2014 14th IEEE-RAS International Conference on
Humanoid Robots (Humanoids)
November 18-20, 2014. Madrid, Spain

Experimental Extraction of Tactile Sensor Specifications for a Minimal Anthropomorphic Robot Hand

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***Abstract*— In this work a new approach is taken towards determining the quantified contribution of tactile acuity to human manual dexterity, and the implications of this approach when applied to the development of artificial fingertip touch sensors for humanoid robots or for prosthetic hands. The interdependence between several dimensions of both tactile acuity and dexterity is investigated. An experimental study was performed on a carefully chosen sample of 30 human subjects, with data acquisition taking place over a total period of 35 hours of testing in a controlled environment. The data were analyzed to extract minimum levels of tactile acuity that would result in manual dexterity performance at 80% of normal. These extracted levels are interpreted to represent minimum specifications for the design of an artificial tactile sensor that would endow a robot hand with acceptable dexterity, and are used in a case study to drive the conceptual design process for a new tactile sensor based on quantum tunneling composite material.**

I. Introduction

The substantial contribution of tactile sensing to human manual dexterity has long been recognized (e.g. [1]). The corollary that the incorporation of tactile sensing capability can make an important contribution to improving the dexterity of robot hands is also well documented in the literature (e.g. [2-4]). To this end, various technologies have been employed to develop sensors or artificial skins that endow robot hands with the sense of touch (e.g. [5-9])

A tenable approach is to use human tactile sensitivity as the gold benchmark, and attempt to achieve comparable capability in the artificial hand (e.g. [10]). However, given the high complexity and capability of the human hand ([11-12]) this target is considered to be at best extremely challenging (with consequential high associated costs) and at worst unattainable. It is therefore worth considering whether it is possible to determine lower target specifications for an artificial hand tactile sensing system, that are based on systematic and quantifiable tests and considerations.

This work extends the philosophy applied in [13], whereby constrained *human* manual dexterity testing is applied to the determination of justifiable reduced specifications for an *artificial* hand. The major objective of the present work involves relating a *quantifiable* measurement of human manual dexterity to the (also quantified) degree of tactile acuity available to the human. This is done by having a set of human subjects undertake multiple manual dexterity tests with varying levels of tactile inhibition applied to their fingertips. An acceptable dexterity cutoff value is then selected (e.g. 80% of that of the uninhibited hand; the actual value will depend upon factors such as the intended use of the hand and the available budget). The minimum specifications for an *artificial* tactile sensor that, based on the quantification methodology employed in the work, would result in a potential dexterity attainment of up to 80% of that of a human, can then be extracted. It is noted that for this level of dexterity to be actually achieved in the artificial system, all of the other components of the system (kinematic structure, actuation, visual feedback system, controller, information database) would need to be equivalent to those of a human; thus the 80% level is viewed as a theoretical *upper-bound* for attainable dexterity.

This paper also includes very preliminary results in the development of a new tactile sensor that is based on some of these reduced specifications.

II. Approach and Methodology

The first task in the present work involved the identification of suitable quantifiable markers for tactile acuity. Two clearly quantifiable parameters that are used extensively in the medical field to assess tactile sensitivity relate to the measurement of the lowest detectable force (normally using the *Semmes-Weinstein Monofilament test*, or SWMT) [14], and of the lowest distance between two point stimuli for which the subject can sense that two stimuli, rather than one, have been applied (the *two point discrimination test*, or TPDT) [15]. These two tests were therefore selected as part of our tactile acuity quantification methodology. A third quality that is discussed extensively in the literature, but that is difficult to quantify accurately, relates to texture perception (e.g. [16], [17]). Texture perception is regarded to be multi-dimensional in nature, with the *rough/smooth* and *soft/hard* dimensions being the most heavily weighted perceptually [18]. There are no standard, widely-used tests that quantify texture perception. In this work a new *texture testing* (TT) approach was taken to attempt to measure and quantify this aspect of hand sensitivity in the rough/smooth dimension, and the results were incorporated in the general evaluation of tactile acuity.

The second challenge involved finding an effective way to reduce the tactile acuity of a human test subject in an incremental manner, in order to measure manual dexterity under conditions of reduced tactile acuity. For health and safety reasons, a non-invasive method was found to accomplish this, as described in section IIIA.

In order to enable correlation with past results, the dexterity was measured using the *box and block test* (BBT) [19], the *nine hole peg test* (NHPT) [20], and the *grooved*

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pegboard test (GPT) [21] as in [13]. These tests are described briefly in section IIID. The analysis to extract a quantified dexterity level for a given condition (i.e., in the present work, for a given level of tactile acuity) was also carried out in the same manner as in [13].

All experiments were carried out on a sample of thirty human subjects. The experiments are categorized into two sets. The first set, referred to as the *calibration tests*, involved establishing the relationship between the physical tactile inhibition applied to the subjects' fingers and the resultant tactile acuity, as measured using the SWMT, TPDT, and TT. The second set, referred to as the *dexterity tests*, involved measuring the subjects' dexterity at different levels of tactile acuity using the BBT, NHPT, and GPT.

The experimental results were analyzed to extract a relationship between the quantified dexterity level and the tactile acuity. By accepting a minimum upper-bound for dexterity at the 80% level (i.e. a 20% reduction in dexterity as compared to the uninhibited hand), it was possible to determine minimum specifications for an artificial skin with respect to force threshold sensitivity and two point discrimination capability.

Finally, the conceptual design of a new tactile sensing skin based on the above specifications was carried out, followed by the development of a first, exploratory prototype and an evaluation of its performance.

III. Experimental Tests

A. The Tactile Inhibitor

When choosing the inhibitor that would be used during the experiments to limit the tactile acuity of the human subjects, certain key properties were considered. As these tests would need to be finished in a short period of time the speed of application of the inhibitor had a very large weight on the selection process. The inhibitor chosen needed to be able to be applied quickly and repeatedly to the volunteers` fingers.

During the tests it was also desirable to be able to have at least three levels of inhibition that when at level three, which was to be the maximum, would cancel out the tactile acuity, completely, if possible. It was also important that there should be a relatively smooth transition in tactile acuity between the first, second and third levels of inhibition, to achieve a more evenly spaced set of results.

Furthermore the inhibitor needed to be able to accommodate a strict form factor. Apart from being in the approximate shape of the human finger, it also needed to be of minimal thickness, so as not to impede hand performance due to physical obstruction. It was decided to limit the maximum inhibitor thickness to 6 mm, which is approximately one half of the observed fingertip thickness (halfway along the nail). Furthermore the inhibitor was only attached to the sensitive part of the fingertip and not to the sides where it could limit the adduction of the fingers.

In light of all of the selection criteria mentioned above, it was decided that the inhibitor should be in the form of a foam film with an adhesive back. This approach was also preferred because this allowed for far better reproducibility of the test.

(a) *(b)*

Figure 1. (a) Neoprene tape inhibitor, (b) Attachment to fingertip

TABLE I. Tactile Inhibition

Level of tactile inhibition	Tape layer thickness
0	0 mm
1	2 mm
2	4 mm
3	6 mm

The specific inhibitor chosen was a 2mm thick black neoprene tape, 10mm in width (Fig. 1). This neoprene tape is designed to be used for vacuum forming applications where different thicknesses can be achieved by layering the tape. Thus multiple layers were used to achieve different levels of inhibition as shown in Table I.

B. Selection of the Test Subjects

The selection criteria used in the identification of these subjects were similar to those used in [13] (except that a wider age bracket was allowed) and served to ensure as homogenous a group as possible. Eligible subjects needed to be male, between the age of 18 and 30, right handed, University Engineering students, have good eyesight (glasses or contact lenses allowed) and have no history of injury or illness that could affect dexterity.

C. Calibration Tests

During all of the calibration tests the subject was seated at a desk in a quiet area. A blackout curtain was set up in front of the subject to occlude his vision, and the subject presented his hands to the test administrator from underneath the curtain. Each of the three calibration tests was administered to all of the thirty subjects under all four levels of inhibition.

The SWMT apparatus, shown in Fig. 2, consists of a set of five nylon monofilaments of the same length but of different diameters, therefore having different buckling loads. The subject`s hand is supported to avoid excess movement. The test administrator presses the filaments in turn up to buckling load against the subject's skin, progressing from the small to the large filaments, and the subject is instructed to say "Yes" when he feels the touch. The smallest force that the test subject can feel is recorded as being his threshold force and constitutes the test score. During the tests, each filament was repeated three times, and a single response was taken as a positive result.

For the TPDT, a set of pronged tools was designed and built (Fig. 3). These tools consist of 20x20x10 mm blocks of PMMA (poly methyl methacrylate), that were drilled using precision CNC control at specific locations. One PMMA block has one hole and the other seven have two holes drilled at increasing distances from each other. The holes were of 1mm diameter, 5mm deep, and their center to center distances were of 1mm, 1.5mm, 2.2mm, 3.3mm, 4.9mm, 7.4mm, and 11mm. After the holes were prepared and cleaned from debris, tapestry needles that had blunt points were cut down to a size of 15mm and pressed into the holes with quick setting glue. During the test the subject's hand was supported as above, and the tools were randomly applied to the fingertip. At each application the subject was instructed to state whether he had been contacted by either one or two points. Applications were repeated until the minimum discrimination distance, constituting the test score, could be reasonably determined.

For the TT, a set of six cylindrical mild steel bars, each 70 cm long and 50 cm in diameter was prepared to serve as gauges (Fig. 4). The first gauge (Gauge 1) was polished. A different external thread was machined on each of the other five gauges, ranging from 0.125 mm amplitude, 0.25 mm pitch (Gauge 2) to 1 mm amplitude, 2 mm pitch (Gauge 6). In the test, the subject was first asked to pass his finger over Gauges 1 and 6 for self-calibration purposes, and advised that these gauges were assigned texture values 0 and 10 respectively. The subject was then asked to pass his finger along one of the other gauges 2 to 5, and assign a roughness score to the gauge. This procedure was repeated for each of the other three gauges.

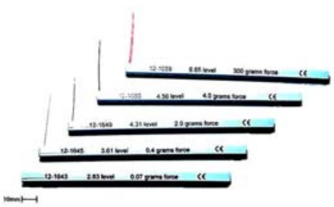


Figure 2. The Semmes-Weinstein Monofilament test apparatus

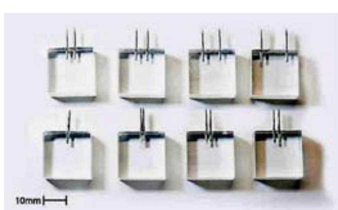


Figure 3. The two point discrimination test apparatus

Figure 4. The texture test apparatus (showing four of the six cylinders)

(a) BBT *(b) NHPT* *(c) GPT*

Figure 5. The dexterity tests apparatus

D. Dexterity Tests

For these tests, the occluding curtain was removed. Each of the three dexterity tests was administered to all of the thirty subjects under all four levels of inhibition.

The BBT (Fig. 5(a)) consists of a box with two partitions, with 150 wooden blocks of side 25 mm placed in the partition corresponding to the hand under test. The subject is instructed to transfer the blocks one at a time to the second partition. The number of blocks that can be transferred in one minute gives the test score. This test measures predominantly the grasping capabilities of the subject.

In the NHPT (Fig. 5(b)) the subject picks up nine pins (6.4 mm diameter, 38 mm length) in turn from a shallow container and places them in a nine-hole pegboard. The time taken to transfer the pegs and then return them to the container gives the test score. This test involves grasp and release functions, refined pinches, moderate hand-eye coordination, and moderate in-hand manipulation.

In the GPT (Fig. 5(c)) the board consists of 25 holes, each of which has a randomly positioned slot. The pegs have a key along one side, and must be rotated appropriately before fitting into the slots. The pegs must be inserted into the board in the correct order. The time taken to transfer and insert the pegs constitutes the test score. This test focuses on precision manipulation and involves more complex visual-motor coordination.

IV. Results and Discussion

For the NHPT and GPT (i.e. where better performance was indicated by a lower numerical score), the dexterity results were extracted as per (1):

$$\mathrm{Dexterity(run)(\%)} = \frac{M(\text{uninhibited run})}{[M(\text{uninhibited run}) + M_d(\text{run})]} \times 100 \quad (1)$$

where a run refers to one set of dexterity tests executed on the thirty subjects (e.g. NHPT at Level 2 inhibition); $\mathrm{Dexterity(run)(\%)}$ refers to the dexterity result, expressed as a percentage of the mean uninhibited performance level; $M(\text{uninhibited run})$ is the mean score obtained when the same test was run on the uninhibited subjects; and $M_d(\text{run})$ refers to the mean of the individual subject degradation (i.e. increases) in scores when the run scores are compared to the corresponding uninhibited run scores.

For the BBT (where better performance was indicated by a higher numerical result), the results were extracted as per (2):

$$\mathrm{Dexterity(run)(\%)} = \frac{[M(\text{uninhibited run}) - M_d(\text{run})]}{M(\text{uninhibited run})} \times 100 \quad (2)$$

where in this case $M_d(\text{run})$ refers to the mean of the individual *decreases* in scores when the run scores are compared to the BBT uninhibited run scores.

For the SWMT and TPDT, the results were expressed in the appropriate units as per (3):

$$\mathrm{Result(run)} = M(\text{run}) \quad (3)$$

where $M(\text{run})$ refers to the mean score in mN for the SWMT and in mm for the TPDT.

For the TT the results for the inhibited runs were extracted from the changes (i.e. increases) in the variance of the scores assigned by the subjects, when compared to the variance for the uninhibited run, and expressed as a percentage of uninhibited performance, as per (4):

$$\text{Result(run)}(\%) = \frac{V(\text{uninhibited run})}{V(\text{run})} \times 100 \tag{4}$$

where $V(\text{uninhibited run})$ is the average variance in the assigned scores for gauges 2, 3, 4 and 5 in the uninhibited run; and $V(\text{run})$ is the average variance in the assigned scores for gauges 2, 3, 4 and 5 in the run under consideration.

Fig. 6 shows the reduction in dexterity that results from a reduction in tactile acuity as measured by the SWMT. As expected, the changes in the dexterity test results seen in the NHPT and GPT are much more pronounced then those seen in the BBT, due to the greater requirement for fine manipulation in the former two tests. Moreover, the reductions in dexterity measured by the NHPT and the GPT are very similar to each other. Similar results can be seen where the tactile acuity is measured using the TPDT, as seen in Fig. 7. The error bars in Fig. 6 and Fig. 7 represent the standard error of the sample mean.

In the case of the TT results, it is seen in Fig. 8 that the ability to perceive texture is greatly diminished upon the application of even just one layer of inhibiting tape, and there are no further discernible reductions as the inhibition level is further increased. This is consistent with the prevailing hypothesis that texture perception is heavily reliant on stimulation of the epidermal ridges on the human fingertips, especially when moving a finger along a surface [22]. The addition of even a single layer of inhibiting tape may have been sufficient to disable this texture sensing mechanism.

It is noted that the standard SWMT five-piece monofilament set that was used in the experiment is designed for medical diagnostic use, and the filaments have buckling loads of 0.69 mN (“normal”), 3.92 mN (“diminished light touch”), 19.62 mN (“diminished protective sensation”), 39.24 mN (“loss of protective sensation”), and 2943 mN (deep pressure sensation only). The large gap in applied force between the fourth and fifth monofilaments meant that those subjects who failed the 39.24 mN test would in a medical test be assigned force thresholds of 2943 mN. In fact the vast majority of subjects in the present tests did pass the 4th filament even under maximum inhibition, suggesting that maximum thresholds for healthy persons, even at Level 3 inhibition, could not be too far from 40 mN. Thus, in order to prevent extensive skewing of the results that would have rendered the test meaningless, the small percentage of subjects who did fail the 4th filament in the SWMT (all of whom eventually passed the 5th filament) were assigned a threshold of 80 mN.

Using the NHPT and GPT as the benchmarks for fine manipulation dexterity, mean force and two-point discrimination thresholds can be extracted for varying levels of functional dexterity. Table II shows these thresholds at 100% and at 80% dexterity. Based on the approach taken in this work, a general conclusion that can be extracted from this result is that a human would still function at 80% of his optimum manual dexterity level if his force threshold and two

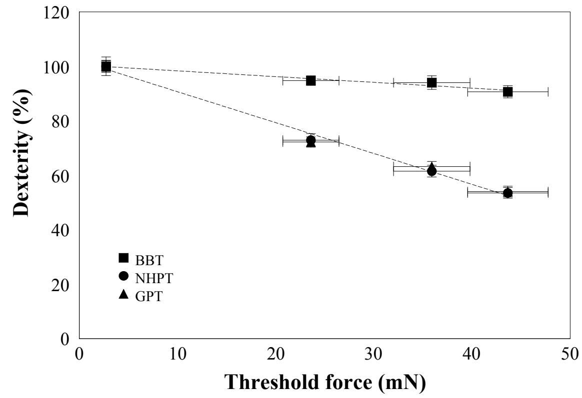


Figure 6. Dexterity test results against SWMT results

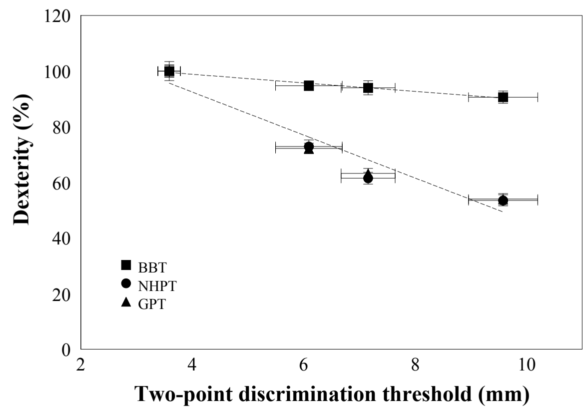


Figure 7. Dexterity test results against TPDT results

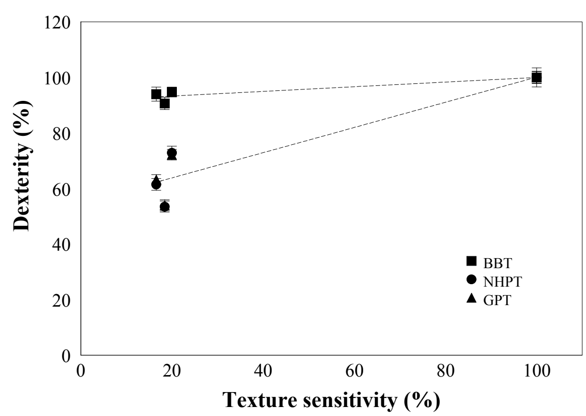


Figure 8. Dexterity test results against TT results

TABLE II. MEAN TACTILE THRESHOLDS FROM THE HUMAN TESTS

Dexterity level	Force threshold	Two-point discrimination threshold
100%	2.7 mN	3.6 mm
80%	19.5 mN	5.6 mm

point discrimination sensitivities were reduced to those shown in the last row of Table II, and if his texture sensing capability were completely removed.

These thresholds can be considered to be minimum specifications for an artificial tactile sensor to be mounted on a humanoid or prosthetic hand, where the objectives are for the device to attain a functional (as opposed to ideal) dexterity level at a lesser cost.

V. CONCEPTUAL DESIGN OF A NEW TACTILE SENSOR

In this section some preliminary, explorative results pertaining to the conceptual design of a low cost fingertip tactile sensor based on the above results are presented. A function analysis of the sensor was first drawn up (Fig. 9). This was followed by the generation of a morphological chart where various potential solutions to address each of the functions shown in Fig. 9 were considered and evaluated. The selected solutions are given in Table III.

It is noted that the development of advanced quantum tunneling composite (QTC) materials to construct tactile sensors has already been applied in the literature for high resolution tactile imaging of texture (e.g. [23]). Due to the more modest specifications of the present work, however, it was envisaged that lower cost, off-the-shelf material could be applied. The main reasons for the choice were that QTC have properties that allow for an accurate, repeatable and robust design. Moreover, the resistance of these composites varies from an almost perfect insulator in the undeformed state, to less than 1Ω in resistance under a very small deflection [24].

Based on the selections of Table III, a set of different conceptual designs was generated. Using 3D CAD software [25] each of these sensor designs was developed and rendered as a 3D sketch. This was done to enable better visualization and improved awareness of the interaction and dimensionality of the systems.

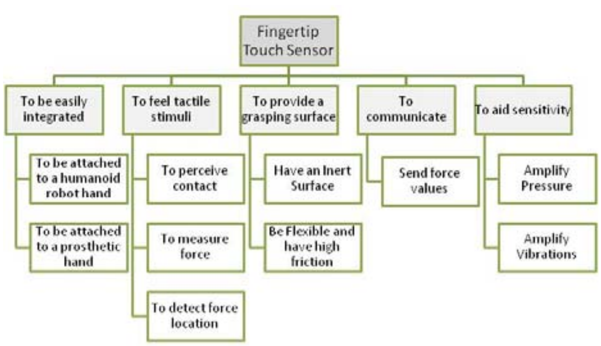


Figure 9. Function analysis of a fingertip tactile sensor

TABLE III. SELECTED FUNCTION SOLUTIONS

Function	Solution
Integration	External skin on finger tip
Transduction	Quantum tunneling composite
Grasping surface material	Flexible silicon
Grasping surface topology	Rough
Controller interface	Multiplexer
Pressure amplification	Pressure concentrator over small area
Vibration amplification	Oscillating cantilevers

Selection of the final concept was performed using a decision matrix. During this selection process, a set of ten criteria that were deemed relevant to the case such as performance, cost and manufacturability were first weighted, and then every concept was given a ranking under each criterion, to achieve a weighted score for each criterion. The winning concept, i.e. the one with the highest total weighted score, is shown in Fig. 10. It consists of a single layer (matrix) of QTC sensors that would be designed to have the required range of actuation by dimensioning the area appropriately. The design emphasizes simplicity: it has only one pair of electrodes and hence would be the easy to interface with a control system. Furthermore this design has the least layers and components inherently making it easier to manufacture and more robust. Perpendicular gold electrodes are separated by a deposited layer of QTC. A simple pressure amplifier covers the contact area and all of these components are embedded in soft silicon.

After the design was complete a proof of concept prototype that conformed to the current available manufacturing capabilities was developed and constructed. The objective of this first prototype was to attempt to reproduce only the tactile *resolution* minimum specification. To keep the production of this sensor as practical as possible the components were designed to be manufactured using 3D printing, and the electrodes fashioned out of thinned copper wire, that would simplify connecting the system to a PCB. A 3D rendering of the design can be seen in Fig. 11(a).

The actual constructed sensor can be seen in Fig. 11(b). System control was achieved via a data acquisition circuit built around an Arduino MEGA and 16-channel multiplexers.

The prototype was first tested for cross talk, and this involved the pressing of one pin point on to the sensor. In theory pressing only one taxel should only induce feedback from the one taxel, however in practice this is not the case, since the mechanical inter relationship between the materials causes cross talk. The results when testing the skin-less sensor

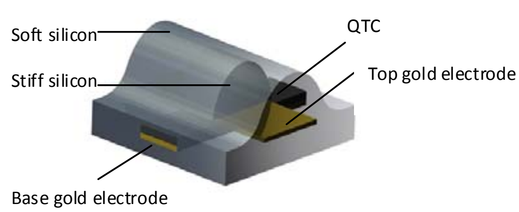
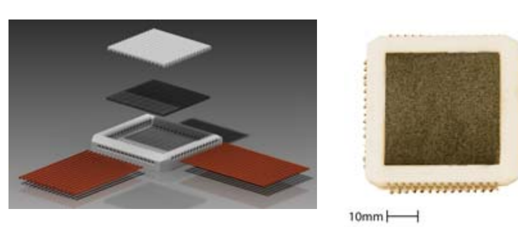


Figure 10. The selected conceptual design



(a) *(b)*

Figure 11. (a) 3D representation of proof-of-concept sensor design; (b) finished 3D printed sensor proof-of-concept with silicon skin and soldered onto PCB

was of an average cross talk amplitude of 30% on 2 taxels, and with the silicon skin this was of up to 46% on up to 7 taxels.

The sensor was checked for spatial resolution using the TPDT apparatus. It was found that the minimum discernible gap was 4.9 mm when the points were kept perpendicular to the electrodes, however this increased to 7.4 mm at oblique angles. This shortcoming can be directly related to the distribution of loads due to cross talk, and it can be concluded that better performance will be achieved once this problem is addressed. The sensor output can be seen in Fig. 12. The minimum force threshold for this prototype was also measured, using a digital weighing scale to which a pin (similar to the ones used in the TPDT apparatus) was affixed, and was found to be around 2 N.

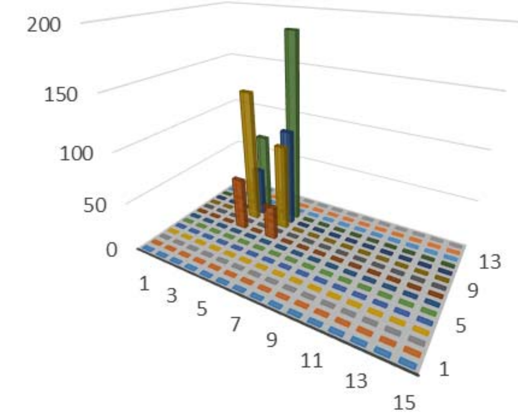


Figure 12. Sensor output for two-point contact stimulation (sensor output units are arbitrary)

VI. CONCLUSION

The sensor that is under development serves as a case study for the exploitation of the main results of this paper, involving the extraction of minimum specifications of a tactile sensor for acceptable dexterity levels. This prototype is a work in progress. From the results acquired in these tests it can be concluded that the sensor may indeed be capable of reaching the design specifications, at least with respect to the resolution. Future work will involve the development of design improvements to address the cross talk problem and to bring the threshold down to the minimum specification. Once these issues are resolved, sensors of this type can be mounted at the fingertips of a teleoperated hand to provide touch feedback to the human via the master device (e.g. haptic glove) for better dexterity. The touch sensors may also be applied to autonomous dexterous hands.

ACKNOWLEDGMENT

This work was partly funded under University of Malta Research Grant IMERP-03-04.

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