Bachelor Work

Fingertip position sensor

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Abstract:
This paper is part of the bachelor work done in an exchange program between ETH Zurich and Northwestern University.
A fingertip position sensor, based on reaction forces, has been developed. The work includes explanation of the working principle of force measurement with strain gages, cantilever beam experiments, a theoretical model to get the finger position and the implementation of it. In the end there is also a discussion about how the device could be further improved to increase its accuracy and sensibility.

Acknowledgments:
I want to thank the members of the LIMS lab and the machine shop for their support and their useful hints. Especially I would like to mention John Glasmire, for letting me taking part in his project and advising me, Prof. Peshkin and Prof. Colgate for the many tips, as well as Bob and Rich for their help with the milling machines, used to produce the device.

Index

1. Introduction

1.1 Task Description

“A new type of tactile display based on ultrasonic vibration is under development at the Laboratory for Intelligent Mechanical Systems. This Bachelor Work project aims at developing a fingertip position sensor for use with the tactile display. The sensor concept is based on measurement of vertical reaction load at a minimum of three support points. The metrics for success are:

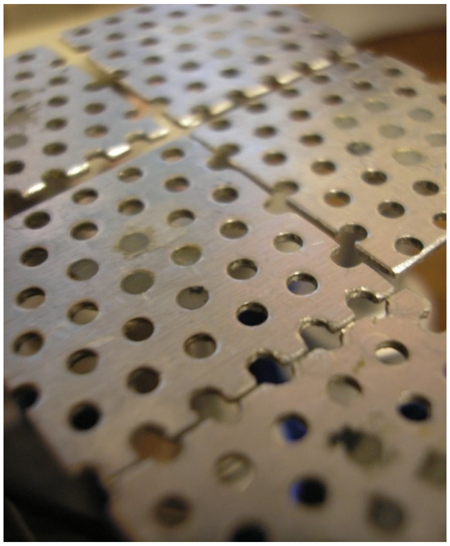
- Development of a mathematical model of the sensor and use of this model to create a decoding algorithm (i.e., one that converts sensor signals into fingertip location)
- Design of the sensor, including mechanical and electronic components ·
- Fabrication of the sensor, including strain gage flexure elements, mounting of strain gages, fabrication of electronics, wiring
- Interface to a real-time computer system
- Development of real-time computer code under QNX for reading sensor signals and computing finger location
- Interface to tactile display (in collaboration with the student developing the display)“

Ed Colgate

1.2 The Tactile Display

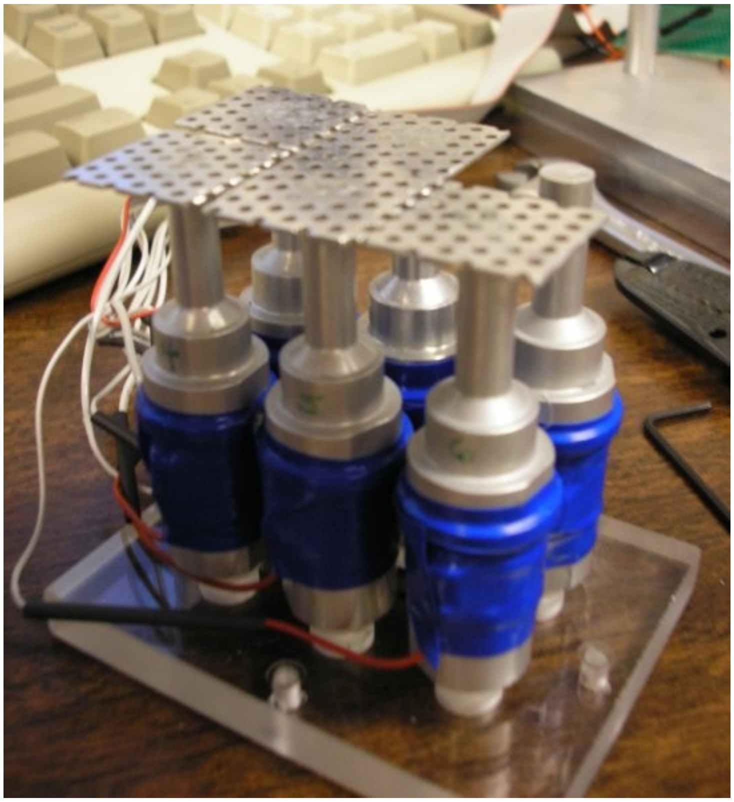
The tactile display developed by John Glasmire at the Laboratory for Intelligent Mechanical Systems, Northwestern University, is a device with a vibrating surface, that changes its surface friction at different frequencies.

The exact working principle that leads to different surface frictions by changing the frequencies is, at the moment this paper is written, still part of research and not yet completely resolved. Theories vary from reduced friction due to less contact time, stick-slip and a thin air film on the surface, on which objects float. Currently the last explanation is the most favored by John Glasmire.



Surface of the tactile display

The aim of this bachelor work is to develop a position feedback for this display. With this feedback, the friction could be changed, according to the position of the finger touching the display, creating imaginary surface structures.

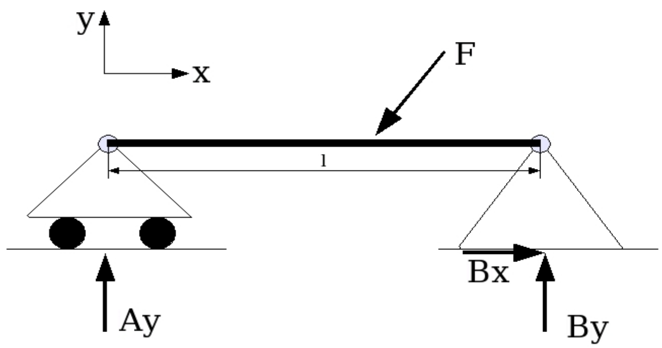


Side view of the tactile display

1.3 First considerations

For the development of the fingertip position sensor it is not necessary to know the exact working principle of the tactile display, and it can thus be simplified as a black box in the further considerations.

In 2D, the calculation of the coordinates of an applied force is applied is rather simple.

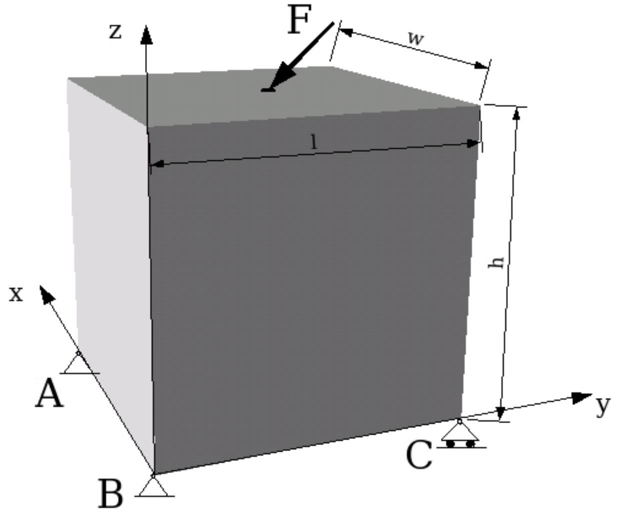


Sum of forces in x-direction: $F_x + B_x = 0$
Sum of forces on y-direction: $F_y + A_y + B_y = 0$
Sum of Moments in point A: $F_y * x + B_y * l = 0$

Thus $x = \frac{-B_y * l}{F_y}$, with $F_y = -A_y - B_y$ *(Equation 1)*

Going from the 2D cantilever to a 3D cube, the same equations apply, but instead of three unknowns (F_x, F_y, x), we have now six unknown entities (F_x, F_y, F_z , x, y, z).

To obtain a solvable set of equations, at least three measuring points are needed.



In point B the cube is constrained in x, y and z direction, but free to tilt, while in point A just y and z are constrained (no force can be taken in x-direction) and in C just the z-direction movement is restricted. This leads to the following equations:

Sum of forces in X-Direction:	$B_x + Fx = 0$	(1)
Sum of forces in Y-Direction:	$A_y + B_y + F_y = 0$	(2)
Sum of forces in Z-Direction:	$A_z + B_z + C_z + F_z = 0$	(3)
Sum of moments around X-Axis:	$-C_z * l - F_z * y + F_y * h = 0$	(4)
Sum of moments around Y-Axis:	$A_z * w + F_z * x - F_x * h = 0$	(5)
Sum of moments around Z-Axis:	$-A_y * w + F_x * y - F_y * x = 0$	(6)

(4) and (5) give us the relations to obtain x and y:

$$y = \frac{F_y * h - C_z * l}{F_z} \quad \text{and} \quad x = \frac{F_x * h - A_z * w}{F_z} \qquad \textit{(Equations 2)}$$

with $F_z = -A_z - B_z - C_z$ (3), $F_x = -B_x$ (1) and $F_y = -A_y - B_y$ (2)

Equations 2 would be much simpler, when h would be 0 and the cube become an planar surface. This effect however can be obtained by shifting the supporting points A, B and C in the top plain. Equations 2 become:

$$y = \frac{-C_z * l}{F_z} \quad \text{and} \quad x = \frac{-A_z * w}{F_z} \text{ , with } F_z = -A_z - B_z - C_z \qquad \textit{(Equations 3)}$$

This is a very nice result, as we now just need to measure three instead of six forces, to obtain the x- and y-coordinates.

2. Force measurement with strain gages

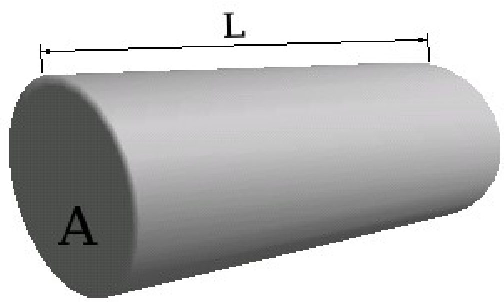
To measure the forces, cantilever beams with mounted strain gages will be used. There are other methods of force measurement, for example piezo-crystals, but strain gages are chosen, first because defined so in the task description, and second, because of their rather linear behavior and simple application.

2.1 Working principle of strain gages

Metal foil strain gages

The resistance of a metal wire depends on the material resistivity ρ , the length and the cross-section area and can be calculated as:

$$R = \frac{\rho * L}{A}$$

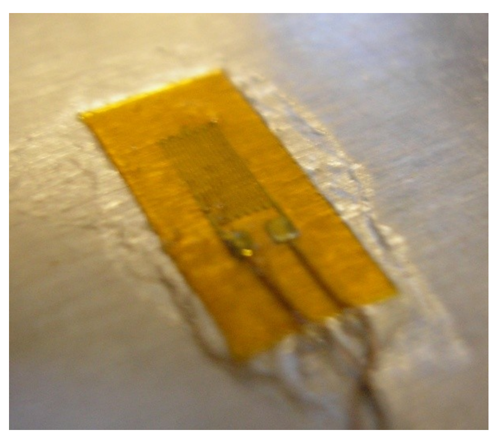


Metal-foil strain gages use this, as the deformation of a wire will result in a change of its resistance. The correlation between resistance change and strain is called gage factor GF.

$$GF = \frac{\Delta R / R}{\Delta L / L} \quad \text{with} \quad Strain(\varepsilon) = \Delta L / L$$ [2] *(Equation 4)*

Metal foil strain gages usually have a gage factor around two.

In metal-foil strain gages the wire is turned several times to make it as long as possible, leading to an increase of the absolute resistance change. By mounting the strain gage directly on the surface of an object, the deformation of the strain gage is related to the deformation of the object, and the resistance change is proportional to the surface strain.



Metal-foil strain gage mounted on a surface

Strain gages can thus be used to measure the forces applied on an object by the caused deformation.

$$\varepsilon_x = \frac{\sigma_x}{E} - \frac{\nu * \sigma_y}{E} + \alpha * \Delta T \qquad \text{(Equation 5)}$$

With $\sigma_{x,y}(stress) = \frac{F_{x,y}}{A_{x,y}}$, E, ν, α :Material constants, ΔT :Temperature change

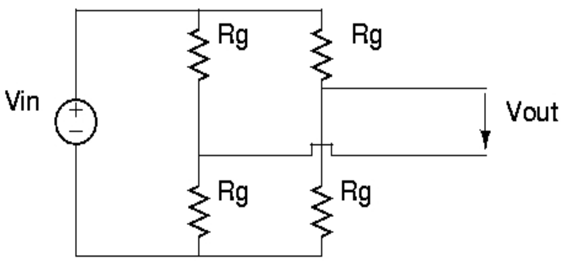
Equation 5 shows that, unfortunately, the strain depends also on the temperature. Further on, the resistivity itself also changes with temperature. Thus, if the temperature can not be kept at a constant level, a correction has to be done. An other source of error is the bonding between strain gage and surface: A gliding glue can effect that the strains are not directly transmitted.

Semiconductor Strain Gages

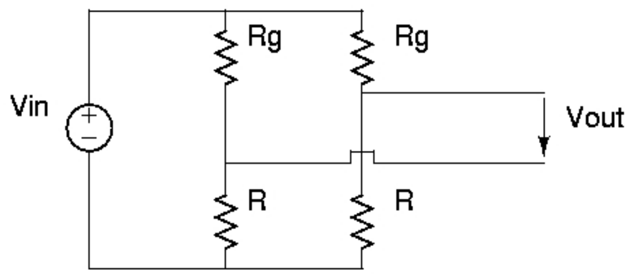
Semiconductor strain gages depend on a different working principle. The resistance change in this strain gages is caused by piezoresistive effects of the used semiconductors. Thus, they measure the change in stress, rather than the change in strain, as metal-foil strain gages do. [2]
The gage factors obtained by the semiconductor strain gages are about fifty times higher as the factors of their metal counterparts. The major drawback is their nonlinearity, what makes software corrections necessary.

2.2 Signal reading - the Wheatstone bridge

There are several approaches to measure the rather small resistance changes of strain gages. The most popular one is probably the Wheatstone bridge, where one, two or four strain gages are placed in the arms of the bridge.



Full bridge



Half bridge

Different configurations are possible. So can just one strain gage (Rg) be used for measurements, while the other strain gages are just dummy-resistors, or strain gages can be attached to opposite sides of a cantilever beam, thus doubling the output signal of the Wheatstone bridge.
In the half bridge, two resistors with the same nominal resistance as the strain gages are inserted to complete the bridge. In the perfect balanced bridge, Vout, measured between the two arms should be zero. A small change in one of the strain gage resistances will now unbalance the bridge, leading to an output voltage Vout.

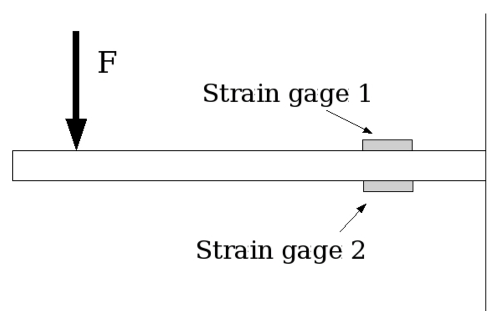
In the case of the measurement with a cantilever beam featuring two strain gages on opposite sites (half-bridge), the relation between strain and output voltage can be computed the following way:

$$V_{OUT} = \frac{V * R_0 * (1+\varepsilon * g)}{R_0 + R_0 * (1+\varepsilon * g)} - \frac{V * R_0 * (1-\varepsilon * g)}{R_0 - R_0 * (1+\varepsilon * g)}$$

$$V * R_0 * \left(\frac{(1+\varepsilon * g)}{(2+\varepsilon * g)} - \frac{(1-\varepsilon * g)}{(2-\varepsilon * g)}\right)$$

with nominal resistance R_0 and strain gage resistances $R_0(1+\varepsilon * g)$, $R_0(1-\varepsilon * g)$ resp. g=Gain Factor

(Equation 6)

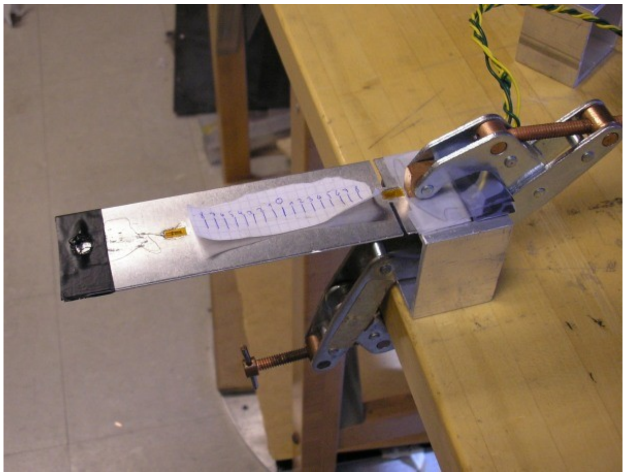


Cantilever with two strain gages attached on opposite sides.

The benefit of this configuration is not only the doubled Wheatstone bridge output, but also that temperature induced resistance changes cancel themselves out.

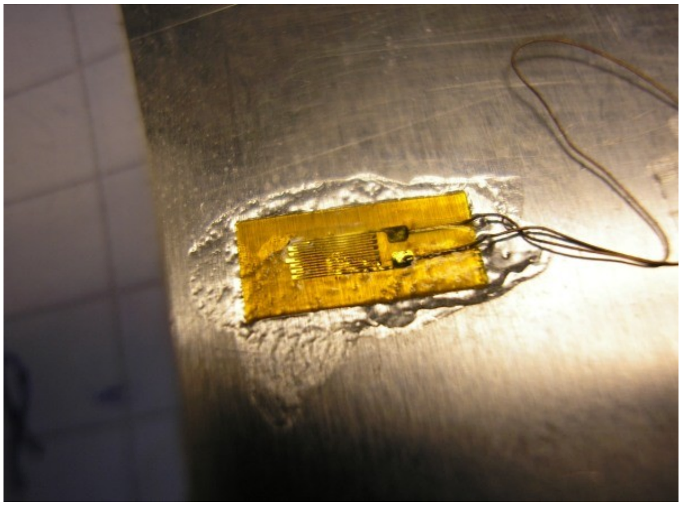
2.3 Cantilever experiments

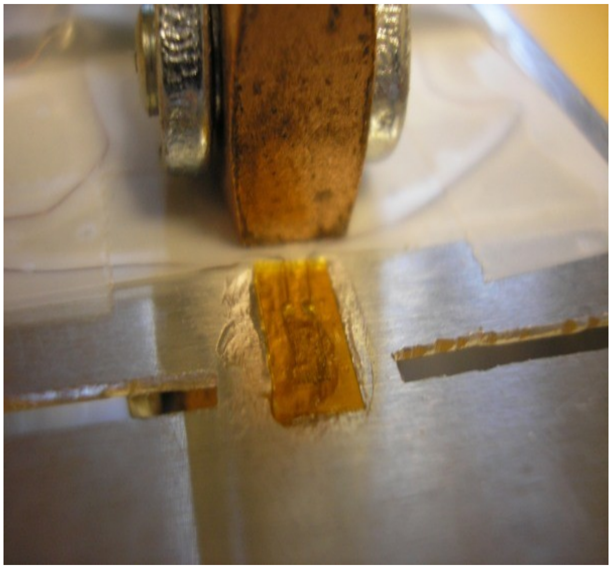
In order to get some practical experience with strain gages and to know the behavior of cantilever beams, some basic cantilever experiments have been done first.


Cantilever with two strain gages

Mechanical part

Four strain gages with nominal resistance 120 Ohm have been glued on a metal plate, serving as the cantilever beam, using a loctyte super glue for multiple materials.
An important lesson already obtained at this point is, that the isolation of the strain gages is very critical, as the thin copper wires tend, when bended, to make instable contacts to the metal surface, leading to unpredictable resistance behavior. Taking first measurements with an Ohmmeter showed, that the changes obtained are not measurable. Thus the metal beam has been sliced on the supporting side, first to weaken the structure, allowing more deformation, and second to concentrate the main bending in the spot the strain gage is placed.
The other part of the beam has not been sliced, as just the two strain gages on the supporting part are used in the further measurements. The two strain gages per side have been chosen to cancel out temperature dependencies in the Wheatstone bridge (The two strain gages should build a thermal equilibrium by exchanging heat trough the metal).


Strain gage glued on metal surface

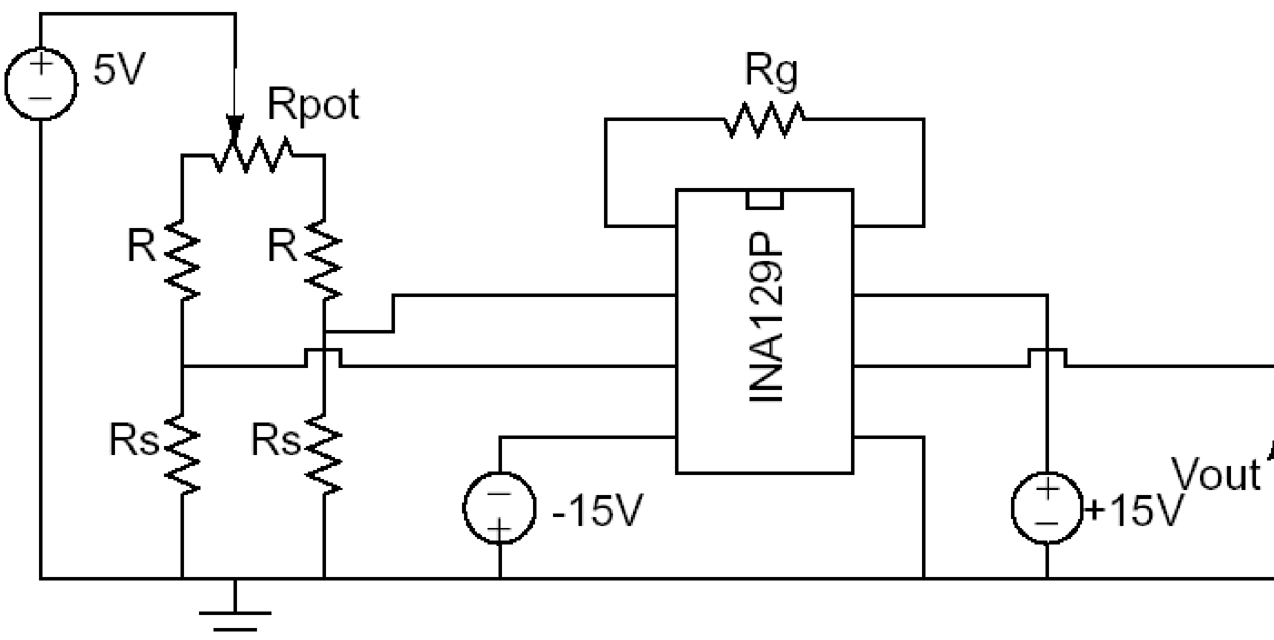

Strain gage and slices on the supporting side

Electrical part

To read the resistance, as discussed before, a Wheatstone half bridge was used. But as the voltage signal of the bridge still is in the millivolt range, a further amplification, using an INA129P Op-amp with controllable gain, is necessary.
Because the bridge is unlikely to be balanced on the default position, a potentiometer serves to balance the arms.

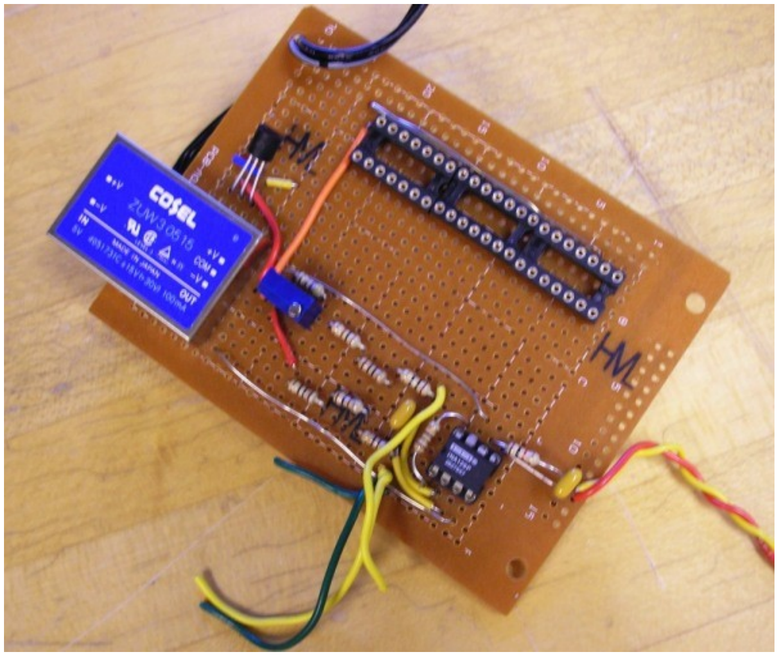
The following electrical parts have been used:

Rpot:	0-50 Ohm
R:	120 Ohm
Rs:	Omega Strain Gages SG-3/120-LY13, 120 Ohm nom. Resistance
INA129P:	Low power Op-Amp with adjustable gain: G=1+49.4kΩ/Rg
Rg:	10 Ohm -> Op-Amp Gain=4941
Power Supply:	5V transformer and Cosel Cosel ZUW3 05 15, 5 to +/- 15 Volt Power supply



Schematics of the electrical part

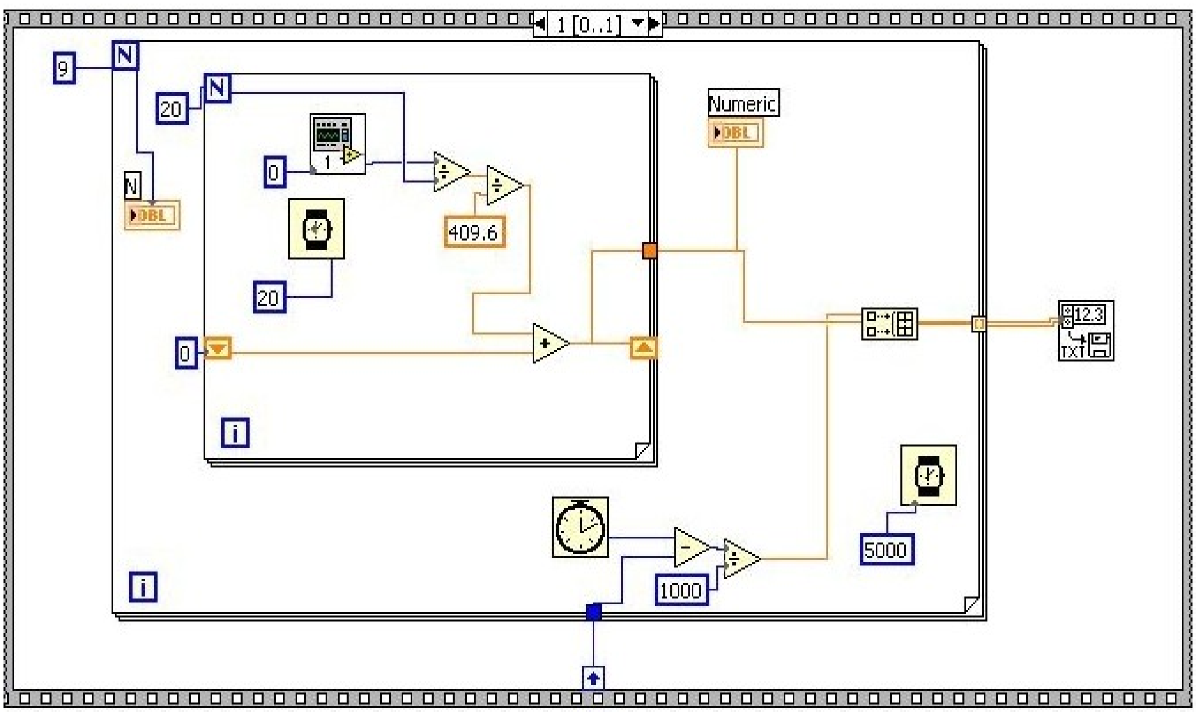
As you can see in the picture of the electrical part, later, 1 F condensers have been inserted across Op-Amp in- and output, as well as a 1kΩ resistor on the output to filter out noise recorded in the first readings.
Another modification that has been done, is to insert a 5 Ohm resistor parallel to the potentiometer to make the adjustable range smaller but more accurate. Further on, it became necessary to insert a LM78L05 5V-voltage regulator, as the 5 Volts obtained directly from the transformer where very noisy.



Picture of the electrical part

Data acquisition

To read and analyze the data, a LabView program was written.

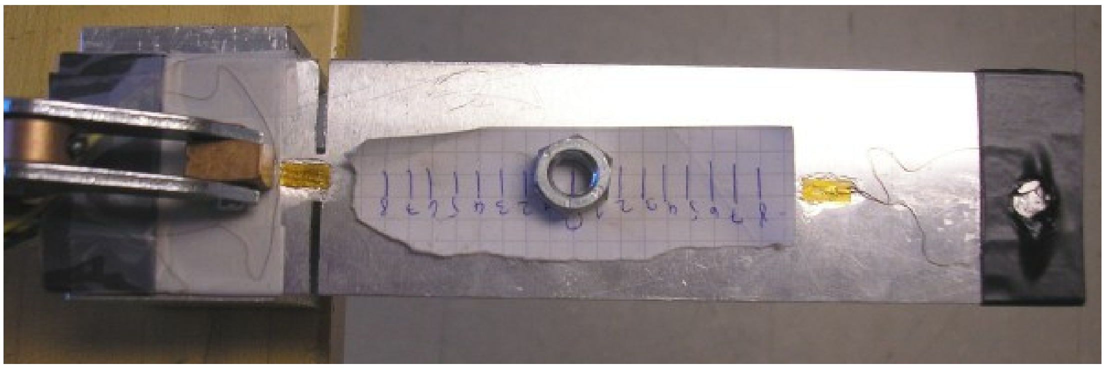


LabView Program

The program featuring a moving average filter abd taking 20 readings per averaged output, acquires a certain number of measurements (in this case 9) and writes them together with a time stamp to a text file that then can be further analyzed.

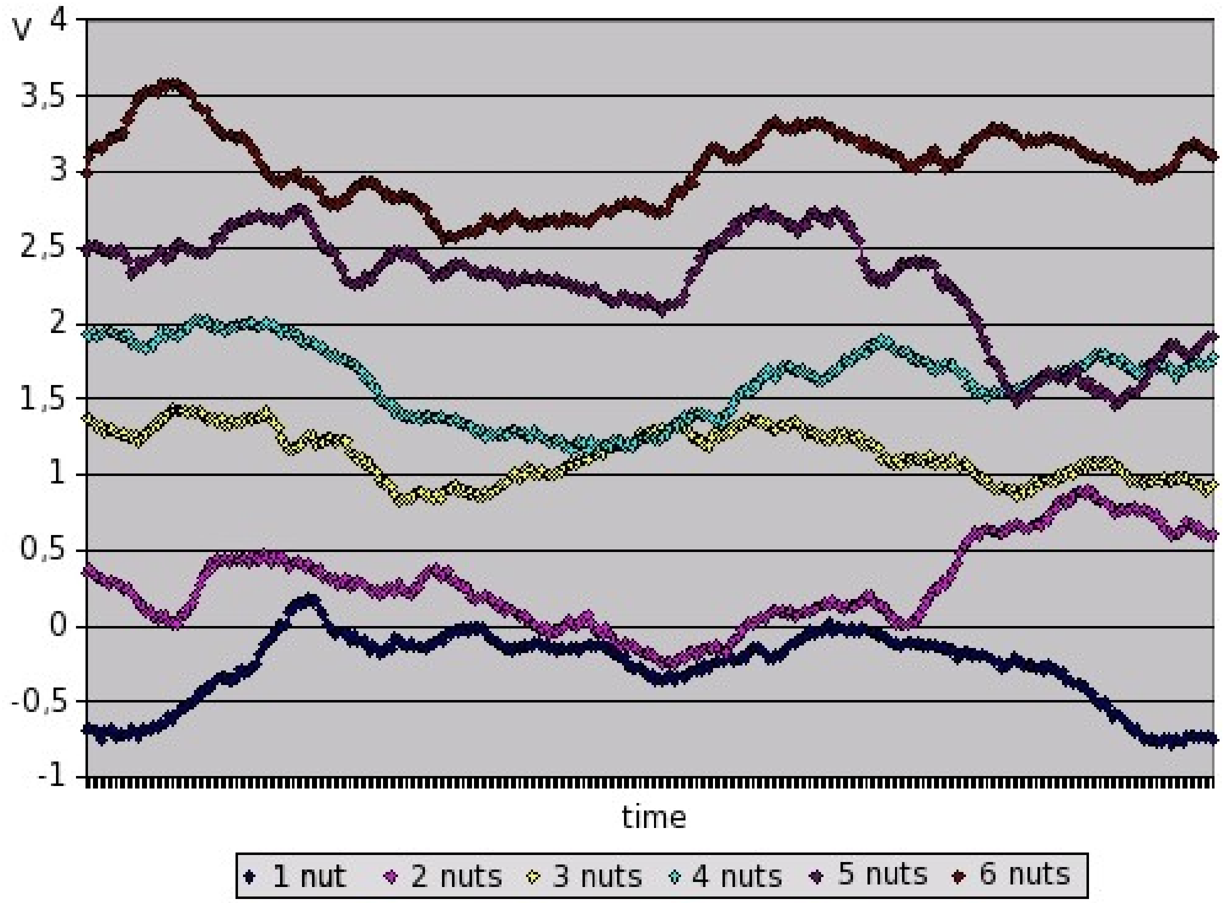
First readings

To take some first measurements with the LabView program described before, a scale has been put on the cantilever beam, on which nuts could be placed and moved to different positions. (The aim of this test was to get qualitative informations, thus the exacts weights in grams are not needed and the nut serves as basic unit)

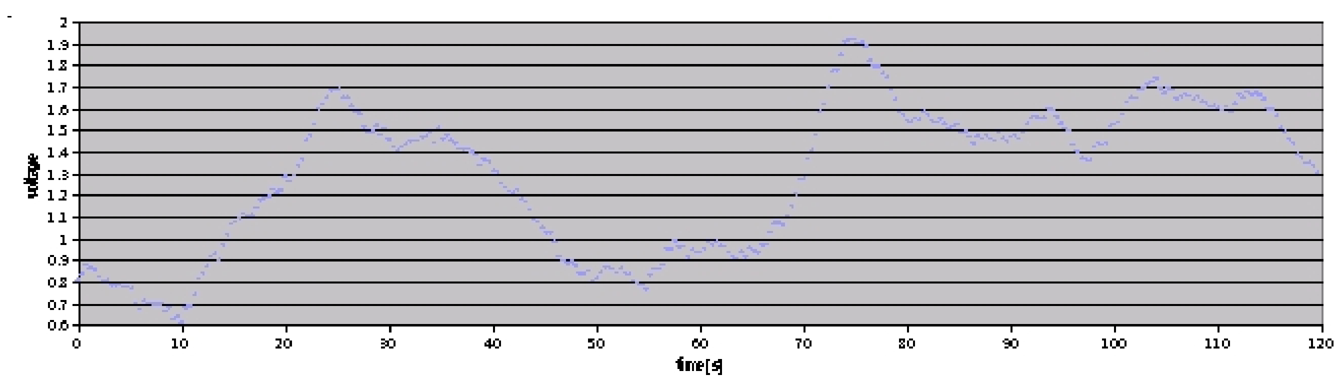


Top view of cantilever with nut

As you can see on the following graphs, the signal was rather noisy, no linearity was showed and no repeatability obtained, as the signal drifted around immensely.
This lead to the already discussed modifications of the circuitry by introducing low-pass filters before and after the Op-Amp as well as the 5V-Voltage regulator.



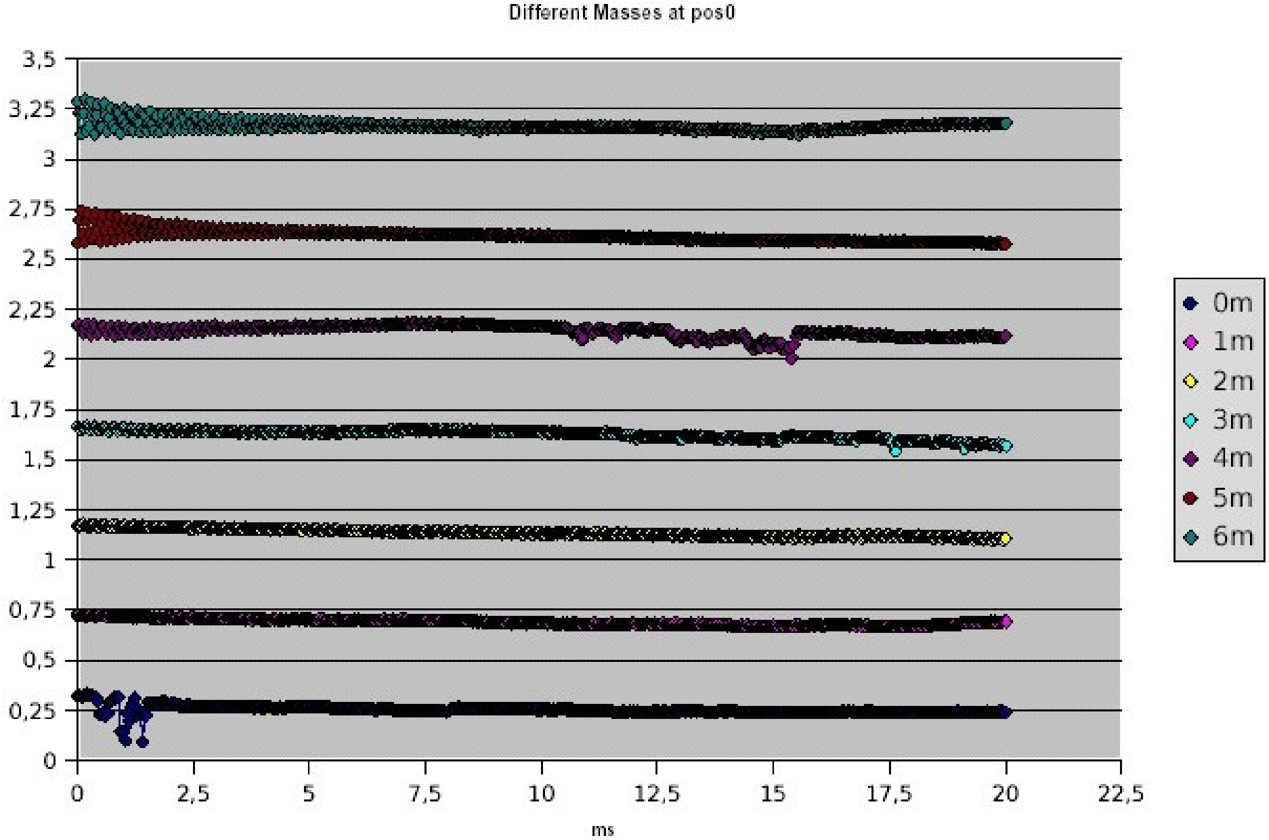
Different weights at position -8 (point on the scale with the biggest distance to the support):Some linearity in weight vs. voltage, but very noisy and drifting.



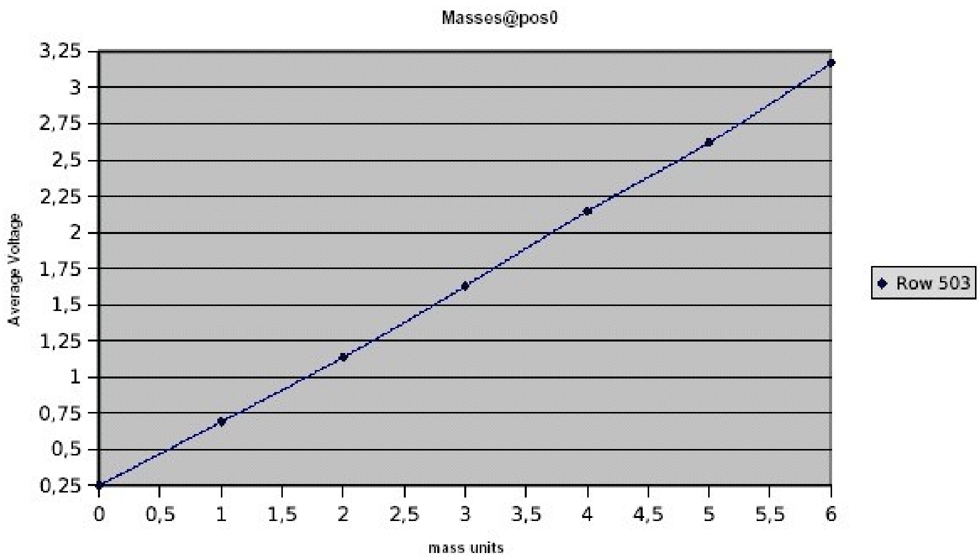
Longtime measurement over 120 seconds, 6 nuts at position zero:
Drift with an amplitude of 1.3 Volts.

Cantilever-Tests

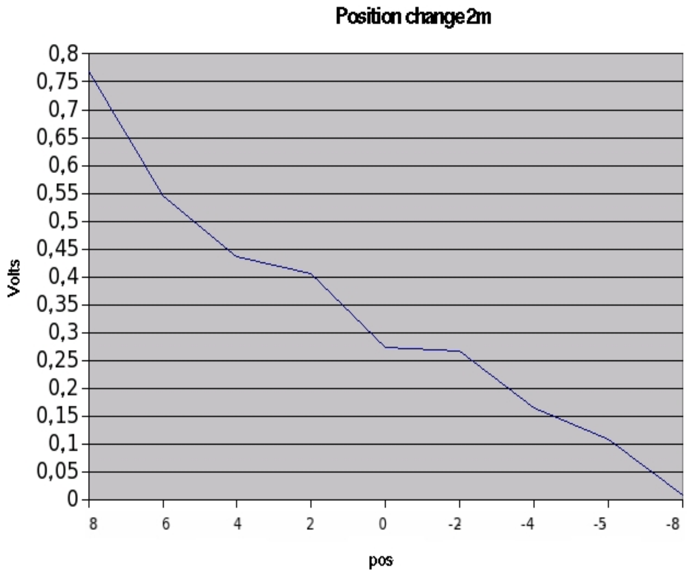
After the this adaptations, similar tests with much better results have been done.



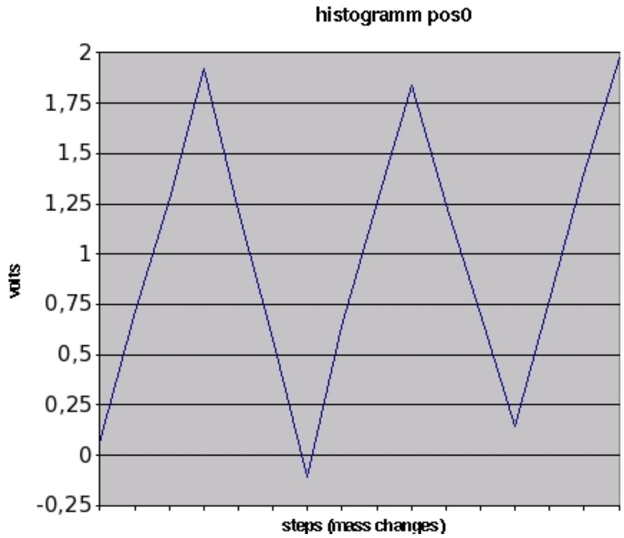
1-6 nuts on position 0, Voltage vs. time: little noise, small drift. Especially the 5 and 6 nuts readings show a swinging in.



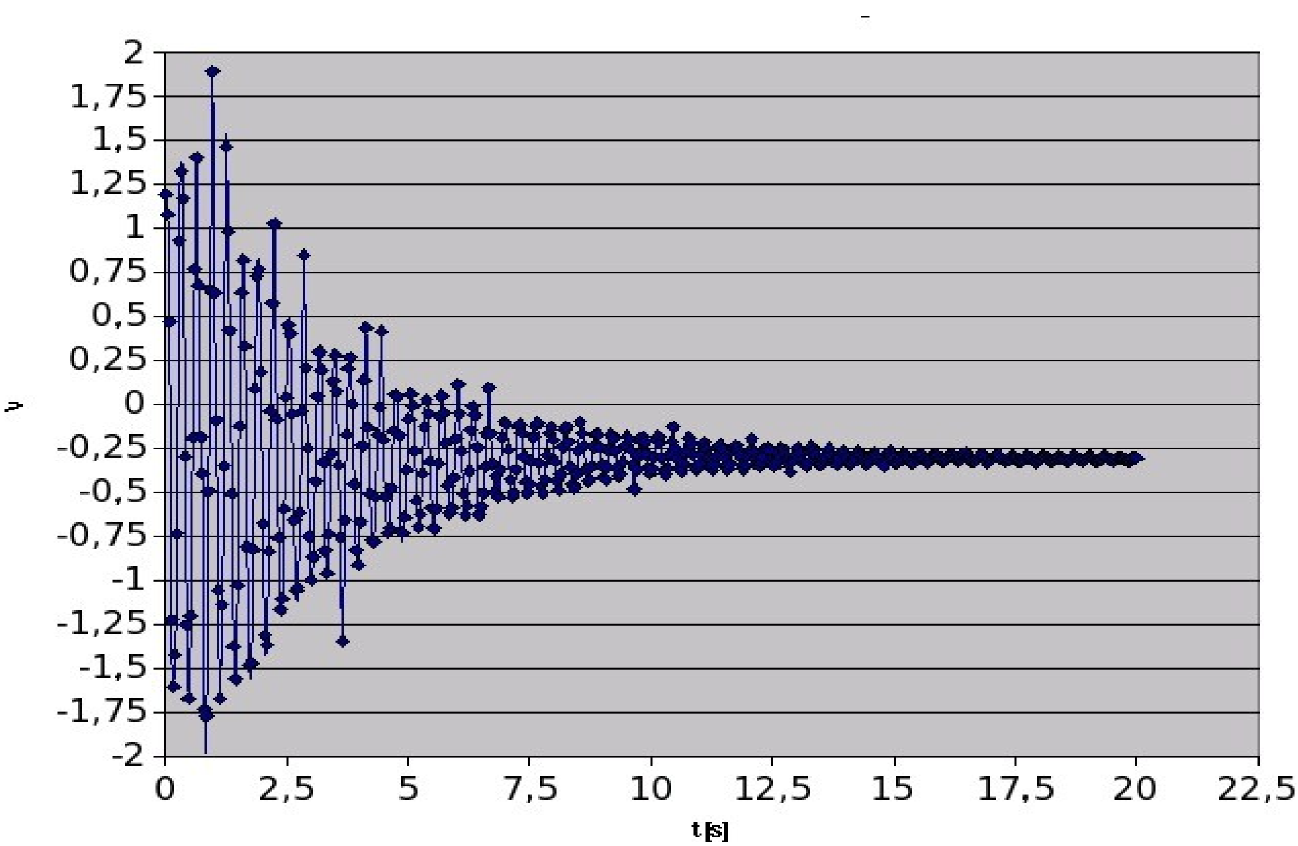
Plotting the same data as masses vs. voltage shows an almost perfect linearity



Changing the position of a mass (two nuts) gives a more or less linear signal



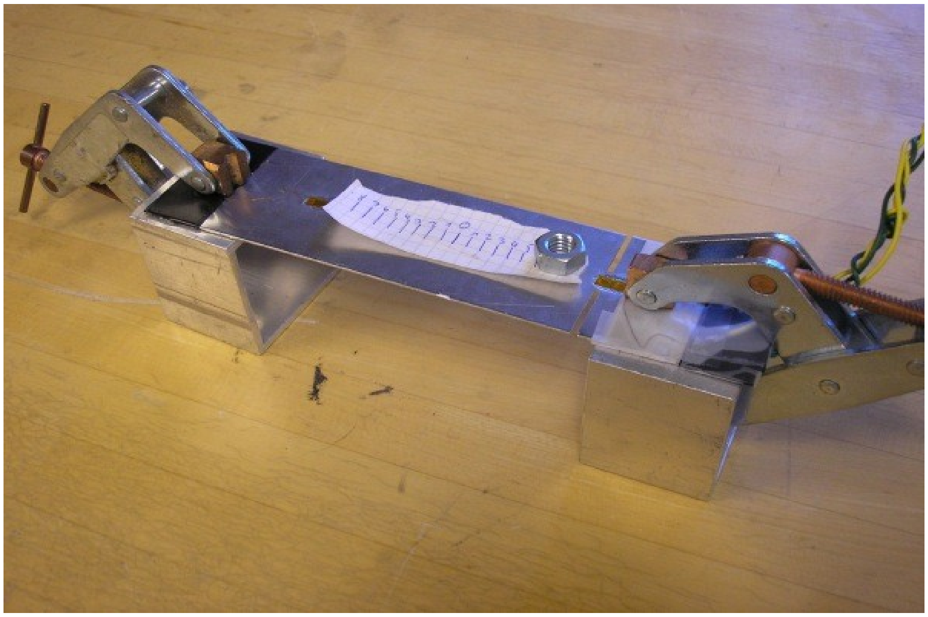
The number of nuts on position zero is changed between 0 and 3. The hysteresis showed is not too bad.



Swinging of the cantilever: Even the swinging in of an exited cantilever can be measured.

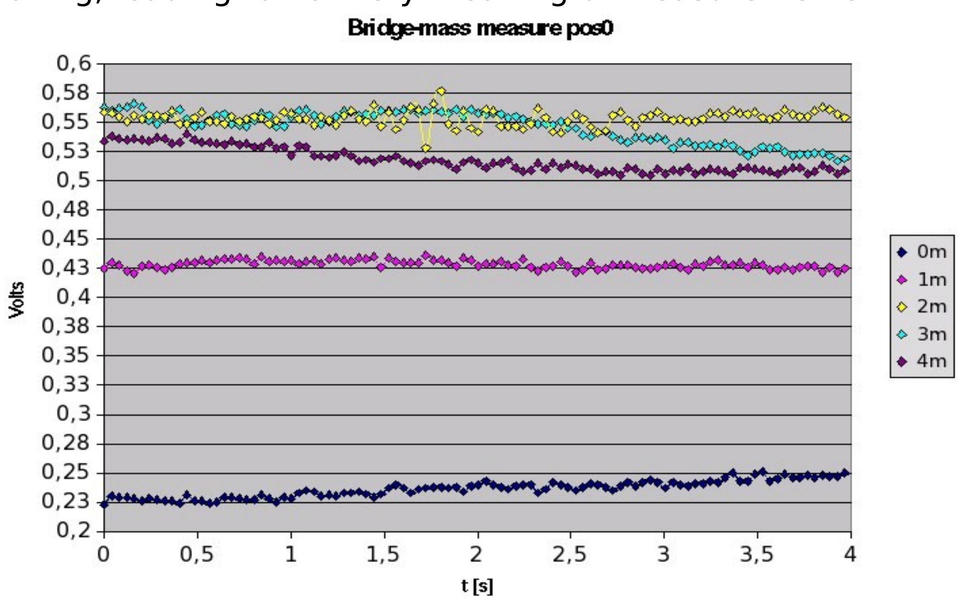
Bridge Tests

Encouraged from these successes, a bridge configuration was set up for testing by simply clamping the other end of the cantilever on a post.



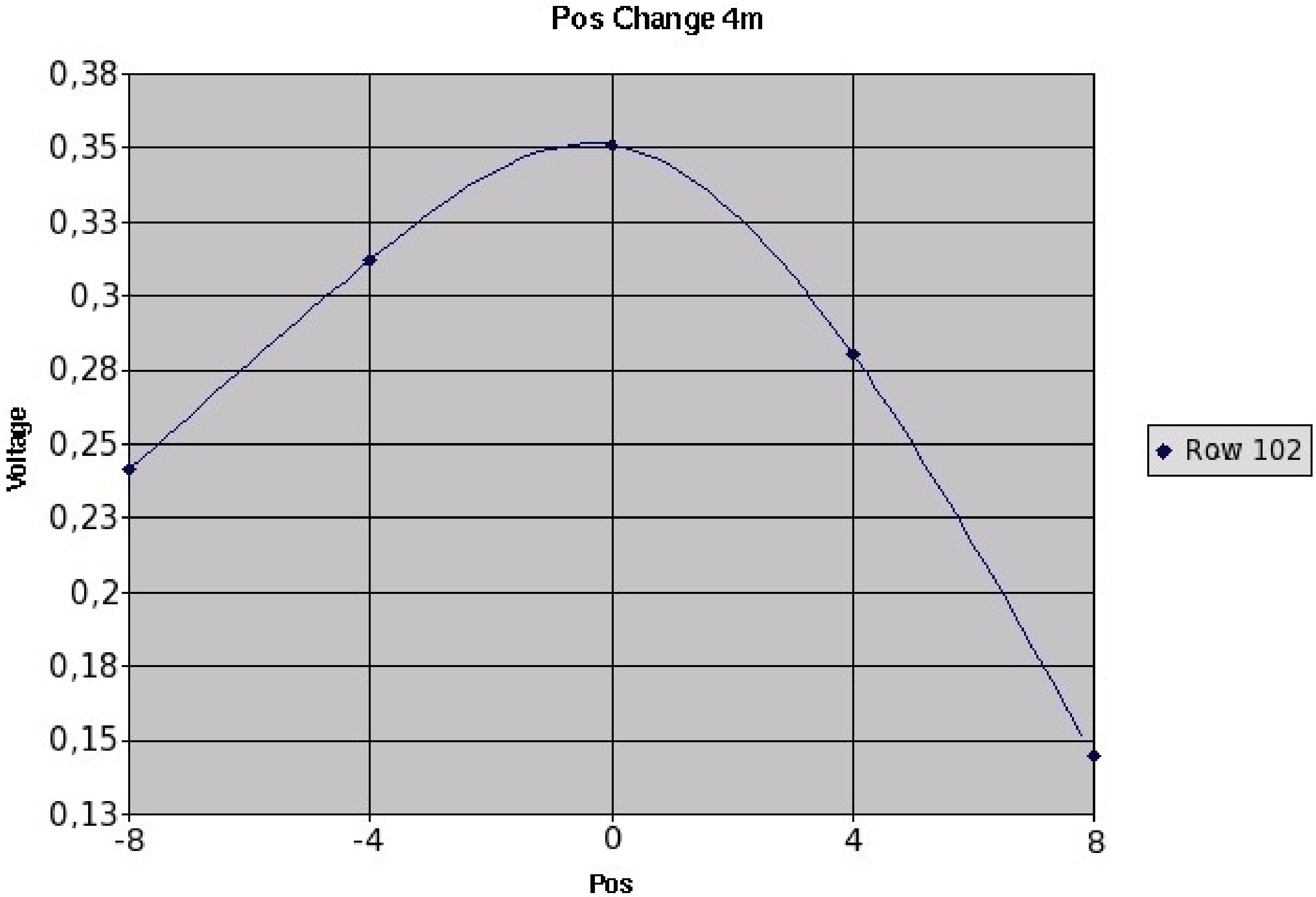
Bridge configuration

But this turned out to be a very bad configuration, as the posts themselves where not fixed, it was neither a bridge with one fixed and one floating end as used in the first considerations on page 9, nor were the two ends completely fixed. Thus the reaction of an applied vertical force was an undefined combination of bending and post moving, leading to not very meaningful measurements.



Different masses (numbers of nuts) on the central position of the bridge: The signals from 2, 3 and 4 nuts are messed up.

And there was jet an other effect: Moving a constant mass over the bridge showed that the sensor would get the most deflection with the mass is in the middle of the bridge. The explanation for this might be, that, as the whole bridge can bend, a mass in the middle of it can cause a bigger hanging trough (remember, the posts were not fixed) as a mass at an endpoint. Thus, for the later application as a position sensor, it will be important, that the area which is sensed itself, is stiff, allowing bending only at the ends, so that the sensor signal is the biggest, when the force source is the nearest.



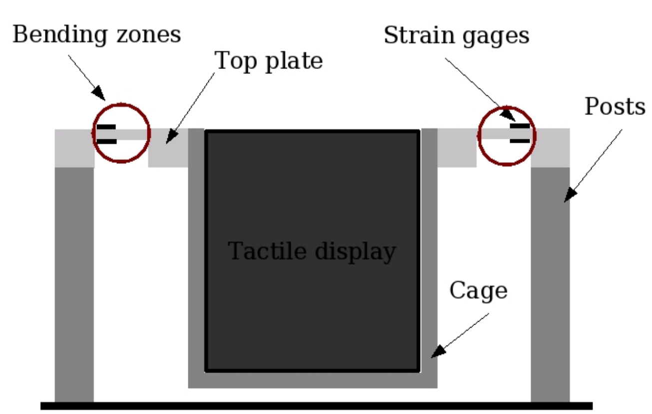
4 nuts changing positions from -8 to 8: Biggest signal at central position

3. Implementation

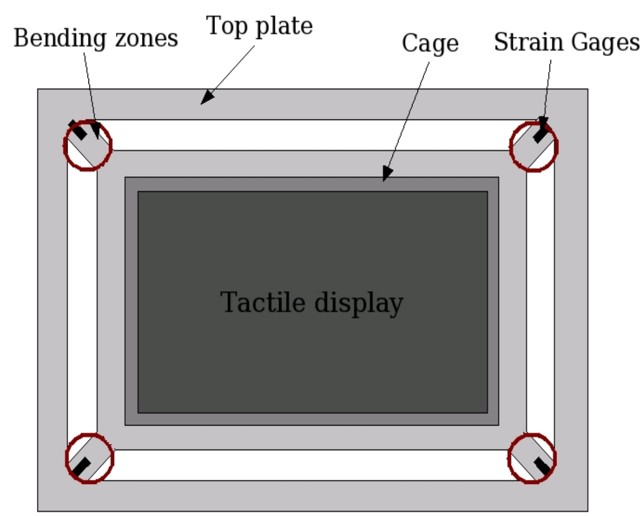
3.1 Mechanical Design

The first considerations (see point 1.3, Equations 3) showed that position sensing with just three force measurements is possible. The problem with the tactile display is, that no sensor can be attached to the surface, as it has to be able to resonance freely. A structure is needed, that holds the tactile display box at its bottom, but measures the forces in the plain of the top surface.

A solution to this is:



Side view: The tactile display is placed inside a cage, which connects to a top plate in the same plane as the display surface and includes the cantilever beams to measure..



Top view: Just three force measurements have to be done, but for stabilization, four support points are better.

The inner dimensions of the cage holding the display are set by the display dimensions and are 3x2.25 inch.

The question is, what are the needed dimensions for the cantilever beams in the bending zone to a) deflect sufficiently under a finger push to give meaningful signals and b) being able to support the display without plastic deformation.

The cantilever bending should look like the following graph, with no slope as boundary conditions on both sides and a symmetry line in the middle.

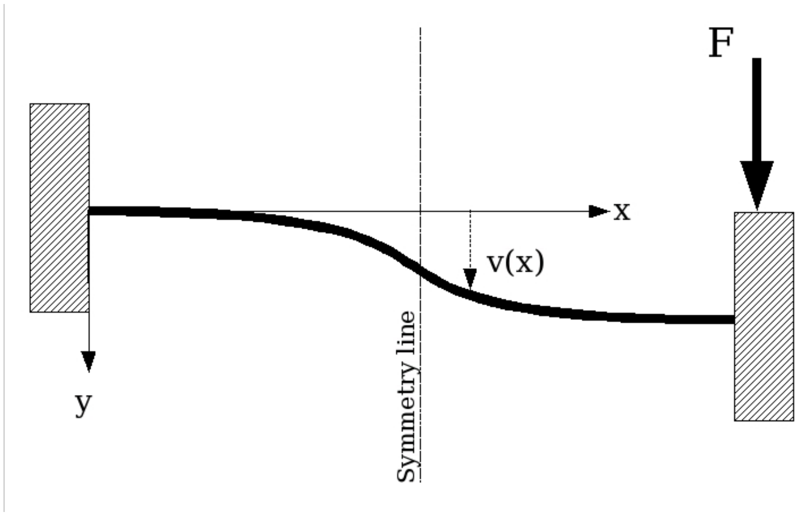
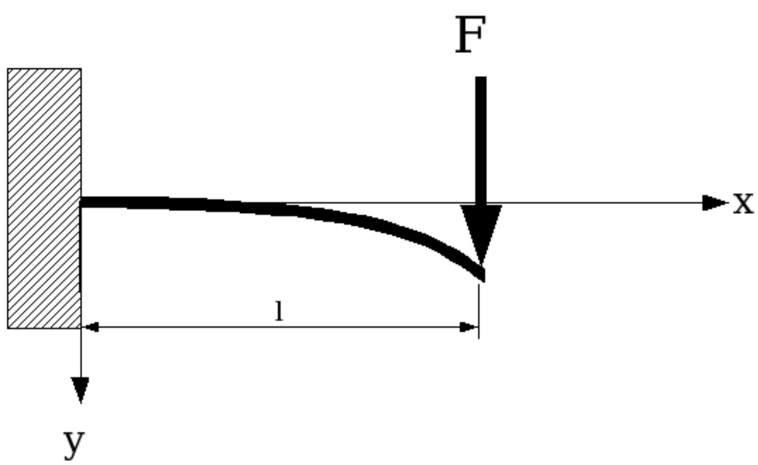


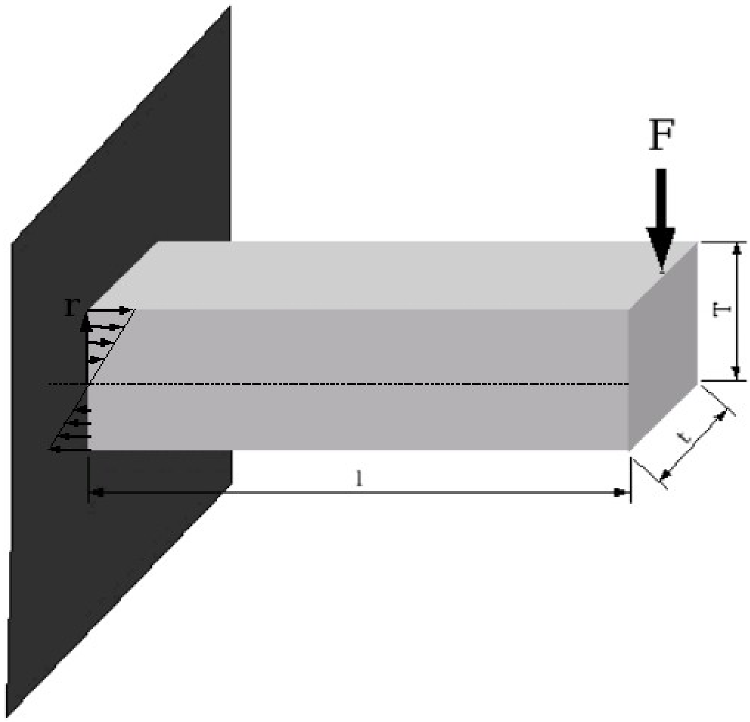
Illustration of the expected bending line of the cantilevers

As there is a symmetry, calculations can be done with half the cantilever and become much easier. It just has to be remembered that “l” is just half the actual length and that the total deflection will be twice the calculated amount.



Half the cantilever beam.

Strain vs. Force in cantilever



3D cantilever beam

The force- strain relation can be obtained in the following way [1]:

$$F l = \int_{-T/2}^{T/2} r * \sigma(r) * t * dr \quad , \quad \sigma(r) = \alpha * r \quad , \quad \alpha = constant$$

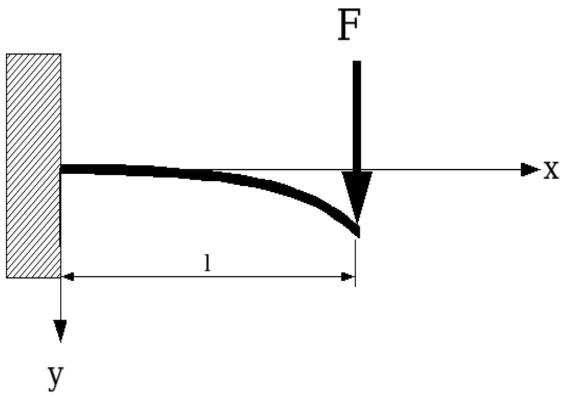
$$F * l = \alpha * t * \int_{-T/2}^{T/2} r^2 * dr = \frac{\alpha * t * T^3}{12}$$

-> $\alpha = \dfrac{12 * F * l}{t * T^3}$

-> $\sigma(r) = \dfrac{12 * F * l * r}{t * T^3}$ -> $\sigma(T/2) = \dfrac{6 * F * r}{t * T^2}$ -

> $\varepsilon = \dfrac{\sigma}{E} = \dfrac{6 * l}{E * t * T^2} * F$ *(Equation 7)*

Deflection of the beam



Half the cantilever beam

$$Q_b(x)=F$$
$$M_b(x)=(l-x)*F$$
$$v''(x)=M_b\frac{(x)}{E*I_z}$$
$$v'(x)=\int M_b\frac{(x)}{E*I_z}*dx=\frac{F}{E*I_z}\int(l-x)*dx$$
$$v'(x)=\frac{F}{E*I_z}*(l*x-\frac{x^2}{2}+C)$$

Boundary condition $v'(0)=0$ ->C=0

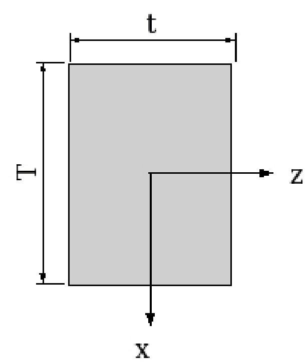
-> $v'(x)=\frac{F}{E*I_z}*(l*x-\frac{x^2}{2})$

$$v(x)=\frac{F}{E*I_z}\int l*x-\frac{x^2}{2}dx=\frac{F}{E*I_z}*(\frac{l*x^2}{2}-\frac{x^3}{6}+C_2)$$

BC: $v''(0)=0$ -> C2=0 -

> $v(x)=\frac{F}{E*I_z}*(\frac{l*x^2}{2}-\frac{x^3}{6})$

(Equation 8)



Beam cross section

$$I_z=\frac{t*T^3}{12}$$

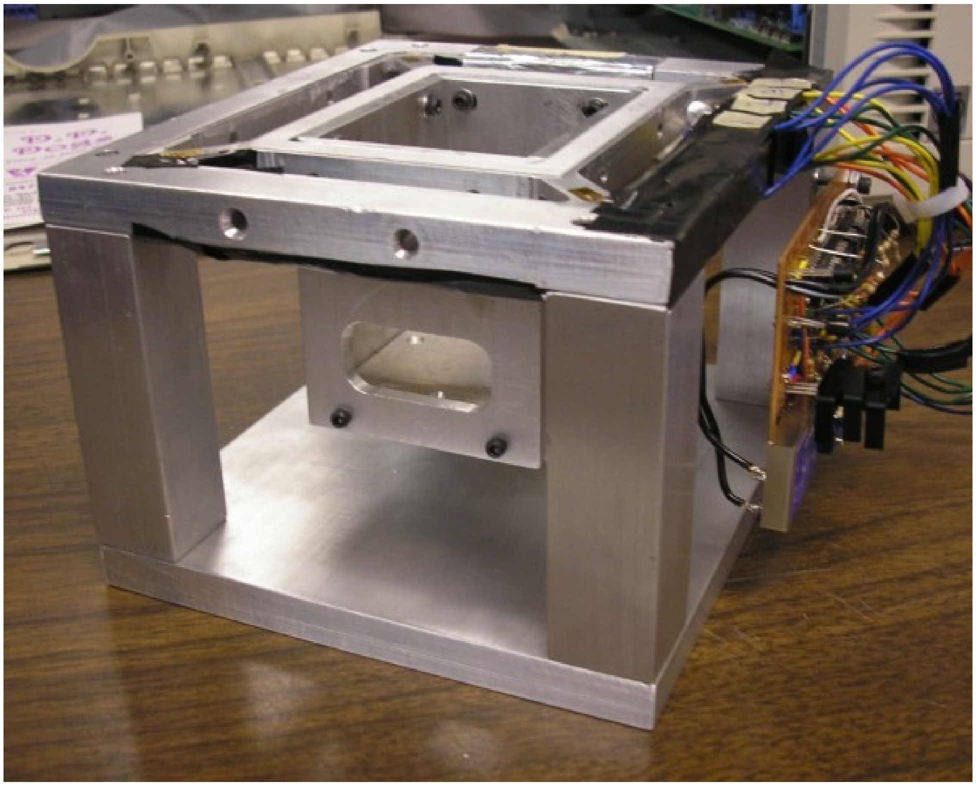
Together with the formula for the Wheatstone bridge (see equation 6) already calculated earlier on, it is now possible to calculate the dimensions to obtain a useful signal.

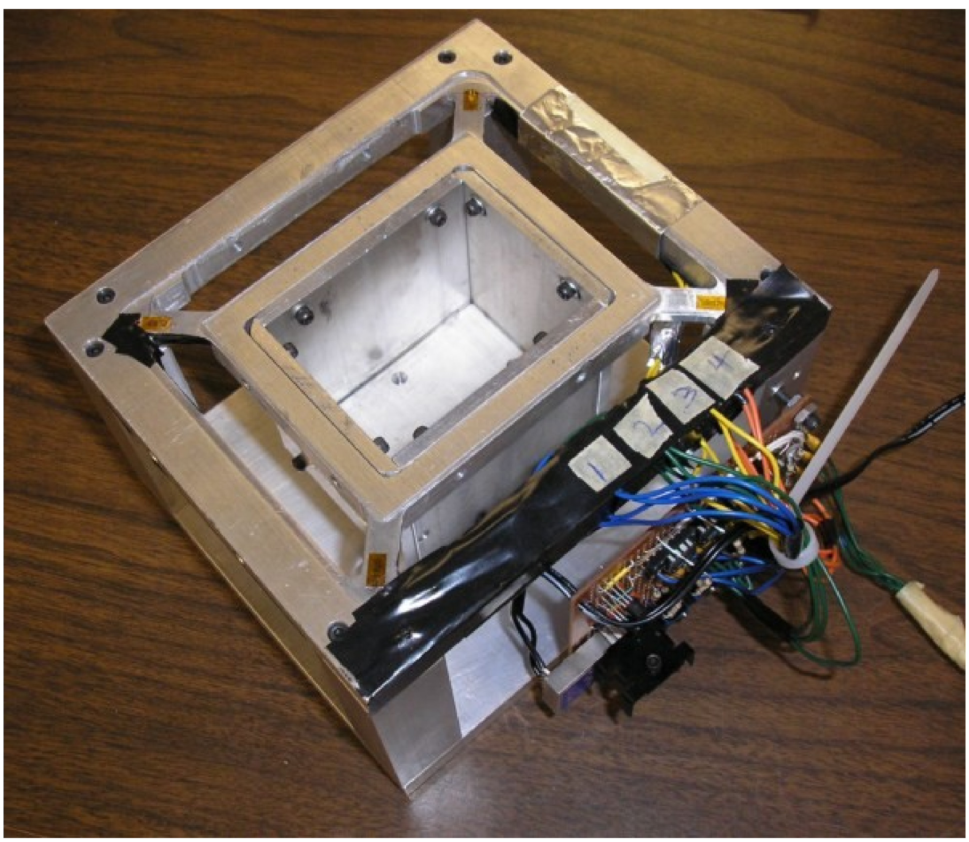
The following spreadsheet has been used to do so. After entering the material constants, dimensions and the equivalent push mass, it would calculate the differences in strain, displacement, resistance and voltage between pushing and not pushing. The data showed are the actual dimensions of the cantilever, that have been chosen to give full scale output (+10V for the ADC converter), using a Op- Amp gain of 2500, and still not showing too much displacement, to avoid deformation.

Calculation of Cantilever dimensions

	american	SI			
(half)Length l:	0,3 in		0,00762 m	1inch=2.54cm	2,54
width w:	0,4 in		0,01016 m		
hight h:	0,15 in		0,00381 m	Strain gage Emax=3%	
E-Module			7,0E+10 N/m^2		
Mass device	240 g		0,24000 kg		
Mass holder	200 g		0,20000 kg		
max push mass	200 g		0,20000 kg		
Force min	Mmin*g/4		1,079E+00 N	Iz=w*h^3/12=	4,7E-11
Force max	Mmax*g/4		1,570E+00 N		
Elasticity e min	6*l*F/(E*w*h^2)		4,779E-06		
Elasticity e max			6,951E-06		
min vert. displacement	F/(E*Iz)*((2*l)^3/2-(2*l)^3/6)		3,9E-7 m		
max vert. displacement			5,6E-7 m		
difference in displacement			**0 mm**		
min Resistance	Ro*(1+e*g)		350,003345 ohm	Gage Factor g	2
max Resistance			350,004866 ohm	Ro	350 ohm
Resistance difference			**0,001521 ohm**		
Wheatstone bridge					
delta u bridge	5V*Ro((1+e*g)/(2+e*g)-(1-e*g)/(2-e*g))				
min			0,00836 V		
max			0,01216 V		
diff			**0,00380 V**		
V diff amplificated			9,5 V	amplification	2500

For 25g (what was determined to be about the amount equal to a slight finger push), a 1.19V signal should be obtained.
However, in reality, the obtained voltage difference was much smaller and the amplification of the Op-Amp had to be increased to 49401, to get some reading. But even with this huge amplification, a 25g push in the middle of the plate is not detectable in the noise of 0.1 V, which is a huge problem. In theory, 25g, with this amplification , should have given 23.47 Volt. This discrepancy will be discussed later on.


Side view of the device without tactile display.

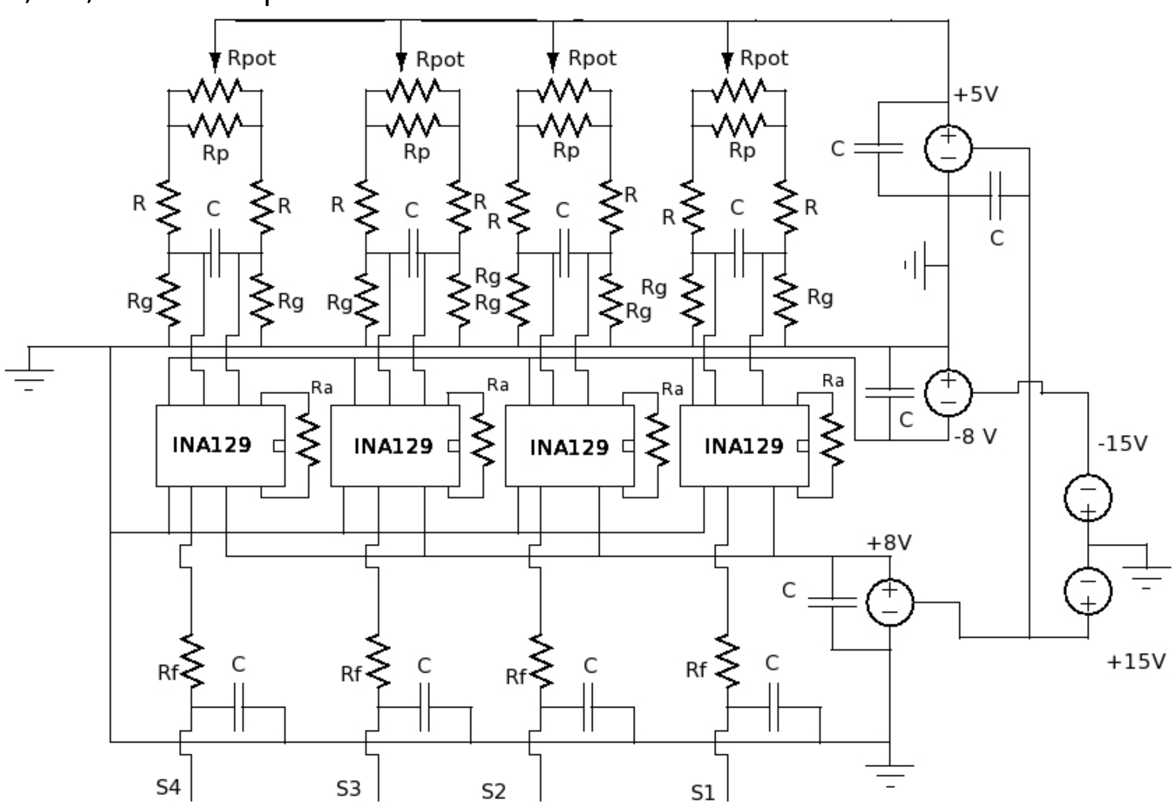


Top view of the device, without tactile display.

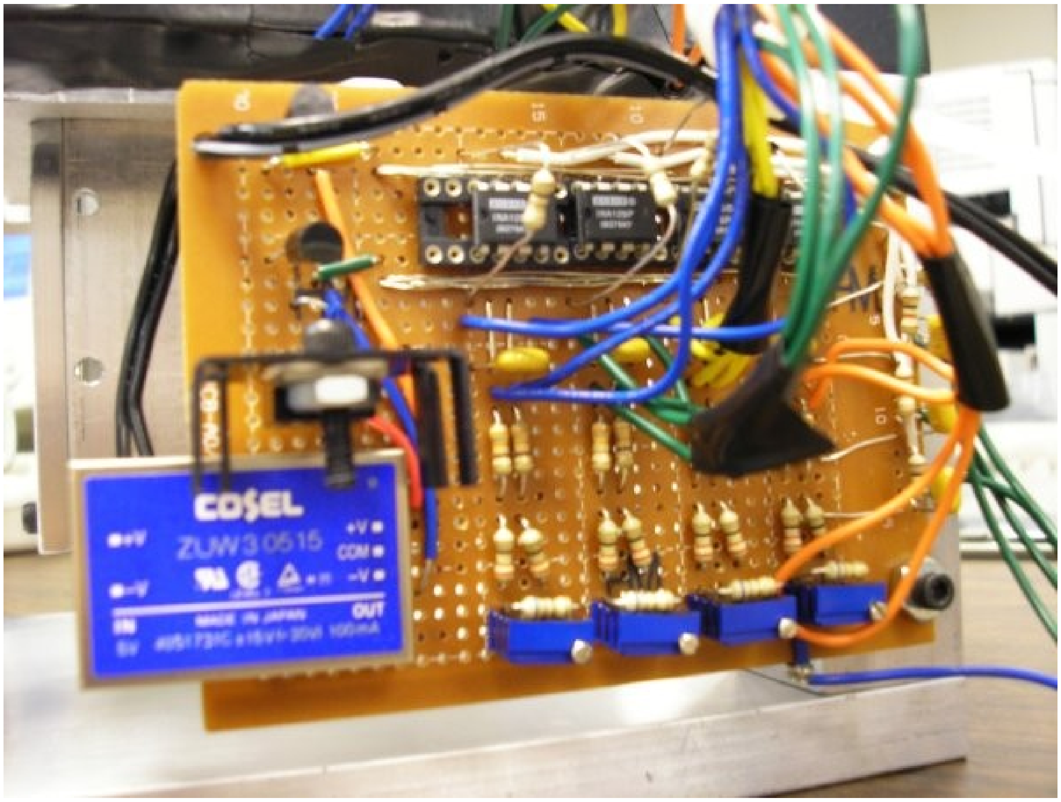
3.2 Electrical Design

The electrical part is basically just four times the circuit used in the cantilever experiments, with a few adaptations. So had the Op-amp driving power to be reduced, as the ADC board of the PC is only working in a +- 10V range (before we had 15V). The 5V voltage controller had to be replaced by a bigger one to be able to supply enough power. Further on, the strain gages used, have 350 Ohm nominal resistance, compared to 120 Ohm in the cantilever experiments (This was completely random, as just no more 120 Ohm Strain Gages were available).
In addition, a lot of condensers have been included to fight the noise, that poses a big problem.

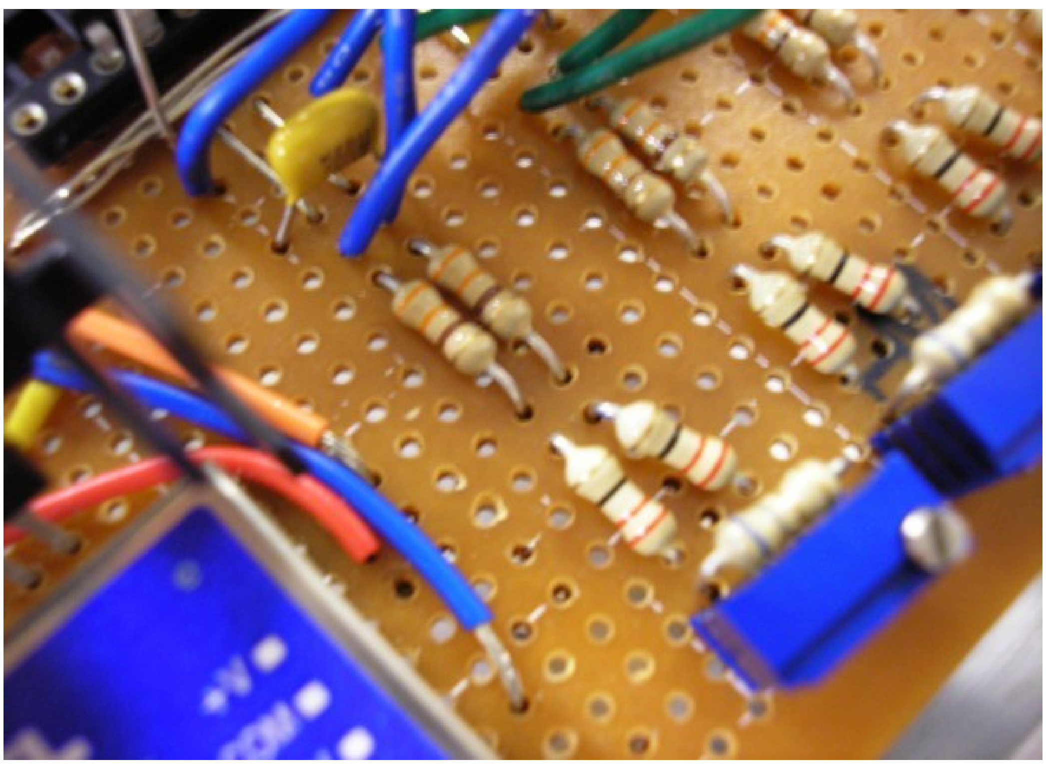
Rpot: 0-50 Ohm
Rp: 5 Ohm (Thus making the 0-4.54 Ohm adjustments possible)
R: 350 Ohm
C: 1 F
Rg: Omega SG-2/350-LY13, nominal resistance: 350 Ohm
INA129P: Low power Op-Amp with adjustable gain: G=1+49.4kΩ/Ra
Ra: 1 Ohm -> G=49401
Rf: 1kΩ
Power Supply: Cosel ZUW3 05 15, 5 to +/- 15 Volt Power supply,
Voltage Controller: L78L08CZ (+8V), L79L08CZ (-8V), LP2954 IT (+5V)
S1, S2, S3, S4: Output Channels



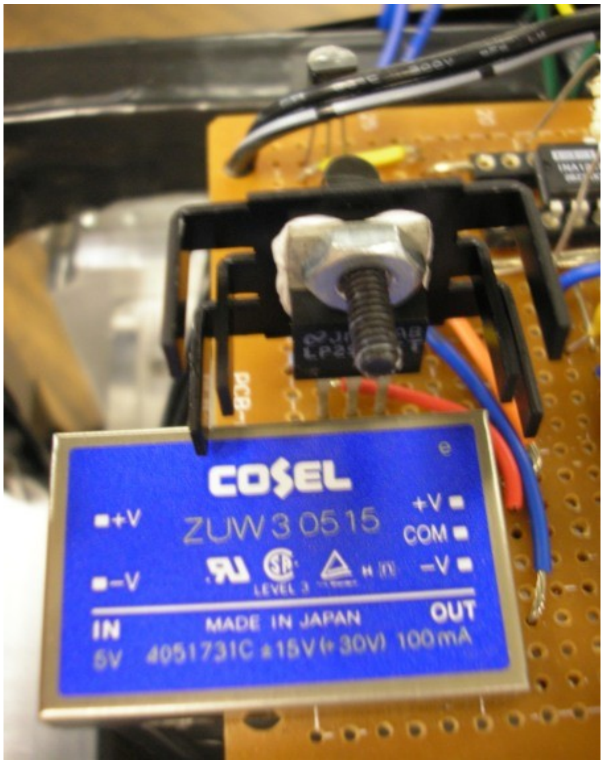
Circuit diagram



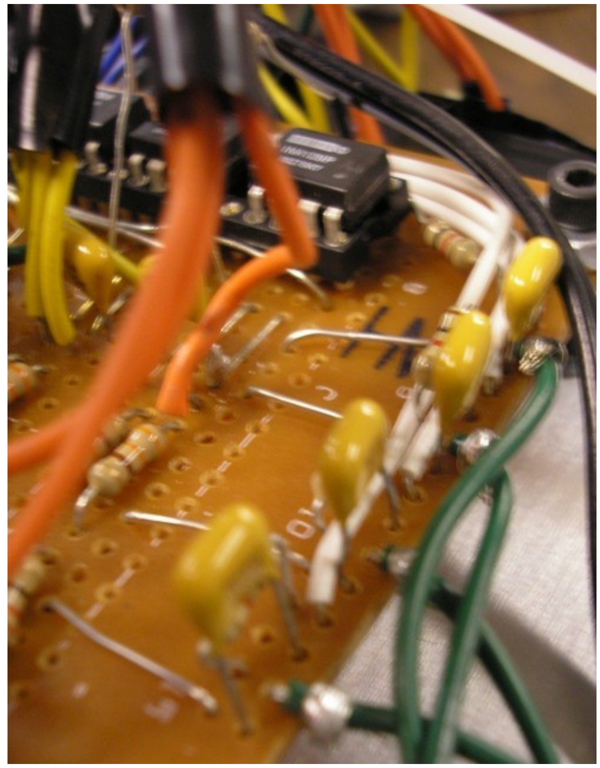
Electronics, top view



Detail of the Wheatstone bridges. (Blue and green wires go to the strain gages)



The Cosel power supply and the 5V voltage regulator with its heatsink



The outputs of the circuit (green wires go to ADC converter)

3.3 Mathematical Model

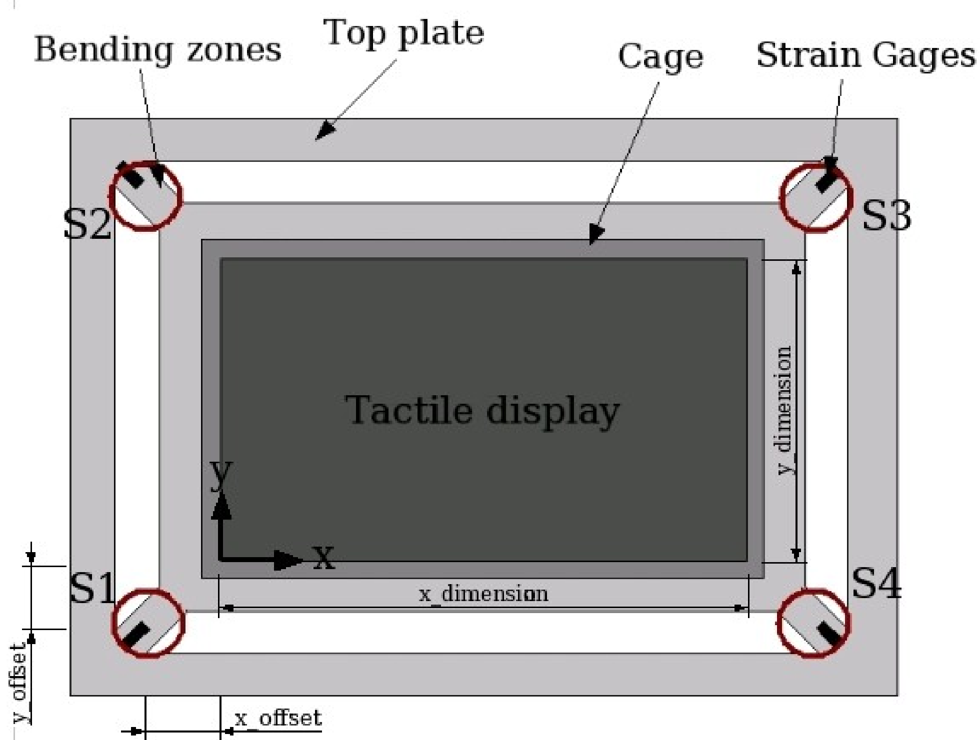
The basics of the mathematical model have already been developed in the first considerations, leading to the following equations (Equations 3):

$x = \frac{-A_z * w}{F_z}$ and $y = \frac{-C_z * l}{F_z}$, with $F_z = -A_z - B_z - C_z$

As there are now 4 instead of 3 measuring points, these equations have to be changed slightly:

$x = \frac{(F_3 + F_4)}{F_{tot}} Dimension_x$, $y = \frac{(F_1 + F_2)}{F_{tot}} * Dimension_y$ with $F_{tot} = F_1 + F_2 + F_3 + F_4$

(Equations 9)



Top plate with coordinate system

The forces F are some multitude of the sensor voltage signals S, minus its offset signal.

$F_1 = (S_1 - offset_1) gain_{1,}$ $F_2 = (S_2 - offset_2) gain_{2,}$
$F_3 = (S_3 - offset_3) gain_{3,}$ $F_4 = (S_4 - offset_4) gain_{4,}$ *(Equations 10)*

It is not necessary to calibrate the sensors such that the force signal is actually a signal in “Newton”. As the equations 9 are just balance equations, the sensors only need to be adjusted to give the same output response to the same force.

The coordinates we obtain from equations 9 and 10 however, quite probably, do not match our coordinate system. It is thus necessary to introduce offset and gain correction variables for x and y to be able to map the results to the required system. (This assumes that the obtained coordinates are only shifted and scaled, but not turned. If the later is the case, a transition matrix would have to be used.)

The final equations are:

$$x=\frac{(F_3+F_4)}{F_{tot}}Dimension_x * Gain_x - offset_x$$

$$y=\frac{(F_1+F_2)}{F_{tot}}Dimension_y * Gain_y - offset_y \qquad \textit{(Equations 11)}$$

with $F_{1.}$ $F_{2.}$ $F_{3,.}$ F_4 according to equations 10, $F_{tot}=F_1+F_2+F_3+F_4$

3.4 Interface to real time computer system – Decoding Algorithm

John Glasmire uses a QNX real time computer system to control the tactile display. Thus it is logical to use the same platform for the position sensor as it has to exchange data, and preferably is a function, that can be included by the program code for the display.
QNX is a real time operation system similar to Unix and Linux. The data acquisition is done with a Servo To Go ISA BUS Servo I/O Card (Model 2) that uses a multiplexer to read 8 ADC channels at 2kHz. The input range is, as mentioned before, +-10V or +-5V. (+-10V are used here)

Software

The code written is an add on to the already existing C-Program for the tactile display.
The program consists of a graphical user interface, where data are outputted and operation parameters can be changed. A main control loop calls data acquisition and other functions.

Graphical user interface of the program

The variables

The variables used by the position sensing code are defined in the file “control.h”, in an additional section (see code in appendix).

***Data* acquisition**

The existing code already included the function read_sensors() (in control.c), which reads out the eight ADC channels, converts the data in voltage and stores them in an array raw_STG_ADC_data[].

To smooth out some of the noise of the voltage signal and avoid single conversion errors to influence the performance, a moving average filter has been written in control.c, which takes a new signal and returns the average over the past 100 signals.

Initialization and Calibration

In the “main” function (in main.c), before the program loop starts, all needed variables are initialized. X- and y- dimension, initial sensor gains, x- and y- offsets as well as x- and y-gain can be edited here. Also the sensitivity (what is a push, and what is noise and has to be ignored) of the device can be set here. The sensor offsets are automatically set (The signal, when no force is applied, should be zero, the offset thus is just the difference between signal and zero).

As the Wheatstone bridge signals are unfortunately drifting over time, is was necessary to be able to compute the offsets again, when needed. This main.c has been modified, that when the user presses the “c”-key, the offsets are set again.

Also the sensor gains can be changed manually in runtime (this makes calibration a lot easier). To do so, four more editable lines (for the gains) have been added to the graphical user interface (gui.c, gui.h, command.c).

Finger position calculation

The finger position calculation has been implemented (in control.c) according to equations 10 and 11. The acquired data are filtered with the moving average filter before being used in the equations.
Additional, there has been set a sensitivity, that defines the level of signal over which voltages have to be regarded as a finger push. If the signal level is below, the x- and y-coordinates are not computed (they freeze at their last value) and a flag is set, telling that no push is recorded. If this would not have been done so, the values for x- and y would jump around extreme values as long as no force is

applied, because the noise signals would be interpreted as small forces, which, as the equations are balance equations, have a huge impact.

The values for the finger position are stored in the global variables double position_x and double position_y.

Data recording

To be able to make a good calibration and also to determine the performance, a few lines have been added to the main.c file, so that if the user presses the key "a", the actual values of sensors and position are written as a new line to the file "position_recording.txt".

Other changes

The number of ADC channels had to be updated in servotogo.h, the rest of the files have not been changed for the position sensing, but are, to have the whole program code, still included in the appendix.

3.5 Calibration

Sensor offsets

The sensor offset calibration is done automatically at program start and can be repeated by pressing “c” if necessary.

Dimensions

The dimensions are given by the length and width of the device. For the program, it does not matter whether they are specified in inches or millimeters, as long as the x-, y-offsets are edited in the same unit.

Sensor gains

To adjust the sensor gains (which is necessary, as the strain gages might not have been placed in exactly the same spot, or other geometrical and electrical influences can produce different readings for the same force), it is practical to determine one sensor as reference sensor.

```
sensor_gain_0=1;        // Here the gain of sensor 1
```

Now, by pushing between sensor1 and sensor 2, respectively sensor 3, the values of the related sensor gains have to be changed until the signal output is the same.

In the current configuration the values became:

```
sensor_gain_1=1.2710;        // sensor2
sensor_gain_3=0.89;          // sensor4
```

The gain of the last sensor is obtained by doing the same between sensor 4 and 3, or sensor 2 and 3.

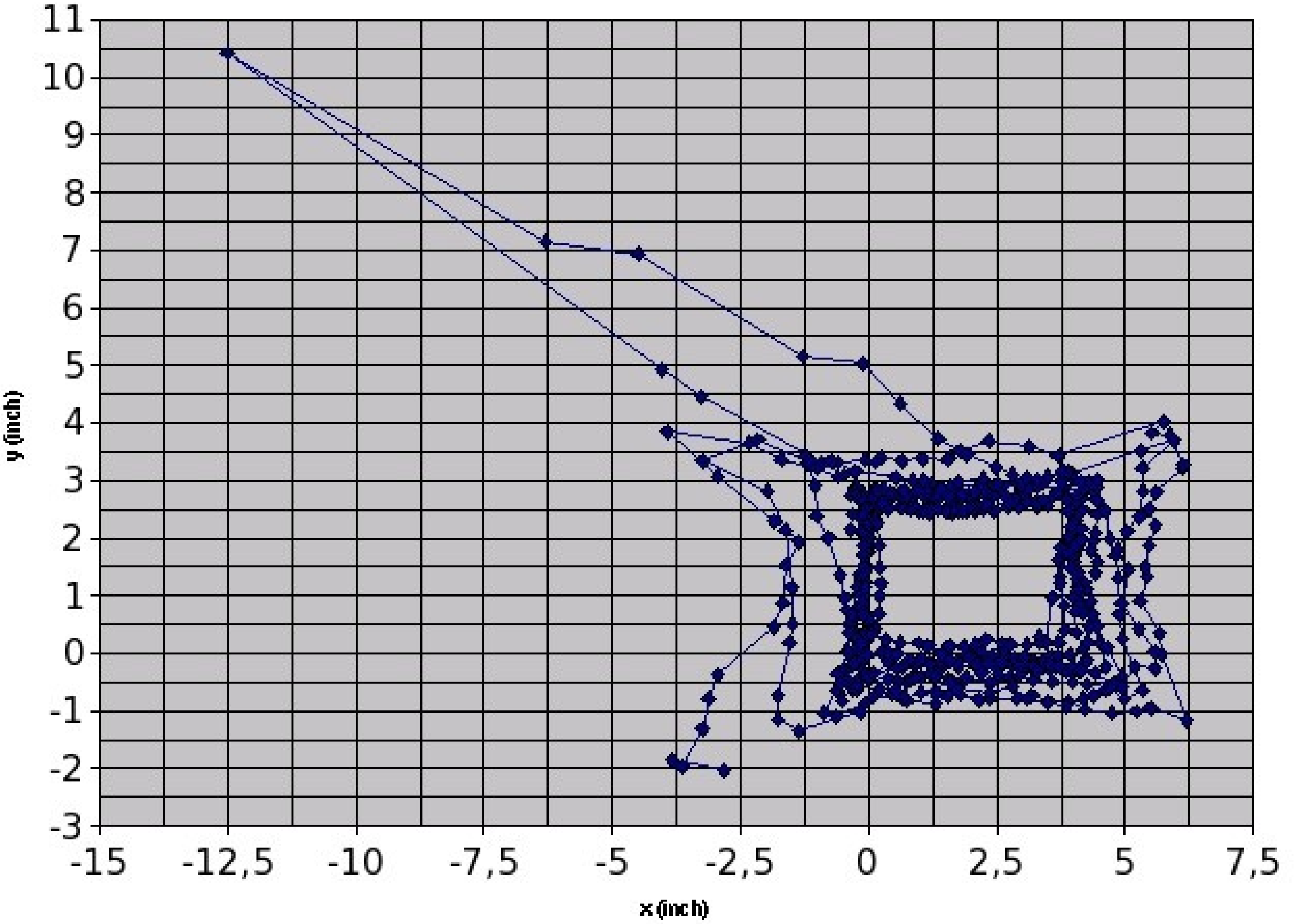
```
sensor_gain_2=1.12;          // sensor3
```

Now all sensors should give the same output when a force is applied in the middle of the plate, or equal forces directly at the cantilever beams.

x-, y- offsets and gains

A first data recording has to be done, on which the finger is moved around the edges of the "touch panel".

The plot of this data should give a rectangle that is not to scale and shifted in x and y:



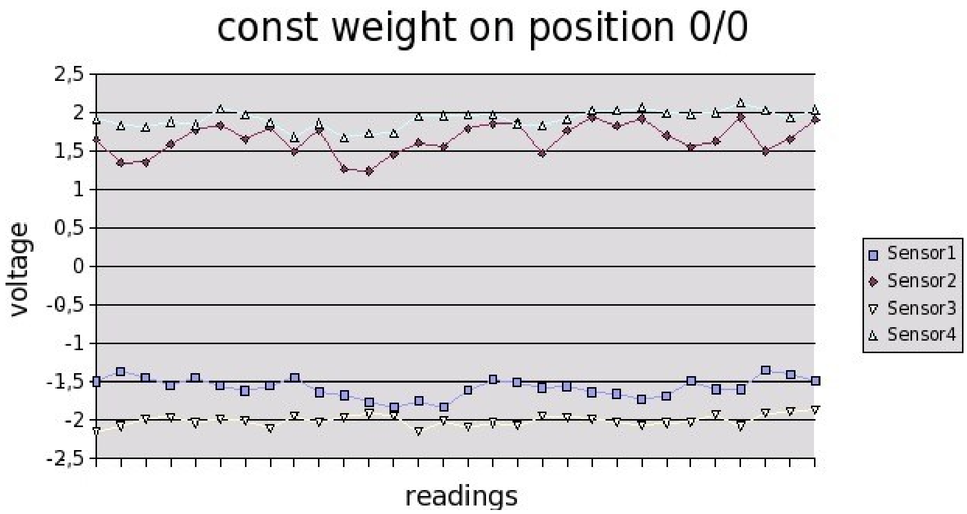
Finger moved around the edges of the display several times.

There are no perfect lines, as first, the finger itself can not touch with a higher accuracy than 0.25 inch, and second, as there are errors and drift in the signal.

Based on this plot, the x- and y- offset and gain values can be set to transform the data in every other coordinate system, that is not rotated to the plate (There, as said before, a transformation matrix would be necessary).

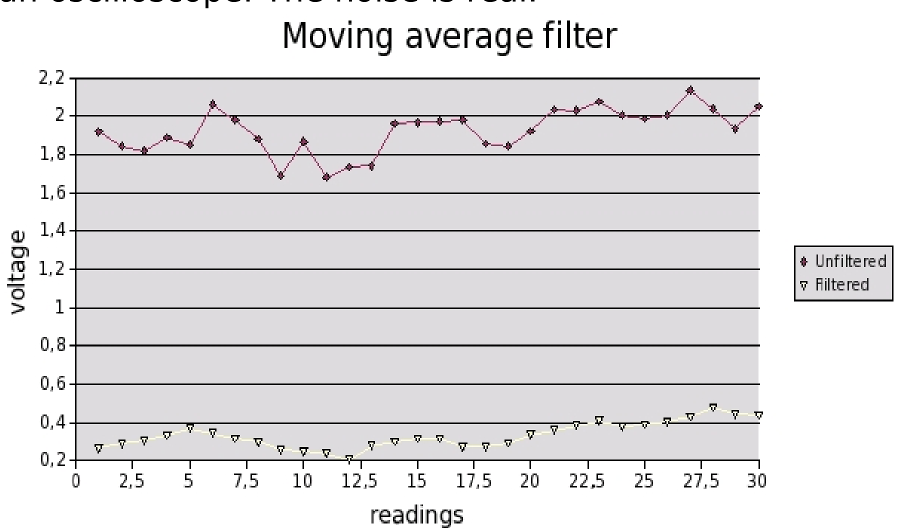
4. Testing

When used the first time, a huge drift of the signal of sensor1 and a medium drift of sensor2 was observed, while sensor3 and 4 where almost stable. The circuitry and the mechanical setup is all the same for the different sensors. As sensor1 is the closest, and sensor2 the second closest to the 5V power regulator and it's heat sink (that becomes quite hot), the idea came up, that this is related to the geometrical orientation of the circuit,
In fact, after a ventilator has been placed next to it, the sensor signals stabilized more or less.



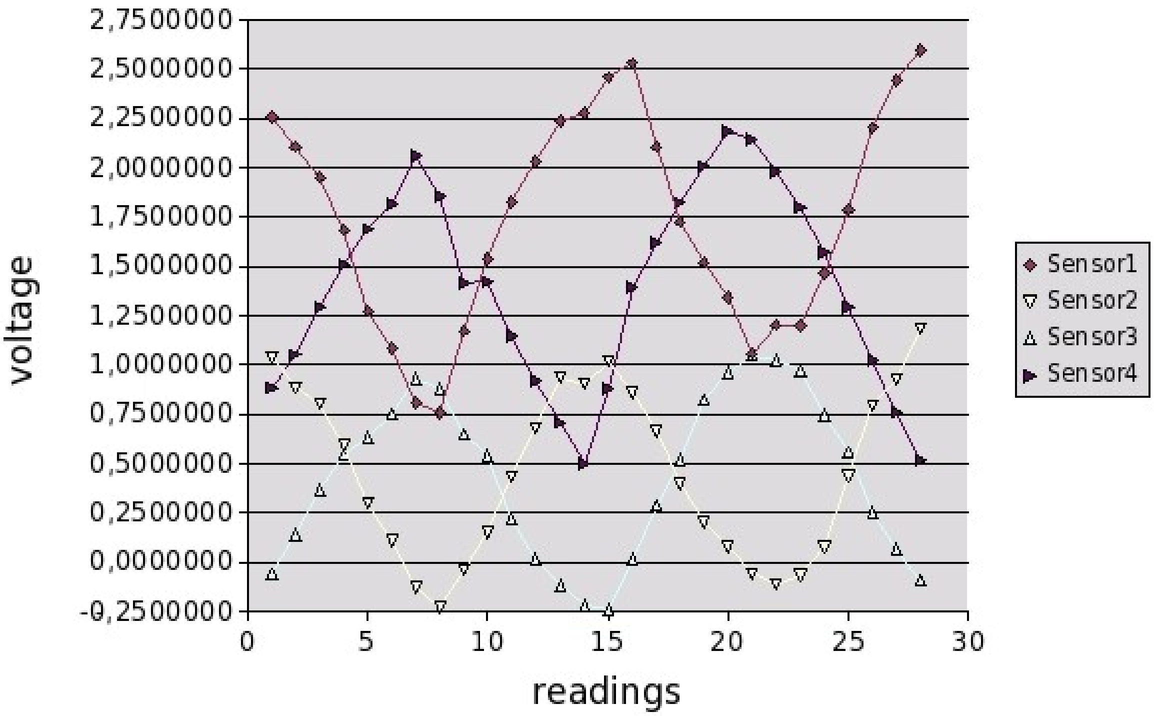
The uncalibrated, unfiltered sensor data.

As the graphic above shows, the signals coming from the sensors contain a lot of noise. This was not unexpected, but the amount is surprising and unfortunate.
That the source of it is not a conversion error or aliasing effect, has it been checked with an oscilloscope: The noise is real.



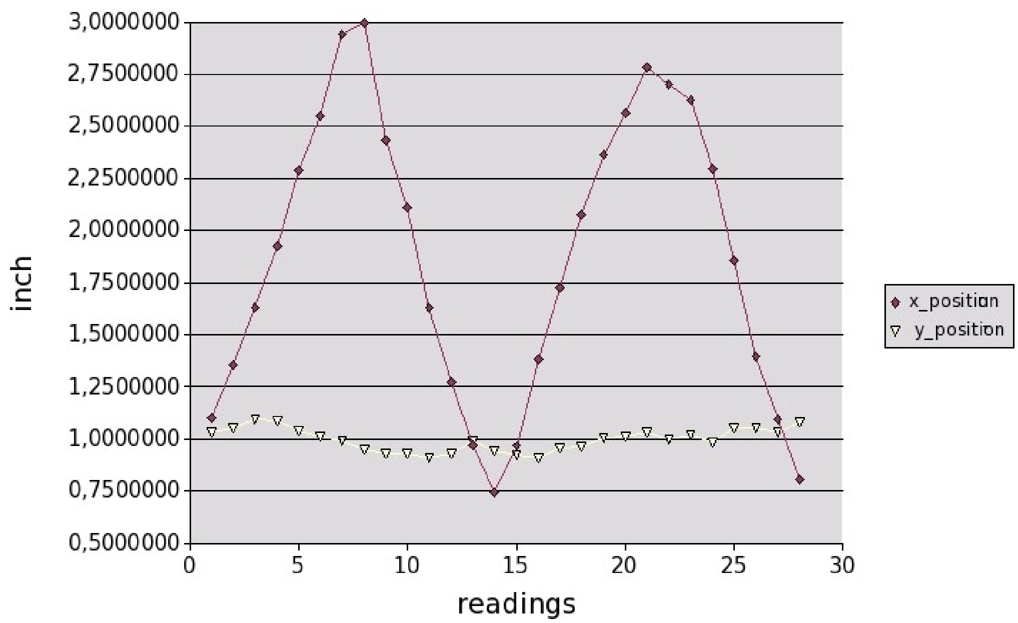
Signal of sensor 4, unfiltered vs. filtered and offset shifted

The moving average filter can smooth the signal a little bit out, but the signal still jumps around about 0.1 V, what makes a force equal to 25g undetectable.

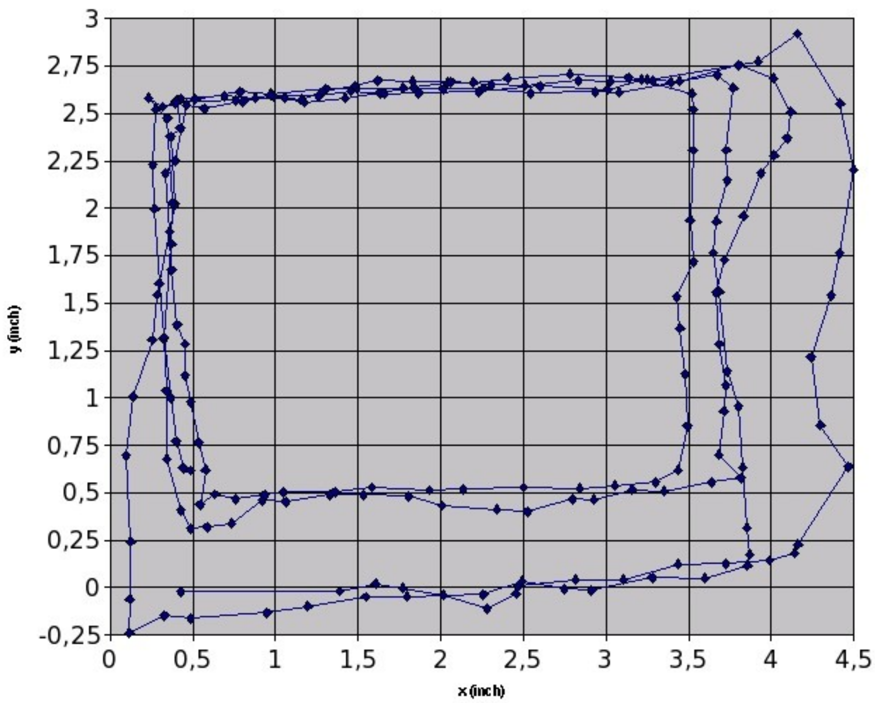


Filtered Sensor responses form moving the finger up and down the x-axis.

But a little harder finger push can be detected and leads, as the figure above shows, to quite meaningful results: While the finger has been moved up and down the x-axis twice, the sensors 1 and 4, placed on this axis, recorded the highest signal with opposite phase.

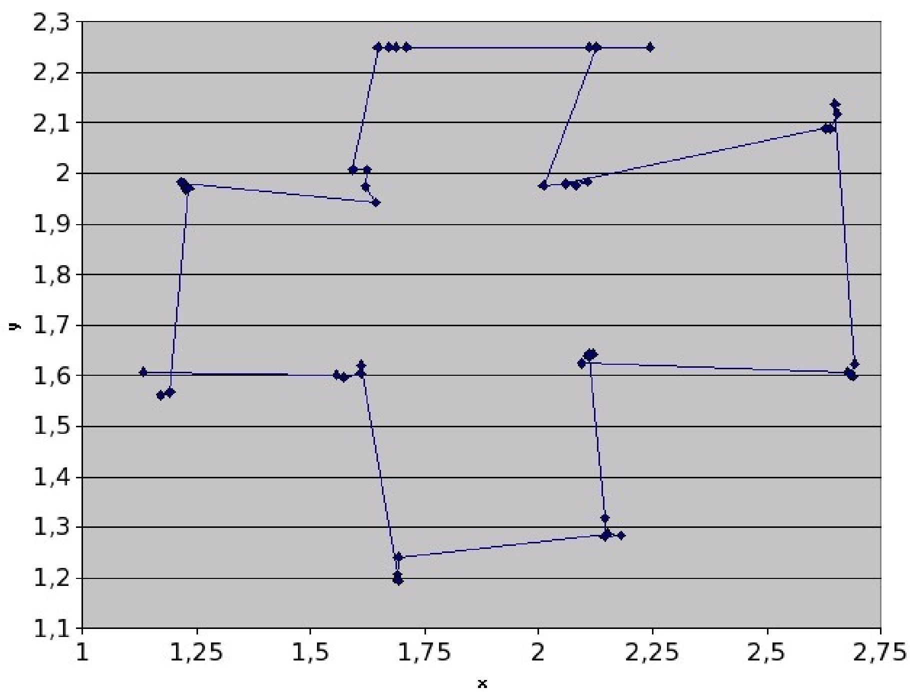


Coordinates computed based on the data above.

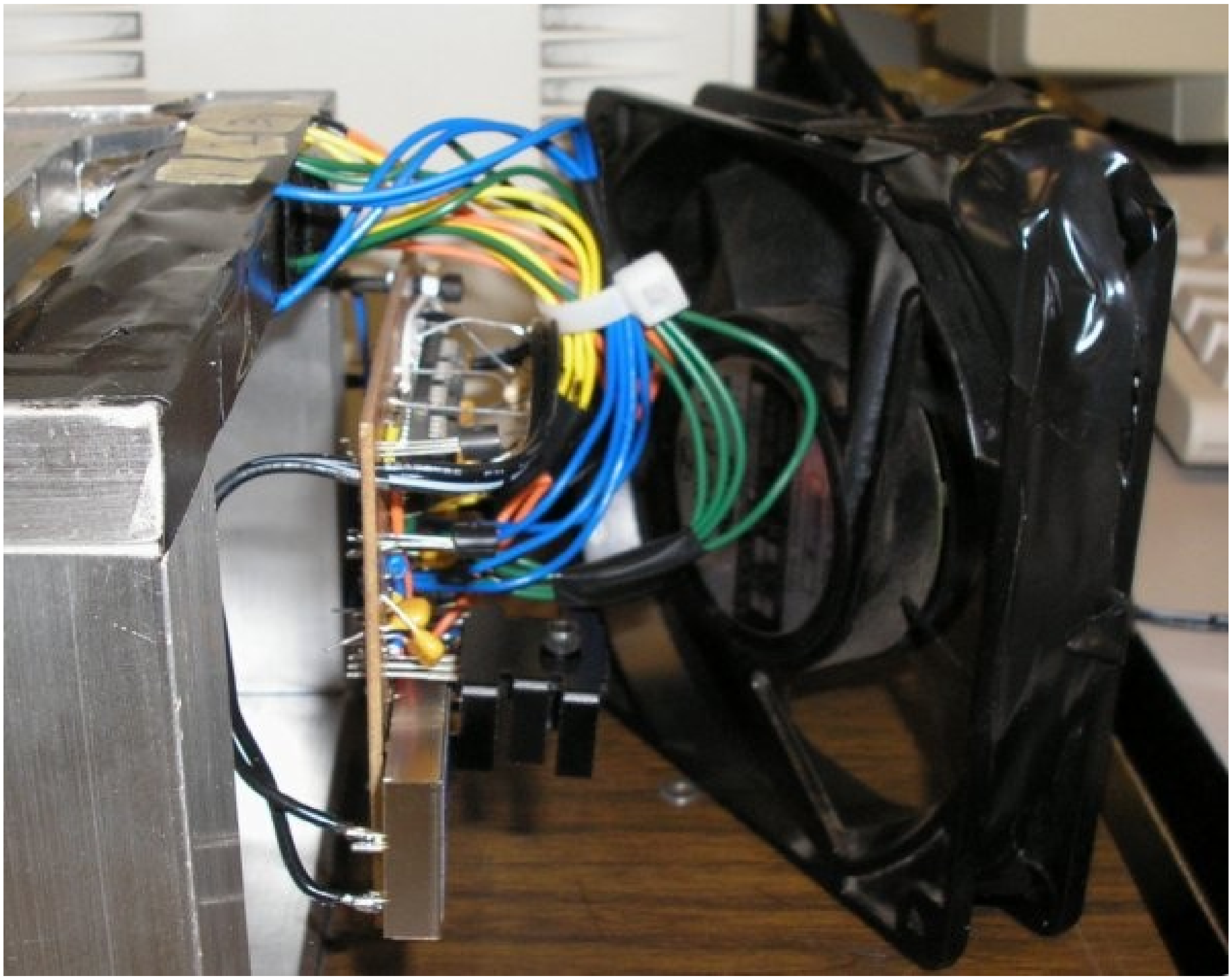


Finger moved around the inner edge of the top plate.
Inaccuracy of approximately 0.5 inch.

Although there is some drift, the dimensions of the rectangle are approximately right (The dimensions of the inner edge is 3x2.25 inch), but there is some inaccuracy. After a plate as been put over the cage, also the "inner positions" could be tested.



Swiss cross


Final setup with ventilator

5. Discussion

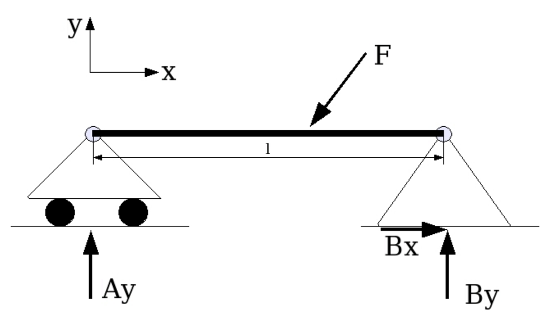
The device produced showed that, although there are some problems (inaccuracy, sensitivity and drift), the concept is working and position sensing with reaction forces is possible. The mathematical model proved to be exact enough, to give some reasonable readings.
In the following, the problems that occurred will be discussed and possible solutions for an improved version of the device stated.

5.1 Problems

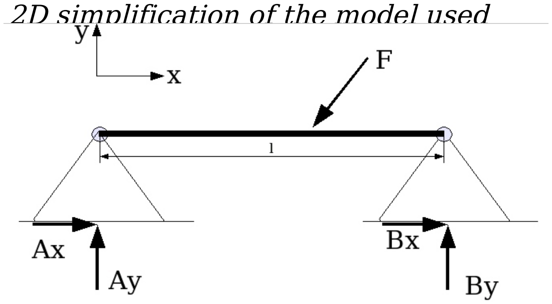
Sensitivity

Probably the biggest problem for the use in combination with the tactile display is the sensitivity of the position sensor. Although it works fine, on a push, the sensitivity is not high enough to record a finger that is just touching, what would be needed to build a haptic display.

There are probably two reasons why this is so. First, the noise of about 0.1 volt is about the amount of voltage change a touching finger is causing and can thus not be distinguished from it.
The second reason is a more miraculous one: According to the calculations made in the dimensioning the signal coming from the Wheatstone bridge is much smaller than expected. A amplification gain of 49401 had to be used instead of the 2500 calculated to get a useful reading. This is 20 times more! Where does this come from? Are there some errors in the mathematical model for the dimensioning?



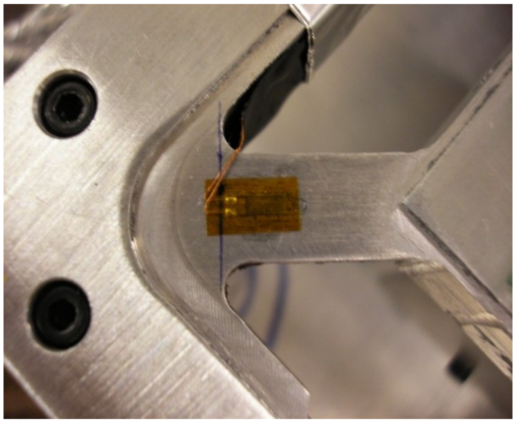
2D simplification of the model used



2D simplification of the reality with all posts fixed.

In fact the model used some simplifications that lead to differences from reality: It has been assumed, that one of the holding points is restricted in x- and y- position, one just in x-position while the rest is floating. In the implementation however, the fixed cantilevers used for the force measurement lead to restrictions in x and y for all the sensing points. This additional forces cause surface stress, that tries to keep the pate from bending trough. As the cantilevers do not actually measure the force but the strain caused by the bending, this would lead to a recording smaller than the actual forces in vertical direction.
Measurements of the surface stress or a solid model simulation would help to determine the

amount of influence on the readings.
But even if it turns out that this surface stress actually plays a major role, it is not an applicable solutions to make the posts floating, instead the effect should be included in the dimensioning calculations, most likely leading to thinner cantilever beams.


Real cantilever geometry

Another difference to the model is that the real cantilever geometry is not cubical, as assumed, because the milling machines do not allow to make exact 90 degree angles. Also here a solid state model could clear if this rounded cantilever edges change the behavior remarkably.

Drift

Unfortunately, the system tends to drift around. To correct this, the sensors have to be calibrated again from time to time by pressing the “c” button (see 3.4 Interface to real time computer system, Software). For a lab setting this might be acceptable but not for a field application.
As the drift improved remarkably by adding a fan, cooling the circuitry (in fact, the readings before could not be used, as there was too much drift), together with the observation that the sensor with its Wheatstone bridge resistors next to the heat sink of the 5V power supply had the most drift, it can be assumed that these resistors are the major cause for the drift. This assumption can be supported further on by the fact that the strain gages themselves, mounted on the different sides of the aluminum cantilever, should be able to exchange heat and thus find a thermal equilibrium, more likely than the air surrounded resistors.

Inaccuracy

The experiments also showed that there is an inaccuracy of about 0.5 inch in both dimensions. The cause of this certainly is a combination of the drift and the noise. While the noise causes random coordinate changes by unbalancing the equations, the drift leads to a shift over time (which can be seen quite good in the diagram of the finger moving around the edges several times on page 41).

5.2 Possible improvements

Making thinner cantilever beams

By doing, so the amount of bending and thus the resistance change in the strain gages could be increased. This would certainly reduce the influence of the noise, as the “useful” signal will be relatively higher. Also the op-amp amplification factor could be reduced, leading to reduced noise amplification. The drawback however is, that at some point, inelastic deformation will occur and produce a hysteresis.

Changing the geometry of the cantilever beams

As the calculations do not match the real geometry, moving the cantilevers from the edges to the centers of the sides, where they could be manufactured symmetrical and closer to the ideal shape, could increase the correlation between model and reality, making a proper dimensioning possible.

Using full Wheatstone bridges with four instead of two strain gages per cantilever

This would have two effects, first the signal is doubled, leading to less noise influence, and second, eliminating the drift caused by the temperature changes in the resistors by replacing them with strain gages in contact with the metal, allowing heat exchange until a thermal equilibrium is found. This would also make the ventilator unnecessary.

Using several strain gages in series

By using several strain gages in series, the voltage across the Wheatstone bridge could be increased, leading to a absolute higher bridge-voltage output. In this way, noise influence could be decreased.

Taking two independent measurements on the cantilevers and using the average

This would smooth out the noise a little bit.

Separating the heat producing part of the electronics from the Wheatstone bridges

As the geometrical placement of the Wheatstone bridges relative to the resistors, is crucial: One might want to place them as far away from the heat sinks, making the ventilator unnecessary by keeping the drift down at the same time.

Lowering the cut off frequencies of the filters

This would be a action limiting the symptoms rather than the causes of the noise, on the cost of reaction speed. It could either be achieved by increasing the capacity C in the circuit or enlarging the kernel of the moving average filter.

Placing the signal conditioning circuitry directly to the cantilevers

Reducing the wire length between strain gages and op-amps would decrease the induction of noise by radio signals.

Enclosing the circuitry in a metal case

Putting a Faraday cage around the circuitry would also reduce the amount of induced noise by radio signals.

Adding a permanent fan

By doing so, the heat producing drift could be removed in an unchanging way (Reorientation of the additional fan leads to changing convection and thus other temperature properties). The problem of the fan itself is, that it produces additional EM signals next to the circuit, adding induced noise.

5.3 Summary

Problem	***Cause***	***Solution***	***Side-effect***
Sensitivity too low	Noise	Making thinner cantilever beams	Too thin cantilevers lead to inelastic deformation
		Full Wheatstone bridges with four instead of two strain gages per cantilever	
		Using several strain gages in series	
		Taking two independent measurements on the cantilevers and using the average	
		Lowering the cut off frequencies of the filters	Reducing system reaction speed
		Placing the signal conditioning circuitry directly to the cantilevers	
		Enclosing the circuitry in a metal case	
	Model used for dimensioning does not match reality (signal not strong enough)	Making thinner cantilever beams	Too thin cantilevers lead to inelastic deformation
		Changing the geometry of the cantilever beams	
		Full Wheatstone bridges with four instead of two strain gages per cantilever	
		Using several strain gages in series	
Drift	Temperature sensitivity of the resistors	Full Wheatstone bridges with four instead of two strain gages per cantilever	
		Separating the heat producing part of the electronics from the Wheatstone bridges	
		Adding a permanent fan	Adding additional noise
Inaccuracy	Drift	See drift under “Drift”	
	Noise	See noise under “sensitivity low”	

6. References

Photos, illustrations and graphics:

All photos, graphics and illustrations are produced by the author.

Papers, Lecture notes:

[1] Hannaford, University of Washington, Lecture Notes on Force Sensing, 2003

Sources on the net:

[2] www.omega.com/literature/transactions/volume3/strain.html