two identical TSG1s were used in the first experiment. 30 participants formed 15 pairs. Each pair performed 20 handshakes which gives 300 handshakes resulting in 600 individual recordings. The participants were guided so that the initiator and follower of each handshake were well defined. This information was then considered in the data analysis.

Based on the findings from the first experiment, two TSG2s were made and used in the second experiment of handshake where 24 participants formed into 4 groups carried out 900 handshakes with 1800 recordings all together.

Data analysis and initial results are shown in the remainder of this chapter.

4.2. Sensor calibration

In order to get accurate measurements, it is necessary to calibrate the sensors before using them for measuring. The calibration is divided into three steps according to the user manual [20]:

- Conditioning: apply force to the new sensor for 20 times to activate the material.
- Equilibration: assign a factor to each sensor cell so that identical measurements are obtained for each cell when the identical pressures are applied.
- Calibration: obtain relationship between raw sensor values and the pressure values with units such as Pascal or mmHg.

Since in TSG the sensor is mounted on a deformable base and covered by tape, the calibration should be carried out after the glove is finished otherwise the characteristics of the sensor are distorted by the materials attached to the sensor. However, the calibration device provided by the manufacturer is designed to use only on a rigid plane surface.

After sensor conditioning, the calibration was divided into two steps. Firstly the sensor was mounted onto a rigid plane. Weights were used to apply well defined forces to the sensor. Repeatability of the 4255N is improved comparing with the FSR sensor. Figure 6 shows the calibration tests results on one sensing block when 500g weight is put onto the sensor.

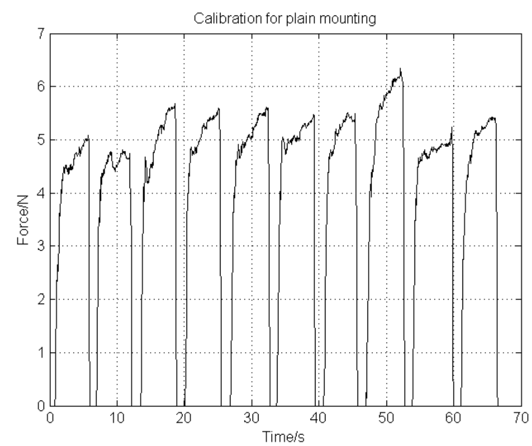

Figure 6 Test result for rigid plane mounting.

However, a noticeable drift is observed. In order to test the drift, a 500g weight is placed on the block and kept for about 40 seconds. The measured drifting is about 3N/min as shown in Figure 7.

Figure 7 Drift test result for plane mounting.

In the next step, the sensor is mounted onto the glove with cover tape. A normal force of 5N is applied to the sensing blocks. For 10 repeated tests, the standard deviation varies from 0.61N to 0.94N from block to block. It is observed that the measurement significantly decreases if the applied force is not perpendicular to the sensor surface, down to 2.9N lowest in the tests. However, when the force is kept perpendicular to the contact surface, the repeatability can be improved. For 5 tests with best performance out of the 10, the standard deviations are 0.36N to 0.45N. Figure 8 shows the results on the glove.

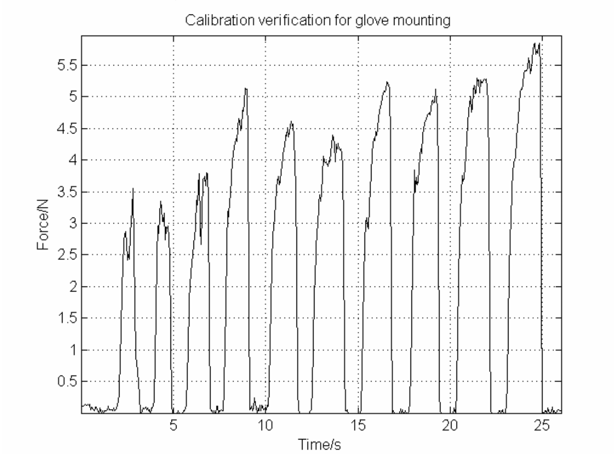

Figure 8 Calibration result of glove mounting.

As shown in the above described tests, the force estimation is distorted by the elasticity of the glove and tape, bending and tension effects, leaning of contact force, etc. However, after the calibration and with the force direction carefully controlled, the measurement results are acceptable when the force value accuracy is not strictly required.

4.3. Data processing and results

From the sensor, raw pressure measurements are stored as integers ranging from 0 to 255. The data are exported as ASCII files and then imported to MATLAB for analysis. The calibration results are used in transferring raw values to Kilopascal unit values.

4.3.1. Statistics of sensing blocks usage. In the results from handshake experiment 1, some sensing blocks give very low outputs throughout the experiments. This fact indicates that not all the covered parts of the hand are active in a common handshake procedure. Inspired by this idea, a statistical process is carried out to the sensing blocks as follows:

- Estimate the force value of each sensing block at each time frame for each trial using the procedure shown in 4.3.2
- Calculate the average of the force of each block for all time frames in each trial
- Set a threshold and count the number of trials when the average force gets beyond it
- Compare the counted numbers of each block being activated

Figure 9 and 10 give two samples of activation statistical results of blocks on the middle link of the ring finger and on the thumb side of the palm. Figure 11 shows the result of activation statistics.

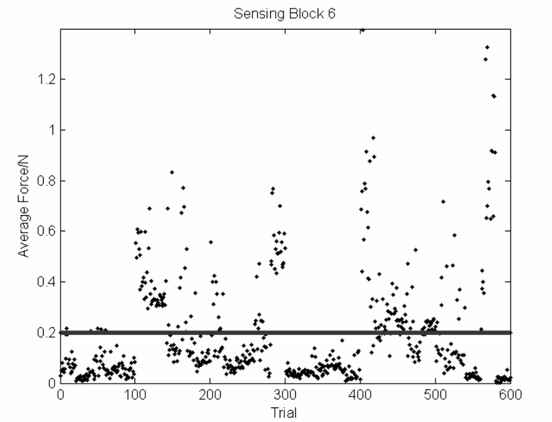

Figure 9 Activation statistics of the middle link of the ring finger.

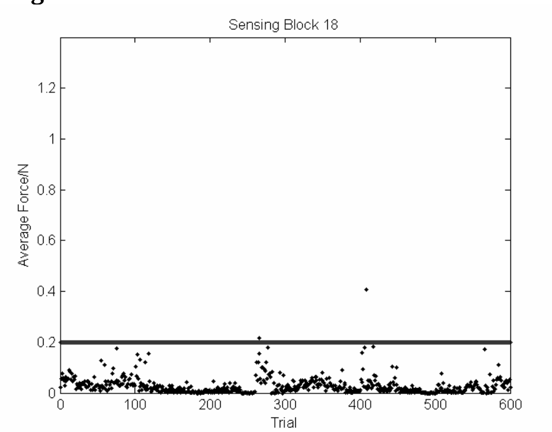

Figure 10 Activation statistics of the thumb side of the palm.

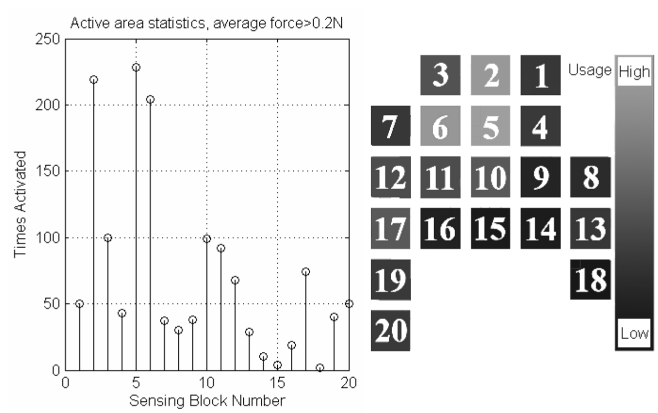

Figure 11 Activation statistics of sensing blocks and the visualization with block numbers.

The thumb appears to be used rarely in the above results. This should be caused by the sensor mounting position problem of the thumb, as in handshake experiment 2 the thumb resulted in the highest forces when the sensors are proper
ly mounted.

In Figure 11, the most activated sensing blocks align in the way that the hand of the handshaking partner is being hold. The gripping person decides how much force to exert, but where the force is mostly densely distributed is determined by where the hand of the partner is. Based on this conclusion, the TSG1 is adapted into TSG2. The sensor blocks are mostly mounted onto the two sides of the hand to measure passive gripped force, since those parts are gripped in most cases, no matter how the two participants are holding their hands. Only 3 blocks are mounted onto the index finger to measure the voluntary exerting force to the partner.

4.3.2. Force estimation. The 4255N grip sensor is sensitive to the pressure signal that is applied on it. An intuitive idea of deriving force value from the pressure data is to multiply the pressure with the area it is applied and get the corresponding force. However, in this particular case there are problems that prevent accurate results when doing so.

The grip force is distributed throughout the whole area in contact. Each small sensor unit can only pick up the pressure that is locally applied to it. As shown in Figure 12 taken from [20] only the black areas are sensitive to pressure. All the other areas as well as the cables are not sensitive to pressure changes.

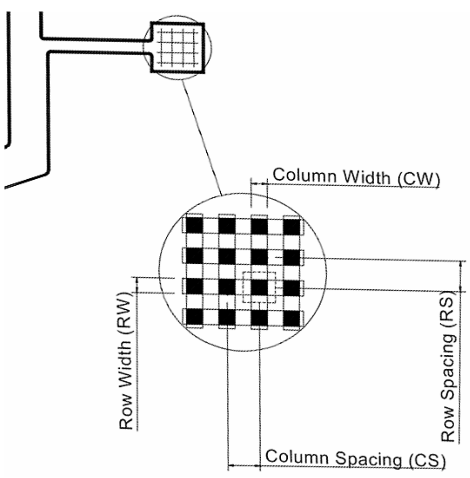

Figure 12 Detailed structure of one sensing block of 4255N, for 4255N, CW=RW=2mm, CS=RS=4mm.

From the nominated values, the sensitive area is only one fourth of the total area of the sensing block. It is assumed that the pressure applied along the hand surface is continuous and slowly changing. Under the assumption the missing information of the insensitive areas can be obtained by interpolating the values of the nearest measurements.

The force estimation is then given by the sum of all pressure values multiplied by the corresponding area.

Figure 13 and 14 give two examples of estimated force from three blocks of TSG1 on the handshake initiator glove and on the follower glove. Figure 14 also shows the bending problem. Temporal information can be extracted, such that the middle finger grips earlier than the ring finger and the index finger grips the latest, for both participants.

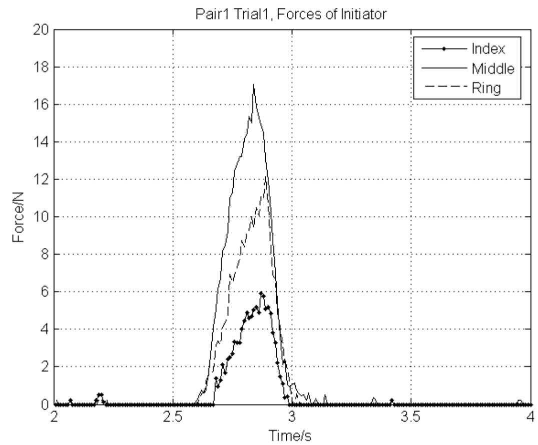

Figure 13 Force estimation of initiator using TSG1, fingertips of index, middle, and ring fingers.

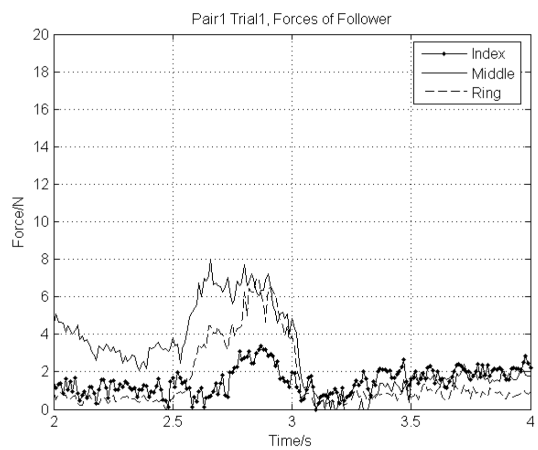

Figure 14 Force estimation of follower using TSG1, fingertips of index, middle, and ring fingers.

4.3.3. Determination of grip force centers. For the large sensitive area covering one side of the hand, it is not sufficient to give only one over-all force estimation. In the later on realization phase, the robot needs more detailed information of how and where to grip with its fingers. Therefore, determination is needed on:

- How many distinctive forces
- Where are they centered
- How large are they

The data is clustered with the hypothesis that the upper part has one center resulting from the gripping by the thumb while the lower part has 4 due to the rest of the fingers. It is observed that the upper part of hand has more than one center visually identified, while the lower part has less than four. Two centers are tried for upper and lower part each with improved results. Figure 15 and 16 give an example of clustering results with force center and force sums in each cluster in Newton.

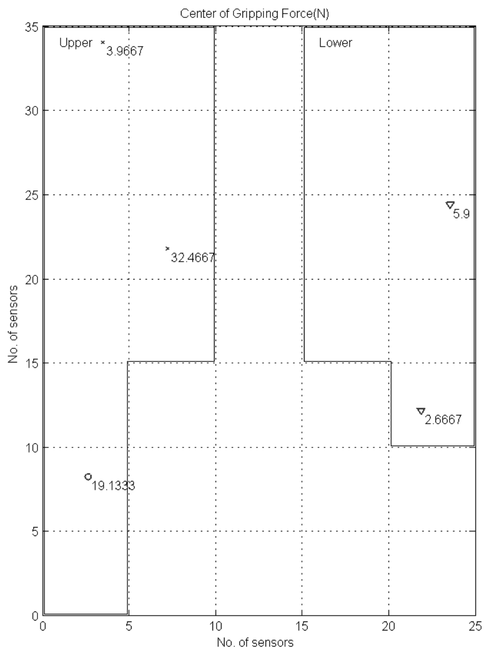

Figure 15 Clustering results of force centers.

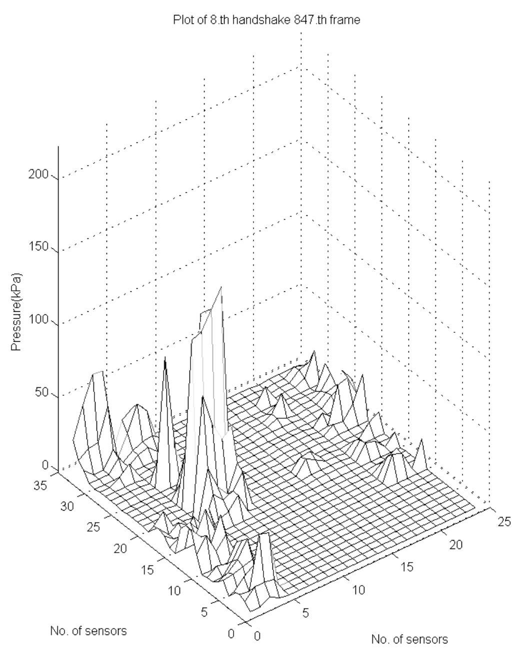

Figure 16 Force center map.

The argument for two force centers in the upper part for one thumb is that the two centers are applied by the two links of the thumb, while the two lower centers show that only two fingers are mainly active during handshake.

5. Conclusions and future work

A tactile sensing glove is built to acquire haptic data of the human interacting with the environment. The mounting position of the sensor can be adjusted so that the sensor units are concentrated to measure the most concerned area. The pressure values are interpolated to get force estimations.

If high accurate force values are required, the current sensor is not sufficient. One approach could be the 3D integrated Silicon sensor with improved dynamic range and flexibility.

The TSG gloves, the original and adapted versions, are suitable for haptic measuring of multiple scenarios of hand and object interaction. They will be used in the future experiments carried out toward haptic enhanced multi-modal interaction.

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