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Fingerprint sensor reliability test

Abstract

We have investigated the surface dependability of the FPC1010 capacitive area sensor regarding long-term normal usage. A silicone model of an index finger slid 1 million times 9 mm across the sensor surface. The applied load was 6.43 N (655g), which corresponds to the 87-percentile usage force. The sensor experienced little but detectable wear, which did not affect the performance of the sensor. We hence conclude that the sensor surface is reliable regarding high-cycle non-abrasive normal office condition wear.

1. Background

Fingerprint Cards develop capacitive fingerprint sensors. These sensors will be used under different conditions and by different customers. In this study we are interested in how well the sensor will endure long-term normal office use.

By normal office use we mean that

- the users are free from abrasive particles such as sand and dirt,
- the sensor is used in a dry and room tempered place,
- the sensor is used in non-aggressive chemical environment,
- the sensor is used by one or many persons,

but we do not include actions such as

- dropping sharp objects on the surface,
- scratching the surface with sharp objects.

In this investigation we have studied a FPC1010 capacitive area sensor with a 25 µm protective layer. There are at least two reasons to choose one million usage cycles. The first reason is customer requirements. The second reason is a discussion arguing that if 250 persons uses the sensor every day of the year, then it will take almost eleven years before one million touches has occurred. A single user uses the sensor substantially less, maybe just once a day under say five years. The total number of cycles in this case is in order of some thousands. In both these examples the environmental severity is low by definition of normal office use. In other applications the severity is much higher with factors such as dirt and humidity. In Figure 1 the different usage definitions are plotted in a two dimensional diagram where number of cycles is on the horizontal axis and the severity is on the vertical axis. The grey shaded area corresponds to the examination of long-term office use. In the area above the number of cycles axis the environment is more severe.

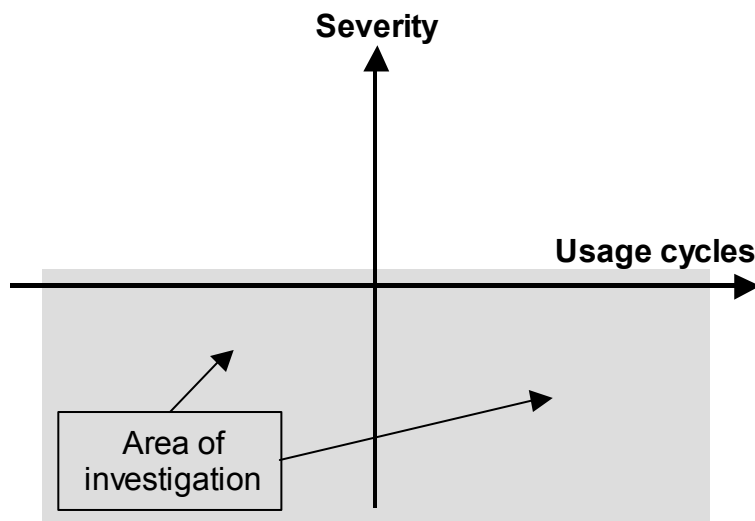


Figure 1 Usage definition

2. Experiment Equipment

We wanted to simulate one million fingertip touches on the sensor surface. From experience and observations we know that the fingertip not only touches the surface but also slides over the surface see Figure 2.

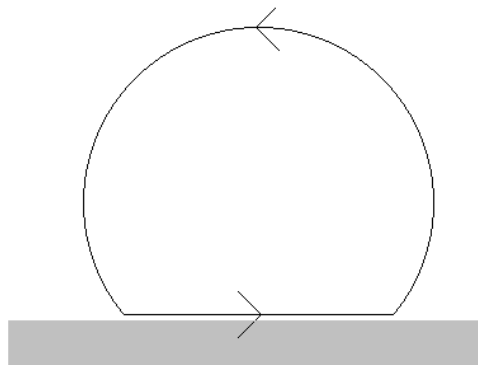


Figure 2 Fingertip movement relative the sensor surface

We designed a wear machine that could simulate this semi circular movement. The principle is shown in Figure 3. A circular movement is transformed into a combined linear backward and a semi circular movement.

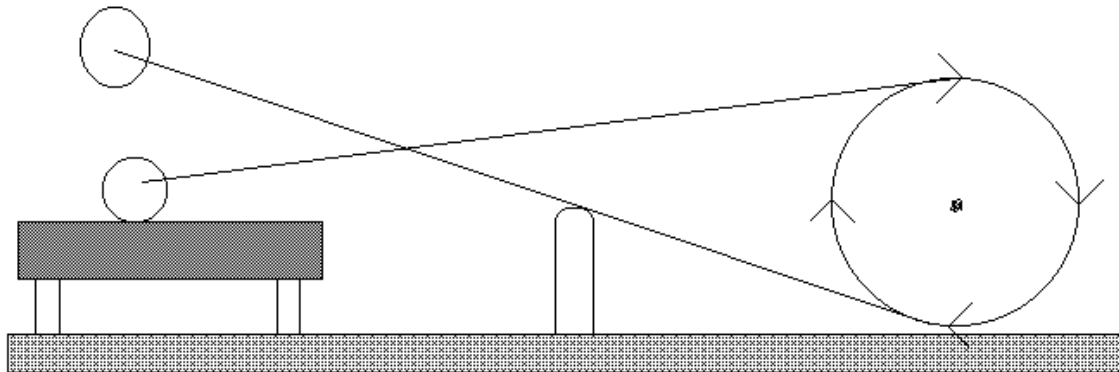


Figure 3 The wear machine principle. The wheel is turning and makes the shaft move along the sensor surface, but an obstacle forces the fingertip to follow the path shown in Figure 2.

The real wear simulation machine is shown in Figure 4. An electrical engine drives the wheel that moves the shaft.

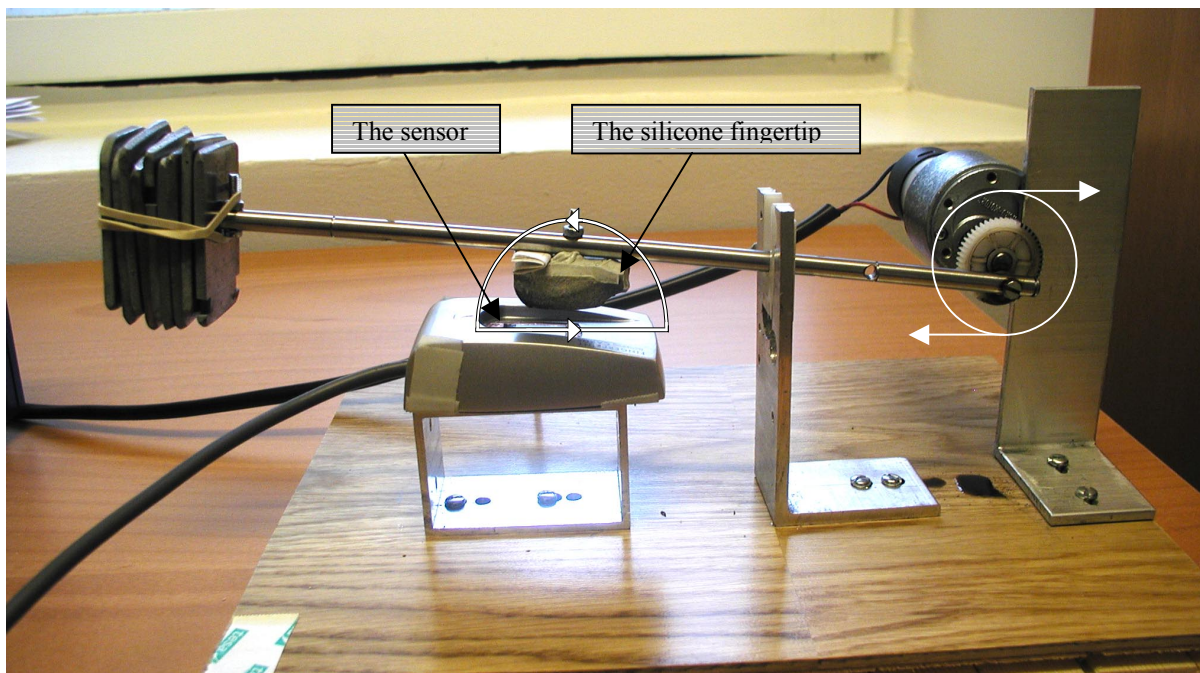


Figure 4 The wear machine in action.

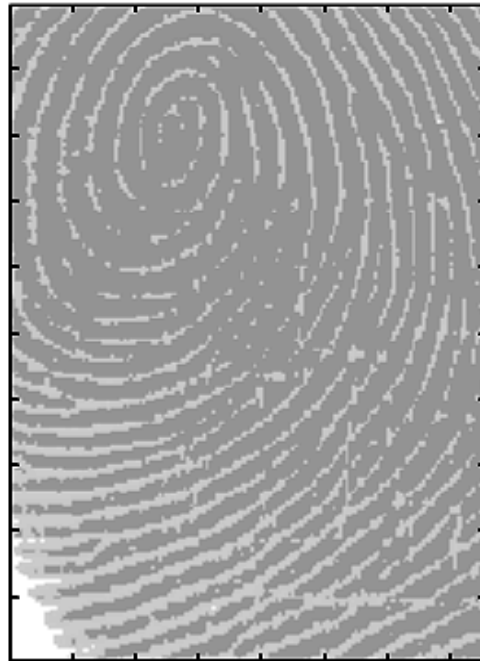
We controlled the cycle frequency by varying the voltage. For this specific engine a voltage of 18.5 V gave a cycle frequency of 1 Hz. The number of cycles was estimated by the elapsed time. As an example the machine turns 100000 cycles under 27 hours, 46 minutes and 40 seconds. The fingertip force was regulated by the weights attached at the end of the shaft.

Fingertip force

The fingertip force used in this experiment was 6.67 N. An experiment¹ showed this value to be the 87 percentile of fingertip forces at a reference group of 9 persons.

3. The test

The simulation started 11 January 2001. As a reference the right index finger of the author was used. In Figure 5 the image of the fingerprint is shown. The picture has 200 rows and 152 columns containing a value between 0 and 255 where 0 is black and 255 is white. The values are between 220 and 255.



0 cycles

Figure 5 Authors right index fingerprint at 0 cycles.

The simulation was paused at 30 time points², when bitmap images were saved. The time points are unevenly distributed due to practical reasons. Figure 6 shows a representative selection of fingerprint images.

¹ See appendix A1.

² See appendix A2.

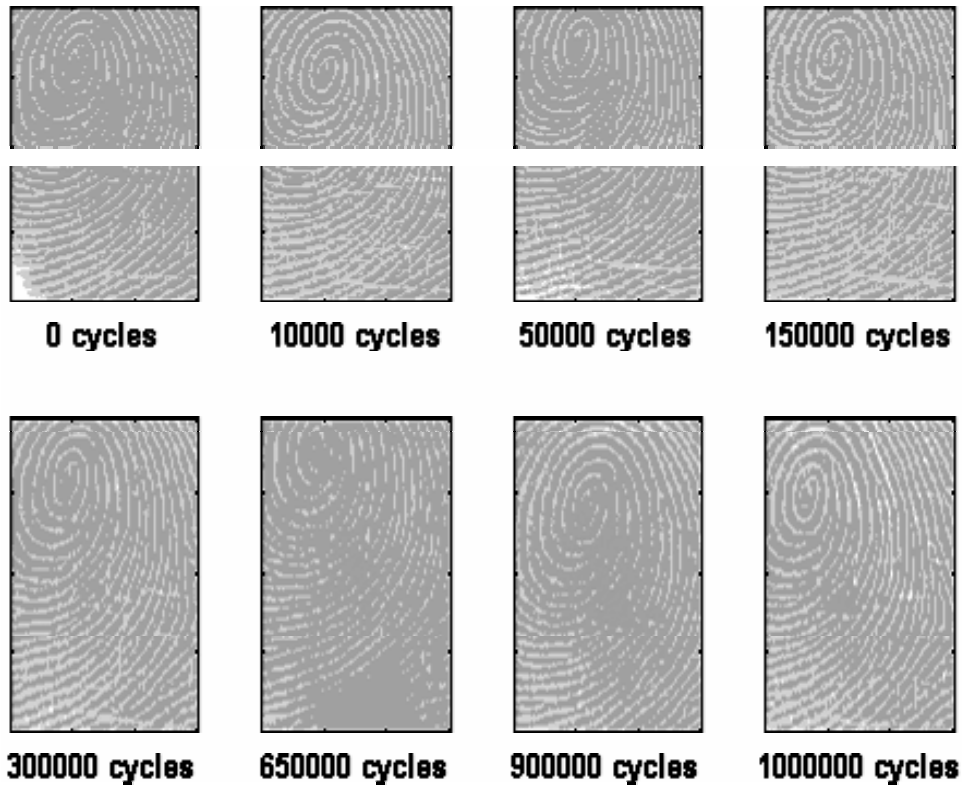


Figure 6 Simulation images

4. Analysis

The analysis is divided into two parts. The first part is a visual investigation of the surface after one million cycles, and the second part is an analysis of the captured fingerprint images.

A visual inspection does not give evidence for a degradation of the sensor. The artificial silicon finger was worn, see Figure 7. As a comment this finger has slid approximately 9 km over the sensor surface and the fingerprints were worn out.



Figure 7 The worn silicone fingertip.

The sensor surface was examined under an Olympus microscope in order to identify the different wear damages. We have identified three different types of damage.

1. Shallow scratches.
2. Surface cracks.
3. Small craters

These three damage types are illustrated in Figure 8. Damages 1. and 2. seems to be situated on the surface and are not deeper than a few μm . The small craters are also shown in higher magnification in Figure 9.

We used the microscope in order to estimate the overall decrease in surface thickness. The microscope has a micrometer focus adjustment and by focusing on the top of the surface and on the silicon substrate the thickness can be estimated. This investigation indicates that the overall wear of the surface was less than $2 - 3\mu\text{m}$. This result is in the neighbourhood of the measurement error.

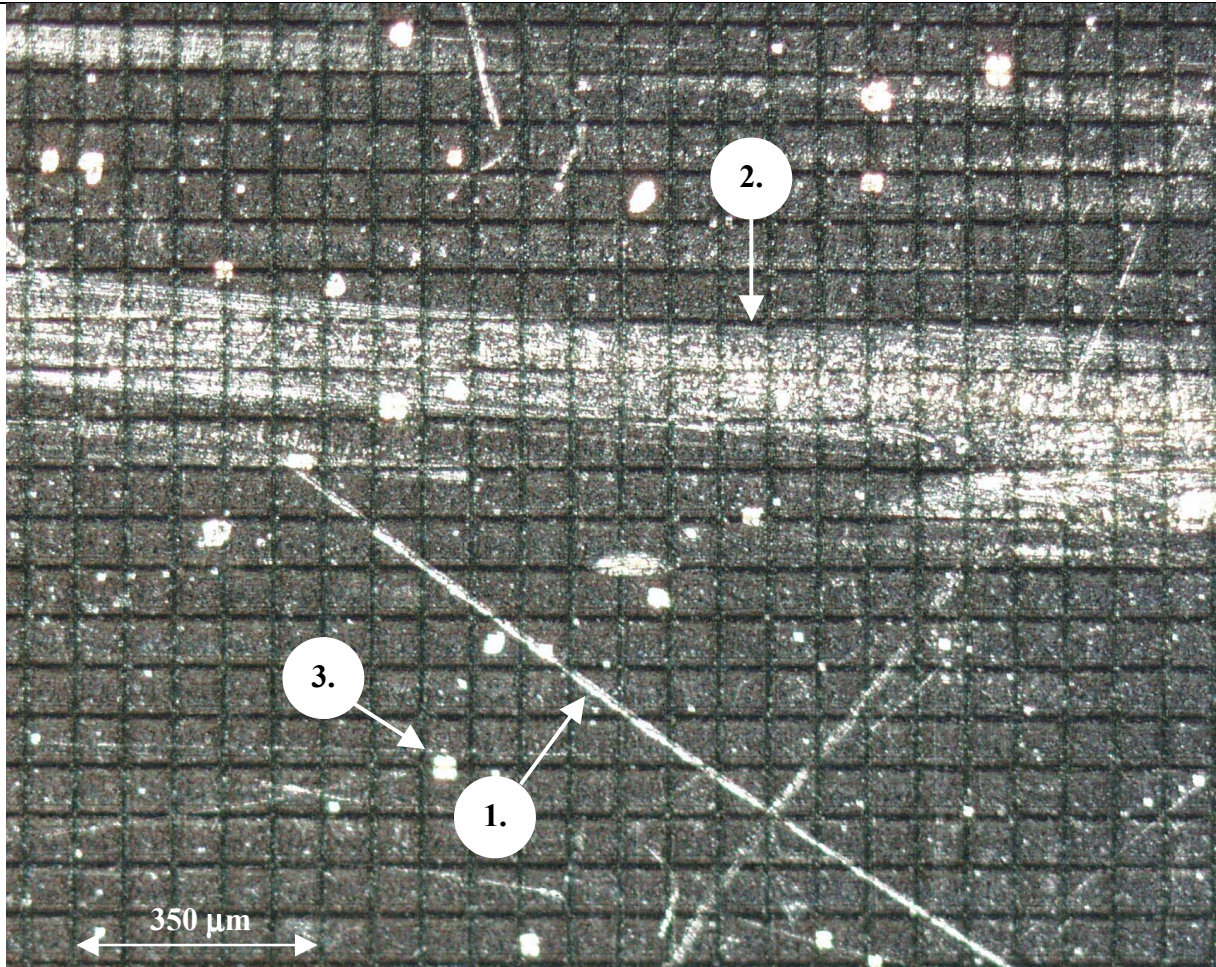


Figure 8 Sensor surface in microscope in polarized light.

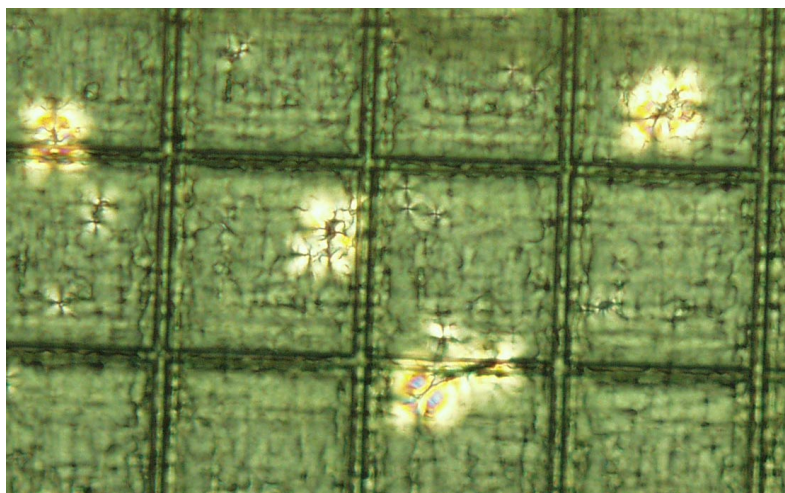


Figure 9 Point defects.

We shall now analytically study the images. It was easy to observe that the sensor was free from pixel failures. The images are recorded as bitmap images. This means that we analyse a matrix with 200 rows and 152 columns. Each number in the matrix can take a value between 0 and 255. 255 correspond to white colour and 0 to black colour. The matrix is transformed into a vector and this vector is analysed in a histogram. The reason for studying the histogram is that wear gives higher capacitance, which gives us a lower mean in the bitmap image. In Figure 10 histograms corresponding to the images shown in Figure 6 are drawn. The histograms range is between 220 and 255 due to the sensor and its software.

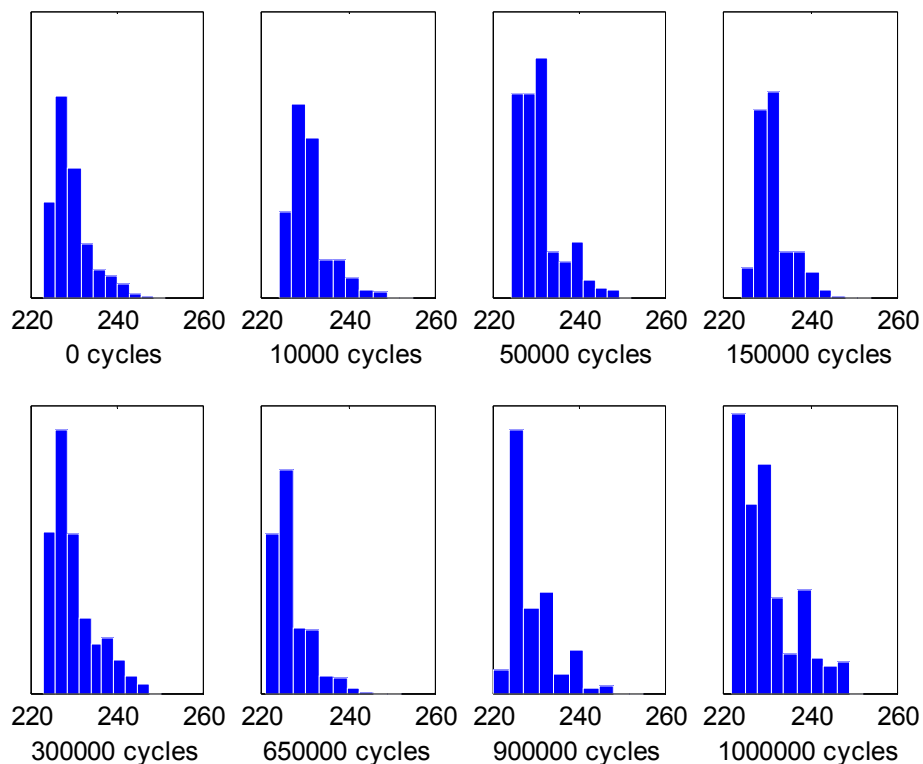


Figure 10 Selected histograms

The mean and standard deviation for each image³ were calculated and plotted versus number of cycles. The results are plotted in Figure 11 and Figure 12. A linear⁴ regression line with 95% confidence limits and a two-sided 95% prediction interval were calculated. Normal theory is used when both confidence and prediction limits are calculated. Figure 13 shows histograms of the residuals, i.e. the model error, and both histograms indicate that the residuals may be normally distributed.

A 95% confidence limit tells us that if the experiment were to be repeated many times at a time point, the mean will be between the limits with 95% probability. The prediction interval tells us that if we could measure one more observation, this value will fall within the prediction interval with probability 95%. Since the prediction interval is a statement of the future value of one observation, the interval is broader than the confidence limit, which tells us about average of the past observations.

As we can see, the measurements are not positioned exactly on the regression line but they are scattered randomly around the curve. The reason is that we have variation due to errors. The main sources of error are:

- Day to day variation of the author's finger. Wear, humidity et c. influences the fingerprint image.
- The position and the force of the finger is not exactly the same each test.

A future variation study should give us the size and sources of the errors.

³ See appendix A2 for a table of data.

⁴ See appendix A3 for motivation.

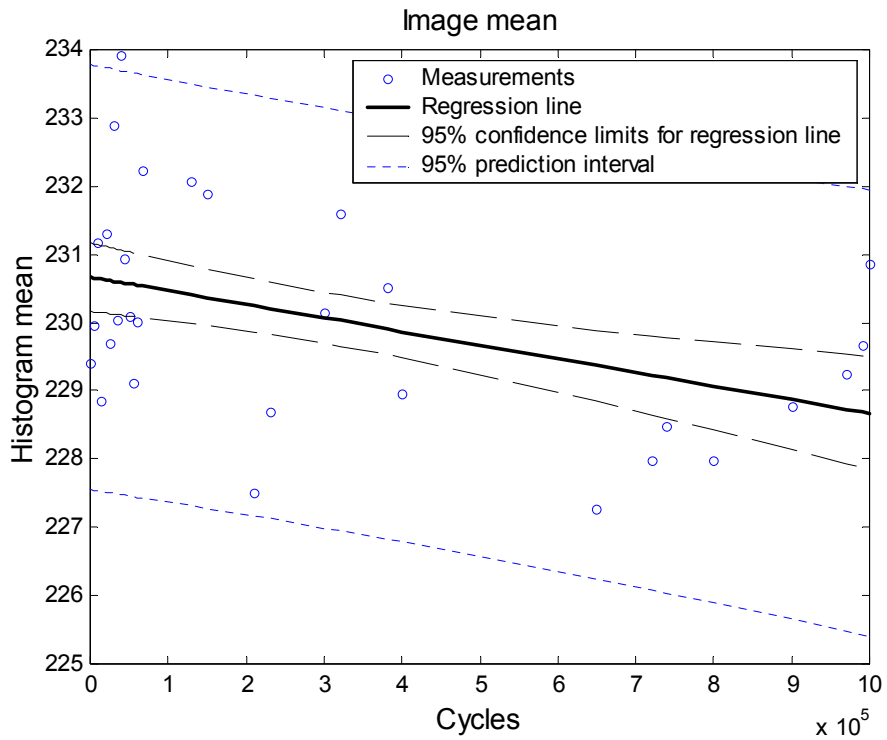


Figure 11 Histogram mean as function of number of cycles.

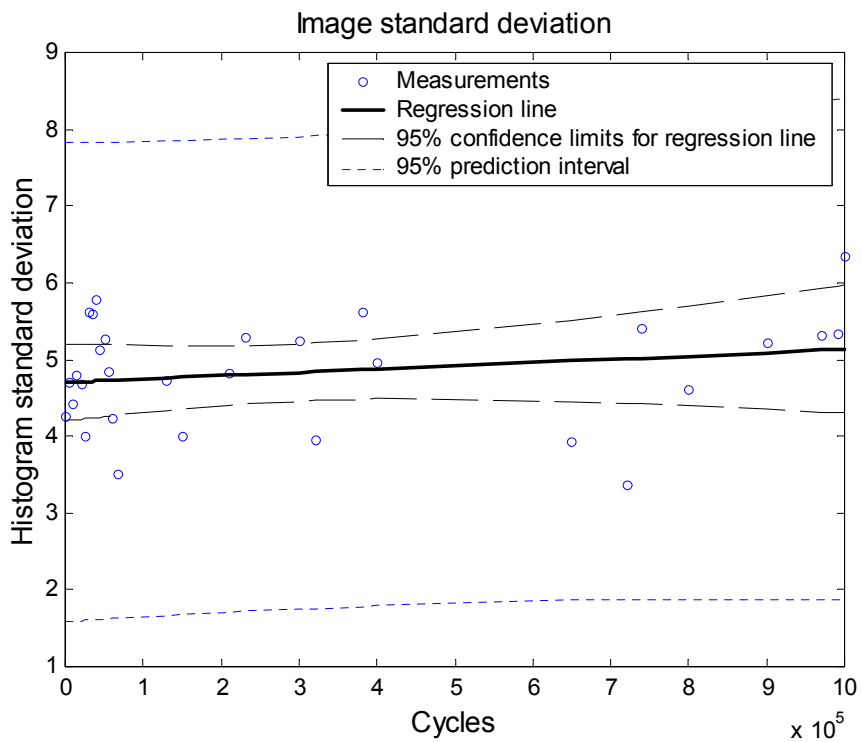


Figure 12 Histogram standard deviation as function of number of cycles.

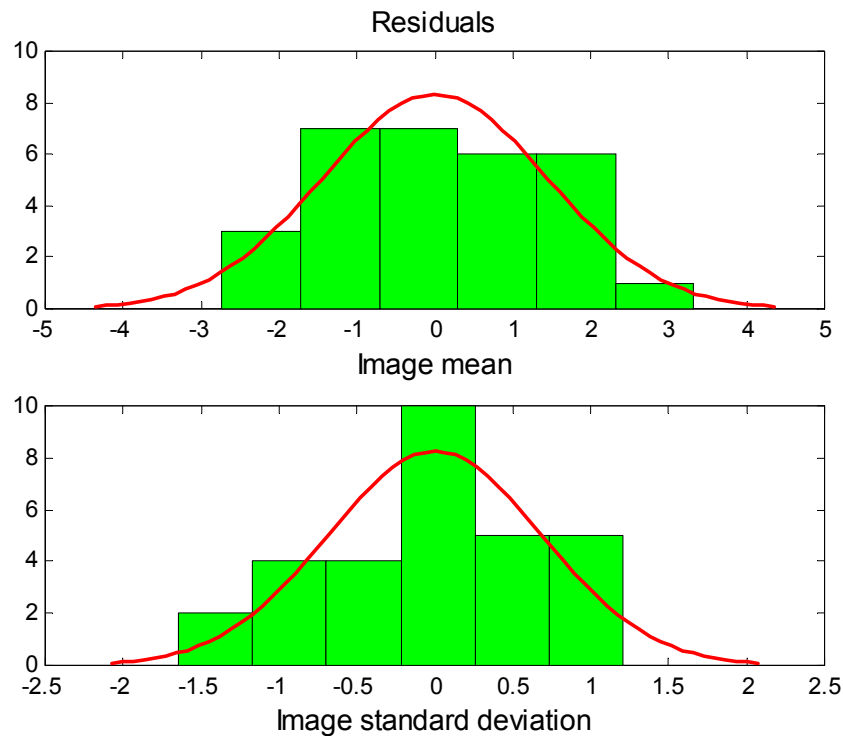


Figure 13 Residual histograms

The slope in the mean value histogram is -1.99×10^{-6} intensity units per cycle. Is this slope significantly lower than zero? The tool to answer this question is ANOVA, analysis of variance. We have performed an analysis⁵ and the result was that the hypothesis that the slope is just due to hazard could be rejected at significance level 0.05. This means that if the real slope were zero then the probability that the slope is equal or less than -1.99×10^{-6} intensity units per cycle by pure chance is less than 5%.

⁵ See appendix A4.

5. Conclusions

We have tested one sensor in a wear simulation machine during one million cycles. The finger slid 9 mm across the sensor and the force was approximately 6.43 N (655 g). The fingertip model was made by ordinary silicone. This experiment was conducted with one sample only. There were no replicas and we have therefore not gained any knowledge about the variation between different sensors and finger models. Microscope analysis has shown some wear on the surface of the protective layer and this corresponds to the observed negative slope in histogram mean.

The conclusion of this experiment is that the sensor is reliable under normal office use as defined in Chapter 1.

A1. The fingertip force

A fingerprint sensor was put on a letter scales and the fingerprint image of the right index finger was measured. During the measurement, the maximum reading from the letter scales was noted. This was repeated five times for each person and altogether 9 persons from a reference group were tested.

Person	Letter scales measurements (g)					Mean	Std
	1	2	3	4	5		
1.	303	321	340	253	215	286	51.4
2.	352	234	225	348	311	294	61.1
3.	185	154	217	236	178	194	32.5
4.	663	641	625	602	767	660	64.0
5.	313	267	233	263	245	264	30.5
6.	463	362	481	271	292	374	96.0
7.	273	160	219	198	179	206	43.5
8.	465	418	351	436	439	422	43.0
9.	689	670	718	743	591	682	58.1

Table 1 Fingertip force measurements.

In Table 1 we can see that the data range is between 154g and 767g. The largest value is almost five times the smallest value. The difference between individuals is much bigger than the difference between measurements. In this case it is obvious, but in other cases one statistical tool to show this is ANOVA analysis.

Five measurements from right index finger. 9 persons.

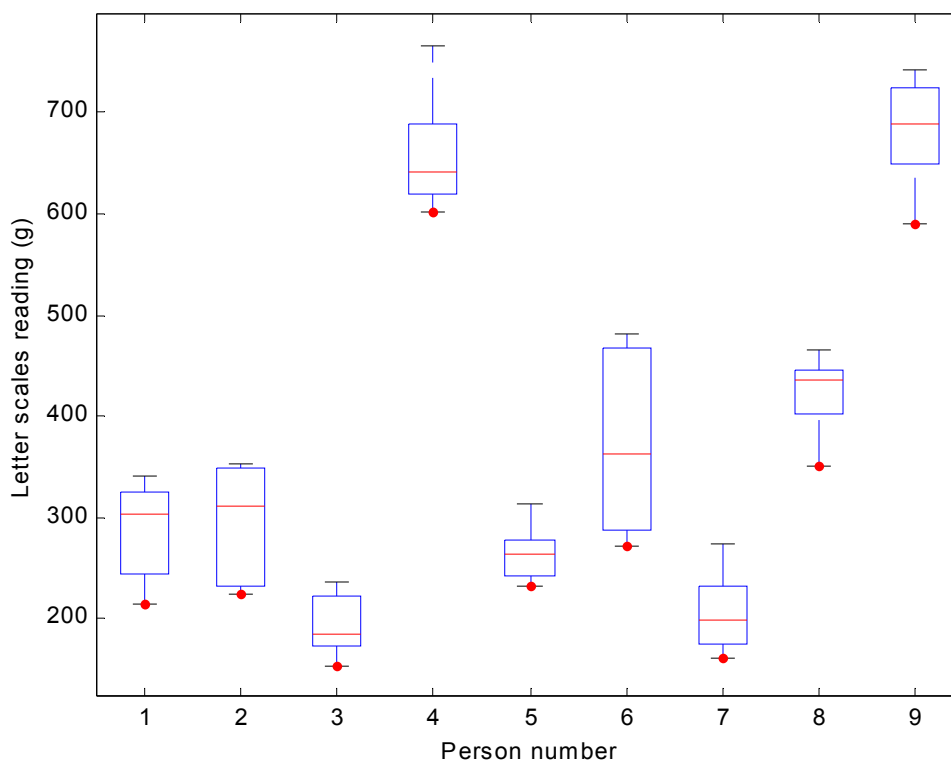


Figure 14 Box plot of experimental data.

In our experiment we chose by practical reasons a fingertip force of 655g. This turned out to correspond to the 87% percentile in the data shown Figure 15.

Empirical cumulative distribution of measured fingertip forces

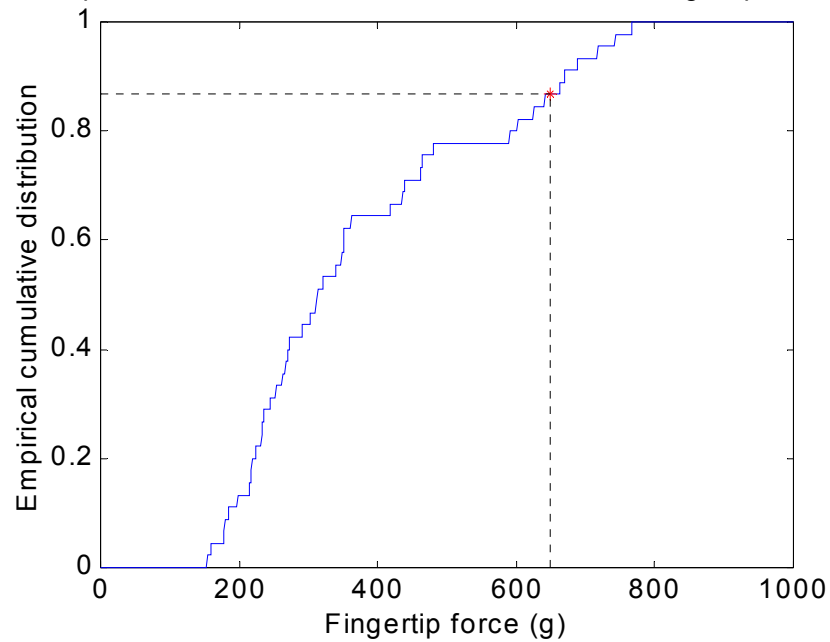


Figure 15 Empirical cumulative distribution of fingertip forces.

The corresponding force was easily calculated by the well known relationship $F = m \cdot g = 0.655 \cdot 9.81 \approx 6.43N$.

A2. Histogram data

Measurement time (cycles)	Histogram mean (intensity units)	Histogram standard deviation (intensity units)
0	229.4194	4.2693
5000	229.9543	4.6995
10000	231.1776	4.4259
15000	228.8572	4.7954
20000	231.3099	4.6880
25000	229.7048	4.0009
30000	232.8800	5.6121
35000	230.0462	5.6035
40000	233.9109	5.7898
45000	230.9323	5.1191
50000	230.0810	5.2649
55000	229.1065	4.8361
61000	230.0092	4.2487
68000	232.2267	3.5143
130000	232.0864	4.7316
150000	231.8944	4.0104
210000	227.5193	4.8212
230000	228.6992	5.2874
300000	230.1441	5.2565
320000	231.5903	3.9627
380000	230.5273	5.6281
400000	228.9626	4.9557
650000	227.2795	3.9237
720000	227.9825	3.3636
740000	228.4885	5.4207
800000	227.9799	4.6132
900000	228.7773	5.2216
970000	229.2542	5.3142
990000	229.6686	5.3374
1000000	230.8709	6.3395

A3. Arguments for using a linear relationship between bitmap value and number of cycles

The bitmap image value is a function of surface wear. This is illustrated in Figure 16 where also a linearisation is included. In Figure 11 and Figure 12 we have used a polynomial regression model of degree 1. Following arguments can motivate this linearisation.

Let

- n be the number of cycles,
- d_0 be the original surface thickness,
- d be the actual surface thickness,
- $w = d_0 - d$ be surface wear,
- C be capacitance,
- V be bitmap image value.

1. Surface wear w is proportional to number of cycles n .

2. Capacitance is proportional to the inverse of the surface thickness, $C \sim \frac{1}{d} = \frac{1}{d_0 - w}$

3. Bitmap image value is proportional to a constant – capacitance, $V = a - b \cdot \frac{1}{d_0 - w}$.

4. Since $w \ll d_0$ V can be linearised $V = a - b \cdot \frac{1}{d_0 - w} = a - b \left(1 + \frac{w}{d_0} + O\left(\left(\frac{w}{d_0}\right)^2\right) \right)$, which can be

simplified to $V = a' - b' \cdot \frac{w}{d_0}$, where a' and b' are constants.

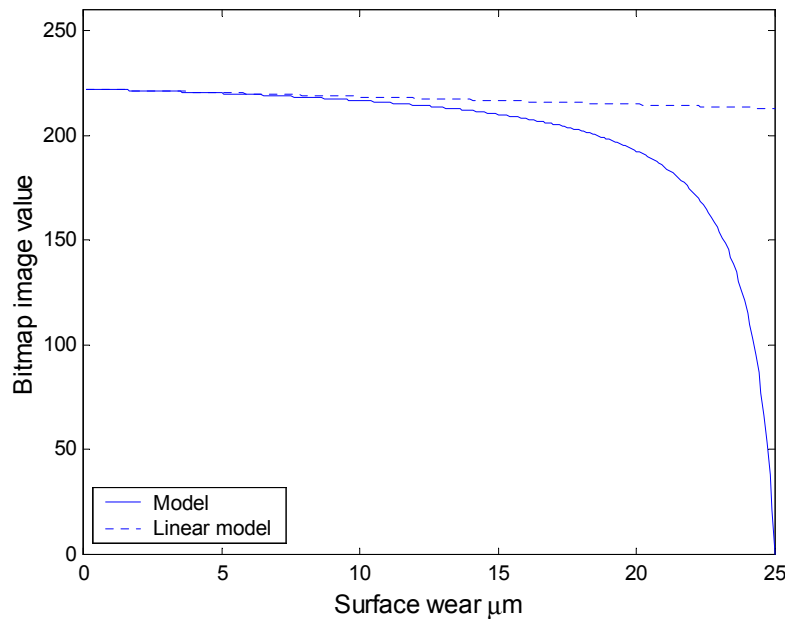


Figure 16 Bitmap image value as function of surface wear.

A4. Test of slope significance

The regression line can be modelled mathematically as

$$X_i = A + B \cdot t_i + \varepsilon_i, i = 1 \dots n$$

where t is number of cycles, A is the intercept and B is the slope. ε_i is the model errors of the model and n is the number samples. One interesting question is if it is possible to reject the hypothesis

$$H_0 : B = 0$$

against

$$H_1 : B \neq 0$$

at the level $\alpha = 0.05$. This question is interesting since the answer will tell us whether the slope is due to physics or to hazard.

The line regression parameters for the mean value were estimated⁶.

$$\hat{A} = 230.7$$

$$\hat{B} = -1.993 \times 10^{-6}$$

The sums of squares used in the analysis are shown in Table 2.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F ₀
Regression	$SS_R = \hat{B}S_{xy} = 14.3$	1	$MS_R = \frac{SS_R}{1} = 14.3$	$\frac{MS_R}{MS_E} = 6.55$
Residual	$SS_E = S_{yy} - \hat{B}S_{xy} = 61.1$	n-2 = 28	$MS_E = \frac{SS_E}{n-2} = 2.18$	
Total	$S_{yy} = 75.45$	n-1=29		

Table 2 Analysis of variance for testing significance of regression for the mean value.

If the model errors are assumed to be normally and independently distributed and the null hypothesis

$$H_0 : B = 0$$

is true then the test statistics $F_0 = \frac{MS_R}{MS_E}$ follows the $F_{1,n-2}$ distribution. A visual inspection of Figure 11

indicates that the model errors may be normally distributed and consequently we reject H_0 if

$$F_0 > F_{\alpha,1,n-2}$$

With $\alpha = 0.05$ and $n = 30$ $F_{\alpha,1,n-2} = 4.20 < F_0 = 6.55$. We can therefore reject the null hypothesis that all variation comes from the model error.

⁶ See any book on linear regression analysis. One good book is "Introduction to linear regression analysis" by Douglas C. Montgomery and Elizabeth A. Peck, 2:nd edition John Wiley & Sons, ISBN 0-471-53387-4.