TACTILE FORCE-SENSING FOR DYNAMIC GRIPPING USING PIEZOELECTRIC FORCE-SENSORS

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Declaration

I, CORNELIUS CHRISTIAAN JACKSON, identity number [redacted], and student number 9812350, do hereby declare that this research project which has been submitted to the Central University of Technology Free State, for the degree MAGISTER TECHNOLOGAIE: ENGINEERING: ELECTRICAL, is my own independent work and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State, and has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

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SIGNATURE OF STUDENT   DATE

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SUMMARY

The purpose of the research was to develop a gripper system where the gripping force can be accurately controlled. Through the dynamic gripping of an automated robot gripper and the use of piezoelectric sensors, a required gripping force for a certain required task is achievable. Piezoelectric film was chosen for its superior sensitivity and structural simplicity over the typical metal-foil strain gauges. A high precision drive, with a Proportional-Integral-Derivative (PID) controller, drives the gripper to achieve exceptional control. Piezoelectric film has a dynamic response in the form of an electric pulse which is excited by an applied deforming force, independent of any external power source. Analyses of the output pulse from the piezoelectric film indicate the velocity, deceleration, and total force the gripper is inducing on the gripped object. The gripping velocity can be determined by calculating the derivative of the pulse received from the piezoelectric film. The gripping deceleration can be determined by the change of this derivative. Total gripping force can be calculated by deriving the integral of the total pulse from the piezoelectric film. The piezoelectric film is a capacitive sensor, thus charged energy is stored in the sensor. The sensor will stay charged until discharged through an external resistor, the internal resistance or a measuring apparatus. This discharging effect should be taken in consideration, because the integral will not indicate the true account of energy induced by the piezoelectric film. As soon as the amount of energy measured from the piezoelectric film exceeds the desired concurrent force, the gripper should stop its gripping motion with its deceleration characteristics taken in *consideration. Overshooting is inevitable, but by identifying actuators for reducing system response time, optimizing deceleration of the gripper closing velocity and compensation through software changes, a requested force can be applied more accurately.*

OPSOMMING

Die doel van die navorsing was om ’n knypersisteem, waarvan die knypkrag akkuraat beheer kan word, te ontwikkel. Die dinamiese vatkrag van ’n geoutomatiseerde robotknyper en die gebruik van piësoëlektriese sensors, maak dit moontlik om die verlangde knypkrag vir ’n sekere taak te bereik. Piësoëlektriese-film is meer gevoelig as en het meer strukturele eenvoud as die tipiese metaal-foelie spannings-ykmaat. 'n Hoë presiesheidsdrywer, met ’n Proporsionele-Integraal-Differensiaalbeheerder (PID), dryf die knyper daartoe om uitsonderlike beheer te behaal. Piësoëlektriese-film het ’n dinamiese reaksie in die vorm van ’n elektriese puls, wat geprikkel word deur toegediende vervormende krag en onafhanklik is van enige uitwendige kragbronne. Ontleding van die piësoëlektriese-film se uitsetpuls dui die snelheid, negatiewe versnelling en totale krag wat die knyper teweeg bring op die geknypte voorwerp. Die knypsnelheid kan bepaal word deur die derivaat van die puls, wat die piësoëlektriese film ontvang, te bereken. Die knyp-negatiewe versnelling kan bepaal word deur veranderinge in die derivaat. Die totale knypkrag kan bereken word deur die integraal van die totale puls van die piësoëlektriese-film af te lei. Die piësoëlektriese-film is ’n kapasitiewe sensor, dus word gelaaide energie in die sensor gestoor. Die sensor sal gelaai bly tot dit ontlaai word deur eksterne- of interne weerstand of ’n meetapparaat. Hierdie ontladingseffek moet in berekening gebring word omdat die integraal nie die ware telling van die energie wat deur die piësoëlektriese film opgewek word, sal aandui nie. Sodra die hoeveelheid energie, wat van die piësoëlektriese-film gemeet is, die gewenste *ooreenstemmende krag oorskry, moet die knyper sy knypaksie stop deur die negatiewe versnellingskaraktereienskappe in ag te neem. Oorskryding is onvermydelik, maar deur die identifisering van drywers wat die sisteemreaksietyd verminder, optimalisering van negatiewe versnelling van die knyper-toemaak-snelheid en kompensering deur sagteware veranderinge, kan 'n verlangde krag meer akkuraat aangewend word.*

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1. INTRODUCTION

The human hand is the most versatile bodily appendage in existence and is used as the perfect model. With these dextrous hands, people can grasp a wide variety of shapes and sizes, perform complex tasks, and switch between grasps in response to changing task requirements. This is possible due to the physical structure of the human hand, using its multiple fingers with many degrees of freedom and sophisticated control capability. Control capability is mostly a result of tactile and force-sensing, especially the ability to sense conditions at the finger-object contact. People's hands become clumsy when deprived of reliable tactile information due to numbness of anesthetized or cold fingers [1].

Mechanical and electrical sensors can be used to give a robot hand similar, but much less impressive, abilities. Force, touch and slip-sensing sensors enable the robot hand to know when it picks something up and when it should stop closing due to the fact that it's picking up something fragile like an egg (example illustration shown in article, Appendix C). A vision operated robot gripper struggles with the actual manipulation during dexterous grasping, because of the significant inaccuracy of three dimensional visual analyses on obstructed objects, illustrated in Figure 1.1. Tactile-sensing can do the fine tuning when gripping. Detecting contact early on and with as little force as possible is very important so as not to damage both objects in the environment as well as the robot itself. Force-sensing capabilities are especially useful in determining that the object is indeed still in the grasp of the robot gripper. This is a very difficult task when using machine vision, because the actual contact points are not visible and three-dimensional analysis is far from accurate. Object and gripper obstructing visual analysis is illustrated in Figure 1.1.

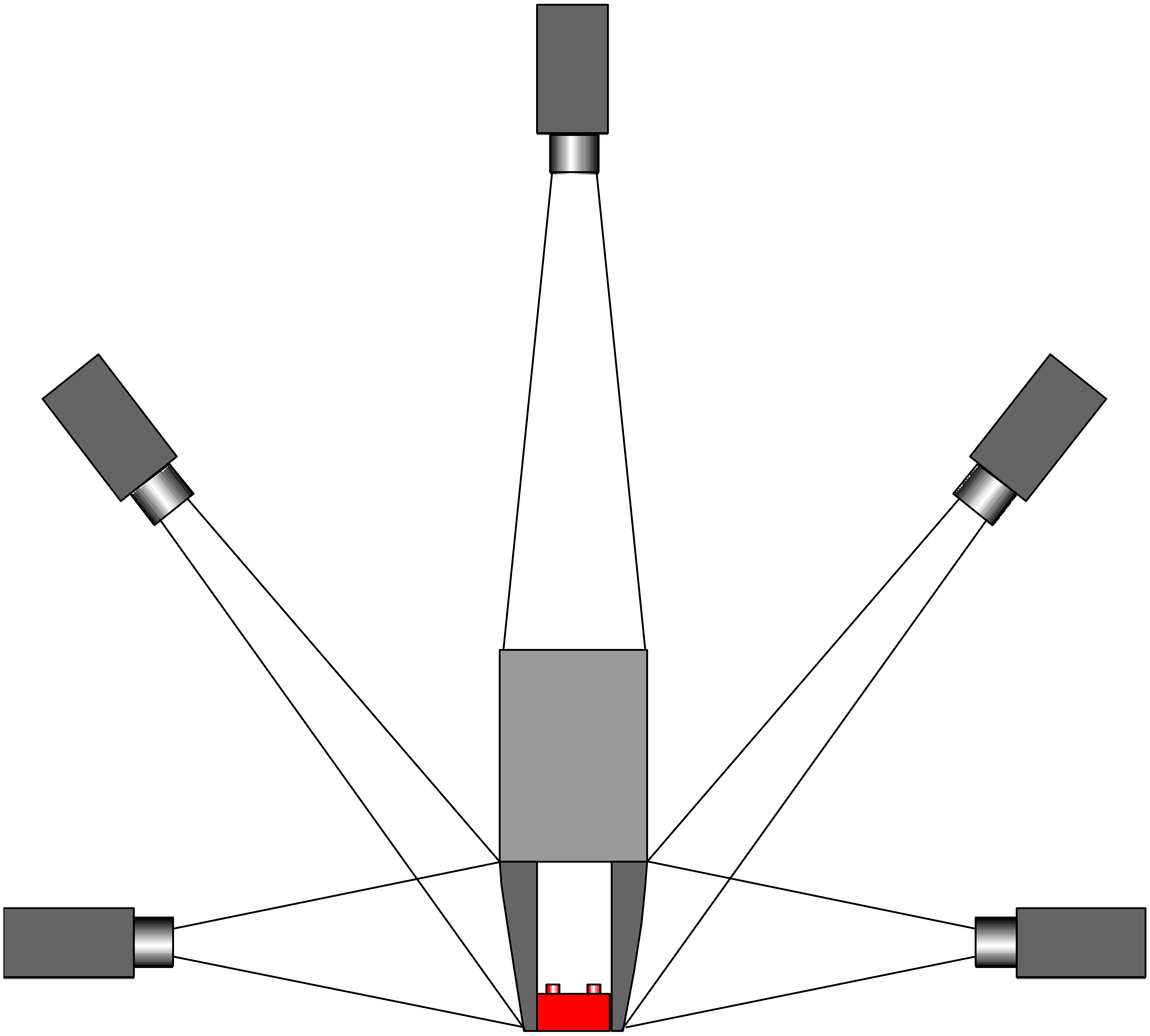


Figure 1.1 Illustrations of contact points not visible in machine vision handling setup.

Dexterous manipulation requires control of forces and motions at the point of contact between the fingers or grippers and the environment, which can only be accomplished through touch. Tactile-sensing can provide information about mechanical properties such as compliance, texture and mass. Tactile events and control discontinuities characterise the dexterous manipulation process. The act of grasping a glass of water, lifting it and replacing it contain several tactile events and discontinuities. Initially the fingertips or gripper approach the glass using velocity control. When contact is sensed at gripper or fingertips, an event is constituted which signals to switch to force control, forming a desired grasp force. Sensing the glass being separated from the table provokes another event that, once again, changes the control. Human subjects reveal that during such tasks people rely on a combination of fast and slow acting tactile-sensors to detect such events as contact, the onset of motion and the onset of slipping [2].

The purpose of this research was to develop an automated gripper system, where the gripping force can be accurately controlled by sensing force at finger-object contact to grasp different objects for movement in an automated environment, using piezoelectric film in its simplest passive form. The following flow diagram depicted in figure 1.2 shows the research steps.

Hypothesis

If piezoelectric film's dynamic response towards force can be used with static force sensing capabilities by monitoring the dynamic response and controlling the gripper fingers with software to react in a static behavior accordingly, then piezoelectric film can be used to control gripper fingers with dexterous manipulation capabilities.

Methodology

Figure 1.2 delineates this dissertation in its theoretical and practical steps. This sequence of research showed the necessary theory that must be kept in mind in order to use the sensors correctly and to acknowledge feasibility of control systems so as to realise the aim of developing a dynamic gripper using feedback from a passive responding piezoelectric film sensor. Extra instrumentation was built and used in order to measure and prove that the results correspond to the hypothesis.

Chapters 1 and 2

Theory background

Title: TACTILE FORCE-SENSING FOR DYNAMIC GRIPPING USING PIEZOELECTRIC FORCE-SENSORS

Literature research: Sensor terminology and utilisation. Gripping control techniques necessary for the design and assembly of the gripper

Chapter 3

Methodology

Testing Piezoelectric Film: Sensor's nature and response

Design and Assembly: Gripper design and construction for sensor installment and in-operation usage

Testing Gripper: Basic operation

Calibration and Noise: Reduction alterations

Gripper Control: Velocity and position software development

Force Control: Gripper control responding to force-monitoring software

Chapter 4

Results

Load Cell Installment: Comparison and correlation of gripping forces to actual applied Newton values via a load-cell

Additional Software: Software corrections and calibration to accommodate overshoot problems and to correspond to Newton values

Documentation Tests: Documentation on a range of gripped forces

Data: analysis and report

Figure 1.2 Research delineation of the dissertation.

2. SENSOR AND CONTROL TERMINOLOGY

A study in sensors was done in order to understand the sensor terminology, utilisation and to appoint the right set of sensors to use within this research, which of course falls under the mechanical range of sensors including strain/force-sensors. For making recurring measurements using strain/force-sensors, with proper accuracy, a gripper with high precision velocity and motion deceleration control is needed to achieve exceptional control. Controlling velocity with different impeding forces makes proper position control important. Different kinds of motion control systems were examined and compared.

2.1 SENSOR AND CONTROL SYSTEMS

Microprocessors being used so frequently result in the use of highly sophisticated instruments. Microprocessors are digital devices that operate on digital information which it manipulates [3]. We live in an analogue, mostly non-electrical world where microprocessors operate on non-digital and non-electrical environments. These artificial intelligent devices must receive information from the outside world.

Sensors are used as interface devices between physical values and electronic circuits that communicate through the moving of electrical charges. Surprisingly the best sensor is usually the simplest sensor. Charles F. Kettering said, “Inventing is a combination of brains and materials. The more brains you use, the less material you need” [3].

2.1.1 Data Acquisition

A sensor is a translator from a generally non-electrical to an electrical value. Electrical, meaning a signal, which can be channeled, amplified, and modified by electronic devices. The output signal of the sensor device may be in the form of voltage, current or charge. These signals will also be in the form of amplitude, phase and frequency. This set of characteristics is called the *output signal format*. This means the sensor has any kind of input with some kind of electrical output properties. A sensor functions as part of a larger system which may incorporate many other detectors, signal conditioners, signal processors, memory devices, data recorders and actuators. The place where sensors are installed is ether intrinsic or extrinsic. It may be positioned at the input of a device to perceive the outside effects and to signal the system about variations in the outside stimuli. Also, it may be an internal part of a device which monitors the device’s own state to cause the appropriate performance. A sensor is always a part of some kind of a data acquisition system. Often such a system may be a part of a larger control system which includes various feedback mechanisms. To select an appropriate sensor, a system designer must address the question: “What is the *simplest* way to sense the stimulus without degradation of the overall system performance?” [3].

All sensors may fall into two categories: *passive* and *active.* The passive sensors directly generate an electric signal in response to an external stimulus. That is, the input stimulus energy is converted by the sensor into output energy without the need for an additional power source. The examples are a thermocouple, a pyroelectric detector and a piezoelectric sensor. The active sensors require external power for their operation, which is called an *excitation signal.* That signal is modified by the sensor to produce the output signal. The active sensors are sometimes called *parametric* because their own properties change in response to an external effect and these properties can be subsequently converted into electric signals. For example, a thermistor is a temperature sensitive resistor. It does not generate any signal, but by passing an electric current through it, its resistance can be measured by detecting variations in current and/or voltage across the thermistor. These variations, presented in Ohms, directly relate to temperature.

Data can be collected from an object via a number of sensors. Some of them are positioned directly on or inside the object. Some sensors perceive the object without a physical contact and, therefore, are called *non-contact* sensors. Examples of such a sensor are a radiation detector and a CCD. Other sensors monitor internal conditions of the data acquisition system itself. Some sensors cannot be directly connected to standard electronic circuits because of inappropriate output signal formats. They require the use of interface devices. Electrical signals from the sensors may be fed into a multiplexer

(MUX), which is a switch or a gate. Its function is to connect sensors one at a time to an analogue-to-digital (A/D) converter or directly to a computer. The computer controls a multiplexer and an A/D converter for the appropriate timing. Also, it may send control signals to the actuator which acts on the object. Examples of the actuators are an electric motor, a solenoid, a relay and a pneumatic valve [3].

2.1.2 Transfer Function

Transfer function is a relationship between the physical input signal and electrical output signal. An *ideal* or *theoretical* output-stimulus relationship exists for every sensor. If the sensor is ideally designed and fabricated with ideal materials by ideal workers using ideal tools, the output of such a sensor would always represent the *true* value of the stimulus. The ideal function may be stated in the form of a table of values, a graph, or a mathematical equation. An ideal (theoretical) output-stimulus relationship is characterised by the so-called *transfer function.* This function establishes dependence between the electrical signal S produced by the sensor, and the stimulus s: $S=f(s)$. The function may be a simple linear connection or a non-linear dependence, for instance logarithmic, exponential, or power function. In many cases the relationship is two-dimensional, that is, the output versus one input stimulus.

2.1.3 Span

A dynamic range of stimuli which may be converted by a sensor is called a *span* or an *input full scale* (FS). It represents the highest possible input value which can be applied to the sensor without causing unacceptably vast inaccuracy. For the sensors with a very broad and non-linear response characteristic, a dynamic range of the input stimuli is often expressed in decibels, which is a logarithmic measure of ratios of either power or force (voltage). It should be emphasised that decibels do not measure absolute values, but a ratio of values only. A decibel scale represents signal magnitudes by much smaller numbers, which in many cases is far more convenient. Being a non-linear scale, it may represent low level signals with high resolution while compressing the high level numbers. In other words the logarithmic scale for small objects works as a microscope and for the large objects, as a telescope.

By definition, decibels are equal to 10 times the log of the ratio of powers, where P_2 is the output power and P_1 is the input power:

$$dB = 10\log\frac{P_2}{P_1} \quad \text{(2.1)}$$

In a similar manner, decibels are equal to 20 times the log of the force, current, or voltage, where S_2 is the output signal and S_1 is the input signal:

$$dB = 20\log\frac{S_2}{S_1} \quad \text{(2.2)}$$

2.1.4 Full Scale Output

Full Scale Output (FSO) is the algebraic difference between the electrical output signals measured with maximum input stimulus and the lowest input stimulus applied. This must include all deviations from the ideal transfer function. For instance, the FSO output in Figure 2.1a is represented by S_{FS}.

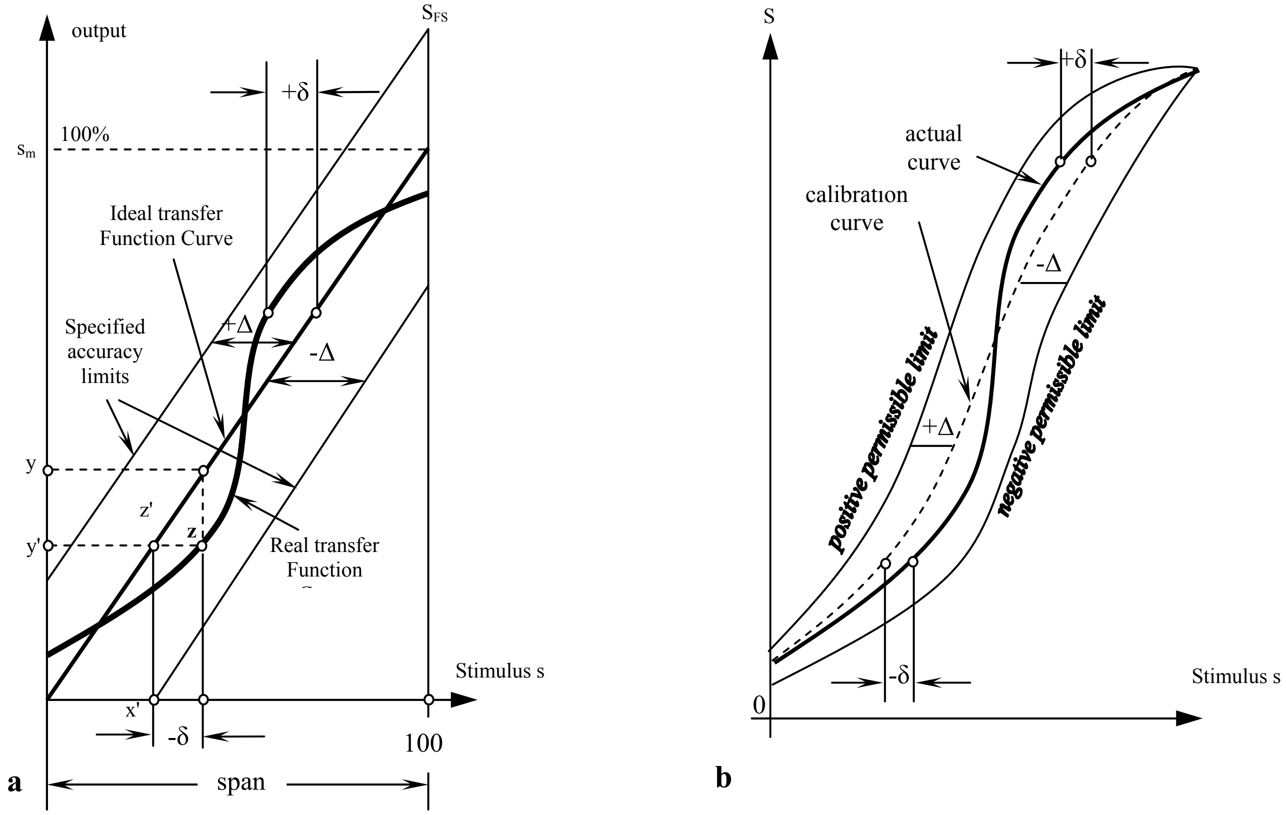


Figure 2.1 Transfer function (a) and accuracy limits (b), error is specified in terms of input value [3].

2.1.5 Accuracy

A very important characteristic of a sensor is *accuracy,* which really means *inaccuracy.* Inaccuracy is measured as a highest deviation of a value represented by the sensor from the ideal or true value at its input. The true value is attributed to the object of measurement and accepted as having a specified uncertainty.

The deviation can be described as a difference between the value which was converted by the sensor into voltage and then, without any error, converted back, and the actual input value.

Figure 2.1a shows an ideal or theoretical transfer function. In the real world, any sensor performs with some kind of imperfection. A possible *real* transfer function is represented by the thick line in Figure 2.1a, which generally may be neither linear nor monotonic. A real function rarely coincides with the ideal. Because of material variations, workmanship, design errors, manufacturing tolerances and other limitations, it is possible to have a large family of real transfer functions, even when sensors are tested under identical conditions. However, all runs of the real transfer functions must fall within the limits of a specified accuracy. These permissive limits differ from the ideal transfer function line by $\pm\Delta$. The real functions deviate from the ideal by $\pm \delta$, where $\delta \leq \Delta$.

The accuracy rating includes a combined effect of part-to-part, variations, hysteresis, dead-band, calibration and repeatability errors. The specified accuracy limits generally are used in the worst case analysis to determine the worst possible performance of the system. Figure 2.1b shows that ±Δ may more closely follow the real transfer function, meaning better tolerances of the sensor's accuracy. This can be accomplished by a multiple-point calibration. Thus, the specified accuracy limits are established not around the theoretical (ideal) transfer function, but around the calibration curve which is determined during the actual calibration procedure. Then, the permissive limits become narrower as they do not embrace part-to-part variations between the sensors and are geared specifically to the calibrated unit. Clearly, this method allows for more accurate sensing, however, in some applications, it may be prohibitive due to the higher cost involved.

Inaccuracy rating may be represented in a number of forms:

- Directly, in terms of measured value (Δ);
- In percent of input span (full scale);
- In terms of output signal [3].

2.1.6 Calibration Error

Calibration Error is inaccuracy permitted by a manufacturer when a sensor is calibrated in the factory. This error is of a systematic nature, meaning that it is added to all possible real transfer functions. It shifts the accuracy of transduction for each stimulus point by a constant. This error is not necessarily uniform over the range and may change depending on the type of error in calibration. For example, let us consider a two-point calibration of a real linear transfer function which is presented by the bold line in Figure 2.2.

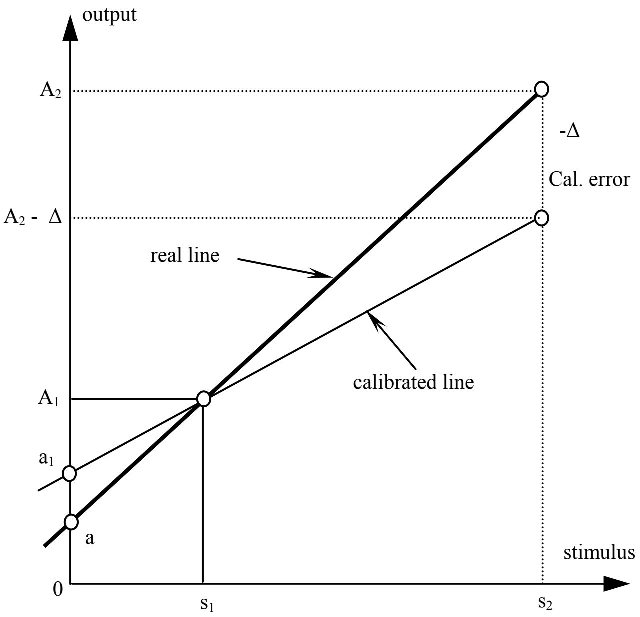


Figure 2.2 Figures showing a calibration error.

To determine the slope and the intercept of the function, two stimuli- s_1 and s_2- are applied to the sensor. The sensor responds with two corresponding output signals, A_1 and A_2. The first response was measured with absolute accuracy; however, the higher signal was measured with error -Δ. This results in errors, in the slope and calculation on the point of interception. A new intercept, a_1 will differ from the real intercept, *a,* by

$$\delta_a = a_1 - a = \frac{\Delta}{s_2 - s_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.3)}$$

and the slope will be calculated with error:

$$\delta = -\frac{\Delta}{s_2 - s_1} \qquad (2.4)$$

2.1.7 Hysteresis

A sensor may give a different reading when measuring the same quantity depending on what "direction" the value has been approached from. Such sensors do not return to the same output value when the input stimulus is cycled up or down. The maximum width of the expected error in terms of the measured quantity is defined as the hysteresis. A *hysteresis error* is a deviation of the sensor's output at a specified point of the input signal when it is approached from the opposite direction (Figure. 2.3). For example, a displacement sensor, when the object moves from left to right, at a certain point produces voltage which differs by 20 mV from than when the object moves from right to left. If the sensitivity of the sensor is 10 mV/mm, the hysteresis error in terms of displacement units is 2 mm. Typical causes for hysteresis are friction and structural changes in the materials [3].

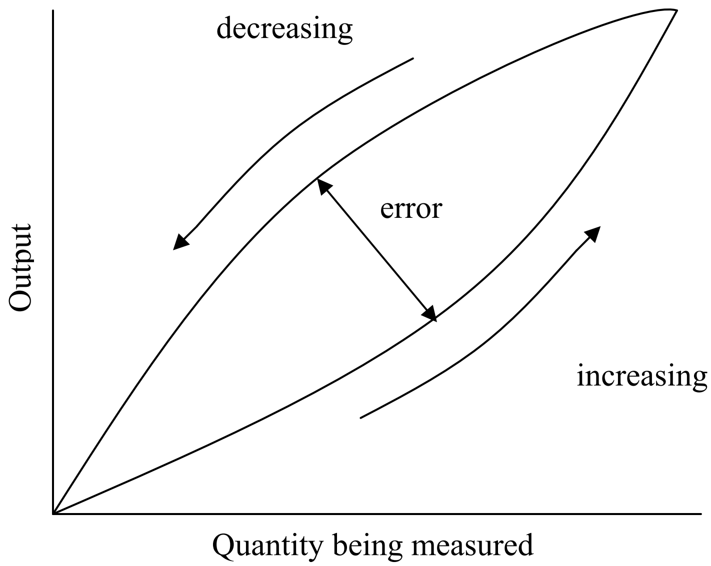


Figure 2.3 Example of a hysteresis loop [4].

2.1.8 Non-linearity

Non-linearity: Often the relationship between input and output is assumed to be linear over the working range. This assumption produces errors, as sensors typically do not have such a linear relationship.

Non-linearity error is specified for sensors whose transfer function may be approximated by a straight line. Non-linearity is a maximum deviation *(L)* of a real transfer function from the approximation straight line. The term “linearity” actually means “non-linearity.” When more than one calibration run is made, the worst linearity seen during any one calibration cycle should be stated. Usually, it is specified either in % of span or in terms of measured value, for instance, in kPa or °C. “Linearity” when not accompanied by a statement explaining what sort of straight line it is referring to, is meaningless. There are several ways to specify non-linearity, depending how the line is superimposed on the transfer function.

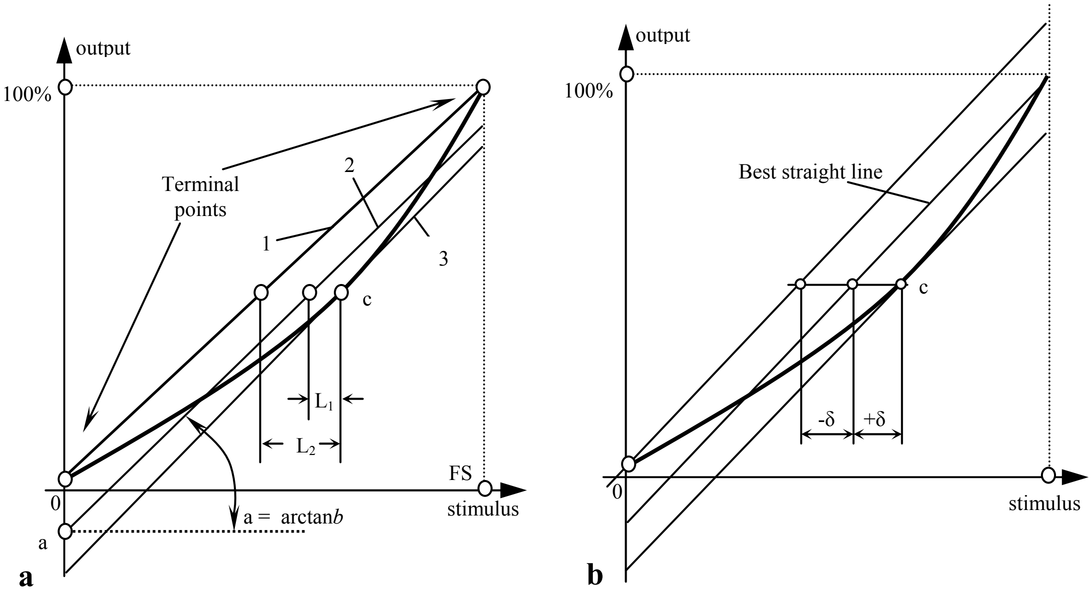


Figure 2.4 Linear approximation of a nonlinear transfer function (a); and independent linearity (b) [3].

One way is to use terminal points (line 1). Here, near the terminal points, the nonlinearity error is the smallest, where as it is higher somewhere in between. Another way to define the approximation line is to use a method of least squares (line 2 in Figure. 2.4a). This can be done in the following manner. Measure several *(n)* output values S at input values *s* over a substantially broad range, preferably over an entire full scale.

Use the following formulas for linear regression to determine intercept *a* and slope *b* of the best fit straight line:

$$a = \frac{\Sigma S \Sigma s^2 - \Sigma s \Sigma s S}{n \Sigma s^2 - (\Sigma s)^2} \quad , \quad b = \frac{n \Sigma s S - \Sigma s \Sigma S}{n \Sigma s^2 - (\Sigma s)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.5)$$

where Σ is the summation of *n* numbers.

In some applications, higher accuracy may be desirable in a particular narrower section of the input range. For instance, a medical thermometer should have the best accuracy in a fever definition region which is between 37 and 38 ºC. It may have a somewhat lower accuracy beyond these limits. Usually, such a sensor is calibrated in the region where the highest accuracy is desirable. Then, the approximation line may be drawn through the calibration point *c* (line 3 in Figure 2.4a). As a result, non-linearity has the smallest value near the calibration point and it increases toward the ends of the span. In this method, the line is often determined as tangent to the transfer function in point *c.*

Independent linearity is referred to the so-called "best straight line" (Figure 2.4b), which is a line midway between two parallel straight lines closest together and enveloping all output values on a real transfer function.

Depending on the specification method, approximation lines may have different intercepts and slopes. Therefore, non-linearity measures may differ quite substantially from one another. A user should be aware that manufacturers often publish the smallest possible number to specify non-linearity, without defining the method utilised.

2.1.9 Saturation

Almost any sensor has its operating limits. Even if it is considered linear, at some levels of the input stimuli, its output signal will no longer be responsive. Further increase in stimulus does not produce a desirable output. It is said that the sensor exhibits a span-end non-linearity or saturation (Figure 2.5) [3].

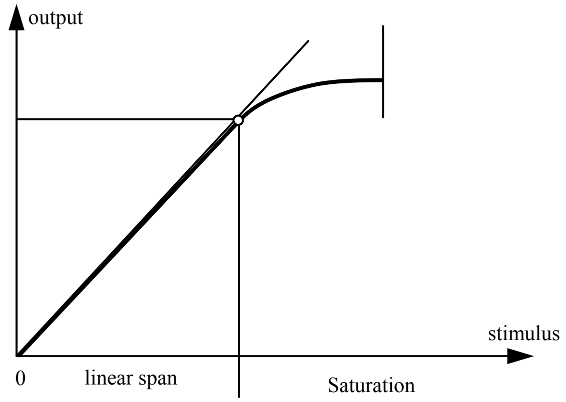


Figure 2.5 Transfer function with saturation.

2.1.10 Repeatability

Repeatability is the ability of the sensor to give the same output for repeated applications of the same input (with all other factors in the environment held constant), without the sensor being disconnected from the input. The *repeatability* (reproducibility) error is caused by the inability of a sensor to represent the same value under identical conditions. It is expressed as the maximum difference between output readings as determined by two calibrating cycles (Figure 2.6), unless otherwise specified. It is usually represented as a percent of FS:

$$\delta_r = \frac{\Delta}{FS} 100\% \quad \text{...(2.6)}$$

Possible sources of the repeatability error may be thermal noise, build-up charge, material plasticity, etc.

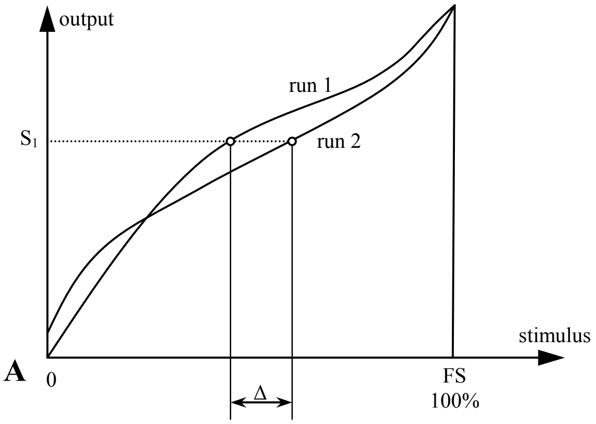


Figure 2.6 Repeatability errors: the same output signal S_1 correspond to two different input signals [3].

2.1.11 Reproducibility

The ability of the sensor to give the same output when measuring a constant input, measured on a number of occasions (i.e. with the sensor being disconnected between measurements). The error is typically expressed as the percentage of full range.

2.1.12 Dead-band

This is a region for which the sensor input-output relationship has a small or a zero slope. This region causes the quantisation levels of the output voltage to be mapped back to unacceptable inaccuracies of the measured value. For example, a flow meter using a rotor with bearing friction might mean that there is no output until the input has reached a particular velocity threshold as can be seen in Figure 2.7.

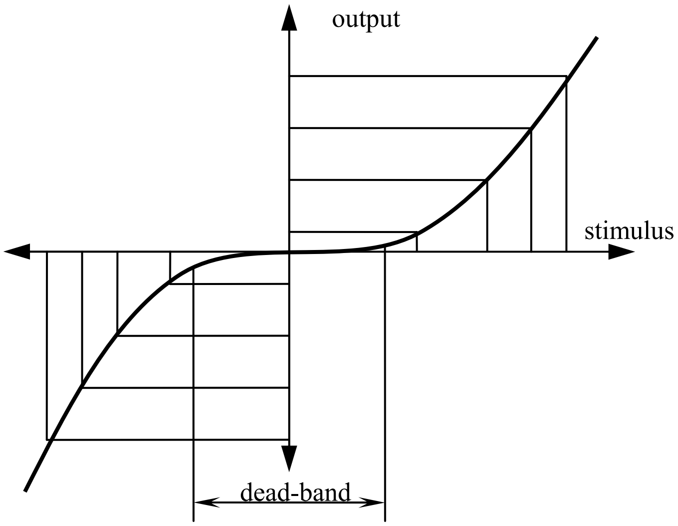


Figure 2.7 Dead-band zone in a transfer function.

These values typically describe *static characteristics* of sensors, that is, values given when steady-state conditions occur. *Dynamic characteristics* refer to changes between the time that the input value changes and the time that the value given by the sensor settles down to the steady state value.

2.1.13 Resolution

The resolution of a sensor is defined as the minimum detectable signal fluctuation. Since fluctuations are temporal phenomena, there is some relationship between the timescale for the fluctuation and the minimum detectable amplitude. Therefore, the definition of resolution must include some information about the nature of the measurement being carried out. The various terms related to sensor resolution are: spatial resolution, spectral resolution, radiometric resolution and temporal resolution.

Spatial resolution of a sensor refers to the area on the ground, which fills the instantaneous field-of-view (IFOV) of the sensor. It is also called the ground element or ground resolution cell.

Spectral resolution can be defined by the limits of the continuous wavelengths (or frequencies) that can be detected in a spectrum.

Radiometric resolution refers to the number of different intensities of radiation the sensor is able to distinguish between. Typically, this ranges from 8 to 14 bits, corresponding to 256 levels of the grey scale and up to 16,384 intensities or "shades" of colour, in each band.

Temporal resolution refers to the precision of a measurement with respect to time. Often there is a trade-off between temporal resolution of a measurement and its spatial precision [5].

When there are no measurable steps in the output signal, it is said that the sensor has *Continuous* or *infinitesimal* resolution (sometimes erroneously referred to as "infinite resolution") [3].

2.1.14 Impedance

Impedance is the ratio of voltage and current flow for a sensor. For a simple resistive sensor, such as a strain gauge or a thermistor, the impedance Z is same as the resistance R, which has units of ohms (Ω). Voltage is shown as V and current as I.

$$Z_R = \frac{V}{I} = R \quad \text{……………………………………..……(2.7)}$$

For more complicated sensors, impedance include the effects of capacitance, C, and inductance, L. Inclusion of these terms make the impedance frequency sensitive, but the units remain in ohms:

$$Z_C = \frac{V}{I} = \frac{1}{jC\omega} \text{ and } Z_L = \frac{V}{I} = jL\omega \quad \text{.............................(2.8)}$$

Where $j = \sqrt{-1}$ is the imaginary number and ω is the driving frequency. The impedance form is particularly good for analysing simple circuits, as parallel and series inductance can be treated just like resistance. Two types of impedance are important in sensor applications: input impedance and output impedance. Input impedance is a measure of how much current must be drawn to power a sensor (or signal conditioning circuit). Input impedance is frequently modelled as a resister in parallel with the input terminals. High input impedance is preferable since the device will then draw less current from the source. Oscilloscopes and data acquisition equipment frequently have input impedances of 1 MΩ or more to minimise this current draw. Output impedance is a measure of a sensor's, or signal conditioning circuit's ability to provide current for the next stage of the system. Output impedance is frequently modelled as a resistor in series with the sensor output. Low output impedance is desirable, but is often not available directly from a sensor. Piezoelectric sensors in particular have high output impedances and cannot source much current (typically micro-amps or less). Op-amp circuits are frequently used to buffer sensor outputs for this reason. Op-amp circuits, especially voltage followers, provide nearly ideal circumstances for many sensors, since they have high input impedance but with substantially lower output impedance [6].

Output impedance of a sensor is the impedance across the output terminals of a sensor presented by a sensor to the associate external circuitry [7]. Output impedance Z_{out} is important to know to better interface a sensor with the electronic circuit. This impedance is connected either in parallel with the input impedance Z_{in} of the circuit (voltage connection), or in series (current connection). Figure 2.8 shows two connections. To minimise output signal distortions, the current generating sensor (b) should have output impedance as high as possible where as the circuit's input impedance should be low. For the voltage connection (a), a sensor with lower Z_{out} is preferable and the circuit should have Z_{in} as high as is practical [3].

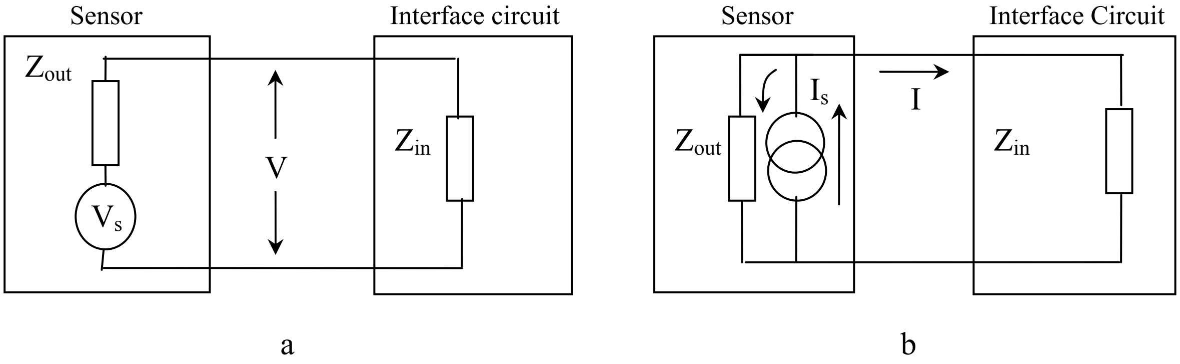


Figure 2.8 Sensor connections to an interface circuit. A: sensor has voltage output. B: sensor has current output.

The output impedance measured between the electrodes has, in piezoelectric sensors, an ohmic resistance in the order of Teraohm (TΩ) and a capacitance in the range of Picofarad (pF). If one electrode is connected to the sensor case, most piezoelectric sensors are designed that way; the insulation resistance becomes identical with the ohmic part or the output impedance [7].

2.1.16 Excitation

Excitation is the electrical signal needed for the active transducer operation. Excitation is specified as a range of voltage and/or current. For some transducers, the frequency of the excitation signal and its stability must also be specified. Variations in the excitation may alter the transducer's transfer function and cause output errors [3].

2.1.17 Dynamic Characteristics

Under static conditions a sensor is fully described by its transfer function, span, calibration, etc. However, when an input stimulus varies, a sensor response generally does not follow with perfect fidelity. The reason for this is that both the sensor and its coupling with the source of stimulus cannot always respond instantly. In other words, a sensor may be characterised with a time dependent characteristic, which is called a *dynamic characteristic.* If a sensor does not respond instantly, it may indicate values of stimuli which are somewhat different from the real, that is, the sensor responds with a *dynamic error.* A difference between static and dynamic errors is that the latter is always time dependent. If a sensor is a part of a control system which has its own dynamic characteristics, the combination may cause oscillations.

Warm-up time is the time between applying to the sensor power or excitation signal and the moment when the sensor can operate within its specified accuracy. Many sensors have a negligibly short warm-up time. However, some detectors, especially those that operate in a thermally controlled environment (a thermostat) may require seconds and minutes of warm-up time before they are fully operational within the specified accuracy limits.

Frequency response is an important dynamic characteristic of a detector as it specifies how fast the sensor can react to a change in the input stimulus. The frequency response is expressed in Hz or rad/sec to specify the relative reduction in the output signal at a certain frequency.

Lower cut-off frequency shows the lowest frequency of stimulus the sensor can process. There are a lot of similarities between definitions of the upper and the lower cutoff frequencies. They are defined in the same terms and the time constants have the same meanings. It should be emphasised that while the upper cut-off frequency shows how fast the sensor reacts, the lower cut-off frequency shows how much slowly changing stimuli the sensor can process.

For a relatively narrow bandwidth sensor (when the upper and lower cut-off frequencies are close to one another), use of time constants becomes inappropriate, because it is almost impossible to separate two exponential slopes in measurements. However, for a broad-bandwidth sensor (when the upper cut-off frequency is much higher, say 50 times), both time constants can be measured quite accurately.

There is a large class of sensors which may respond to constant stimuli. Such sensors have a dc response, therefore $\tau_L=\infty$ and $f_L=0$. Figure 2.9 shows typical responses of sensors which are the result of various combinations of cut-off frequencies.

Phase shift at a specific frequency defines how the output signal lags behind in representing the stimulus change. The shift is measured in angular degrees or radians. If a sensor is a part of a feedback control system, it is very important to know its phase characteristic. Phase lag reduces the phase margin of the system and may result in overall instability.

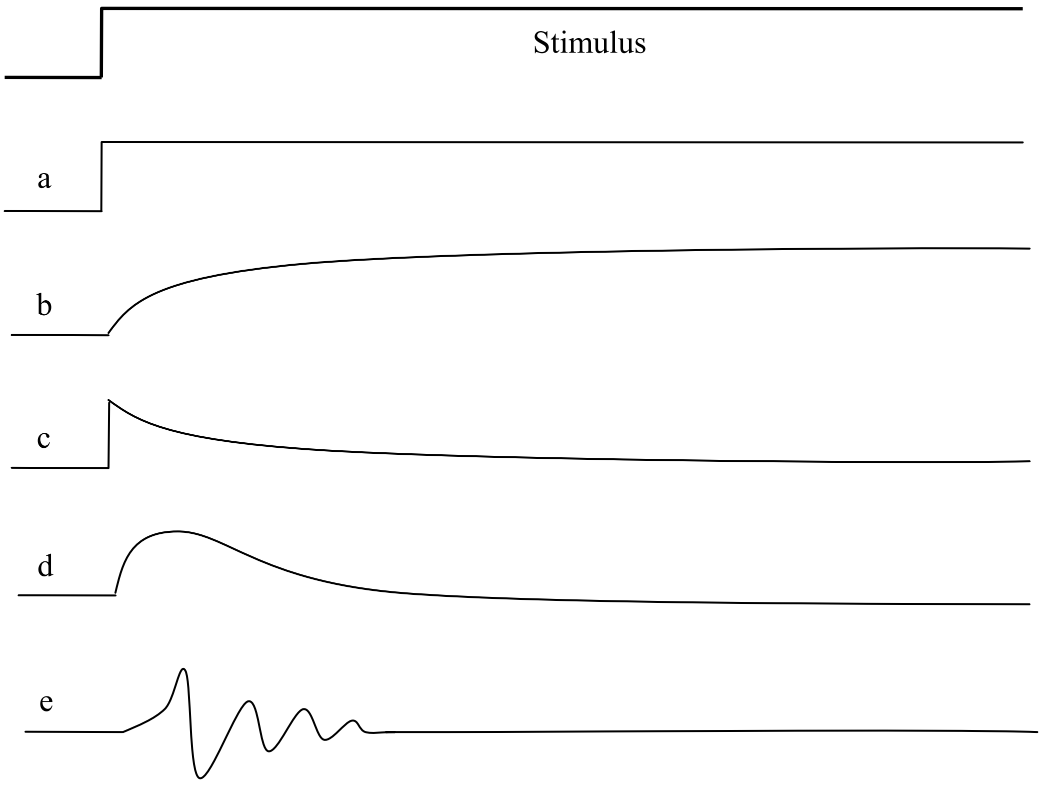


Figure 2.9 Types of responses. A – unlimited upper and lower frequencies; b – first order limited upper cut-off frequencies; c – first order limited lower cut-off frequencies; d – first order limited both upper and lower cut-off frequencies; e – narrow bandwidth response (resonant).

Resonant (natural) frequency is a number expressed in Hz or rad/sec which shows where the sensor's output signal increases considerably. Many sensors behave as linear, first-order systems which do not resonate. However, if a dynamic transducer's output conforms to the standard curve of a second-order response, the manufacturer will state the natural frequency and the damping ratio of the transducer. The resonant frequency may be related to the mechanical, thermal, or electrical properties of the detector.

Generally, the operating frequency range for the sensor should be selected well below (at least 60%) or above the resonant frequency. However, in some sensors, the resonant frequency is the operating point. For instance, in glass breakage detectors (used in security systems) the resonant makes the sensor selectively sensitive to a narrow bandwidth which is specific for the acoustic spectrum produced by shattering glass. Damping is the progressive reduction or suppression of the oscillation in the sensor, having higher than the first order response. When the sensor's response is as fast as possible without overshoot, the response is said to be critically damped as shown in Figure 2.10. Under-damped response is when the overshoot occurs and the over-damped response is slower than the critical. The damping ratio is a number expressing the quotient of the actual damping of a second-order linear transducer by its critical-damping.

The second order transfer function must include a quadratic factor: $s^2 + 2\zeta\omega_n s + \omega_n^2$, where ω_n is natural frequency (rad/sec), s is the complex variable, and ζ is the damping ratio. For a critically-damped detector $\zeta = 1$. The damping factor is defined as:

$$z = \frac{\sigma}{\varpi_n} = \frac{\sigma}{\sqrt{\sigma^2 + \omega^2}} \quad \ldots\ldots(2.9)$$

where σ is the real part of a complex variable. For an oscillating response, as shown in Figure 2.10, a damping factor is a measure of damping, expressed (without sign) as the quotient of the greater by the lesser of a pair of consecutive swings in opposite directions of the output signal, about an ultimately steady-state value [3].

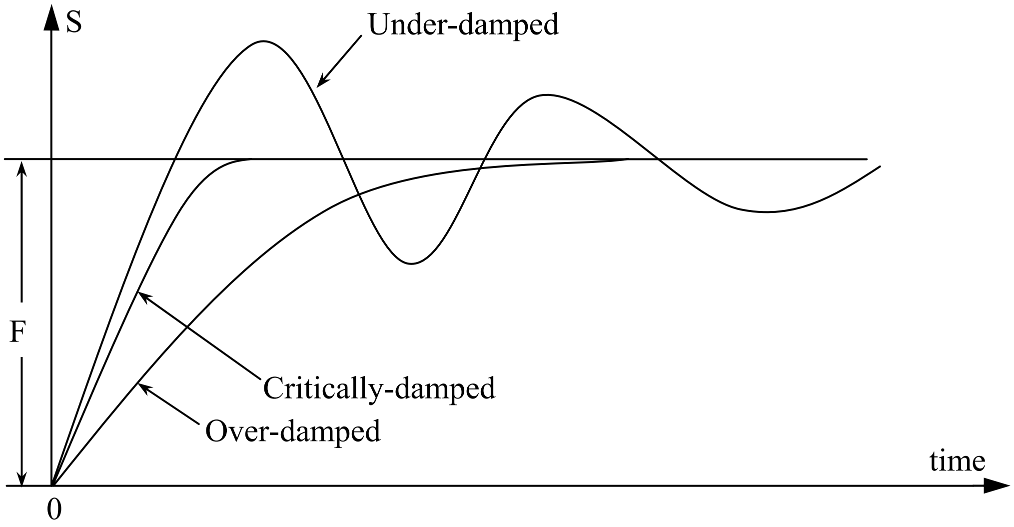


Figure 2.10 Responses of sensors with different damping characteristics.

2.1.18 Environmental Factors

Storage conditions are non-operating environmental limits to which a sensor may be subjected during a specified period without permanently altering its performance under normal operating conditions. Usually, storage conditions include the highest and the lowest storage temperatures as well as maximum relative humidity at these temperatures. Depending on the sensor’s nature, some specific limitation for the storage may need to be considered. For instance, maximum pressure, presence of some gases, or contaminating fumes, etc.

Short and long-term stabilities (drift) are parts of the accuracy specification. The short-term stability is manifested as changes in the sensor’s performance within minutes, hours or even days. Long-term stability is one of the most important requirements for the sensors that are used for precision measurements. Aging greatly depends on environmental storage and operating conditions, how well the sensor components are isolated from the environment and what materials are used for their fabrication. A powerful way to improve long-term stability is to pre-age the component at extreme conditions. The extreme conditions may be cycled from the lowest to the highest. For instance, a sensor may be periodically swung from freezing to hot temperatures. Such accelerated aging not only enhances stability of the sensor’s characteristics, but also improves the reliability as the pre-aging process reveals many hidden defects. Environmental conditions to which a sensor is subjected do not include variables which are measured by the sensor. All these factors may, and usually do, affect the Sensor’s performance. Both static and dynamic variations in these conditions should be considered. Some environmental conditions are of a multiplicative nature - that is they alter a transfer function of the sensor, for instance changing its gain.

Environmental stability is quite broad and usually a very important requirement. Both the sensor designer and the application engineer should consider all possible external factors which may affect the sensor's performance. A piezoelectric accelerometer may generate spurious signals if affected by a sudden change in ambient temperature, electrostatic discharge, formation of electrical charges (triboelectric effect), vibration of a connecting cable, electromagnetic interferences (EMI), etc. If, indeed, the environmental factors degrade the sensor's performance, additional corrective measures may be required. For instance, placing the sensor in a protective box, electrical shielding, using a thermal insulation, or a thermostat.

Many sensors change with temperature and their transfer functions may shift significantly. Special compensating elements are often incorporated either directly into the sensor or into signal conditioning circuits, to compensate for temperature errors. Temperatures will also affect dynamic characteristics, particularly when they employ viscous damping. A relatively fast temperature change may cause the sensor to generate a spurious output signal. However, when the temperature changes fast, the sensor will generate electric current which may be recognised by a processing circuit as a valid response to a stimulus, thus causing a false positive detection [3].

2.1.19 Reliability

Reliability is the ability of a sensor to perform a required function under stated conditions for a stated period. It is expressed in statistical terms as a probability that the device will function without failure over a specified time or a number of uses. It should be noted that reliability is not a characteristic of drift or noise stability. It specifies a failure, that is, temporary or permanent, exceeding the limits of a sensor's performance under normal operating conditions.

The qualification tests on sensors are performed at combinations of the worst possible conditions. One approach is 1000 hours, loaded at maximum temperature. This test does not qualify for important impacts such as fast temperature changes. The most appropriate method of testing would be accelerated life qualification. It is a procedure that emulates the sensor's operation, providing real-world stresses, but compressing years into weeks. Goals behind these tests are to identify first failure points that can then be strengthened by design changes; and to identify the overall system practical life time. One possible way to compress time is to use the same profile as the actual operating cycle, including maximum loading and power-on, power-off cycles, but expanded environmental highest and lowest ranges (temperature, humidity and pressure). The highest and lowest limits should be substantially broader than normal operating conditions performance characteristics may be outside specifications, but must return to those when the device is brought back to the specified operating range [3].

2.1.20 Application Characteristics

Design, weight and overall dimensions are geared to specific areas of applications. Price may be a secondary issue when the sensor's reliability and accuracy are of paramount importance. If a sensor is intended for life support equipment, weapons, or spacecraft, a high price tag may be well justified to assure high accuracy and reliability. On the other hand, for a very broad range of consumer applications, the price of a sensor often becomes the corner stone of a design [3].

2.1.21 Uncertainty

No matter how accurate the measurement is, it's only an approximation or estimate of the true value of the specific quantity subject to measurement, which is the stimulus. Thus, the result of measurement should be considered complete only when accompanied by a quantitative statement of its uncertainty.

When taking individual measurements under noisy conditions one expect that stimulus s is represented by the sensor as having a somewhat different value s', so that the error in measurement is expressed as:

$$\delta = s' - s \quad \text{...} (2.10)$$

The difference between the error that is specified by equation 2.10 and uncertainty should always be clearly understood. An error can be compensated to a certain degree by correcting its systematic component. The result of such a correction can unknowingly be very close to the unknown true value of the stimulus and, thus, will have a very small error. Yet, in spite of a small error, the uncertainty of measurement may be very large so one cannot really trust that the error is indeed that small. In other words, an error is what one unknowingly gets when measuring, while uncertainty is how large one thinks that error might be [3].

2.1.22 Sensitivity

The sensitivity of a sensor is defined in terms of the relationship between physical input signal and output electrical signal. It is generally the ratio between a small change in electrical signal to a small change in physical signal. As such, it may be expressed as the derivative of the transfer function with respect to physical signal. Typical units are volts/Kelvin, millivolt/kilopascal, etc. A thermometer would have "high sensitivity" if a small temperature change result, in a large voltage change [8].

2.1.23 Noise

All sensors produce some output noise in addition to the output signal. In some cases, the noise of the sensor is less than the noise of the next element in the electronics, or less than the fluctuations in the physical signal, in which case it is not important. Many other cases exist in which the noise of the sensor limits the performance of the system based on the sensor. Noise is generally distributed across the frequency spectrum. Many common noise sources produce a white noise distribution, which is to say that the spectral noise density is the same at all frequencies. Johnson noise in a resistor is a good example of such a noise distribution. A distribution of this nature adds noise to a measurement with amplitude proportional to the square root of the measurement bandwidth. Since there is an inverse relationship between the bandwidth and measurement time, it can be said that the noise decreases with the square root of the measurement time [9].

2.1.24 Stability

Stability is the ability of the sensor to give the same output when measuring a constant input, measured over a period of time. With the physical variable remaining unchanged, the measured reading may go on shifting randomly – commonly known as "drift". Such a drift at the zero value of variable is called "zero drift". Zero drift can be, broadly, caused by two reasons.

The sensor may respond to changes in other quantities, apart from the variable of interest. One or more of these may change, though the measured variable may remain unchanged, resulting in the drift. A typical example is a gas sensor, which is meant to respond to changes in the concentration of the gas concerned in air. The sensor is often sensitive to changes in the concentration of other gases, such as hydrogen and moisture. Changes in the environmental conditions under which the sensor functions, also cause such drift.

A second cause is drift due to some undesirable change or effect associated with the sensor itself. As an example, consider a strain gauge bridge. It is intended to sense changes in the strain of objects. The same is converted into an output through temperature changes, where the increase of temperature will expand the volume of the object, causing a drift from the desired output [10].

2.1.25 Response Time:

In technology, response time is the time a system or functional unit takes to react to a given input [11]. The time that elapses after a constant input (step) up to the time the sensor gives an output that has reached some percentage (say 95%) of the value of the input. The above is depicted in Figure 2.11. The time constant is 63.2% of the response time [11].

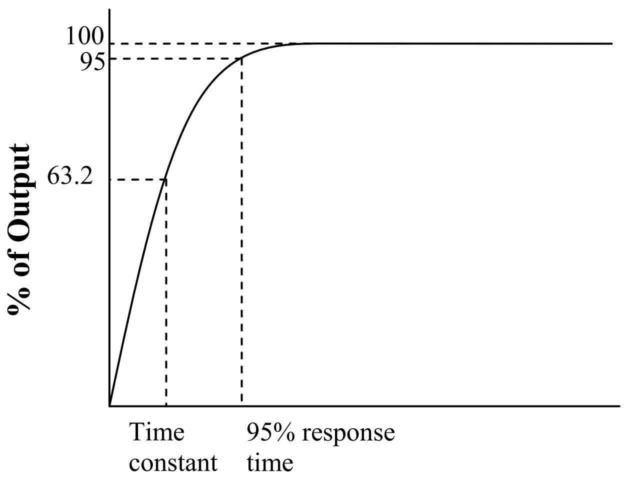


Figure 2.11 Response time of a system reacting on an input reaching 95 % of the input value.

2.1.26 Rise Time:

Time taken to rise to some specified percentage of the steady state value. It is often the time to rise from 10% to 90% of the steady state value [11].

2.1.27 Settling Time:

Settling time is the time taken to settle within some percentage of the steady state value [11].

2.1.28 Bandwidth:

All sensors have finite response times to an instantaneous change in physical signal. In addition, many sensors have decay times, which would represent the time after a step change in physical signal for the sensor output to decay to its original value. The reciprocal of these times correspond to the upper and lower cut-off frequencies, respectively. The bandwidth of a sensor is the frequency range between these two frequencies [11].

For different applications there are different precise definitions. For example, one definition of bandwidth could be the range of frequencies beyond which the frequency function is zero. This would correspond to the mathematical notion of the support of a function (i.e., the total "length" of values for which the function is non-zero). A less strict and more practically useful definition will refer to the frequencies, where the frequency function is *small*. Small could mean less than 3 dB below (i.e. less than half of) the maximum value, or more rarely 10 dB. It could also mean below a certain absolute value. As with any definition of the *width* of a function, many definitions are suitable for different purposes. A baseband bandwidth is a specification of only the highest frequency limit of a signal. A non-baseband bandwidth is the difference between highest and lowest frequencies. As an example, the (non-baseband) -3dB bandwidth of the function depicted in the Figure 2.12 is $\Delta f = f_2 - f_1$, whereas other definitions of bandwidth would yield a different answer [11].

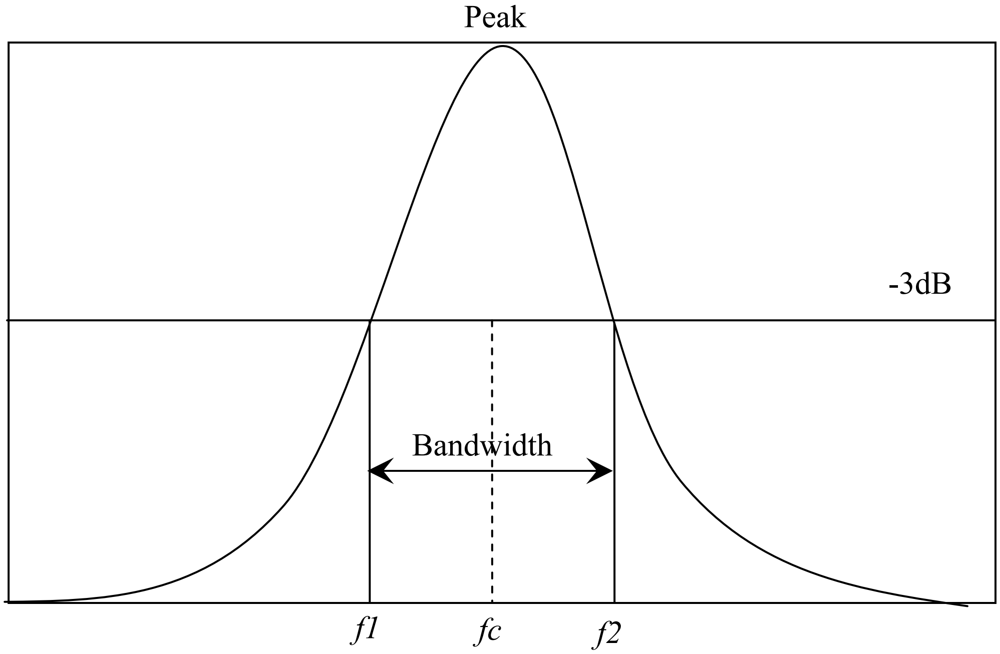


Figure 2.12 Graph of a power spectral density, illustrating the concept of -3dB (or half-power) bandwidth. The vertical axis here is proportional to power (square of fourier magnitude); the frequency axis of this symbolic diagram can be linear or logarithmically scaled.

2.1.29 Physical Sensing Principals

Since a sensor is a converter of generally non-electrical effects into electrical signals, one and often several transformational steps are required before the electric output signal can be generated. These steps involve changes of the types of energy, where the final step must produce an electrical signal of a desirable format. There are several physical effects which cause generation of electrical signals in response to non-electrical influences. Examples are the thermoelectric (Seebeck) effect, piezoelectricity and photoeffect.

If, for instance, one wants to detect displacement of an opaque object, a fiber-optic sensor can be employed. A pilot (excitation) signal is generated by a photodiode, transmitted via an optical fiber to the object and reflected from its surface. The reflected photon flux enters the receiving optical fiber and propagates toward a photodiode where it produces an electric current representing the distance from the fiber-optic end to the object. We see that such a sensor involves transformation of electrical current into photons, propagation of photons through some refractive media, reflection and conversion back into electric current. Therefore, such a sensing process includes two energy conversion steps and as well as a manipulation of the optical signal [3].

2.1.30 Strain Sensitivity

Usually, electrical resistance changes when the material is mechanically deformed. This is called the *piezoresistive effect.* In some cases, the effect is a source of error. On the other hand, it is successfully employed in sensors which are responsive to stress, σ

$$\sigma = \frac{F}{a} = E\frac{dl}{l} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.11)$$

where *E* is Young's modulus of the material, *F* the applied force and *a* the cross-sectional area where it is acting upon. In this equation, the ratio *dl/l* = *e* is called *strain,* which is a normalised deformation of the material. Volume *υ* of the material stays constant, while the length l increases and the cross-sectional area becomes smaller, where ρ is the receptivity and R the resistance.

$$R = \frac{\rho}{\upsilon} l^2 \text{..(2.12)}$$

After differentiating, we can define sensitivity of resistance with respect to wire elongation

$$\frac{dR}{dl} = 2\frac{\rho}{\upsilon} l \text{......................................(2.13)}$$

It follows from this equation that the sensitivity becomes higher for the longer and thinner wires with high specific resistance. Normalised incremental resistance of the strained wire is a linear function of strain, *e,* and it can be expressed as

$$\frac{dR}{R} = S_e e \text{...(2.14)}$$

where S_e is known as the *gauge factor* or *sensitivity* of strain gauge element. For metallic wires it ranges from 2 to 6. It is much higher for the semiconductor gauges where it is between 40 and 200.

Early strain gauges were metal filaments. The gauge elements were formed on a backing film of electrically isolating material. Today, they are manufactured from constantan (copper/nickel alloy) foil or single crystal semiconductor materials (silicon with boron impurities). The gauge pattern is formed either by mechanical cutting or photochemical etching. When a semiconductor material is stressed, its resistivity changes depending on the type of the material and the doping dose. However, the strain sensitivity in semiconductors is temperature dependent, which requires proper compensation when used over a broad temperature range [3].

2.1.31 Piezoelectric Effect

The piezoelectric effect is the generation of electric charge via a crystalline material upon subjecting it to stress. The effect exists in natural crystals, such as quartz (chemical formula SiO_9), and poled (artificially polarised) man-made ceramics as well as some polymers, such as Polyvinylidene Difluoride (PVDF). It is said that piezoelectric material possesses ferroelectric properties. The name was given by an analogy with ferromagnetic properties. A quartz crystal is cut along its axes x, y, and z. Crystalline material can develop electric charge on its surface in response to a mechanical deformation.

To pick up an electric charge, conductive electrodes must be applied to the crystal at the opposite sides of the cut shown in Figure 2.13. As a result, a piezoelectric sensor becomes a capacitor with a dielectric material which is a piezoelectric. The dielectric acts as a generator of electric charge, resulting in voltage V across the capacitor. Although charge in a crystalline dielectric is formed at the location of an acting force, metal electrodes equalise charges along the surface making the capacitor not selectively sensitive. However, if electrodes are formed with a complex pattern, it is possible to determine the exact location of the applied force by measuring the response from a selected electrode.

The piezoelectric effect is a reversible physical phenomenon. That means that applying voltage across the crystal produces mechanical strain. It is possible, by placing several electrodes on the crystal, to use one pair of electrodes to deliver voltage to the crystal as well as the other pair of electrodes in order to pick up charge resulting from developed strain. This method is used quite extensively in various piezoelectric transducers.

The magnitude of the piezoelectric effect in a simplified form can be represented by the vector of polarisation where x,y,z refer to a conventional orthogonal system related to the crystal axes [12].

$$\mathbf{P}=\mathbf{P}_{xx}+\mathbf{P}_{yy}+\mathbf{P}_{zz}\ ,\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.15)$$

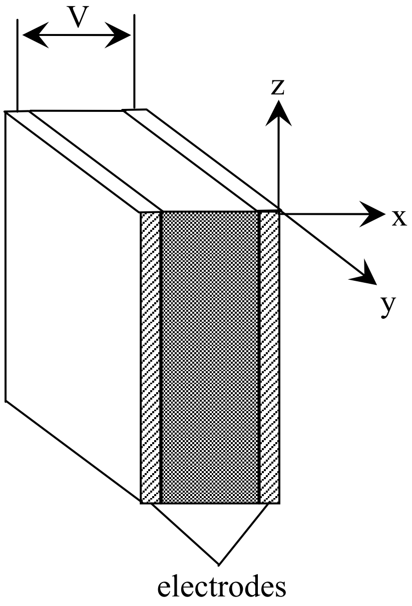


Figure 2.13 Piezoelectric sensor is formed by applying electrodes to a poled crystalline material.

$$P_{xx}=d_{11}\boldsymbol{\sigma}_{xx}+d_{12}\boldsymbol{\sigma}_{yy}+d_{13}+\boldsymbol{\sigma}_{zz}\,,$$

$$P_{yy}=d_{21}\boldsymbol{\sigma}_{xx}+d_{22}\boldsymbol{\sigma}_{yy}+d_{23}+\boldsymbol{\sigma}_{zz}\,,$$

$$P_{zz}=d_{31}\boldsymbol{\sigma}_{xx}+d_{32}\boldsymbol{\sigma}_{yy}+d_{33}+\boldsymbol{\sigma}_{zz}\,,\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.16)$$

In terms of axial stress, σ, we can note the position of where constants d_{mn} are the piezoelectric coefficients along the orthogonal axes of crystal cut. Dimensions of these coefficients are C/N (Coulomb/Newton), i.e., charge unit per unit force.

Piezoelectric sensors are responsive only to a changing stress rather than to a steady level of it. In other words, a piezoelectric sensor is an AC device, rather than a DC device. Piezoelectric sensitivities *(d* coefficients) are temperature dependent. For some materials (quartz), sensitivity drops with a slope of -0.016% / ^{0}C. For the others (PVDF films and ceramics), at temperatures below 40 °C, it may drop and at higher temperatures it increases with a raise in temperature. The stability of permanent polarisation relies on the coercive force of the dipoles. In some materials, polarisation may decrease with time. To improve stability of poled material, impurities have been introduced in the basic material with the idea that the polarisation may be “locked” into position [12].

PVDF is a semi-crystalline polymer with an approximate degree of crystallinity at 50%. Like other semi-crystalline polymers, PVDF consists of a lamellar structure mixed with amorphous regions. The chemical structure of it contains the repeat unit of doubly fluorinated ethene CF_2---CH_2:

PVDF molecular weight is about 10^5, which corresponds to about 2000 repeat units. The film is quite transparent in the visible and near-IR region, and is absorptive in the far infrared portion of electromagnetic spectrum. The polymer melts at about 170 ^{0}C. Its density is about 1780 kg/m^3. PVDF is a mechanically durable and flexible material. In piezoelectric applications, it is usually drawn, uniaxially or biaxially, to several times its length. Elastic constants, for example Young’s modulus, depend on this draw ratio. Thus, if the PVDF film was drawn at 140 ^{o}C to the ratio of 4:1, the modulus value is 2.1 GPa, while for the draw ratio of 6.8:1 it is 4.1 GPa. Resistivity of the film also depends on the stretch ratio. For instance, at low stretch it is about 6.3. 10^{15} Ω·cm, while for the stretch ratio 7:1 it is 2.10^{16} Ω·cm [3].

PVDF does not have a higher, or even as high a piezoelectric coefficient as other commonly used materials, like $BaTiO_3$ or PZT. However, it has a unique quality in that it does not depolarize while being subjected to very high alternating electric fields. This means that even though the value of d_{31} of PVDF is about 10% of PZT, the maximum strain observable in PVDF will be 10 times larger than in PZT, since the maximum permissible field is a hundred times greater for PVDF. The film exhibits good stability: when stored at 60 ^{0}C it loses its sensitivity by about 1-2% over six months [3].

The piezoelectric elements may be used as a single crystal or in a multilayer form, where several plates (films) of the material are laminated together. This must be done with electrodes placed in-between. Figure 2.14 shows a two-layer force-sensor. When an external force is applied, the upper part of the sensor expands while the bottom compresses. If the layers are laminated correctly, this produces a double output signal.

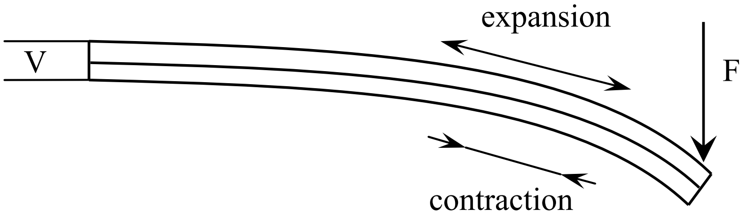


Figure 2.14 Laminated two-layer piezoelectric sensor.

Double sensors can have either a parallel connection, as shown in Figure 2.15a, or a serial connection as in Figure 2.15c. The electrical equivalent circuit of the piezoelectric sensor is a parallel connection of a stress-induced current source *(i),* leakage resistance *(r),* and capacitance *(C).*

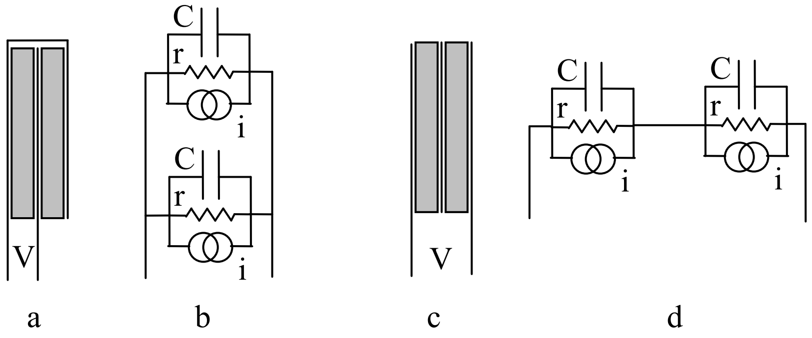


Figure 2.15 Parallel (a) and serial (c) laminated piezoelectric sensors and their corresponding equivalent circuits (b and d).

Depending on the layer connection, equivalent circuits for the laminated sensors are as shown in Figures 2.15b and d. The leakage resistors *r* are very large (of the orders of 10^{12}-$10^{14}\Omega$,) which means that the sensor has an extremely high output impedance. This requires special interface circuits, such as charge and current-to-voltage converters, or voltage amplifiers with high input resistances.

Piezoelectric effect is the prime means of converting mechanical deformation into electrical signal and vice versa in the miniature semiconductor sensors. Since silicon does not possess piezoelectric properties, such properties can be added on by depositing crystalline layers of the piezoelectric materials. The three most popular materials are zinc oxide (ZnO), aluminium nitride (AlN) and the so-called solid solution system of lead-zirconite-titanium oxides $Pb(Zr,Ti)O_3$ known as PZT ceramic - basically the same material used for fabrication of discrete piezoelectric sensors as described above. Zinc oxide, in addition to the piezoelectric properties, also is pyroelectric. It was the first and most popular material for development of ultrasonic acoustic sensors, surface acoustic wave (SAW) devices, microbalances, etc. One of its advantages is the ease of chemical etching. The zinc oxide thin films are usually deposited on silicon by employing the sputtering technology.

Aluminum nitride is an excellent piezoelectric material because of its high acoustic velocity and its endurance when subjected to humidity and high temperature. Its piezoelectric coefficient is somewhat lower than in ZnO but higher than in other thin-film piezoelectric materials, excluding ceramics. The high acoustic velocity makes it an attractive choice in the GHz frequency range. Usually, the AlN thin films are fabricated by using the chemical vapor deposition (CVD) or reactive molecular beam epitaxy (MBE) technologies. However, the drawback of using these deposition methods is the need for high heating temperature (up to 1300 ^{o}C) of the substrate.

The PZT thin films possess a larger piezoelectric coefficient than ZnO or AlN and also a high pyroelectric coefficient, which makes it a good candidate for fabrication of the thermal radiation detectors. A great variety of deposition techniques is available for the PZT, among which are the electron-beam evaporation, RF sputtering, ion-beam deposition, epitaxial growth by RF sputtering, magnetron sputtering, laser ablation, and sol-gel [3].

2.1.32 Piezoelectric Film Properties:

Piezo film is a flexible, lightweight, tough engineering plastic available in a wide variety of thicknesses and large surface sizes. Its properties as a transducer include:

- Wide frequency range: 0.001 Hz to 10^9 Hz.
- Vast dynamic range: (10^{-8} to 10^6 psi or μ torr to Mbar).
- Low acoustic impedance: close match to water, human tissue and adhesive systems.
- High elastic compliance.
- High voltage output: 10 times higher than piezo ceramics for the same force input.
- High dielectric strength: withstanding strong fields (75V/μm) where most piezo ceramics depolarize.
- High mechanical strength and impact resistance (10^9 - 10^{10} Pascal modulus).
- High stability: resisting moisture (<0.02% moisture absorption), most chemicals and oxidants as well as intense ultraviolet and nuclear radiation.
- Can be fabricated into unusual designs.
- Can be glued with commercial adhesives.

One major advantage of piezo film over piezo ceramic is its low acoustic impedance which is closer to that of water, human tissue and other organic materials. For example, the acoustic impedance ($Z_O = \rho\ \upsilon$) of piezo film is only 2.6 times that of water, whereas piezo ceramics are typically 11 times greater. Z_O is the characteristic acoustic impedance, ρ is the density of the medium and υ is the longitudinal wave speed. A close impedance match permits more efficient transduction of acoustic signals in water and tissue.

However Piezo film does have limitations for certain applications. It makes a relatively weak electromechanical transmitter when compared to ceramics, particularly pertaining to resonance and low frequency applications. The copolymer film has maximum operating/storage temperatures as high as 135^{o}C, while PVDF is not recommended for use or storage above 100 ^{o}C. Also, if the electrodes on the film are exposed, the sensor can be sensitive to electromagnetic radiation. Good shielding techniques are available for high EMI/RFI environments. Table 1. lists typical properties of piezo film. Piezo film has low density and excellent sensitivity, and is mechanically tough. The compliance of piezo film is 10 times greater than the compliance of ceramics. When extruded into thin film, piezoelectric polymers can be directly attached to a structure without disturbing its mechanical motion. Piezo film is well suited to strain sensing applications requiring very wide bandwidth and high sensitivity. As an actuator, the polymer's low acoustic impedance permits the efficient transfer of a broadband of energy into air and other gases [4].

Table 1 Typical Properties of Piezoelectric Film [4]

Symbol	Parameter	PVDF	Copolymer	Units
t	Thickness	9, 28, 52, 110	<1 to 1200	µm (micron, 10-6)
d_{31}	Piezo Strain Constant	23	11	10^{-12} $\frac{m/m}{V/m} or \frac{C/m^2}{N/m^2}$
d_{33}		-33	-38	
g_{31}	Piezo Strain Constant	216	162	10^{-3} $\frac{V/m}{N/m^2} or \frac{m/m}{C/m^2}$
g_{33}		-330	-542	
k_{31}	Eletromechanical Coupling Factor	12%	20%	
k_t		14%	25-29%	
C	Capacitance	380 for 28 µm	68 for 100µm	pF/cm^2 @ 1KHz
Y	Young's Modulus	2-4	3-5	10^9N/m^2
V_0	Speed of Sound Stretch: Thickness	1.5	2.3	10^3 m/s
		2.2	2.4	
p	Pyroelectric Coefficient	30	40	10^{-6} C/m^2 º K
ε	Permittivity	106-113	65-75	10^{-12} F/m
$\varepsilon / \varepsilon_0$	Relative Permittivity	12-13	7-8	
ρ_m	Mass Density	1.78	1.82	10^3 kg/m
ρ_e	Volume Resistivity	$>10^{13}$	$>10^{14}$	Ohm meters
R	Surface Metallisation Resistivity	<3.0	<3.0	Ohms/square for NiA1
R		0.1	0.1	Ohms/square for Ag Ink
tan δ_e	Loss Tangent	0.02	0.015	@ 1KHz
	Yield Strength	45-55	20-30	10^6N/m^2 (stretch axis)
	Temperature Range	-40 to 80...100	-40 to 115…145	º C
	Water Absorption	<0.02	<0.02	%H_2O
	Maximum Operating Voltage	750 (30)	750(30)	V/mil(V/µm), DC, @25ºC
	Breakdown Voltage	2000 (80)	2000 (80)	V/mil(V/µm), DC, @25ºC

Operating properties for a typical piezoelectric film element:

The DT1 element is a standard piezo film configuration consisting of a 12x30 mm active area printed with silver ink electrodes on both surfaces of a 15x40 mm die-cut piezo polymer substrate.

- **Electromechanical Conversion**

  (1 direction) 23 x 10^{-12} m/V, 700 x 10^{-6} N/V

  (3 direction) -33 x 10^{-12} m/V

- **Mechanoelectrical Conversion**

  (1 direction) 12 x 10^{-3} V per microstrain, 400 x 10-3V/µm, 14.4V/N

  (3 direction) 13 x 10^{-3} V/N

- **Pyroelectrical Conversion**

  8V/ °K (@ 25 °C)

- **Capacitance**

  1.36 x 10^{-9} F; Dissipation Factor of 0.018 @ 10 KHz; Impedance of 12 KΩ @ 10 KHz

- **Maximum Operating Voltage**

  DC: 280 V (yields 7 µm displacement in 1 direction)

  AC: 840 V (yields 21 µm displacement in 1 direction)

- **Maximum Applied Force (at break, 1 direction)**

  6-9 kgF (yields voltage output of 830 to 1275 V) [4]

2.1.32 Force and Strain sensors

$$F = ma \quad \text{..(2.17)}$$

The SI unit of force is derived from Newton’s second law indicated in equation 2.17 and is one of the fundamental quantities of physics. The measurement of force is required in mechanical and civil engineering, for weighing objects, designing prosthesis, etc. Where F is force, *m* is mass and *a* is acceleration. Whenever pressure is measured, it requires the measurement of force. It could be said that force is measured when dealing with solids, while pressure, when dealing with fluids (i.e., liquids or gases). That is, force is considered when action is applied to a spot and pressure is measured when force is distributed over a relatively large area.

Force-sensors can be divided into two classes: quantitative and qualitative. A quantitative sensor actually measures the force and represents its value in terms of an electrical signal. Examples of these sensors are strain gauges and load cells. The qualitative sensors are threshold devices which are not concerned with the good fidelity of representation of the force value. Their function is merely to indicate whether a sufficiently strong force is applied or not. That is, the output signal indicates when the force magnitude exceeds a predetermined threshold level. An example of these detectors is a computer keyboard where a key makes a contact only when it is pressed with sufficient pressure. The various methods of sensing force can be categorised as follows [13]:

- By balancing the unknown force against the gravitational force of a standard mass;
- By measuring the acceleration of a known mass to which the force is applied;
- By balancing the force against an electromagnetically developed force;
- By converting the force to a fluid pressure and measuring that pressure;
- By measuring the strain produced in an elastic member by the unknown force.

In modern strain sensors the most commonly used method is measuring the strain produced in an elastic member. In most sensors, force is not directly converted into an electric signal. Some intermediate steps are usually required. For instance, a force-sensor can be fabricated by combining a position-sensor and a force-to-displacement converter. The latter may be a simple coil spring, whose compression displacement x can be defined through the spring coefficient k and compressing force F as: $x = kF$ [3].

2.1.33 Strain-gauges

A strain-gauge is a resistive elastic sensor whose resistance is a function of applied strain (unit deformation). Since all materials resist to deformation, some force must be applied to cause deformation. Hence, resistance can be related to applied force. That relationship is generally called the *piezoresistive* effect and is expressed through the gauge factor S_e of the conductor [equation (2.14)]:

For many materials $S_e \approx 2$, with the exception of platinum for which $S_e \approx 6$ [14]. For small variations in resistance not exceeding 2% (which is usually the case), the resistance of the metallic wire is

$$R=R_0(1+x) \qquad (2.18)$$

where R_0 is the resistance with no stress applied, and $x=S_e e$. For semiconductive materials, the relationship depends on the doping concentration. Resistance decreases with compression and increases with tension. A wire strain gauge is composed of a resistor bonded with an elastic carrier (backing). The backing, in turn, is applied to the object where stress or force should be measured. Obviously, that strain from the object must be reliably coupled to the gauge wire, while the wire must be electrically isolated from the object. The coefficient of thermal expansion of the backing should be matched to that of the wire. Many metals can be used to fabricate strain gauges. The most common materials are alloys Constantan, Nichrome, Advance, and Karma. Typical resistance varies from 100 to several thousand ohms. To possess good sensitivity, the sensor should have long longitudinal and short transverse segments, so that transverse sensitivity is no more than a couple of percent of the longitudinal. The gauges may be arranged in many ways to measure strains in different axes. Typically, they are connected in Wheatstone bridge configurations. It should be noted that semiconductive strain-gauges are quite sensitive to temperature variations. Therefore, interface circuits or the gauges must contain temperature compensating networks [3].

2.1.34 Tactile-Sensors

The tactile-sensors are a special class of force or pressure transducers which are characterised by their small thickness. This makes the sensors useful in the applications where force or pressure can be developed between two surfaces that are in close proximity to one another. Examples include robotics where tactile-sensors can be positioned on the “fingertips” of a mechanical actuator to provide a feedback upon developing a contact with an object, very much like tactile-sensors work in human skin. They can be used to fabricate “touch screen” displays, keyboards and other devices where a physical contact has to be sensed. A very broad area of applications is in the biomedical field where tactile-sensors can be used in dentistry for the crown or bridge occlusion investigation or in studies of forces developed by a human foot during locomotion. They can be installed in artificial knees for the balancing of the prosthesis operation, etc. In mechanical and civil engineering, the sensors can be used to study forces developed by fastening devices.

Several methods can be used to fabricate tactile-sensors. Some of them require a formation of a thin layer of a material which is responsive to strain. A simple tactile-sensor producing an “on-off” output can be formed with two leaves of foil and a spacer. The spacer has round (or any other suitable shape) holes. One leaf is grounded and the other is connected to a pull-up resistor. A multiplexer can be used if more than one sensing area is required. When an external force is applied to the upper conductor over the opening in the spacer layer, the conductor flexes and upon reaching the lower conductor, makes an electric contact, grounded by the pull-up resistor. The output signal becomes zero, indicating the applied force. The upper and lower conducting leaves can be fabricated by a silk-screen printing of conductive ink on the backing material, like Mylar® or polypropylene. Good tactile sensors can be designed with piezoelectric films, such as polyvinylidene fluoride (PVDF) used in active or passive modes. An active ultrasonic coupling touch sensor with the piezoelectric films is illustrated in where three films are laminated together (the sensors also have additional protective layers which are not shown in the diagram). The upper and the bottom films are PVDF, while the centre film is for the acoustic coupling between the other two. The softness of the centre film determines sensitivity and the operating range of the sensor. The bottom piezoelectric film is driven by an AC voltage from an oscillator. This excitation signal results in mechanical contractions of the film which are coupled to the compression film and, in turn, to the upper piezoelectric film, which acts as a receiver.

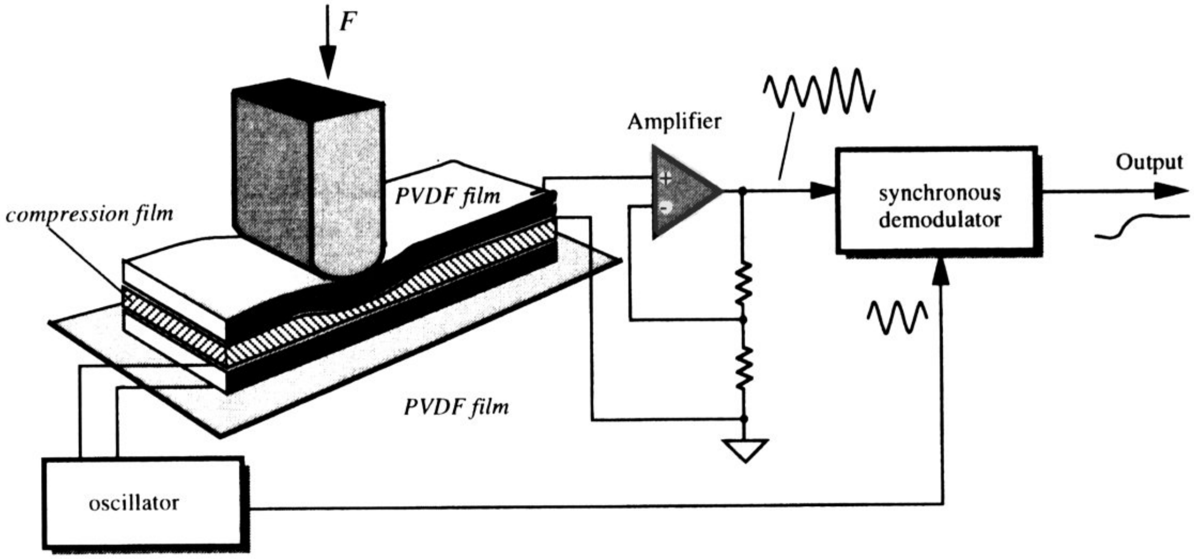


Figure 2.16 Active piezoelectric tactile-sensor.

Since piezoelectricity is a reversible phenomenon, the upper film produces alternating voltage upon being subjected to mechanical vibrations from the compression film. These oscillations are amplified and fed into a synchronous demodulator. The demodulator is sensitive to both the amplitude and the phase of the received signal. When compressing force F is applied to the upper film, mechanical coupling between the three-layer assembly changes. This affects the amplitude and the phase of the received signal. These changes are recognised by the demodulator and appear at its output as a variable voltage.

Within certain limits, the output signal linearly depends on the force. If 25 μm PVDF films are laminated with a 40 μm silicone rubber compression film, the thickness of an entire assembly (including protective layers) does not exceed 200 μm. The PVDF film electrodes may be fabricated with a cell-like pattern on either the transmitting or receiving side. This would allow us to use electronic multiplexing of the cells to achieve spatial recognition of applied stimuli. The sensor also can be used to measure small displacements. Its accuracy is better than ±2 μm over a few millimeters range. The advantage of this sensor lies in its simplicity and the fact that it has a DC response, that is, in the ability to recognise static forces [3].

2.1.35 Piezoelectric Force-Sensors

Piezoelectric effects can be used in both passive and active force-sensors. One example of an active approach is shown previously in Figure 2.16. However, for quantitative measurements, the applied force shall be related to the mechanical resonant of the piezoelectric crystal. A basic idea behind the sensor's operation is that certain cuts of quartz crystal, when used as resonators in electronic oscillators, shift the resonant frequency upon being mechanically loaded. The equation describing the natural mechanical frequency spectrum of a piezoelectric oscillator is given by:

$$f_n = \frac{n}{2l}\sqrt{\frac{c}{\rho}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.19)$$

where *n* is the harmonic number, *1* is the resonance-determining dimension (e.g., the thickness of a relatively large thin plate or the length of a thin long rod), *c* is the effective elastic stiffness constant (e.g., the shear stiffness constant in the thickness direction of a plate or Young's modulus in the case of a thin rod), and *ρ* is the density of the crystal material.

The frequency shift induced by an external force is due to non-linear effects in the crystal. In the above equation, the stiffness constant *c* changes slightly with the applied stress. The effect of the stress on the dimension (strain), or the density, is negligible. The minimal sensitivity to external force can occur when the squeezed dimension is aligned in certain directions for a given cut. These directions are usually chosen when crystal oscillators are designed, for their mechanical stability is important. However, in the sensor applications, the goal is just the opposite. For example, the diametric force has been used for a high-performance pressure transducer illustrated in Figure 2.17 [3].

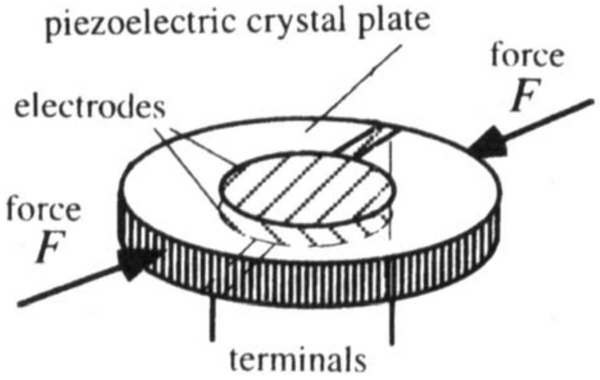


Figure 2.17 Piezoelectric disk resonator as a diametric force-sensor.

A qualitative force-sensor can be designed by using piezoelectric material in the passive mode. That is, there is no oscillation and the sensor directly converts mechanical stress into an electrical signal. This however, only makes it exclusively sensitive to changing stimuli and insensitive to a constant force. A simple piezoelectric force rate sensor is shown in Figure 2.18 [3].

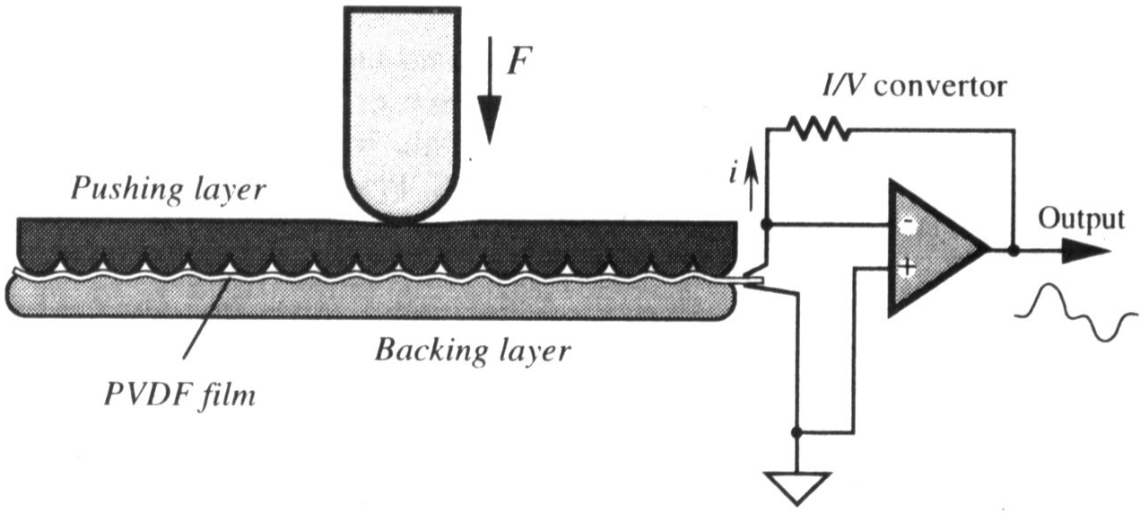


Figure 2.18 Piezoelectric force-rate sensor.

The sensor consists of three layers, where the PVDF film is laminated between a backing material (for instance, silicone rubber) and a pushing layer. The pushing layer is fabricated of a plastic film (for instance, Mylar®) whose side facing the PVDF film is preformed to have a corrugated surface. Upon touching the sensor, the PVDF film is stressed by the grooves of the pusher. This results in a generation by the film of electric charge. The charge flows out of the film through a current-to-voltage *(I/V)* converter which produces a variable output voltage. The amplitude of that voltage within certain limits is proportional to the applied force. A modified version of such a sensor was built for a medical application where minute movements of a sleeping infant had to be monitored in order to detect cessation of its breathing. The sensor was placed under the mattress in a crib. A body of a normally breathing infant slightly shifts with each inhale and exhale due to a moving diaphragm. This results in a displacement of the body's center of gravity which is detected by the sensor [3].

2.2 Gripper Mechanics and Motion Control Systems.

Gripper mechanics forms an integral part of the development of the proposed gripper and depends on the type of motion control used. Precision in the control of the gripper mechanics highly influences the accuracy, quality, reliability, repeatability and reproducibility of the gripper force measurements. The outcome of the research was highly dependant on the gripper mechanics and motion control. Care has been taken in selecting the mechanics and motion control for this research. A couple of motion control systems where examined to find the proper system for this research.

2.2.1 Pneumatic-Controlled System

Proportional pressure controller (PPC) valves are very popular pneumatic systems.

Operation of a MAC PPC valve:

The PPC valve is an innovative product which converts an electrical signal into a proportional pneumatic output. The PPC is unlike conventional I/P or V/P transducers. It offers much more in terms of performance, features and reliability. The valves are operated by the PPC's closed loop electronic control circuit. Feedback is obtained from one or two transducers. A balanced poppet, fast response and high flow valves provide performance characteristics for the PPC [15].

The PPC controls output pressure by constantly measuring its down stream pressure and comparing it to the command signal. If a higher pressure is commanded, the PPC quickly responds by actuating the fill valve, increasing the output pressure until it is equal to the pressure represented by the command signal. Conversely, if a lower pressure is required, the PPC will energise the exhaust valve, decreasing output pressure until the correct pressure is achieved. All of this happens very quickly to smoothly maintain the correct pressure. This approach to pressure control provides a small, light and cost-effective unit.

Unlike voice coil units, the PPC is not affected by vibration or mounting position. Unlike large direct solenoid proportional units, the PPC is small and light, drawing little power and producing little heat. Unlike units that utilise unbalanced air valves, the PPCs balanced valves provide high flow, extremely fast and repeatable response times as well as eliminating “undershoot” and “overshoot” problems normally associated with unbalanced valve designed units.

The linearity parameter shows the capability of the unit to follow the input signal according to an ideal straight line curve as shown in Figure 2.19. These PPCs exhibit excellent linearity throughout the pressure range.

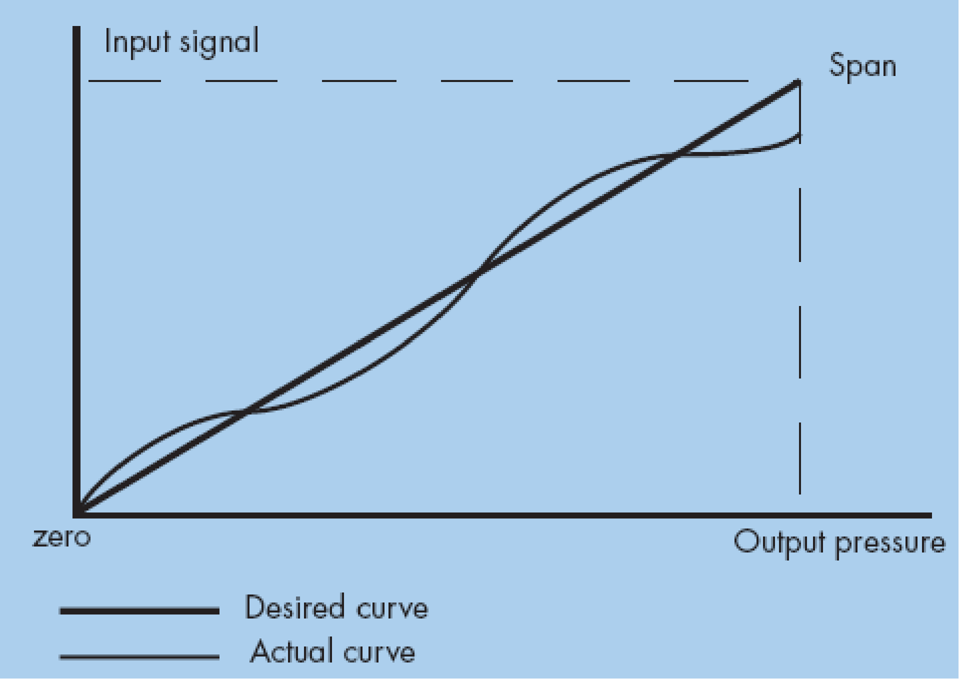


Figure 2.19 Capability to follow the input signal according to an ideal straight line curve.

Using a PPC system, gripper mechanics will result in a pneumatic actuator-based gripper design, example shown in Figure 2.20 [16].

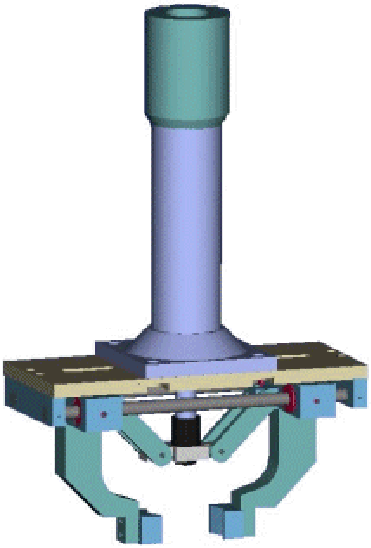


Figure 2.20 Pneumatic gripper example.

2.2.2 Motor-Controlled System.

Servomotors is a good option for motor control, because they can be controlled by a PID (proportional-integral-derivative) controller which can provide excellent velocity, position and torque management. A **proportional-integral-derivative controller** is a common feedback loop component in industrial control systems.

The controller takes a measured value from a process or other apparatus and compares it with a reference set point value [17]. The difference (or "error" signal) is then used to adjust some input to the process in order to bring the process' measured value back to its desired set point as could be seen in the illustration Figure 2.21. Unlike simpler controllers, the PID can adjust process outputs based on the history and rate of change of the error signal, which gives more accurate and stable control. PID controllers do not require advanced mathematics to design and can be easily adjusted to the desired application, unlike more complicated control algorithms based on optimal control theory.

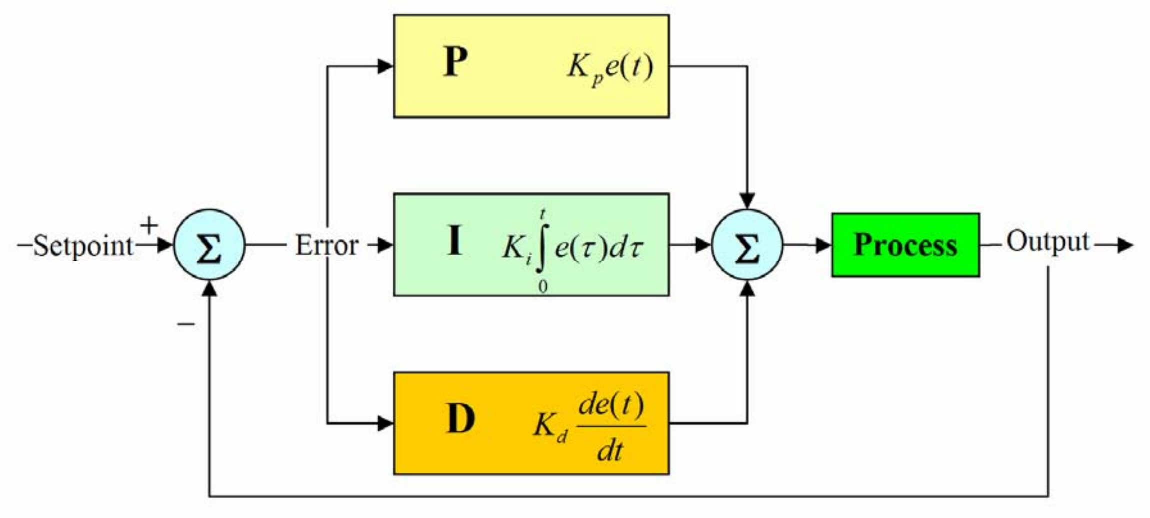


Figure 2.21 Typical PID controller.

Control Loop Basics

Intuitively, the PID loop tries to automate what an intelligent operator with a gauge and a control knob would do. The operator would read a gauge showing the output measurement of a process, and use the knob to adjust the input of the process until the process's output measurement stabilises at the desired value on the gauge. In older control literature this adjustment process is called a "reset" action. The position of the needle on the gauge is a "measurement", "process value" or "process variable". The desired value on the gauge is called a "set point" (also called "set value"). The difference between the gauge's needle and the set point is the "error" [7].

A control loop consists of three parts:

- Measurement by a sensor connected to the process (or the "plant"),
- Decision in a controller element,
- Action through an output device ("actuator") such as a control valve.

As the controller reads a sensor, it subtracts this measurement from the "set point" to determine the "error". It then uses the error to calculate a correction to the process's input variable (the "action") so that this correction will remove the error from the process's output measurement. In a PID loop, correction is calculated from the error in three ways: cancel out the current error directly (Proportional); the amount of time the error has continued uncorrected (Integral) and anticipates the future error from the rate of change of the error over time (Derivative). A PID controller can be used to control any measurable variable which can be affected by manipulating some other process variable.

Theory:

The PID loop adds positive corrections, removing error from the process's controllable variable (its input). This "up a bit, down a bit" movement of the process's input variable is how the PID loop automatically finds the correct level of input for the process. "Turning the control knob" reduces error, adjusting the process's input to keep the process's measured output at the set point. The error is found by subtracting the measured quantity from the set point. "PID" is named after its three correcting calculations, whose sum constitutes the output of the PID controller.

- **Proportional** - To handle the immediate error, the error is multiplied by a constant *P* (for "proportional") and added to the controlled quantity. *P* is only valid in the band over which a controller's output is proportional to the error of the system. For example, for a heater, a controller with a proportional band of 10 °C and a set point of 20 °C would have an output of 100% at 10 °C, 50% at 15 °C and 10% at 19 °C. Note that when the error is zero, a proportional controller's output is zero.
- **Integral** - To learn from the past, the error is integrated (added up) over a period of time, and then multiplied by a constant *I* (making an average) and added to the controlled quantity. A simple proportional system either oscillates, moving back and forth around the set point because there's nothing to remove the error when it overshoots, or oscillates and/or stabilises at a too low or too high value. By adding a proportion of the average error to the process input, the average difference between the process output and the set point is continually reduced. Therefore, eventually, a well-tuned PID loop's process output will settle down at the set

point. As an example, a system that has a tendency for a lower value (heater in a cold environment), a simple proportional system would oscillate and/or stabilise at a too low value because when zero error is reached *P* is also zero thereby halting the system until it again is too low.

- **Derivative** - To handle the future, the first derivative (the slope of the error), over time, is calculated and multiplied by another constant, *D*, and also added to the controlled quantity. The derivative term controls the response to a change in the system. The larger the derivative term, the more rapidly the controller responds to changes in the process's output. Its *D* term is the reason a PID loop is also sometimes called a "predictive controller." The *D* term is reduced when trying to dampen a controller's response to short term changes. Practical controllers for slow processes can even do without the *D* term.

Limitations

The PID controller algorithm itself has some limitations. In practice, most problems arise from instrumentation connected to the controller. One common problem is "integral windup". It might take too long for the output value to ramp up to the necessary value when the loop first starts up. Sometimes this can be fixed with a more aggressive differential term. Sometimes the loop has to be "preloaded" with a starting output. Another option is to disable the integral function until the measured variable has entered the proportional band.

Some PID loops control a valve or similar mechanical device. Wear of the valve or device can be a major maintenance cost. In these cases, the PID loop may have a "dead-band" to reduce the frequency of activation of the mechanical device. This is accomplished by designing the controller to hold its output steady if the change would be small (within the defined dead-band range). The calculated output must leave the dead-band before the actual output will change. Then, a new dead-band will be established around the new output value.

Another problem with the differential term is that small amounts of noise can cause large amounts of change in the output. Sometimes it is helpful to filter the measurements, with a running average, or a low-pass filter. However, low-pass filtering and derivative control cancel each other out, so reducing noise by instrumentational means is a much better choice. Alternatively, the differential band can be turned off in most systems with little loss of control. This is equivalent to using the PID controller as a PI controller.

The proportional and differential terms can also produce undesirable results in systems subjected to instantaneous "step" inputs (such as when a computer changes the set point). To avoid this, some PID algorithms incorporate various schemes:

- **Derivative of output;** Many industrial PID systems actually measure the differential of the output quantity, which is always continuous (i.e. never has a step function) and usually moves in the same direction as the error.
- **Set point weighting;** Set point weighting uses several set points. The errors from the two set points are combined to reduce upsets. Some schemes slowly

> reduce the proportion of error from an "old" set point and increase the proportion of error from a "new" set point. Other schemes have multiple set points controlled by different outside controllers. The error in the integral term must be the true control error in order to avoid steady-state control errors. These parameters do not affect the response to load disturbances and measurement noise.

Digital implementations of a PID algorithm may have limitations owing to the sampling rate of the data as well as the limits of internal calculation and precision. For example, very old programmable logic controller (PLC) systems may have used only 12 or 16 bits to represent internal variables. Additionally, some software implementations do not correctly handle internal overflow or extreme values, or may arbitrarily limit the values for the adjustable gain parameters. Another problem faced with PID controllers is that they are linear. Thus performance of PID controllers in non-linear systems (such as HVAC systems) is variable. Often PID controllers are enhanced through methods such as scheduling or fuzzy logic.

Implementation

A PID loop can be implemented with any physical system that can produce ratiometric behavior and integration. Software PID loops are the most stable, because they do not wear out and the cost has been decreasing. PID controller functionality is a common feature of PLCs used by many factories.

A PID controller can also be purchased for industrial uses as a panel-mounted controller. These often control only one or two loops and are still used for small stand-alone systems where a PLC or computer control is unnecessary.

Electronic analogue controllers are now very inexpensive, and can be made from a solid-state or tube amplifier, a capacitor and a resistor. Electronic analogue PID control loops were often found within more complex electronic systems, for example, the head positioning of a disk drive, the power conditioning of a power supply, or even the movement-detection circuit of a modern seismometer. Nowadays, they are replaced with digital controllers implemented in microcontrollers or field-programmable gate array (FPGA) [18].

2.3 Conclusion

The study of the literature regarding relevant sensors, actuators and systems presents a better understanding of the available technologies and terminology. Problem anticipation is much improved with this theoretical background and gives an idea of the feasibility, method of designing and assembly of a force-sensing gripper system.

3 Development of Gripper: Gripper Control, Force-Sensing, Interpretation Software and Feedback Control

A complete functional force-sensing gripper system is dependent on using the right technology and the right methods in applying this type of niche. A thorough investigation of the relevant technologies and methods reduces design and assembly setbacks that can occur during this research.

3.1 Investigation of a Suitable Gripper Sensor and Movement Mechanics

3.1.1 Sensors Suitable for Gripper Finger-Tip Force-Sensing

A wide variety of sensors can be used to measure force at finger-tip contact. They all have their own advantages and disadvantages. Strain gauges, such as metal foil gauges connected in a Wheatstone bridge configuration, can be used at the finger base, sensing the deformation that represents the strain. The strain can then be used to calculate the stress the finger is experiencing. By knowing the stress, the applied force to the finger-tip can be calculated. Excitation is needed for stain gauges to generate a workable electric output, because they are piezoresistive. Excited sensors have a warm-up time, due to the resistance that changes with the excitation current that heats up the sensor. This method includes extra complicated mechanical construction which will enlarge the finger size. Using load cells for tactile-sensing can be seen as the sensation of tensing muscles, knowing how hard they are gripping, but still not measuring the sensation at the fingertips. The best results would be yielded by using a combination of as many sensors as possible.

Another interesting piezoresistive force-sensor is the force sensitive resistor (FSR) whose resistance varies with applied pressure. This sensor also needs an excitation current and amplification circuitry to determine the applied force. FSR's are inherently subject to wear and tear, and getting consistent values out of them is difficult [19]. This sensor was not used in this research.

The third sensor that is suitable for finger-tip force-sensing is the piezoelectric film. The piezoelectric effect can be used in both passive and active force-sensors. In its simplest form this sensor is passive, that is, its output signal is generated by the piezoelectric film without the need for an excitation signal. Passive sensors on their own are seen as not being suitable for finger-tip force-sensing, because they show no signal with a constant force, only with changing forces. Human fingers have passive and active sensors to function as they do, but without passive sensors it will not know the specific force it is applying. Although no references of this method could be found, passive piezoelectric film sensors, in their basic form, can be used with the same advantages as an active piezoelectric film. This is possible if the piezoelectric film is monitored and its signal as well as electronic pulse is integrated. This information can indicate the change in force applied to the film. Knowing the rate and amount of force change, the constant force can be calculated, as proven in this research.

Active ultrasonic coupling force-sensors can be designed with piezoelectric film. This design would consist of two piezoelectric films acoustically coupled by a compression film. The bottom piezoelectric film is then driven by an AC voltage that makes the piezoelectric film vibrate, passing the vibration over to the compression film and, in turn, to the upper piezoelectric film, which acts as a receiver. Force information is in the phase changes between the inducing and receiving films. The softness of the centre film determines sensitivity as well as the operating range of the sensor. The advantages of this sensor are in its simplicity and a DC response, that is, in the ability to recognise static forces.

Charles F. Kettering said the following, “Inventing is a combination of brains and materials [3]. The more brains you use, the less materials you need”. Keeping this in mind, the first option that comes to mind is the passively operating piezoelectric film sensor. This option involves much more programming, but at the sensing point it will be the smallest, cheapest and the simplest. Program reproduction is easy and inexpensive; the only cost is the micro controller and analogue-to-digital converter IC (integrated circuit), which is relatively cheap, due to the fact that it is being mass produced.

3.1.2 PVDF Piezoelectric Film-Sensor’s Pro’s and Cons

Piezoelectric film sensors have a couple of positive and negative properties when designing a system. Piezoelectric film has a wide span, which presents a high input value that can be applied to the sensor without causing unacceptably vast inaccuracy. The hysteresis loop of forward and reverse stimulus of the piezoelectric film is close to none. In this application, only forward stimulus is used, so hysteresis will have no effect, except for sensing the gripper leaving the object.

Possible sources of the repeatability error for piezoelectric film sensors may be thermal noise, build-up charge, material plasticity, electrostatic discharge, formation of electrical charges (triboelectric effect), vibration of the gripper motor and electromagnetic interferences (EMI). Piezoelectric film sensors have good pyroelectric properties. Rapid temperature changes affect a piezoelectric film’s electric output. Keeping a constant working temperature, good thermal insulation and filtering out ultra low frequencies, this problem is easily overcome. Build-up charge is eliminated by discharging it constantly at a high enough rate, using a relatively high load compared to the input and output impedances. PVDF has very good properties of elasticity but the gripper fingers deformation is sensed by the piezoelectric film which will definitely result in a material plasticity problem [20]. Material plasticity effect can be reduced by increasing finger elasticity and software error correction. These interferences cause the output of the piezoelectric film to drift from zero. Such a drift at the zero value of a variable is called "zero drift". The sensor may respond to changes in other quantities, apart from the variable of interest. One or more of these may change, though the measured variable may remain unchanged, resulting in the above-mentioned drift. If, indeed, the environmental factors degrade the sensor's performance, additional corrective measures may be required, for instance, placing the sensor in a protective box and electrical shielding.

Repeatability error because of vibration from the gripper motor can be kept at a minimum by reducing the vibration itself via good lubrication and filtering it out.

Piezoelectric film sensors have a good linear transfer function, which prevents it from having a dead-band. Resolution of the piezoelectric film does not present any limitations, because analogue-to-digital converters have much less resolution. Piezoelectric sensors in particular have high output impedances and cannot source much current (typically micro-amps or less). Data-Acquisitioning equipment has high input impedance which can sense low current signals produced by the piezoelectric film. As mentioned above, a relatively low resistance resistor can discharge the potential build-up in the high impedance network [7]. Dynamic characteristics present themselves in the system of a piezoelectric film sensor and the delay of the reacting motor-actuator operated gripper. Frequency response of the piezoelectric film sensor, without any load, looks like Figure 2.9 (a) in paragraph 2.1.17 as it has a very wide frequency range. However, it has a unique quality in that it does not depolarise while being subjected to very high alternating electric fields. The film exhibits good stability: when stored at 60 ^{o}C it loses its sensitivity by about 1-2% over six months. PVDF is a mechanically durable and flexible material.

3.1.3 Gripper Mechanics Suitable for Gripper Finger-Tip Force-Sensing

Precision in the control of the gripper mechanics will highly influence the accuracy, quality, reliability, repeatability and reproducibility of the gripper force measurements. Outcome of the research is highly dependant on the gripper mechanics and motion control. Care has been taken in deciding the mechanics and motion control for this research.

Pneumatic grippers have good control over gripping intensity, but not that much over velocity and position control. Passive force-sensing using piezoelectric films requires full control over the torque, position and velocity control. Choice of gripper control for this research is the PID motor control system.

Servomotors are a good option for motor control, because they can be controlled by a PID controller which can provide excellent velocity, position and torque management.

3.2 Force-Sensing Gripper System Design

The research focused on the response of the piezoelectric film for use as a tactile force-sensor - this required an exceptionally controllable gripper. A simplified linear gripper was implemented for this purpose. Piezoelectric film was placed on the gripper fingers as the sensor that was to be investigated. Silicon adhesive was used between the film and gripper for possible replacement of the film. Only one side was equipped with the tactile-sensor, but only for experimental purposes. In practice, all the fingers could be equipped to improve the gripper functionality. Response of the piezoelectric film, undergoing physical stimuli is monitored by a computer equipped with an analogue-to-digital converter, the "NI PCI-6024E/CB-68LP", a powerful graphical development tool with LabVIEW™. The "NI PCI-6024E/CB-68LP" has a maximum sampling rate of 200 kS/s, 16 analogue inputs with 12-bit resolution, two 12-bit resolution analogue outputs, eight digital I/O lines and two 24-bit counters with NI-DAQ driver software to simplify configuration and measurements.

Gripper movement is controlled according to the response of the piezoelectric film being monitored by LabVIEW™ software, as could be seen in a schematic representation in Figure 3.1.

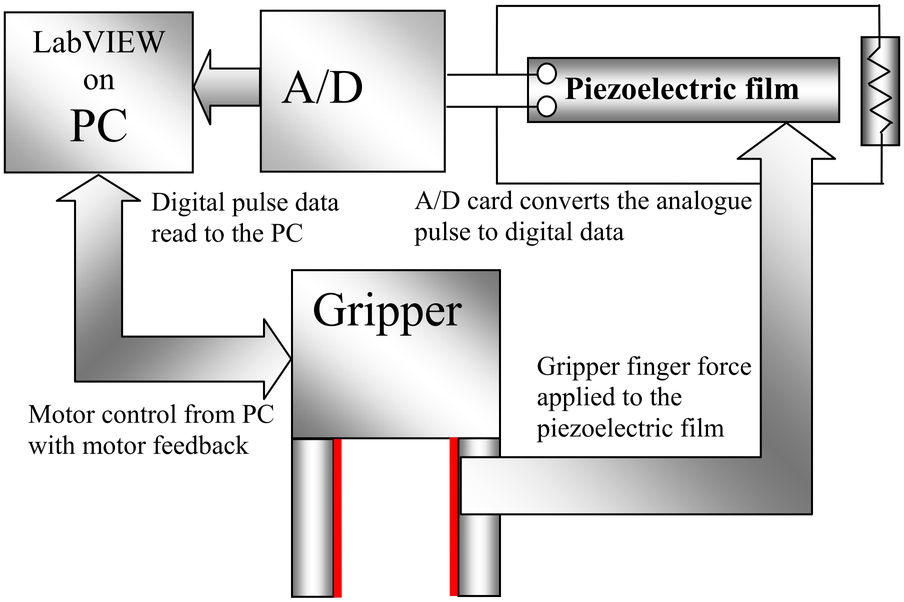


Figure 3.1 Basic connection of the piezoelectric film to the gripper and LabView™.

3.1 Gripper Design

For making recurring measurements with the proper accuracy using piezoelectric film, a gripper with a high precision drive was needed to achieve exceptional control. The gripper was powered by a PID controlled 80W Maxon EC 32 brushless motor fixed with a 9 bit optical encoder. The motor has a maximum speed of 15 200rpm, stall torque of 480mNm, maximum continuous torque of 57.7mNm at 5000rpm and rotor inertia of 20gcm^2. More motor and PID controller detail is available in appendix B. This specification explains the range of ability of this motor, its feedback and its control. The motor does not stop instantly, it has a preset deceleration. Deceleration of the gripper due to the preset motor deceleration results in an overshoot. This means the gripper close its fingers a little while longer after it was told to stop resulting in overshoot. So it must decelerate as fast as possible to reduce the overshoot as much as possible. Decelerating the motor generates back-emf, increasing the voltage which can damage the PID controller [21]. This is prevented by placing a big capacitor and resistor close to the motor's power inlet in order to damp the charge [22]. Double bevel gears with a "1:2" gear ratio are used for the transmission from the motor to two linear screw shafts. The linear screw shafts are responsible for the linear movement, of the gripper fingers. The screw shaft thread has a very fine pitch (1mm) to increase the gear ratio to 20 motor rotations for 1cm linear finger movement individually. The mechanical design is illustrated in Figure 3.2.

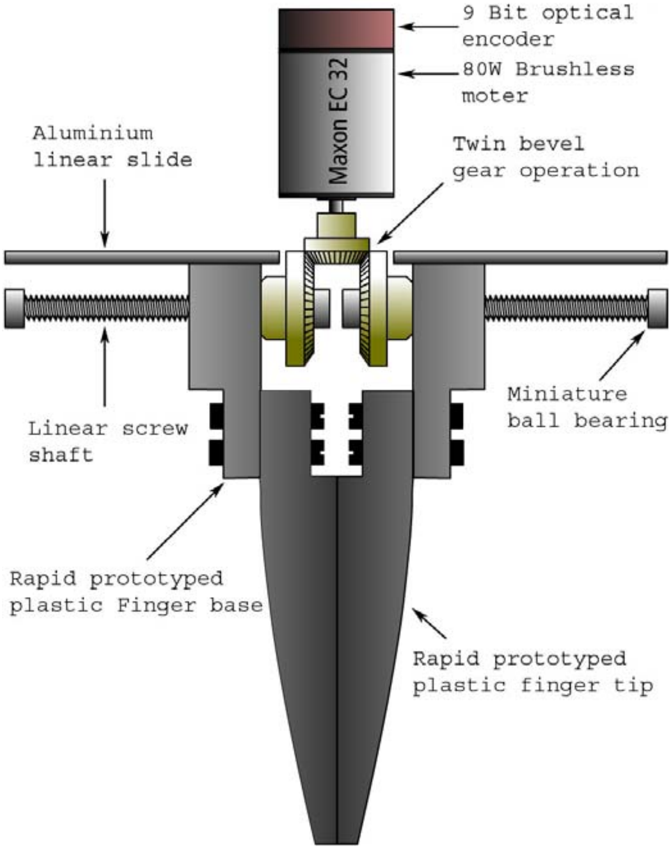


Figure 3.2 Twin bevel gear transmissions via a fine screw shaft for linear gripping movement.

Linear screw shafts with fine pitch thread has the advantage of being braked by the linear nut's friction on the screw shaft when a linear force is applied on the fingers, preventing the fingers from moving away from the object to be gripped. The fingers are secured by a linear sliding bar, as sliding in the direction the screw shafts forces the fingers in motion. The gripper parts not commercially available were designed in 3D modeling software called Solid Edge® and were prototyped into nine hard, semi-rigid, plastic material parts shown in Figure 3.3.

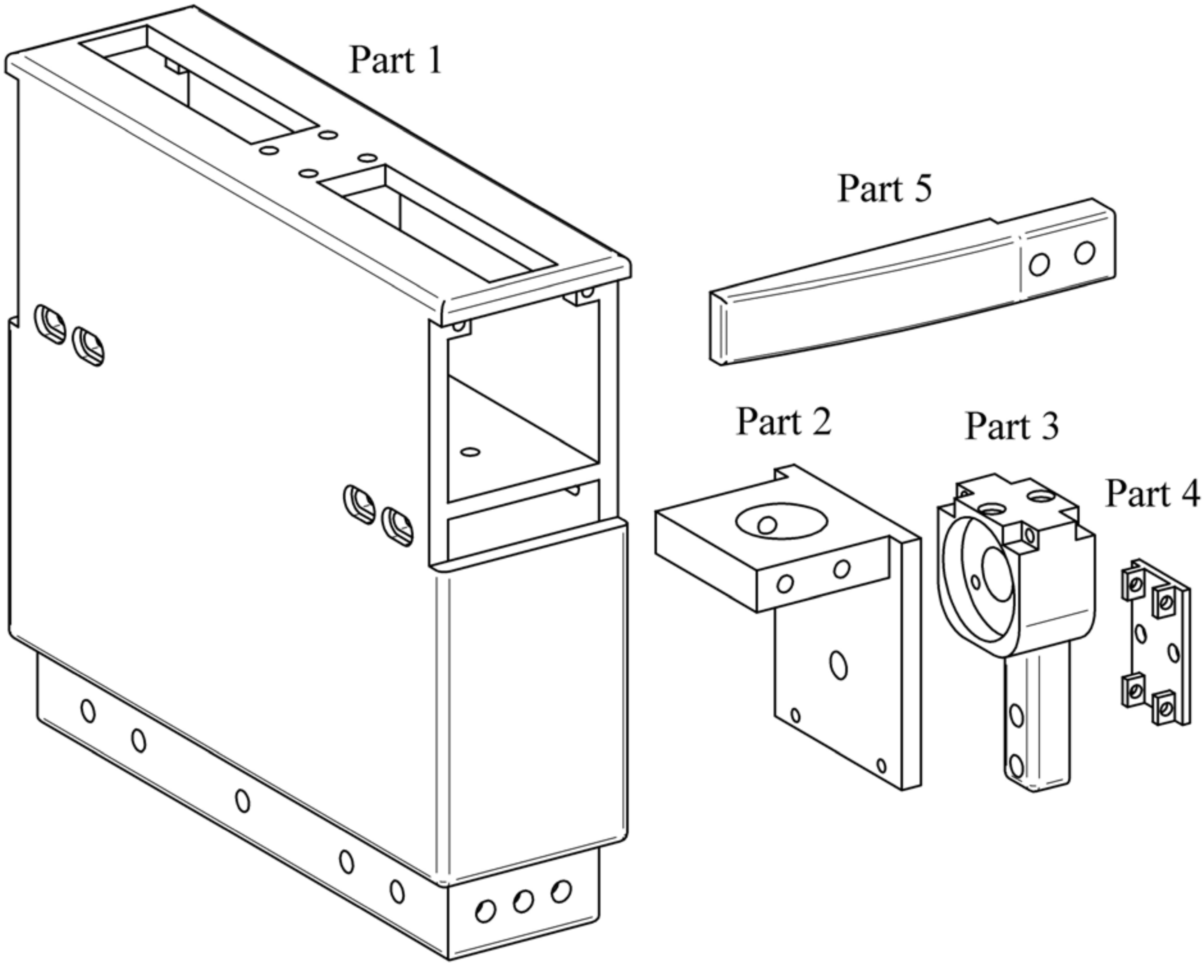


Figure 3.3 Five different parts designed in Solid Edge® for rapid prototyping.

Commercially available parts such as bevel gears, bearings, screw shafts and linear slides used in the construction of the gripper are shown in Figure 3.4. The gripper is able to grip objects up to a maximum of 9cm (CD size).

Figure 3.4 Commercially available parts used in the assembly of the gripper mechanics.

3.2 Using Piezoelectric Film

The sensitivity of piezoelectric film as a receiver of mechanical work input is remarkable and can be shaped in all different shapes and sizes, as can be seen in Figure 3.5.

The piezoelectric film used in this research is the DT2-052K/L with rivets from MEASUREMENT SPECIALITIES, INC. (MSI). This sensor has an active sensing length of 62 mm, width of 12 mm, thickness of 64 µm and a capacitance of 1.44 nF.

Figure 3.5 Piezoelectric films on the market (left); example of the piezoelectric film used in this research (right).

The DT series of piezoelectric film sensors' elements are rectangular elements of piezoelectric film with silver ink screen printed electrodes. They are available in a variety of sizes and thicknesses. Lead attachment is accomplished using a riveted lug going through 12" (300 mm) of 28 AWG wire. The DT film element produces more than 10 millivolts per micro-strain. The capacitance is proportional to the area and inversely proportional to the thickness of the element. The DT elements are supplied with a thin urethane coating over the active electrode area to prevent oxidation to the top surface of the silver ink. In its simplest mode, the film behaves like a dynamic strain gauge except that it requires no external power source and generates signals greater than those from conventional foil strain gauges after amplification. Frequency response is thus free from any limitations imposed by the need for high gains and extends up to the wavelength limit of the given transducer [3].

The extreme sensitivity is largely due to the format of the piezoelectric film material. The film's lack of thickness makes, in turn, a very small cross-sectional area and thus relatively small longitudinal forces create very large stresses within the material. It is easy to exploit this aspect to enhance the sensitivity parallel to the machine axis. If a laminated element of film is placed between two layers of compliant material then any compressive forces are converted into much larger longitudinal extensive forces. In fact, this effect tends to predominate in most circumstances since most substances are, to some extent, compliant and the ratio of effective sensitivity in the axis 1 (length) versus axis 3 (thickness) directions is typically 1000:1, as indicated in Figure 3.6.

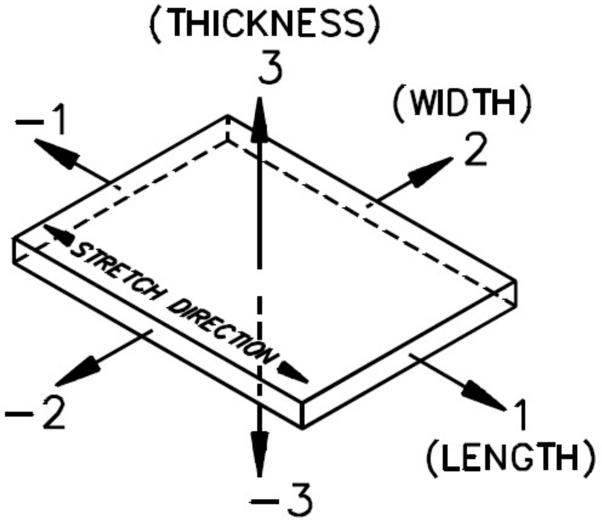


Figure 3.6 Numerical classification of piezoelectric film axes.

Piezoelectric film transducers may often cover a much larger area than normal strain gauges, so, for meaningful results, any direct comparisons should be performed in a uniform strain field. The gripper fingers were prototyped into a hard plastic with definite compliancy. The piezoelectric film covers a relatively large area on the finger. Obviously "point"-type transducers could be used where required, although the capacitance of a very small area will require consideration. The low frequency limit of operation is defined by the greatest resistive load achievable, or by the largest capacitance load that still allows the signal to be easily detected. Operation down to fractions of Hz can be achieved using either conventional charge amplifiers or, since signal levels are relatively high, simple high impedance FET buffer circuits [20].

3.3 Piezoelectric Film Response Result.

Applied forces with the use of the software controllable gripper stay uniformly due to repetitive program sequences. The arrival and departure of applied forces produce perfect inverse voltage replicas, the arrival deceleration and departure acceleration are kept the same. Only arrival forces are used in this practical application, so the departure signals are filtered out. Noise definitely interferes with the electrical output from the piezoelectric film because of its broad acceptance of electromagnetic, vibration, audio and thermal noise. Noise filtering and shielding are necessary to generate a workable signal.

A small piece of grounded PCB glued to the base of the piezoelectric film sensor shields it from electromagnetic interference so that it will not drift from zero.

All filtering is done using software, because it is easily modified. The piezoelectric film produces electrical energy according to the characteristics of the gripper finger material and dimensions. The material used is, to a relatively great extent, compliant and the gripper finger is thin, which is why the piezoelectric film bends easily and produces electrical energy mostly due to the deformation of the finger and little due to the direct object contact (as shown in Figure 3.6.)

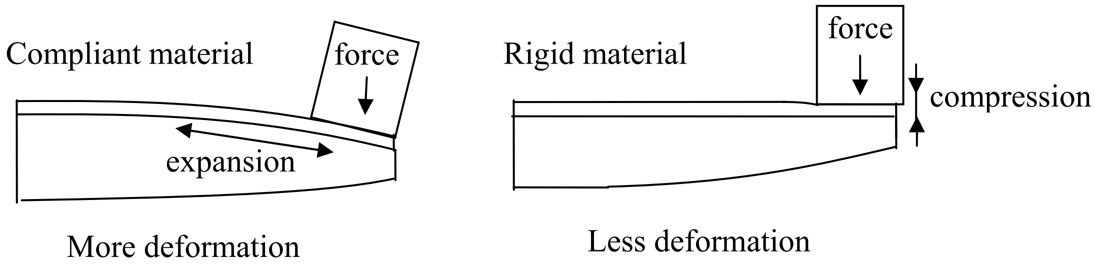


Figure 3.6 Different types of film deformation takes place with applied forces.

Piezoelectric film sensors produce an electric charge due to deformation. Deforming the sensor along its thickness produces much less charge than deforming it along its length. Different assembly methods will decrease the sensitivity due to physical contact, rather than contact causing film deformation, as a result of fingers deformation. Using a more rigid finger, more electrical energy will be produced because of the direct object contact.

The purpose of this research was to develop a system that can determine a static force applied to a robot finger using piezoelectric film sensors in its simplest, most passive form. For this research, the deforming finger is a good method to achieve good sensitivity. Experimentation shows whether object contact dimensions play a role in the electrical energy produced. A flat surface might, for instance, produce different amounts of electrical energy than round surfaces for the same force applied.

The electrical equivalent of the piezo film element is a voltage source in series with a capacitance, indicated in Figure 3.7.

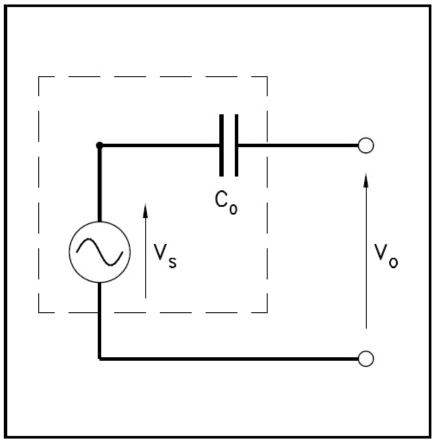


Figure 3.7 Piezo film element as a simple voltage generator.

The dashed line represents the "contents" of the piezo film component. The voltage source V_S is the piezoelectric generator itself and this source is directly proportional to the applied stimulus (pressure, strain, etc). This voltage will absolutely follow the applied stimulus - it is a "perfect" source [4].

Adding in, the effect of connecting up measuring equipment is shown in Figure 3.8. The measuring equipment is modelled simply as a pure resistance, although in reality there will be a very small capacitance associated with the probes and cables (usually in the region of 30 to 50 pF). This can be neglected if the film capacitance is significantly higher in value.

The voltage measured across the load resistor R_L will **not** necessarily be the same voltage developed by the "perfect" source (V_S). To see why, it is helpful to redraw this circuit in another way.

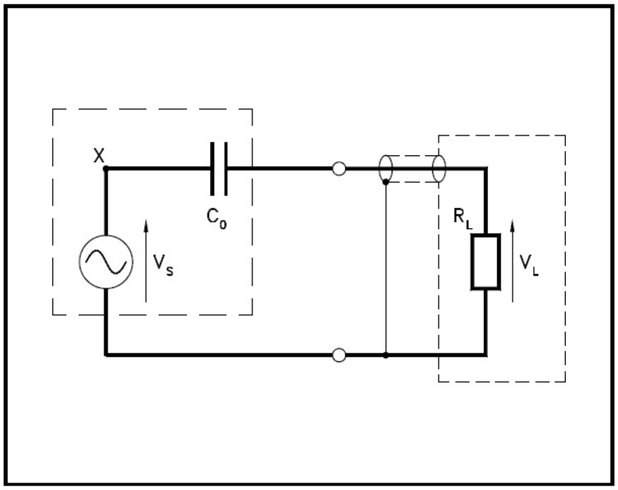


Figure 3.8 Adding measuring equipment as a resistive load.

With the circuit shown in Figure 3.8 redrawn as in Figure 3.9, it is easier to see why the full source voltage does not always appear across the resistive load. A *potential divider* is formed by the *series* connection of the capacitance and the resistance, as shown in Figure 3.9. Since the capacitance has impedance which varies with frequency, the share of the full source voltage, which appears across $R_{L,}$ also varies with frequency [4].

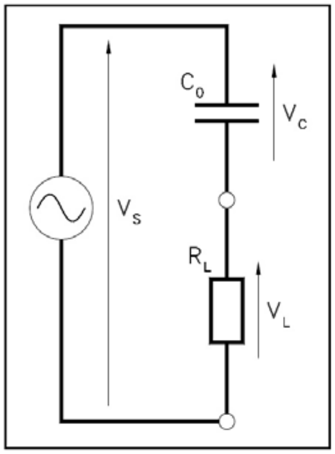


Figure 3.9 Piezo film potential dividing equivalent circuit.

3.4. Force Calculation

Because the piezoelectric film is used in its passive mode, there is no DC voltage level from where applied forces can be derived. Incoming voltage levels should be integrated in real time to calculate the energy induced in the piezoelectric film by the force being applied. The total energy, up to a certain point, corresponds to the force applied to the piezoelectric film. Different results between the force and the integrated energy from the piezoelectric film are due to capacitive properties of the piezoelectric film, accumulating the energy induced from all the stresses applied to the piezoelectric film, including noise through sound and vibrations from the gripper structure. In stopping the piezoelectric film from accumulating all the repeatability errors, a high resistance value is used to drain all the accumulated energy from the piezoelectric film to ground at a slow enough rate to still calculate the area under the pulse generated by the film. Measuring apparatus also has input impedance that discharge the energy stored in the piezoelectric film, but that resistance is too high. The resistor also drains the energy from the piezoelectric film induced by the measured force. Normally, without a grounding resistor, the energy stays in the piezoelectric film's internal capacitance once force was applied on the film and the force is maintained. With a resistor connected to ground, the energy does not stay in the film but flows back into the ground shown in Figure 3.10.

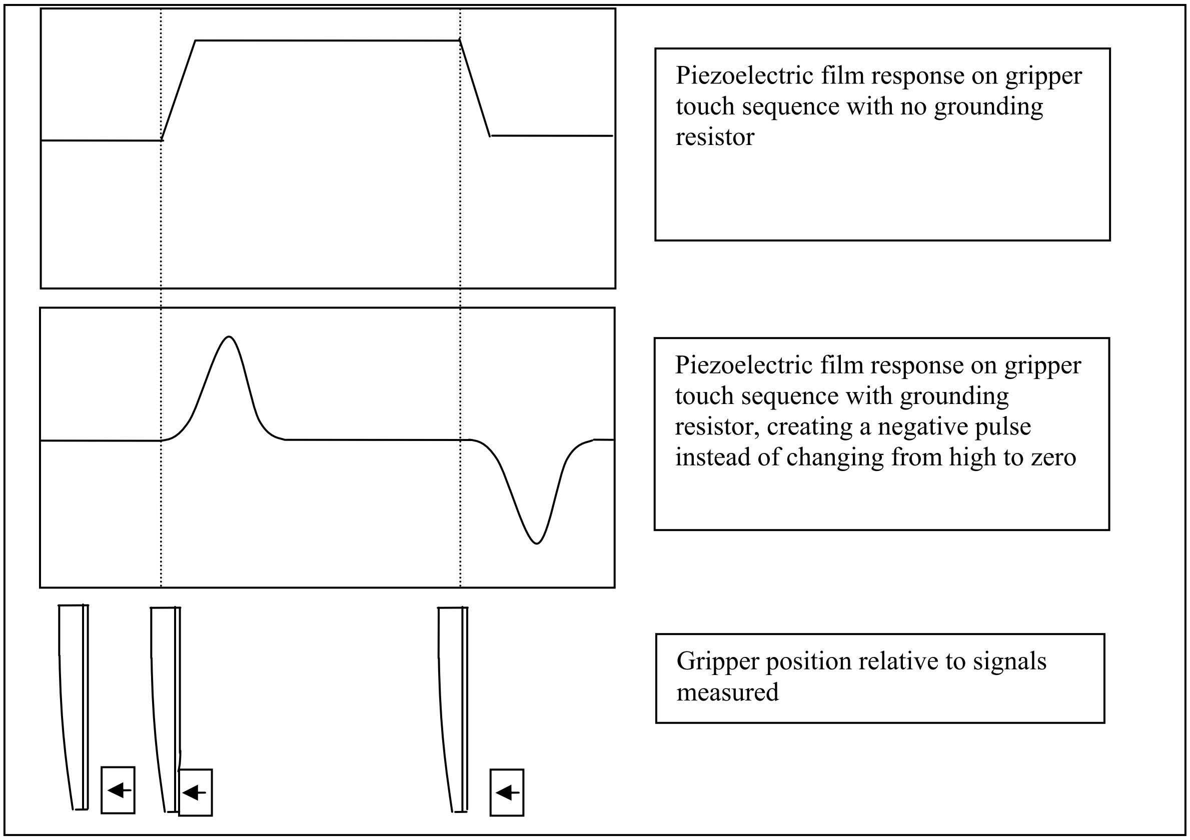


Figure 3.10 Effect of the grounding resistor.

This is why you cannot convert a constant measured voltage straight to force. The integration formula for discreet wave forms is used to convert the electric pulse to energy, where W is the wattage of the pulse and N is the number of samples, shown in equation 3.1.

$$Joule = W \times Time = (\sum_{n-1}^{N} W_n) \times \frac{Time}{N} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.1)$$

The input voltage pulse has a load of 7.4MΩ, which will result in very low wattage. Figure 3.11 shows the wattage pulse of a typical gripping sequence.

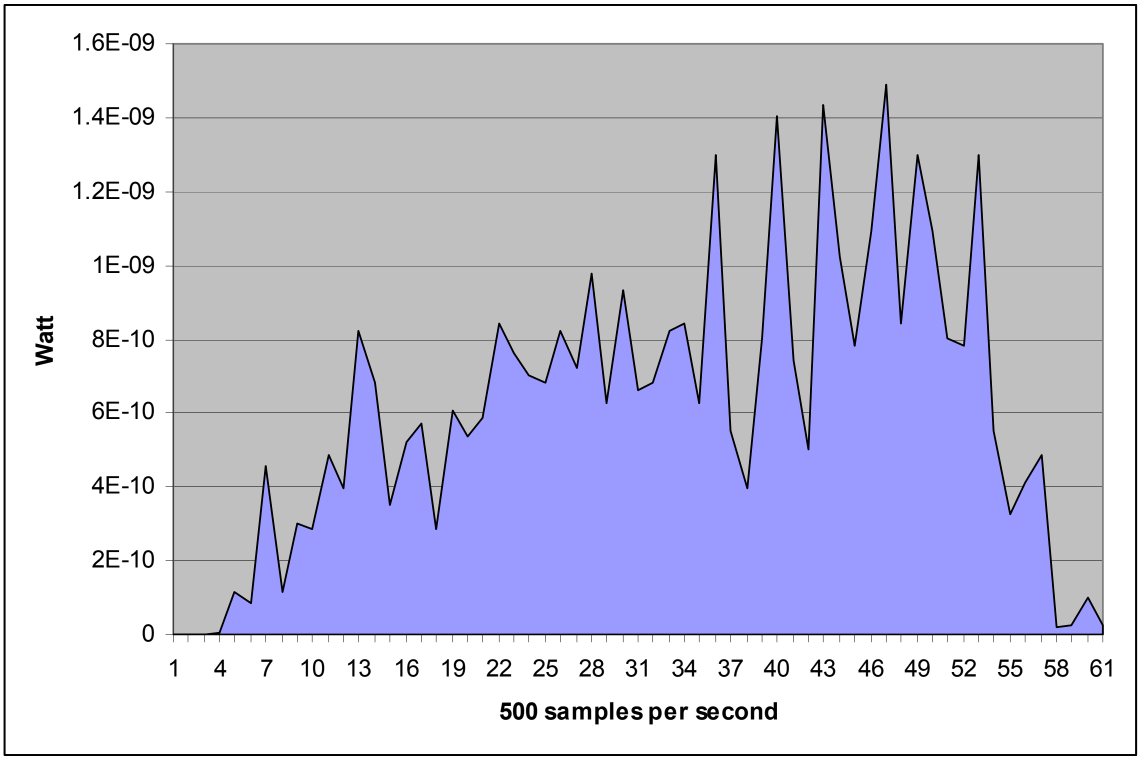


Figure 3.11 Typical touch pulse showing the wattage over time.

Measurement equipment was set to measure 500 samples per second. Calculation of the Joules generated by the piezoelectric film during this touch instance is done by dividing the wattage by 500 samples per second to get the Joules per second. That amount is then summed to give the total Joules for this pulse instance. Figure 3.12 shows the accumulation of Joules up to the total Joules for this touch instance.

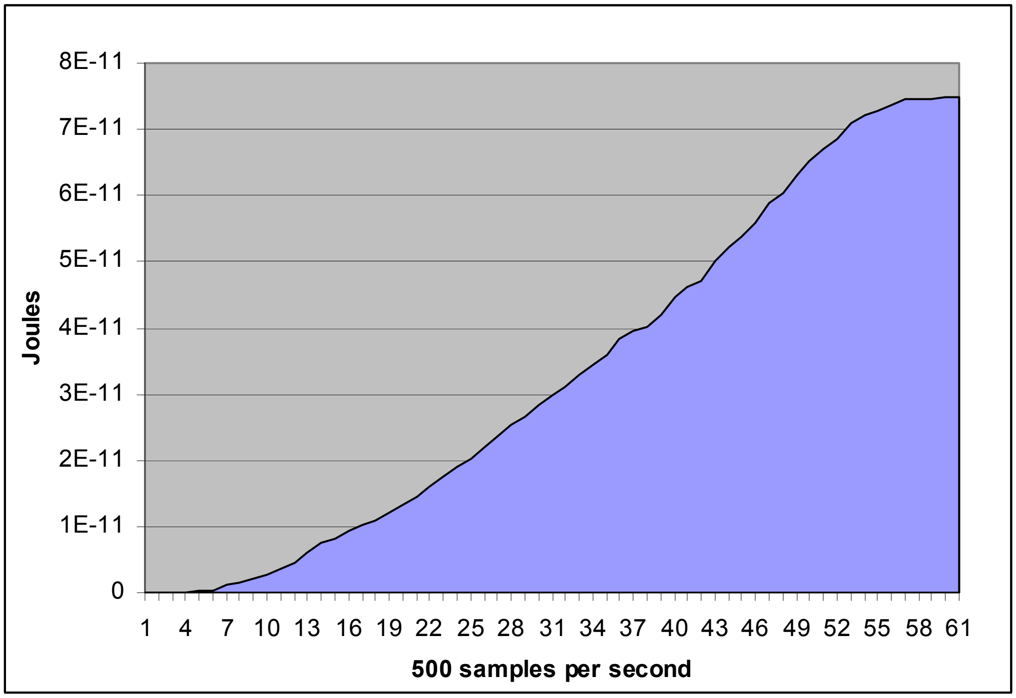


Figure 3.12 Typical touch pulse showing the accumulation of the joules produced by the piezoelectric film over a 7.4 MΩ load.

To get an idea how the real force compares with the integrated energy from the film, a strain gauge was used to get the exact pressure applied to the film, illustrated in Figure 3.13. This output of the strain gauge was ultimately used as feedback on applied forces throughout this research.

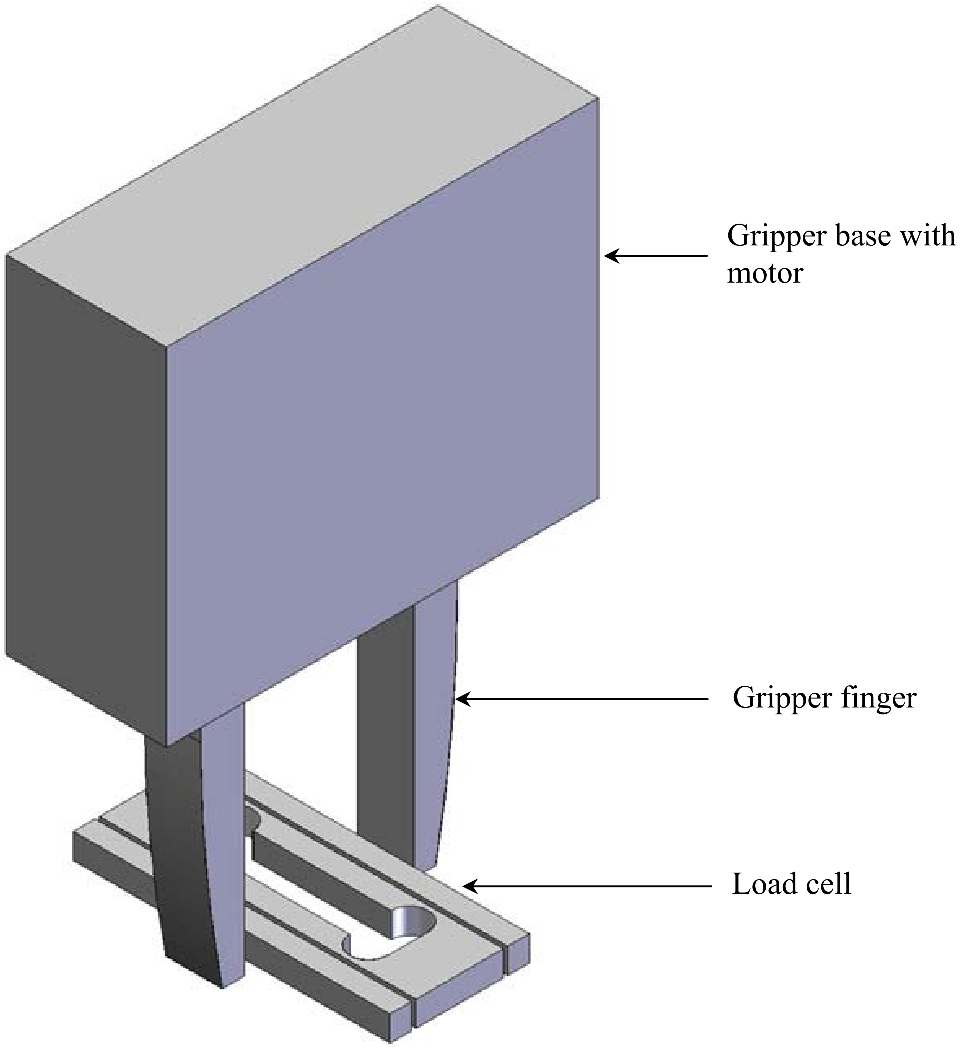


Figure 3.13 Static measure block with strain gauges to measure the true forces.

3.5 Software

National Instruments™ LabVIEW™ was used for the controlling, filtering and monitoring software. RS232 communication was used for the interface between the EPOS 24/5 motor controller, to be viewed in Figure 3.14 and LabVIEW™, running on a personal computer (PC). LabVIEW™ uses an analogue-to-digital converter to monitor the output of the piezoelectric film.

Figure 3.14 Maxon Epos 24/5 5A DC motor-positioning controller used to control the gripper motor interfaced with LabView™.

The LabVIEW™ software analyses the force-induced pulses and controls the motor accordingly. Motor control includes the velocity control, positioning control and current control. Information needed to control the motor can be attained from the Epos 24/5 controller, such as current consumption, and by using the 9 bit optical encoder (0.7 degrees resolution), current motor velocity and position. This dynamic gripper control loop is showed in Figure 3.15.

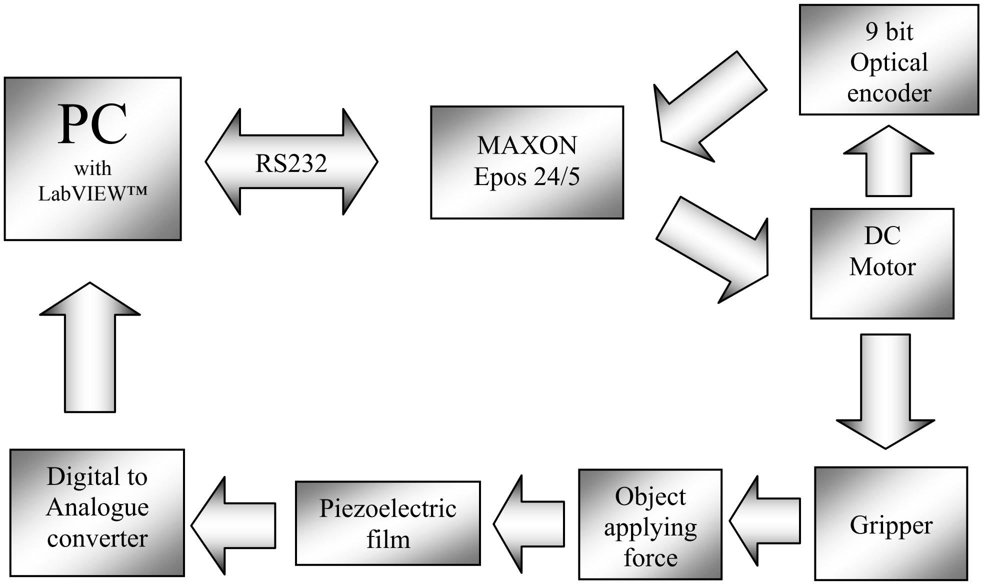
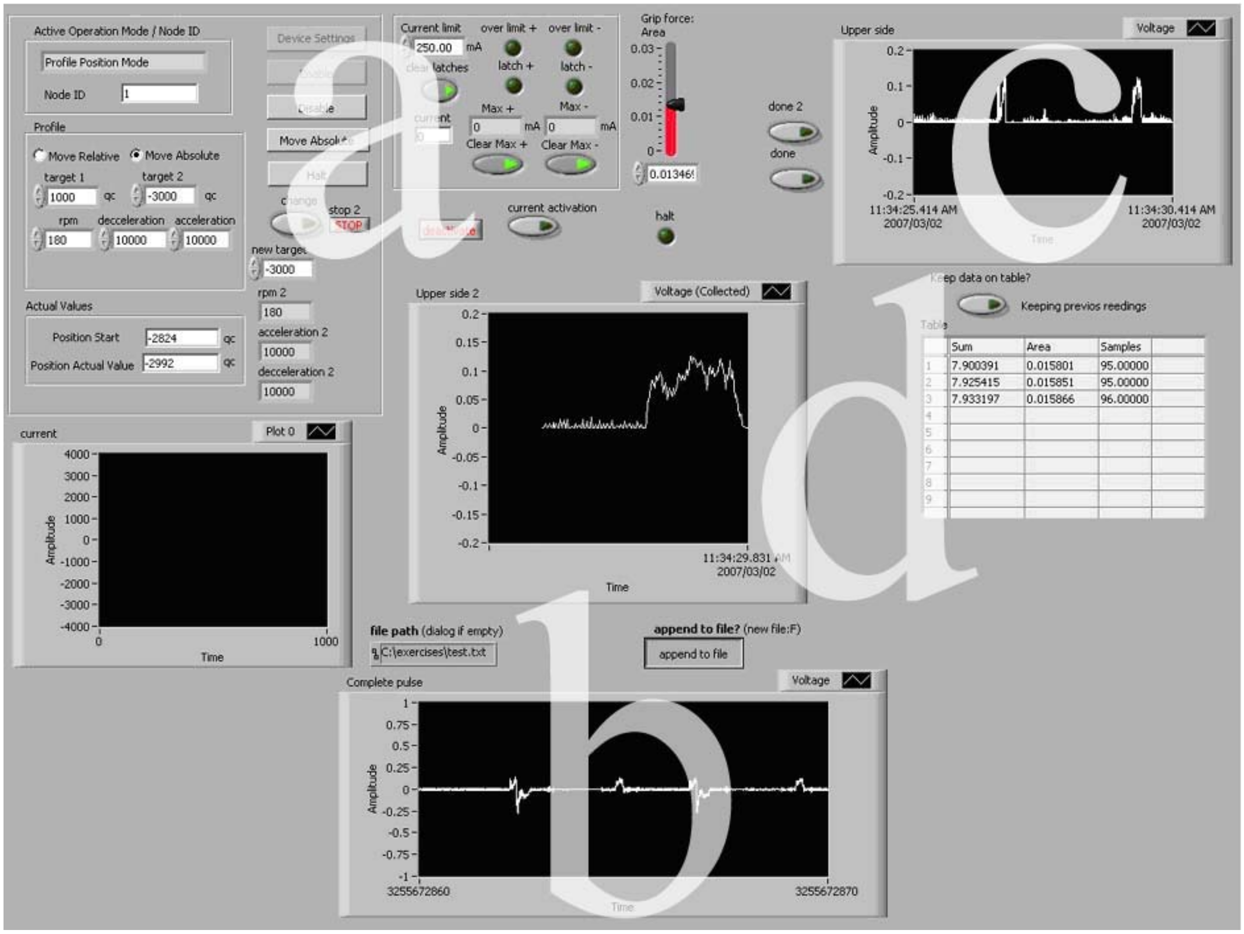


Figure 3.15 Dynamic gripper control loop.

The software consists of mainly the gripper-control software and the force-monitoring software which is in combination the force-control software. The front panel of this software is shown in Figure 3.16 to be discussed in paragraph 3.7.



Active Operation Mode / Node ID: Profile Position Mode

Node ID: 1

Profile: ○ Move Relative ● Move Absolute

target 1: 1000 qc

target 2: -3000 qc

rpm: 180

decceleration: 10000

acceleration: 10000

new target: -3000

rpm 2: 180

acceleration 2: 10000

decceleration 2: 10000

Actual Values

Position Start: -2824 qc

Position Actual Value: -2992 qc

Current limit: 250.00 mA

Max +: 0 mA

Max -: 0 mA

current: 0

Grip force: Area: 0.01346

file path (dialog if empty): C:\exercises\test.txt

append to file? (new file:F): append to file

Keep data on table?: Keeping previos reedings

Table

	Sum	Area	Samples	
1	7.900391	0.015801	95.00000	
2	7.925415	0.015851	95.00000	
3	7.933197	0.015866	96.00000	
4				
5				
6				
7				
8				
9				

Figure 3.16 LabView™, representing a) control panel for speed, force, ampere, acceleration/deceleration, direction and position control , b) arrival and departure pulses generated by a gripping sequence , c) departure pulses filtered out showing only the arrival pulses generated by a gripping sequence, d) tabling, displaying and recording of the pulse area, samples and voltages.

3.6. Gripper Control Software

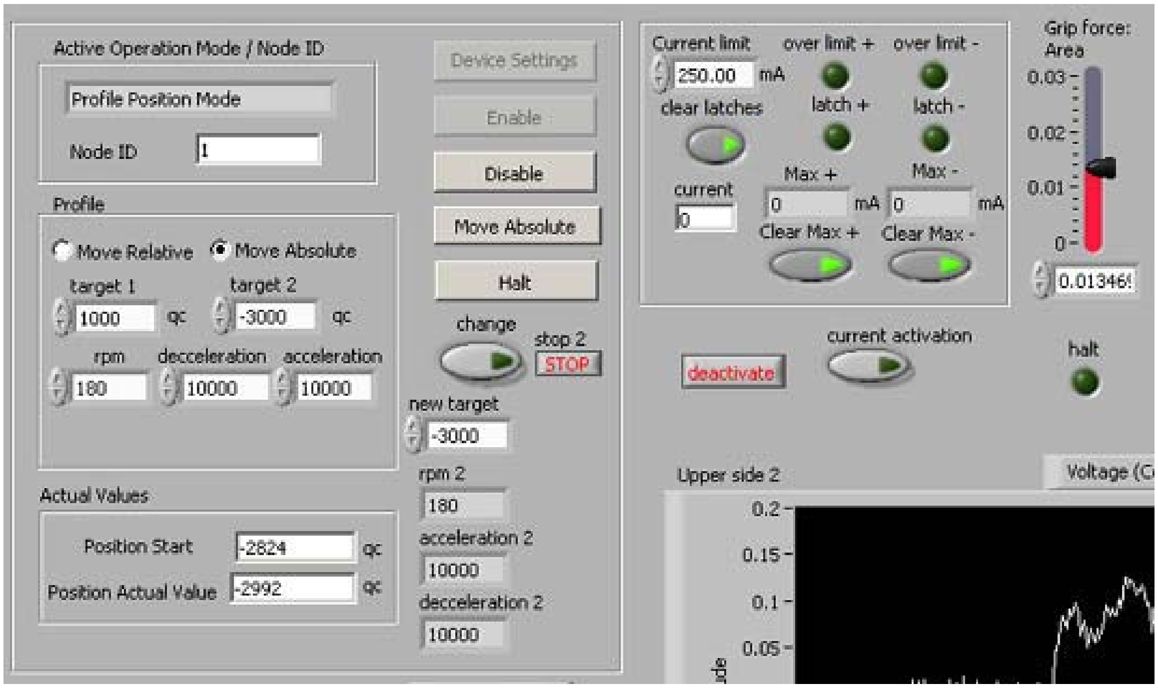
It must be kept in mind that the software was developed for experimental, research purposes and not for industrial implementation purposes.

Controlling the motor consists of instructions given to the PID controlled Epos 24/5 motor controller and reacting on data retrieved from this controller. The position of the motor's optical encoder is constantly monitored, so that the gripper finger position is known. Configurations such as velocity, acceleration and deceleration are written to the controller to establish the operating variables. Target gripper positions (physical encoder positions) are given to the controller. The gripper performs then the instruction according to the preset operating variables.

3.7. Force-Monitoring and Control Software

The Joule calculation was not necessary for programming purposes. It was also not necessary to use the Joule calculations to monitor the force applied to the object, but joule conversion is useful for performance indication. The Joules are proportionate to the direct summation of the incoming voltage. The force control is done directly by the summation of the incoming voltage samples. In order to know the Joules produced by the piezoelectric film, it is easy to convert the summed voltage to Joules.

Voltage from the piezoelectric film is monitored for doing the necessary calculations and alterations to have the motor respond, controlling the force the gripper is applying on the piezoelectric film. The 80Watt motor used to control the finger movement has enough power to rip the whole gripper apart. In case the piezo film is not connected, the force setting is too high or failure from the software occurs, the motor will not stop and will strip the bevel gears or break the fingers. To prevent this from happening, current control was implemented to stop the motor. Fig. 3.17 illustrates the LabVIEW™ front-page used to set the current limit for the finger movement which shows the current limit in both finger movement directions, opening and closing. A latching indicating light and maximum current text box is implemented, indicating such an over current occurrence and indicating the current value in such a situation. This current limit is easily adjustable to the operators needs.



Active Operation Mode / Node ID: Profile Position Mode
Node ID: 1

Profile
○ Move Relative ● Move Absolute
target 1: 1000 qc
target 2: -3000 qc
rpm: 180
decceleration: 10000
acceleration: 10000

Actual Values
Position Start: -2824 qc
Position Actual Value: -2992 qc

new target: -3000
rpm 2: 180
acceleration 2: 10000
decceleration 2: 10000

Current limit: 250.00 mA
current: 0
Max +: 0 mA
Max -: 0 mA

Grip force: Area: 0.01346

Figure 3.17 Gripper control software panel.

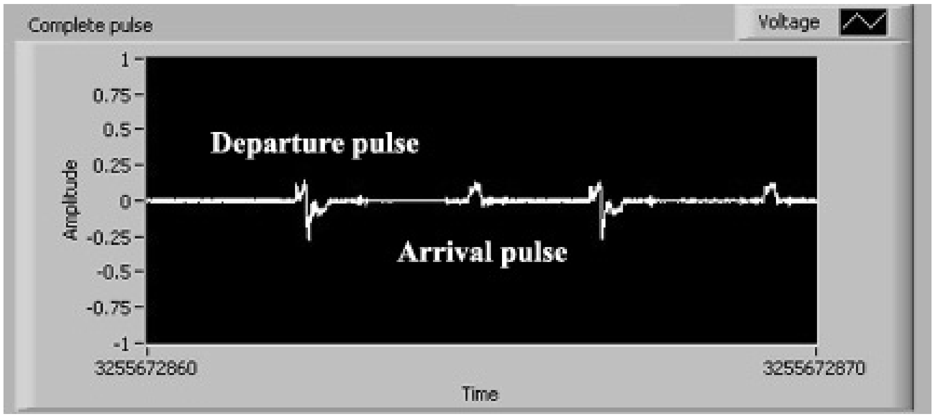


Figure 3.18 Arrival and departure pulses generated by a gripping sequence.

As earlier explained in Figure 3.10, the piezoelectric film generates a negative pulse when the film is held in a deformed state and then released. In Figure 3.18 the LabVIEW™ panel shows the graph of the pulses from left to right. The graph starts with the gripper already in a gripping position. It then shows the gripper leaving the object and with the second pulse the gripper is gripping the object again.

The second pulse is created by deforming the piezoelectric film and holding it there in the gripped position. The negative pulses must be filtered using only the positive pulses which represents the gripper object contact force, shown in Figure 3.19. The lower amplitude of the noise forming part of the pulses are also subtracted from the rest of the pulse so that most of the noise signals can be ignored, reducing noise-related interference.

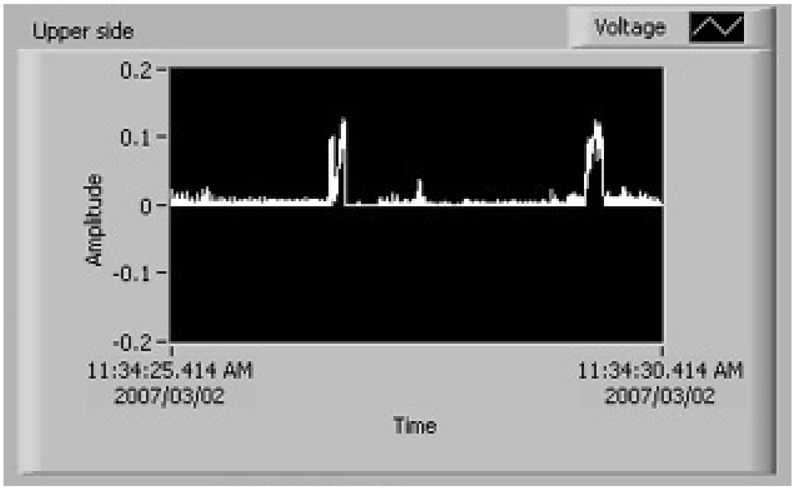


Figure 3.19 Departure pulses filtered out showing only the arrival pulses generated by a gripping sequence.

Identifying a touch instance is done by counting the number of samples that the pulse is above zero and discarding it as a touch pulse whenever the number is below 25 samples. Measuring at 500 samples per second, a touch pulse more than 25 samples is a pulse taking more than 50ms to form. As soon as it returns to zero, the sample count is captured. This acts as an ultra low pass filter. Large noise pulses, like something bumping into the gripper or even the departure pulses can sometimes seem like a touch instance. It was found experimentally that these noise pulses never exceed 25 pulse samples. This means any pulses less than 25 samples would be disregarded as a touch instance. This method ensures that noise pulses do not interfere. The touch instance voltage samples are then summed together giving the summed voltage samples which are used to indicate the force controlling the gripper. A requested value of summed voltage, identified as a touch pulse, limits the force accordingly. The summed touch voltage is monitored real-time, initiating a halt instruction to the motor when it is exceeding the requested amount. A simplified version of such calculations can be seen in Figure 3.20.

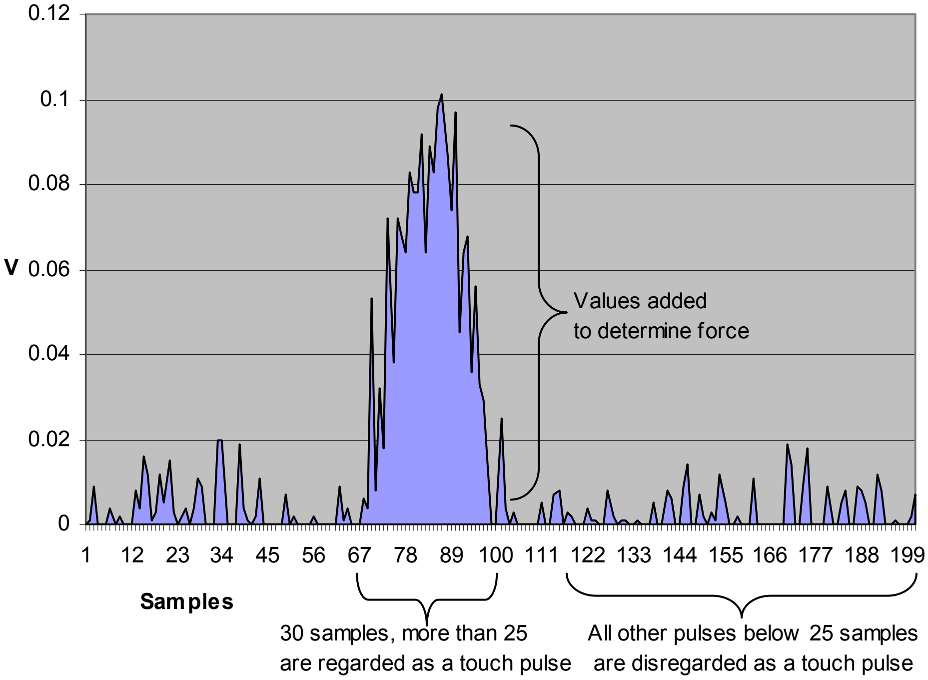
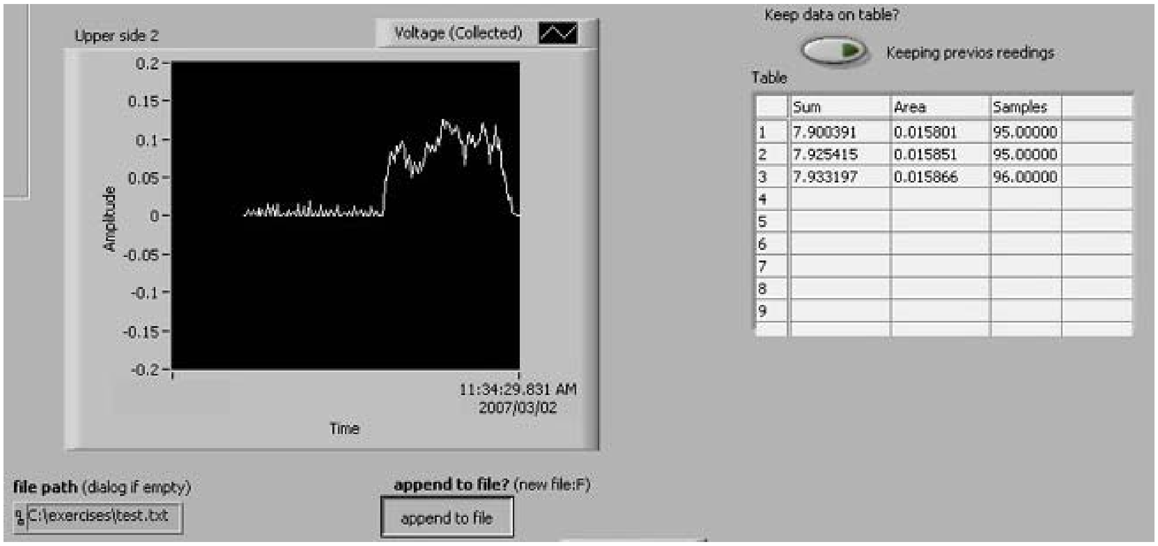


Figure 3.20 Example of calculating and obtaining a touch pulse.

The LabVIEW™ coding responsible for the path of the voltage from the piezoelectric film sensor to the summed voltage touch pulse controlling the force is shown in Appendix A.

The touch pulse is then saved to a text file on the PC for further analysis and documentation, as can be seen in Figure 3.21.



Keep data on table?
Keeping previos reedings

Table

	Sum	Area	Samples	
1	7.900391	0.015801	95.00000	
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4				
5				
6				
7				
8				
9				

file path (dialog if empty)
C:\exercises\test.txt

append to file? (new file:F)
append to file

Figure 3.21 Tabling, displaying and recording of the pulse area, samples and voltages.

3.8 Overview of System Development

Rapid prototyping, PID and LabVIEW™ in turn proved to be sufficient tools in constructing a more than adequate gripper in order to perform the necessary tests on the piezoelectric film.

Piezoelectric film in its basic passive form is indeed capable of taking passive and active measurements. Piezoelectric film sensors are very susceptible to noise. Indicated by this research and development, it is possible to do adequate force readings and control the gripper accordingly without noise interference. Recording the pulse data itself as well as the multiple pulse readings presents the opportunity to analyse and compare them with each other.

4 Gripping Results and Calibration

Data received from the piezoelectric film was captured to a file for analysis. Captured data was compared in sequence with Microsoft Excel©. Analysed data indicated the nature of the piezoelectric film towards the gripper control as well as the gripper mechanics itself. A main area of interest in the transfer function is the linearity or non-linearity of the force applied to the piezoelectric film and the voltage produced by the piezoelectric film over the resistance of the measuring equipment. The induced Joules is, to a great extent linearly proportional to the applied force of the response from the piezoelectric film towards the area calculated under the touch pulses [20].

Plasticity of the gripper finger material is also an area of interest. The material the fingers are made of has elastic properties up to a certain strain, moving into its plastic region. This is, in effect, a reduction of strain the finger can resist against the applied forces [23]. External measurement, for example a load cell giving the correlation between software readings and real Newton measurements, are necessary for a calibrated system. With the force-voltage transfer function, piezoelectric film response repeatability, gripper finger plasticity and external Newton correlation known, the software can be adapted to realise a working solution.

4.1 System Control Response

Measurements were taken to determine the shortcomings this system has for applying accurate forces. These Measurements gave an indication for hardware and software calibration and error correction realising the results of this research.

A sequence of 15 increasing force values, in the form of the summed voltage value, converted to area below pulse, received from the piezoelectric film pulse, were requested 5 times each via the software. The readings were compared with the actual concurring force values using the strain gauge. The requested values are produced in the form of summed voltage values received from the piezoelectric film pulse. This data was recorded and analysed in Microsoft Excel$^{©}$. In Figure 4.1, it can be seen how concurrent the repeated measurements are, giving satisfactory repeatability.

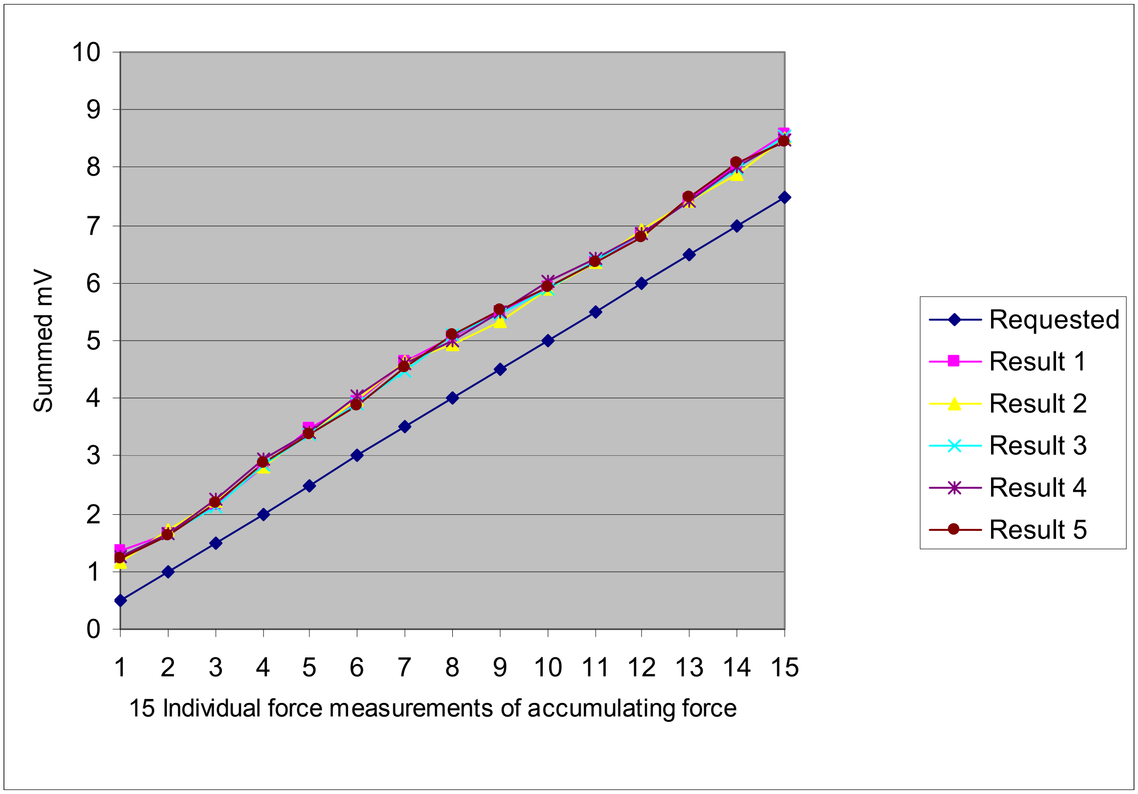

Figure 4.1 Requested pulse sequence in 15 linearly increasing values of gripper force and its 5 sets of result and measurements.

The results are constantly deviating from the requested values due to the deceleration of the gripper motor.

Linearity is of a workable nature but when ignoring the constant deviation, there is a kind of saturation, as can be seen in Figure 4.2.

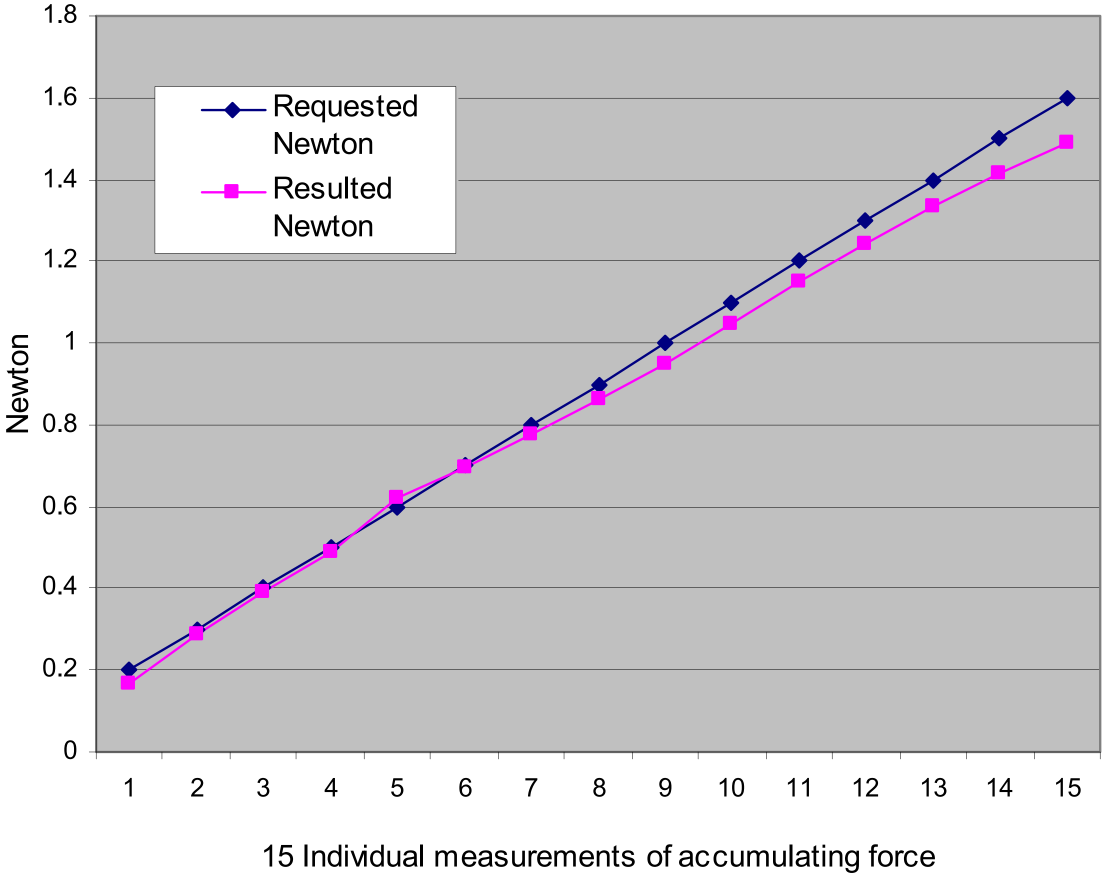

Figure 4.2 Requested Newton grip force compared with the measured results after error correction and showing the linearity between the two.

Linearity error is caused due to the gripper finger deformation properties, going in to its plastic region with high enough forces, resulting in too much strain on the finger, thereby causing it to lose its elasticity (Figure 4.3.).

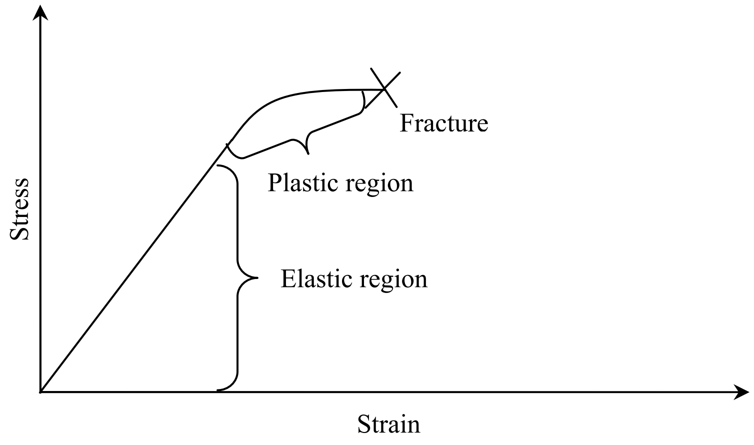

Figure 4.3 Deformation theory of plasticity: shear stress component with respect to a shear strain component, under increasing strain loading (Hooke's law) [24].

The gripper still stops closing at the correct requested and anticipated force - the fingers only loses grip afterwards, thereby losing linearity.

4.2 Force Control

The summation of the voltage is used to control the requested force, due to it being proportionate to the integral of this force pulse. System input is from the analogue-to-digital converter, connected to the piezoelectric film output parallel connected to a 7.4MΩ resistor. Previously shown Figure 4.1 depicts the repetitiveness of the measurements for concurrency. Sufficient relationship between gripper response and the requested software instructions ensures the expected measurements resulting from force controlled by the summation of the piezoelectric voltage samples. This gripper response does not equal the software instructions, due to the gripper motion deceleration after the software instruction is met and the motor is halted. Gripper motion deceleration decreases the accuracy of the gripper response according to the instruction that was given via the software. Figure 4.4 shows the accumulating voltage summation, the sequence of where requested values are met and the gripper reacting, with a system response delay on the voltage measurements.

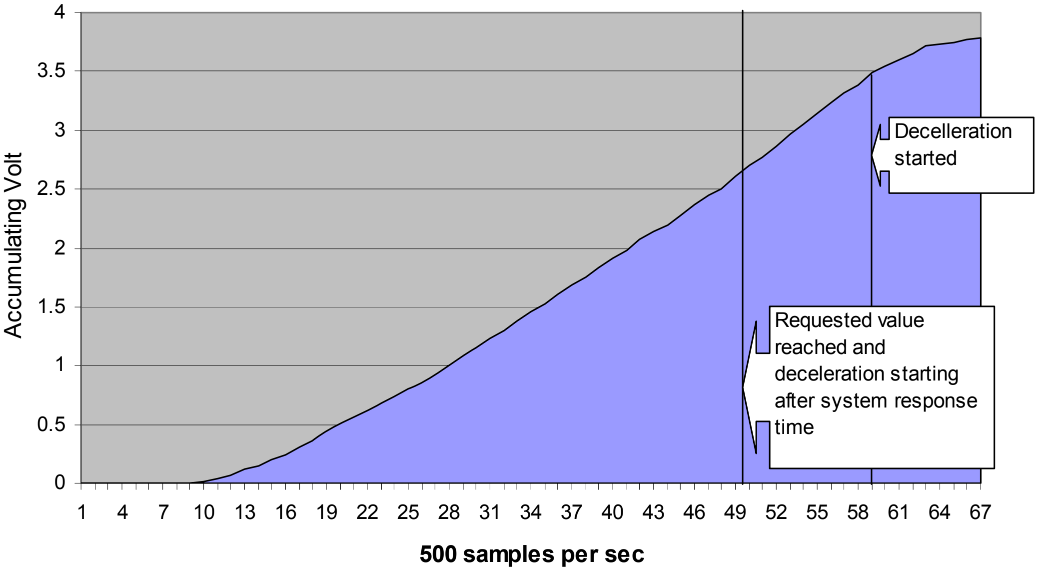

Figure 4.4 Accumulating voltage summation of a touch pulse, indicating the requested value and the time at which the motor starts to decelerate.

Figure 4.5 shows how accuracy increases with higher deceleration; the overshoot summed voltage decreases with higher deceleration so that the total pulse voltage summation is closer to the requested value. The requested value is 2.6 summed voltage units. The first pulse is over by 1.171 summed voltage units and the second pulse is over by 0.859 summed voltage units.

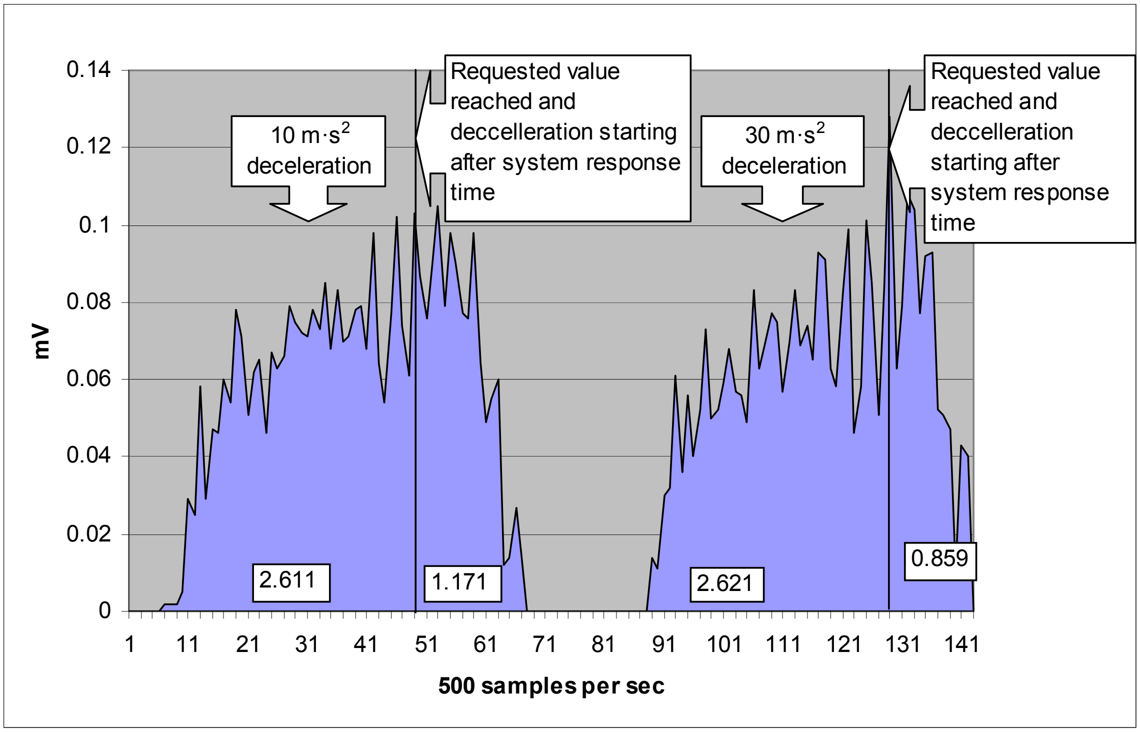

Figure 4.5 Accuracy increasing with higher deceleration (readings in summed voltage units).

Infinite deceleration and instant system response would have been ideal, giving perfect results, but with this deceleration a close to perfect result can be obtained using error correction by optimising the software settings.

After the overshoot is theoretically canceled by reducing the initial requested values to counteract the overshoot the only disadvantage in using a low deceleration rate is that the minimum force that can be accurately performed increases, as shown with the black cross in Figure 4.6.

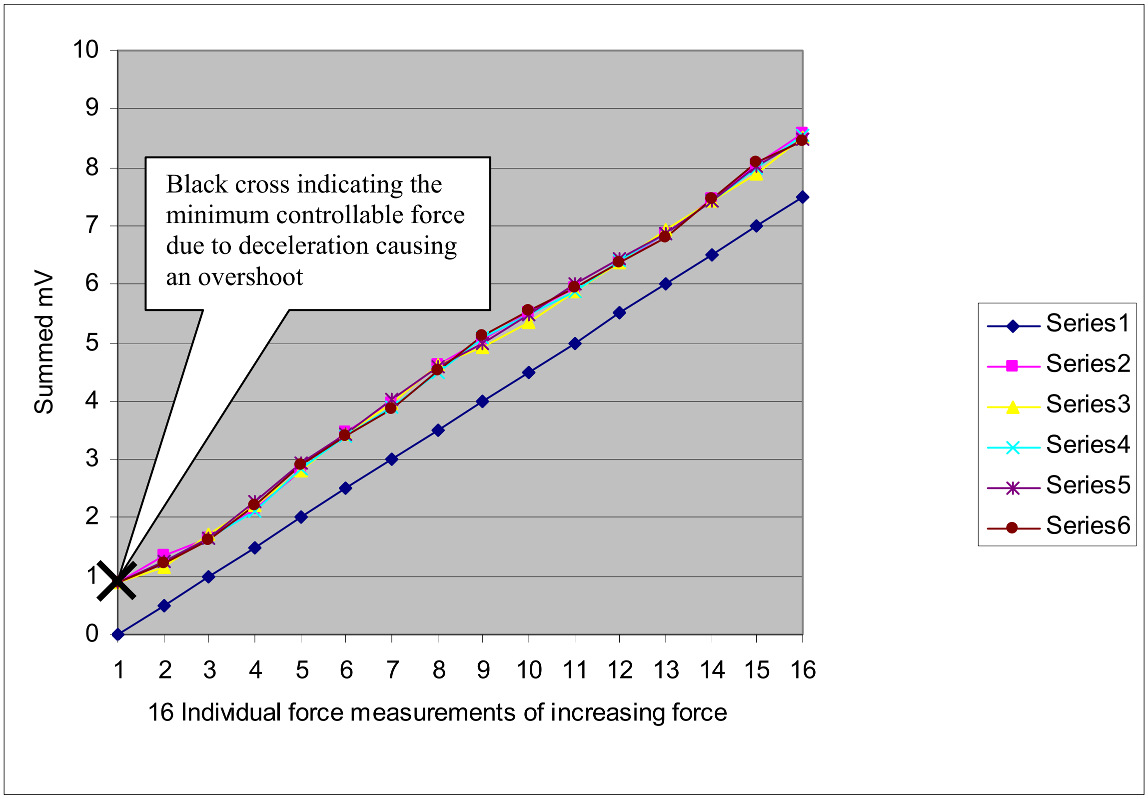

Figure 4.6 Deceleration is responsible for a minimum controllable force.

Deceleration of the combined finger linear movement is kept at 10 m·s^2 to illustrate the error correction and minimum force that can be performed more noticeably. Deceleration can easily be increased up to a maximum of 50 m·s^2, which will reduce the overshoot radically. Deceleration responsible for the difference between requested and resulted measurements can be seen in Figure 4.5.

Readings in Figure 4.6 show clear recurring results and a sufficient constant deviation from the instructed value.

With this accurate result expectancy, combined with adequate linearity, the software requested value can be lowered by the mean concurring error, which should bring the requested and resulted measurements much closer together, at the same time, raising the minimum accurately useable force. The mean error values are derived from five force accumulating sets of results starting at ± 0.023 up till ± 1.43 Newton in 15 intervals. All the error values of these measurements were summed together and divided by the total number of these error values. To convert summed voltage to Newton, actual measurements were made with an external calibrated strain gauge. Now with these values, the software could be altered to fulfill the requested Newton. All requested voltage summations are then reduced by the mean error, which is 0.9 summed mV at 500 samples per second. This in return makes, 0.9 summed mV, the minimum controllable concurred force, which is 0.017142 Newton. Results for this alteration are shown in Figure 4.2. From sample nine upward a decrease in force intensity can be seen - this is due to the plasticity of the finger indicated in Figure 4.8 and the fact that measurements are made 5 seconds after the gripper is stopped, allowing the fingers to loosen the grip while moving into its plastic region.

Initially the gripper stops according to the correct force, but then the finger’s deformation enters its plasticity region, reducing the force the finger is applying to the object.

Watching the output of the strain gauge shown in Figure 4.7, an initial result immediately reduces until it stabilizes, indicated in Figure 4.8.

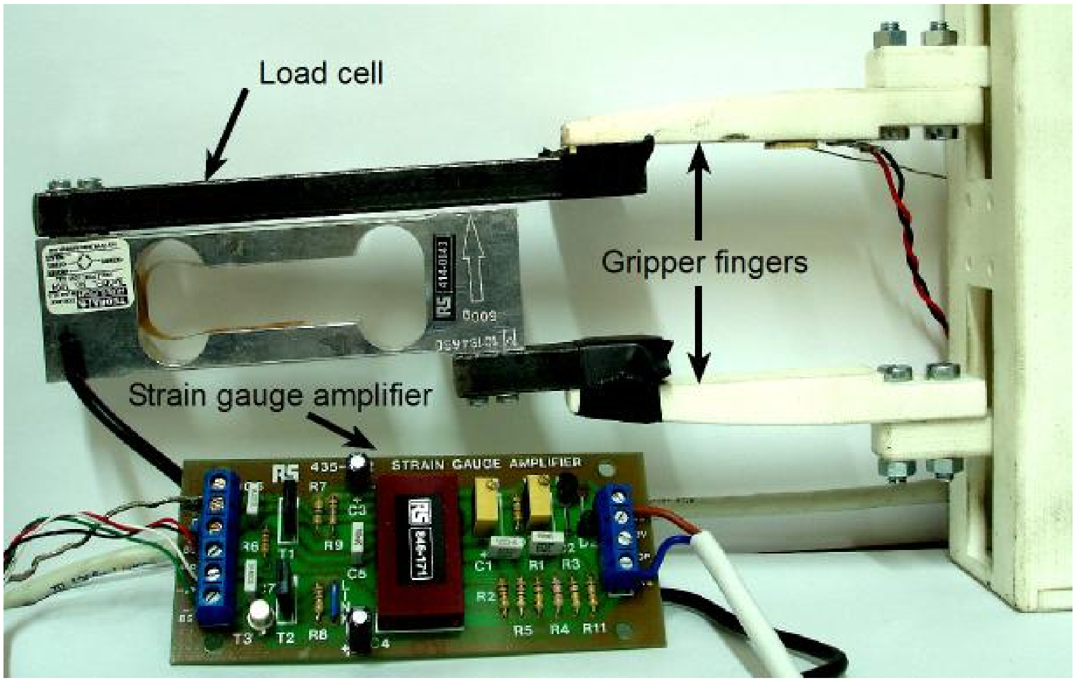

Figure 4.7 Load cell taking force readings from the gripper.

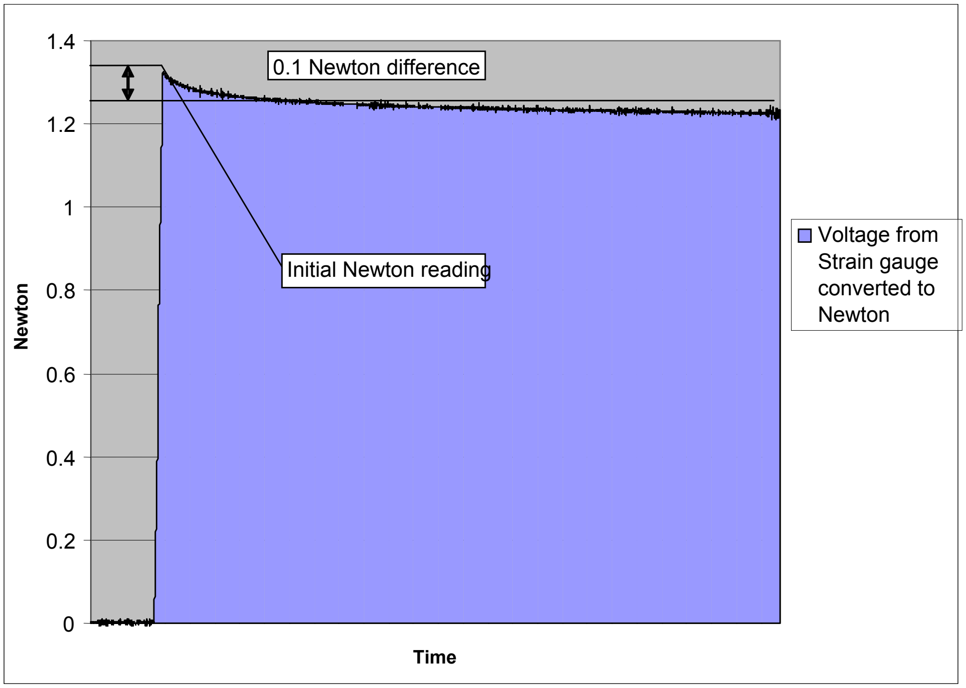

Figure 4.8 Finger losing tension over a period of time while moving into plastic deformation.

More detail on the load cell is available in Appendix B.

Using the same force values as in Figure 4.2 and taking the readings from the strain gauge immediately, the initial result equals the requested Newton, as can be seen in Figure 4.9. As the finger starts to deform plastically the force on the strain gauge starts to decrease, hence the deviation towards higher forces.

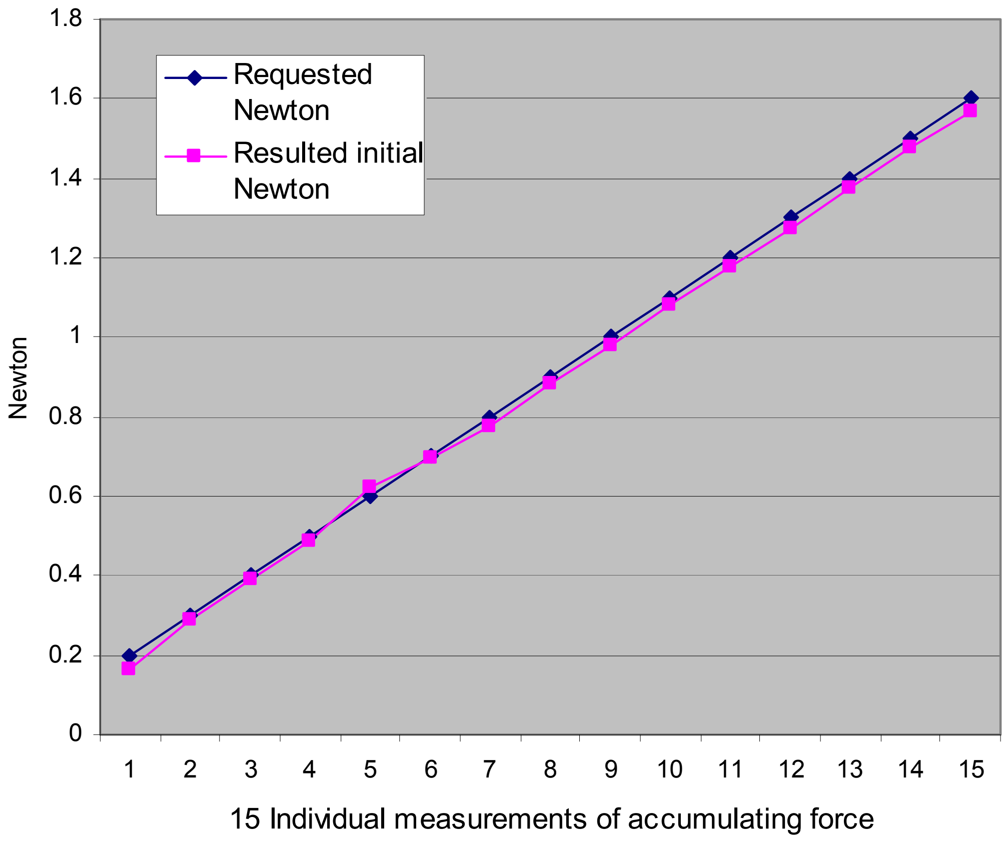

Figure 4.9 Requested Newton compared with initial Newton readings before finger moved into its plastic region.

4.3. Conclusion

The control of this force-sensing gripper is done by a desktop computer running LabVIEW™, an analogue-to-digital PCI card and a PID control box. Using this system, Figure 4.10 presents a possible user-friendly front panel for a functioning application.

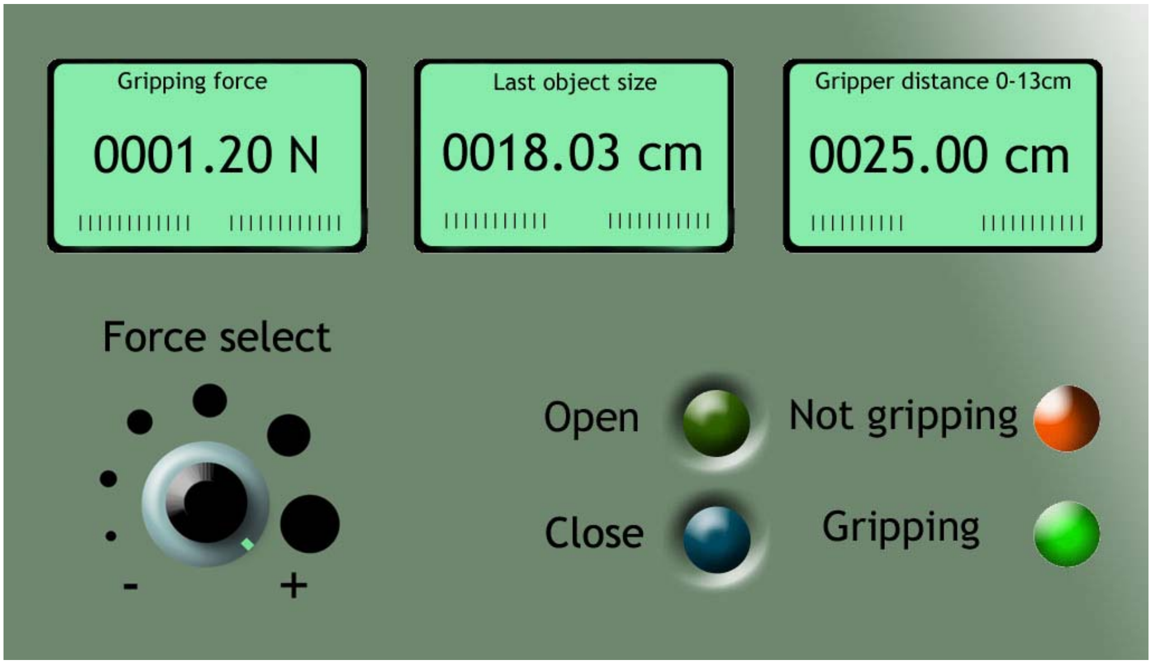

Figure 4.10 Example of a simplified front panel for practical use.

For further development, moving to a practical installation, a microcontroller with an analogue-to-digital converter integrated circuit (IC) can take over the work of the desktop computer and analogue-to-digital PCI card. The microcontroller issues commands to the PID control box via a serial link and receives sensor response through an analogue-to-digital input. This input can be processed on the microcontroller and the resulting commands can be fed back to the PID controller.

5. Conclusion

PVDF (Polyvinylidene Difluoride) has great potential in tactile research. Human touch sense consists of passive and active force sensors. Dragging your finger over a texture reveals the nature of the texture rather than pressing your finger against it. Sensing both static and dynamic forces with PVDF piezoelectric film sensors presents a solution for developing human-like tactile sensing using the same sensor.

Determining an accurate static force with a piezoelectric film is not a straight forward operation. Piezoelectric sensors themselves are responsive only to a changing stress rather than to a steady level of it. In other words, a piezoelectric sensor is an AC device, rather than a DC device. The properties of this sensor prevent it from being utilised as a static force-sensor without certain known constants and signal processing.

This research shows that force can be accurately determined using a piezoelectric film in its simplest passive form, given that the impact velocity and deceleration are known. Impact velocity and deceleration are easily controlled and reproduced with the PID controlled servomotor used to control the linear motion of the gripper fingers. In this application the impact velocity and deceleration stayed the same, so the software could be adjusted according to this scenario on an external measuring device. A load cell measuring the force applied by the fingers was used to calibrate the software. Controlling the force the gripper applies to an object can be realised with a constant deviation. This deviation is due to the gripper motion deceleration. The deceleration can be increased significantly, reducing the overshoot error. The deceleration was kept on $30\text{m}\cdot\text{s}^2$ for better overshoot exemplification purposes. With a constant deceleration the initial force request can be reduced accordingly to provide room for the extra force produced by the deceleration overshoot. Reducing the initial requested force increases the minimum controllable force, depending on the deceleration. The increase of the deceleration value results in less force deviation, giving it a better minimum limit of controllable force.

Requested and resulted force measured on a strain gauge stray from linearity towards higher forces. Gripper finger plasticity is responsible for this phenomenon. Initial impact provides the requested force, hence stopping the gripper from closing; this force imposes tension in the finger, bending the finger into its plastic region so that the force on the piezoelectric film drops from the initial force. This plastic strain can be prevented by using a more elastic and rigid material, meaning a material that will not bend easily. However, if it does bend, the material should not deform plastically. Using the gripper finger's deformation curve, the software can compensate for this plasticity.

Compared to three dimensional analysis, using it to handle objects on finger object level, which needs an expensive set of machine vision cameras and heavy processing power, using piezoelectric film sensors for dynamic fingertip force-sensing is a much cheaper, simpler and more accurate solution. Machine vision and image recognition will still be needed if the gripper must be positioned over the object which is being gripped, but much less intensely, due to the fact that the piezoelectric force-sensors takes over the touch recognition and touch intensity. Using the piezoelectric film sensor in its simplest, “off the shelf” passive form, no extra manufacturing is needed, keeping the touch system simple and inexpensive. Charles F. Kettering said the following: “Inventing is a combination of brains and materials. The more brains you use, the less material you need.”[3]

With the use of LabVIEW™, control electronics and a motor-controlled gripper, acceptable touch sense can be successfully given to fingers by using piezoelectric film sensors, in their basic passive form, as feedback.

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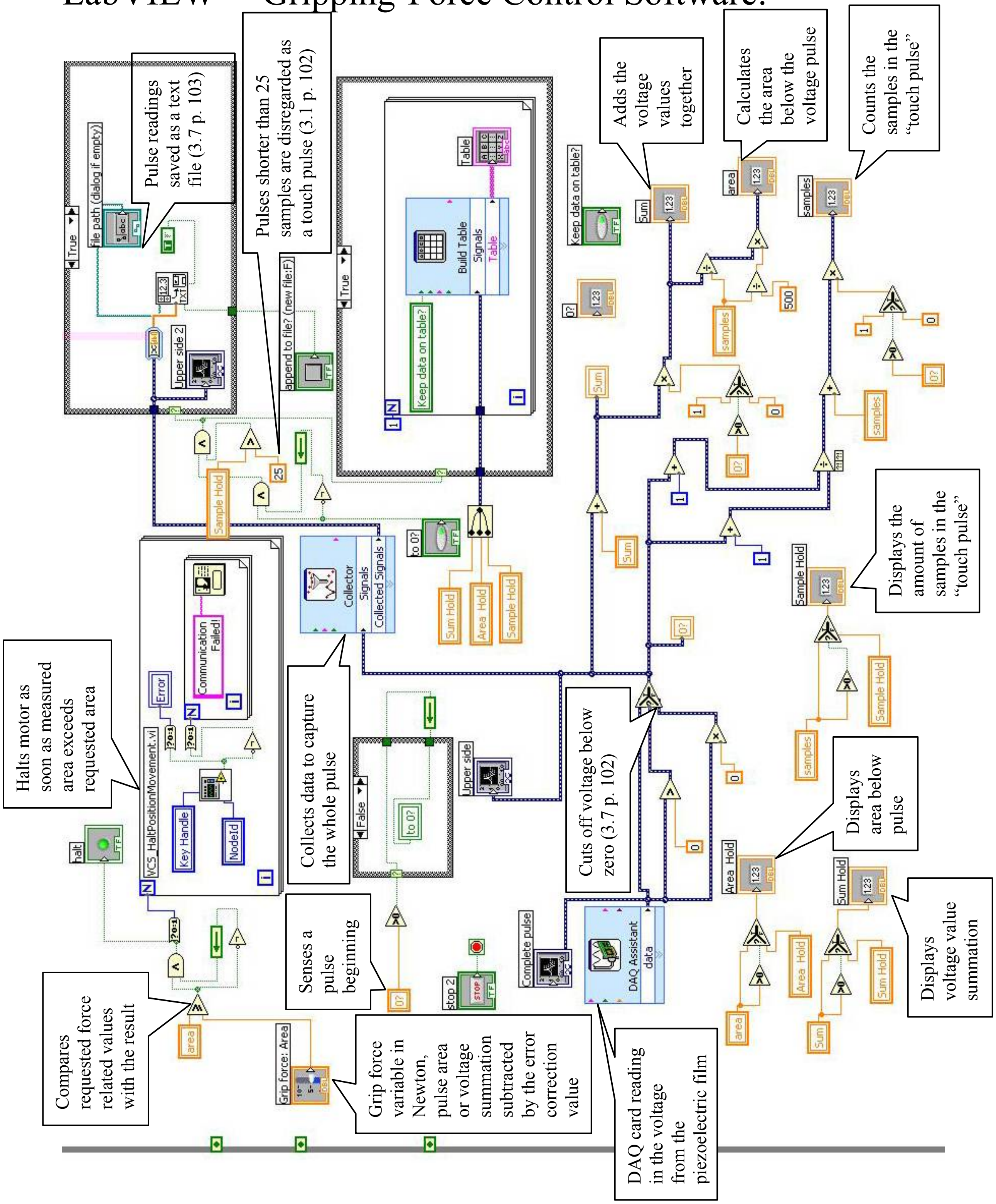
Appendix A

LabVIEW™ Gripping-Force Control Software:



Pulse readings saved as a text file (3.7 p. 103)

Pulses shorter than 25 samples are disregarded as a touch pulse (3.1 p. 102)

Adds the voltage values together

Calculates the area below the voltage pulse

Counts the samples in the “touch pulse”

Displays the amount of samples in the “touch pulse”

Halts motor as soon as measured area exceeds requested area

Collects data to capture the whole pulse

Cuts off voltage below zero (3.7 p. 102)

Displays area below pulse

Displays voltage value summation

Senses a pulse beginning

Compares requested force related values with the result

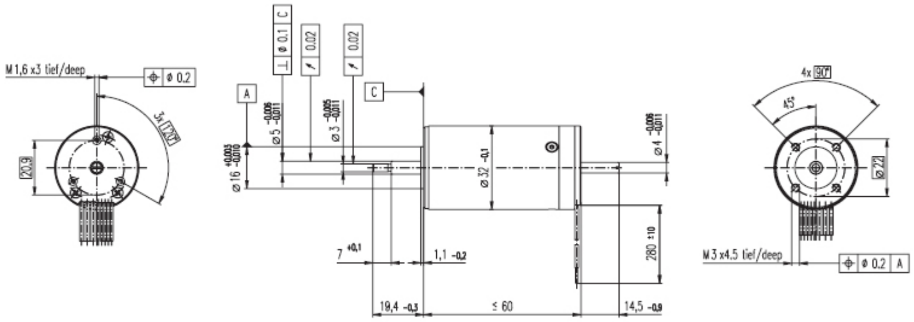
Grip force variable in Newton, pulse area or voltage summation subtracted by the error correction value

DAQ card reading in the voltage from the piezoelectric film

Appendix B

Motor Datasheet:

EC 32 ∅32 mm, brushless, 80 Watt, CE approved



M 1:2

🟥 Stock program
☐ Standard program
▨ Special program (on request)

	Motor Data		**Order Number** 118891
	Values at nominal voltage		
1	Nominal voltage	V	12.0
2	No load speed	rpm	15100
3	No load current	mA	901
4	Nominal speed	rpm	13600
5	Nominal torque (max. continuous torque)	mNm	38.3
6	Nominal current (max. continuous current)	A	5.91
7	Stall torque	mNm	443
8	Starting current	A	59.2
9	Max. efficiency	%	77
	Characteristics		
10	Terminal resistance phase to phase	Ω	0.203
11	Terminal inductance phase to phase	mH	0.0300
12	Torque constant	mNm / A	7.48
13	Speed constant	rpm / V	1280
14	Speed / torque gradient	rpm / mNm	34.6
15	Mechanical time constant	ms	7.24
16	Rotor inertia	gcm²	20.0

Specifications

	Thermal data	
17	Thermal resistance housing-ambient	5.4 K / W
18	Thermal resistance winding-housing	2.5 K / W
19	Thermal time constant winding	15.4 s
20	Thermal time constant motor	1180 s
21	Ambient temperature	-20 ... +100°C
22	Max. permissible winding temperature	+125°C
	Mechanical data (preloaded ball bearings)	
23	Max. permissible speed	25000 rpm
24	Axial play at axial load < 8 N	0 mm
	> 8 N	max. 0.14 mm
25	Radial play	preloaded
26	Max. axial load (dynamic)	5.6 N
27	Max. force for press fits (static)	110 N
	(static, shaft supported)	1200 N
28	Max. radial loading, 5 mm from flange	28 N
	Other specifications	
29	Number of pole pairs	1
30	Number of phases	3
31	Weight of motor	270 g

Values listed in the table are nominal.

Connection Motor (Cable AWG 22)

red	Motor winding 1
black	Motor winding 2
white	Motor winding 3

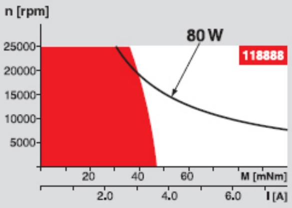
Connection Sensors (Cable AWG 26)[1]

green	V_{Hall} 4.5 ... 24 VDC
blue	GND
red / grey	Hall sensor 1
black / grey	Hall sensor 2
white / grey	Hall sensor 3

Wiring diagram for Hall sensors see page 26

[1] Not lead through in combination with resolver.

Operating Range



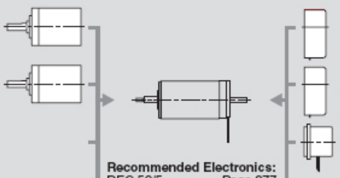
Comments

🟥 **Continuous operation**
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

☐ **Short term operation**
The motor may be briefly overloaded (recurring).

—— **Assigned power rating**

maxon Modular System Overview on page 16 - 21



Planetary Gearhead
∅32 mm
0.75 - 4.5 Nm
Page 230

Planetary Gearhead
∅32 mm
1.0 - 6.0 Nm
Page 232

Encoder HEDS 5540
500 CPT,
3 channels
Page 255

Encoder HEDL 5540
500 CPT,
3 channels
Page 257

Resolver Res 26
∅26 mm
10 V
Page 264

Recommended Electronics:

DEC 50/5	Page 277
DECV 50/5	278
DEC 70/10	278
DES 50/5	279
EPOS 24/5	286
EPOS P 24/5	287
EPOS 70/10	287
MIP 50	289
Notes	**20**

Load Cell Datasheet:

Model 1004

Single Point Load Cells

NEW!

Features

- Capacities: 0.3 kg - 3 kg (0.6 lbs - 6 lbs)
- Aluminum construction
- Single point 200 mm x 200 mm
- IP66 protection
- Total error better than 0.0067% of rated output

Model 1004 is a very low capacity, very high precision single point load cell designed for direct mounting in low capacity scales and precision balances.

The unit is suitable for applications including jewelry scales, analytical balances, medical equipment, medical and pharmaceutical research and low level force measurement.

The model 1004 offers up to 30,000 divisions short term precision at stable room temperature. A special two-stage humidity resistant protective coating assures long term reliability.

An overload protection device should be included in the application design. A threaded hole is provided in the loading end of the load cell for this purpose.

VISHAY

Transducers

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Darmstadt-Eberstadt

France
SEEA sa
16 Rue Francis Vovelle
28000 Chartres
France

Model 1004

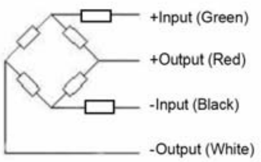
Single Point Load Cells

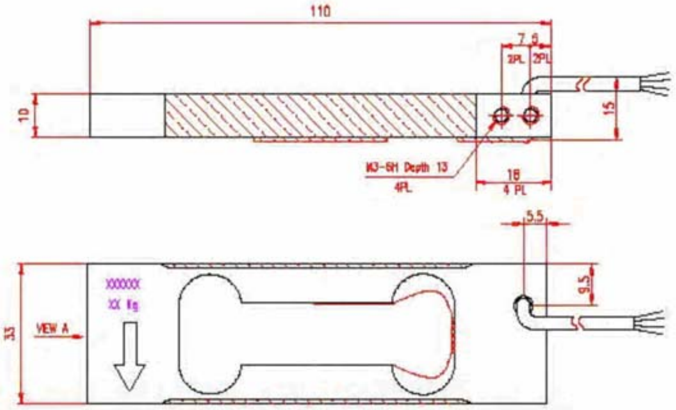
GRADE	JW	UNITS
Rated Capacity	0.3, 0.6, 1.5, 3	kg
Rated Output	0.9 ±0.1	mV/V
Rated Output Tolerance	0.1	± mV/V
Zero Balance	0.04	± mV/V
Total Error (at constant room temperature)	0.0067	±% of Rated Output
Zero Return (creep) in 2 minutes	0.0033	±% of Applied Load
Temperature Effect: On Zero	0.004	±% of Rated Output/°C
Temperature Effect: On Output	0.002	±% of Applied Load/°C
Eccentric loading error	0.0033	±% of Load / cm
Maximum recommended platform size	20 by 20	cm
Temperature Effect: Compensated	+5 to +45	°C
Temperature Effect: Safe	-30 to +70	°C
Maximum Safe Static Overload (central loading)	150	% of Rated Capacity
Ultimate Static Overload (central loading)	250	% of Rated Capacity
Excitation: Recommended	10	VAC or VDC rms
Excitation: Maximum	15	VAC or VDC rms
Input Impedance	415 ± 20	Ohms
Output Impedance	350 ± 3	Ohms
Insulation Resistance	>2000	MegaOhms
Deflection of Rated Capacity (Central Loading)	<0.4	mm
Cable Length	0.4	m
Weight (nominal)	0.06	kg
Cable Type	0.4 m, 4-wire, 28 AWG, spiral shield, PVC jacket	
Color Code	+exc-grn, +sig-red -exc-blk, -sig-wht	
Construction	Aluminum	
Platform Size	200 x 200	mm
Compensation Circuit Type	Balanced	
Environmental Protection	IP66	
Outline Dimension Drawings	273.000.00-3	

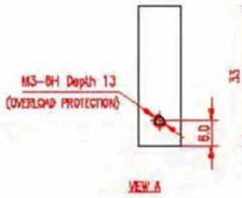
Recommended bolt fixing torqueL 1.4nm (1.0 lbf.ft)

Outline Dimensions All Capacities (in mm)

Wiring Schematic







Epos 24/5 PID Motor Controller Datasheet:

EPOS Positioning control unit

Standardised, extendable	CANopen standard CiA DS-301 and DSP-402. Can easily be integrated into existing CANopen systems. Interactive with other CANopen modules Alternatively controllable through serial interface (RS232)
Flexible, modular	The same technology for DC and EC motors. Configurable inputs and outputs for limit-switches, reference switches, brakes and for other sensors and displays near the drive.
Easy start-up procedure	Graphic user interface (GUI) with many functions and wizards for start-up procedure, automatic control settings, I/O configuration, tests.
Simple programming	Numerous prepared IEC 61131-3 libraries for CAN-Master units of various PLC manufacturers and Windows-DLLs for PC-Master.
Latest technology	Digital position, speed and current-torque control. Sinusoidal commutation for high synchronism with EC motors

EPOS is a modular constructed digital positioning controller. It is suitable for DC and EC motors with incremental encoder with a power range from 1 - 700 watts.
A number of operating modes provides flexible application in a wide range of drive systems in automation technology and mechatronics.

Point to point
The "CANopen Profile Position Mode" helps position the motor axis from point A to point B. Positioning is in relation to the axis zero point (absolute) or current axis position (relative).

Position control with anticipatory control (feed forward)
The combination of controlling feedback control and controlling feed forward measures provides ideal control. Anticipatory control reduces control error. EPOS supports acceleration and speed anticipatory control.

Speed control
In "CANopen Profile Velocity Mode", the motor axis is moved with a set speed. The motor axis retains speed until a new speed is set.

Torque control
Under "current mode", a constant torque can be controlled on the motor shaft. The sinusoidal commutation used produces minimum torque ripple.

Reference route
The "CANopen homing mode" is for referencing to a special mechanical position. There are more than 30 methods available for finding the reference position.

Electronic gearhead
In "Master Encoder Mode", the motor follows a reference input produced by an external encoder. A gearhead factor can also be defined using software parameters. Two motors can be very easily synchronised using this method.

Step/Direction
In "Step/Direction Mode" the motor axis is moved gradually with a digital signal. This mode can replace stepping motors. It can also allow the use of EPOS to PLC controls without CAN interface for example.

Capture inputs (position marker)
EPOS digital inputs can be configured so that the current position value can be saved when a positive and/or negative flank of an input appears.

Technical data page 286 / 287

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May 2007 edition / subject to change

EPOS P 24/5
Matched with DC brush motors with encoder or brushless EC motors with Hall sensors and encoder, from 5 to 120 watts.

EPOS 70/10
Matched with DC brush motors with MR-encoder or brushless EC motors with Hall sensors or MR encoder, from 80 to 700 watts.

Master version (programmable)	Slave version
Electrical data	
11 - 24 VDC	11 - 70 VDC
11 - 24 VDC	11 - 70 VDC
0.9 x V_{cc}	0.9 x V_{cc}
10 A	25 A
5 A	10 A
10 kHz	10 kHz
1 kHz	1 kHz
1 kHz	1 kHz
25 000 rpm	25 000 rpm
15 µH / 5 A	25 µH / 10 A
Inputs	
H1, H2, H3	H1, H2, H3
A, A\, B, B\, I, I\ (max. 1 MHz)	A, A\, B, B\, I, I\ (max. 1 MHz)
6 digital inputs	8 digital inputs
2 analog inputs 10-bit resolution, 0 … +5 V	2 analog inputs 10-bit resolution, 0 … +5 V
Configurable with DIP switch 1 … 7	Configurable with DIP switch 1 … 7
Output	
4 digital outputs	4 digital outputs
+5 VDC, max 100 mA	+5 VDC, max 100 mA
+5 VDC, max. 30 mA	+5 VDC, max. 30 mA
V_{cc}, max. 1300 mA	+5 VDC (R_i = 1 kΩ)
Interface	
RxD; TxD (max. 115 200 bit/s)	RxD; TxD (max. 115 200 bit/s)
high; low (max. 1 Mbit/s)	high; low (max. 1 Mbit/s)
Indicator	
Bi-colour LED	Bi-colour LED
Ambient temperature / Humidity range	
-10 … +45°C	-10 … +45°C
-40 … +85°C	-40 … +85°C
20 … 80 %	20 … 80 %
Mechanical Data	
Approx. 180 g	Approx. 330 g
105 x 83 x 24 mm	150 x 93 x 27 mm
Flange for M3-screws	Flange for M3-screws
Order Number	
323232 EPOS P 24/5	**300583** EPOS 70/10

Accessories	
309687 DSR 50/5 Shunt regulator	**235811** DSR 70/30 Shunt regulator
Various cable see page 291	Various cable see page 291

Additional information

Modes of Operation
- CANopen profile position-, profile velocity- and homing mode
- Position-, velocity- and current-mode
- Digital position reference by Pulse-Direction or master encoder
- Sinusoidal or Trapezoid Commutation for EC motors
- Velocity and acceleration feed forwarding
- Sinusoidal or Trapezoid Commutation for EC motors

Communication
- Communication through CANopen and/or RS-232
- Gateway RS232 to CAN

Inputs / Outputs
- Optional configurable digital inputs e.g. for limit switches and reference switches
- Optional configurable digital outputs e.g. for brakes
- Optional analog inputs

Available software
- EPOS Studio
- Windows DLL
- IEC 61131-3 Libraries
- Firmware

Available documentation
- Getting Started
- Cable Starting Set
- Hardware Reference
- Firmware Specification
- Communication Guide
- Application Notes

Cable

A comprehensive range of cables is available as an option. Details can be found on page 291.

Appendix C

Publication:

Force Sensing for Dynamic Gripping, Using a Piezoelectric Sensor

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***Abstract*—There is a quest in the field of robotics for an automated dynamic gripper with characteristics as close as possible to that of the human hand. In this paper an automated robot gripper is described that achieves preset levels of gripping force for a certain task. It utilises dynamic gripping through the use of piezoelectric sensors. Analysis of the output pulse from the piezoelectric film indicates the velocity of gripping, deceleration and the total force the gripper is inducing on the gripped object. Piezoelectric film is chosen for its superior sensitivity and structural simplicity over the typical metal-foil strain gauges. The paper shows that, compared to three dimensional analysis, object handling using dynamic fingertip force sensing is a cheaper and more accurate solution.**

I INTRODUCTION

Throughout recent history it has been proven that tendencies on the manufacturing floor are a reflection of the changes in the customers' demands. Thus, it can be assumed that manufacturing systems of the next generation will have to incorporate more flexibility and intelligence to accommodate changes in customer demands [1]. Components transported with, and exiting from any automated transportation system should be handled with care and preferable automatically, depending on its physical characteristics. The ideal tool for this would have the same operational characteristics as the human hand.

The human hand is the most versatile gripper in existence and is the ideal model to try and simulate. With our dexterous hands, people can grasp a wide variety of shapes and sizes, perform complex tasks, and switch between grasps in response to changing task requirements [2]. Control capabilities is mostly a result of tactile and force sensing, especially the ability to sense conditions at the finger-object contact. The modern tendency is towards automation and the quest therefore is to find possible automated solutions to simulate the human hand when picking up different kind of objects from a transportation system.

This research project focuses on force sensing for an automated robot's gripper. Because of the significant inaccuracy of three dimensional visual analysis, visually operated robot grippers normally struggles with the actual manipulation required for dexterous grasping of a fragile component. However, tactile sensing can do the fine tuning when gripping, whilst detecting contact early and utilising as little force as possible is very important in order not to damage handled objects or the robot itself. Fig. 1 shows the developed gripper handling a fragile object. This would be difficult using vision, because the actual contact points are not visible and three-dimensional analysis is fairly inaccurate. Dexterous manipulation requires control of forces and motions at the point of contact between the fingers or grippers and the object, which can only be accomplished through touch sensing [3].

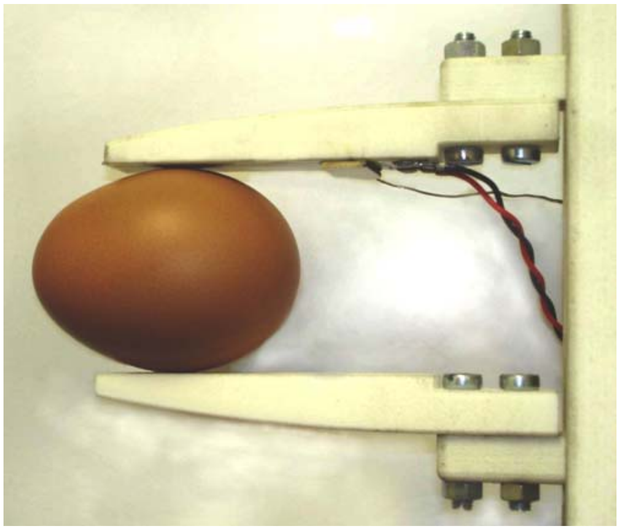


Fig.1. Gripper handling a fragile object

II PIEZOELECTRIC FILM

The sensitivity of piezoelectric film as a receiver of mechanical work input is awesome. In its simplest form the film behaves like a dynamic strain gauge except that it requires no external power source and generates signals greater than those from conventional foil strain gages after amplification. Frequency response is thus free from any limitations imposed by the need for high gains and will extend up to the wavelength limit of the given transducer [4].

The extreme sensitivity of piezoelectric film is largely due to the format of the material used. The limited thickness of the film creates, in turn, a very small cross-sectional area and, thus, relatively small longitudinal forces create very large stresses within the material. It is easy to exploit this aspect to enhance the sensitivity parallel to the machine axis. If a laminated element of film is placed between two layers of compliant material then any compressive forces are converted into much larger longitudinal extensive forces.

In fact, this effect tends to predominate in most circumstances since most substances are compliant to some extent and the ratio of effective sensitivity in the length versus thickness directions is typically 1000:1. Piezoelectric film transducers may often cover a much larger area than normal strain gauges, so any direct comparisons should be performed in a uniform strain field for meaningful results.

Obviously "point"-type transducers could be used where required although the capacitance of a very small area will require consideration. The low frequency limit of operation will be defined by the greatest resistive load achievable, or by the largest capacitance load that still allows the signal to be easily detected. Operation down to fractions of 1Hz can be achieved using either conventional charge amplifiers or, since signal levels are relatively high, simple high impedance FET buffer circuits [5].

III GRIPPER MECHANICS

For making recurring measurements with sufficient accuracy using piezoelectric film, a gripper with exceptional control is required – necessitating a high precision drive. The gripper developed in this project is powered by a Proportional-Integral-Derivative (PID) controlled 80W Maxon EC 32 brushless motor fitted with a 9 bit optical encoder. The motor has a maximum speed of 15 200 rpm, stall torque of 480mNm, maximum continuous torque of 57.7mNm at 5000rpm and very small rotor inertia.

Finite deceleration of the gripper results in overshoot during gripping, so it must decelerate as fast as possible. Decelerating the motor generates energy that flows to the power supply, increasing the voltage which might damage the PID controller. This can be prevented by placing a high-value capacitor close to the motor's power input.

Double bevel gears with a "1:2" gear ratio are used for the transmission from the motor to two linear screw shafts. The linear screw shafts are responsible for linear movement of the gripper fingers. The screw shaft has thread with a very fine pitch (1mm) so as to create a gear ratio of 20 motor rotations for 1cm linear finger movement. Having a fine enough thread creates the advantage of the fingers appearing to being braked when a linear force is applied on the fingers. This tends to prevent the fingers from moving away from the object once drive power is removed.

The gripper parts were designed in Solid Edge and prototyped into a hard, rigid, plastic material. This plastic has a degree of elasticity that contributes to the deformation of the piezoelectric film, which prevents recurring force measurements on different areas, closer or further from the gripper fingers' mounting points. Hence, the object should always be gripped the same distance from the ends of the fingertips, otherwise the fingers might bend by different amounts with the same force being applied, resulting in different readings.

Limited elasticity in the gripper fingers is beneficial, since it may prevent damage to fragile but rigid objects when applying excessive amounts of force. With a perfectly rigid gripper, an object such as an egg might be more likely to break in such a case. Since the gripper does not respond immediately on sensing that the preferred force has been reached, it will tend to overshoot whilst applying maximum force – which can cause a fragile object to break.

If an elastic material is used to bond the sensor to the finger, the object contour also plays a role in the response of a piezoelectric film. A round surface will have a much smaller contact area than a flat object, inducing different pressure over different areas, bending, or deforming the film sensor differently. For recurring measurements, the same objects must be used, or the piezoelectric film must be covered by a thin rigid layer distributing the pressure evenly over the piezoelectric film. This will cause an overall sensitivity reduction, because the average deformation on the piezoelectric film will be much less. Adding corrugations to the surface in contact with the piezoelectric film will in turn increase the deformation induced to the piezoelectric film.

The gripper as developed can grip objects up to a maximum size of 9cm.

IV GRIPPER CONTROL SOFTWARE

One of the main purposes of the software is to enable maximum possible control over the manner in which the gripper grips the object.

National Instruments LabVIEW was used for the development of the software controlling the gripper whilst RS232 communication was used for the interface between the EPOS 24/5 motor controller and the LabVIEW environment. An analogue to digital converter is used to interface the output of the piezoelectric film to the LabVIEW system.

The software analyses force-induced pulses and controls the motor accordingly – ideally in accordance with specified criteria set during programming. Motor control includes velocity control, positional control and current control. Information required for the control of the motor can be attained from the Epos 24/5 controller.

V FORCE CALCULATION

Because the piezoelectric film is dynamic, pressure cannot be derived from a static voltage level. Incoming voltage levels should be integrated in real time to determine the energy induced in the piezoelectric film by the force applied to it. The total energy generated by the piezoelectric film will correspond to the force applied to the film. Relatively small differences may occur between the applied force and the integrated energy from the piezoelectric film due to capacitive properties of the piezoelectric film, accumulating the energy induced from all the stresses applied to the piezoelectric film - including noise through ambient sound and vibrations from the gripper structure.

Stopping the piezoelectric film from accumulating noise-induced energy, a high resistance resistor (7.5 MΩ in this case) is used to drain all the accumulated energy from the piezoelectric film to ground at a resistance-dependant rate. Measuring apparatus also has a particular, finite input impedance that will discharge the energy stored in the piezoelectric film, but that resistance itself is too high to negate the requirement for an external resistor. The resistor referred to will drain the energy from the piezoelectric film that was induced by the measured force as well.

Normally, without a grounding resistor, the energy will stay in the capacitor once force has been applied to the film and is maintained. It is similar to a sponge absorbing water and when you squeeze it, it will release the water and stay in this state until you release it, allowing the sponge to absorb water once again. With a resistor connected to ground the energy will not stay in the film but will flow back to ground. This is why you can't convert the measured voltage directly to force.

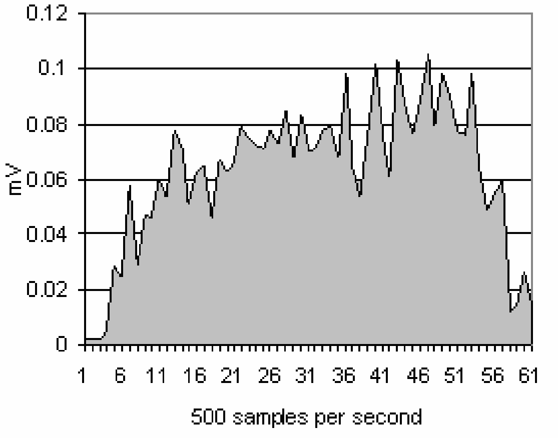
Fig. 2 shows a typical measured voltage pulse from the piezoelectric film during a pressure (grip) cycle. The output voltage increases with a corresponding increase in gripping force. Once the final, specified force is being exerted on the object, the gripper's motion is stopped but the force is maintained. However, due to the reasons discussed above, the output voltage from the piezoelectric film decreases to zero. Noise from the motor and gear motion is responsible for the spiky appearance of the voltage pulse.

Using (1) the measured output voltage can be converted to energy generated. In Equation 1 W represent the watts, calculated using the film's output voltage over a 7.5 MΩ resistor, whilst the N represent the number of pulses taken.

$$Joule = \frac{W}{\sec} = \frac{\sum_{n-1}^{61} W_n}{N} = 74.9\mu J \qquad [1]$$

In order to compare the output of the sensor to that of a strain gauge, the measurement as shown in Fig. 3 was made. The relative outputs of the strain gauge and piezoelectric sensor were determined for a range of different, predetermined values and are shown in Fig. 4. The outputs are surprisingly similar - if shown in different units. Obviously, on condition that the transfer between the different units is accurate, very similar outputs will result from the two types of sensor.

Fig. 5 shows the same characteristics, but in this case the output of the piezoelectric sensor has been integrated and converted to voltage. The measured force again corresponds very well with the strain gauge output. The concurrency of the two sets of values is satisfying in that the requested force, controllable with software, proved to be accurately predictable.



Time (in samples taken)

Fig.2. Typical output voltage pulse of gripper.

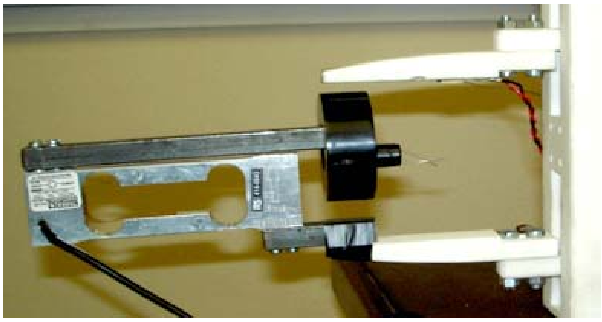


Fig.3. Static strain gauge measuring true forces

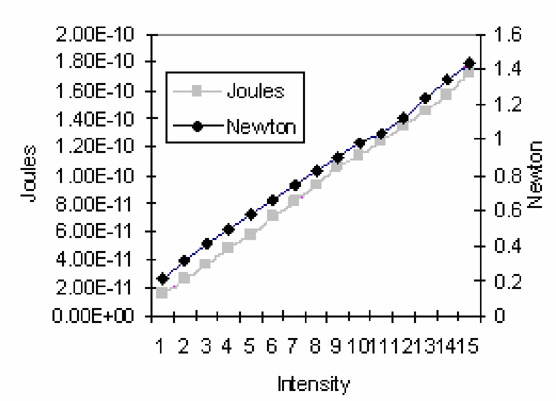


Fig.4. Output of the piezoelectric sensor compared to that of a strain gauge.

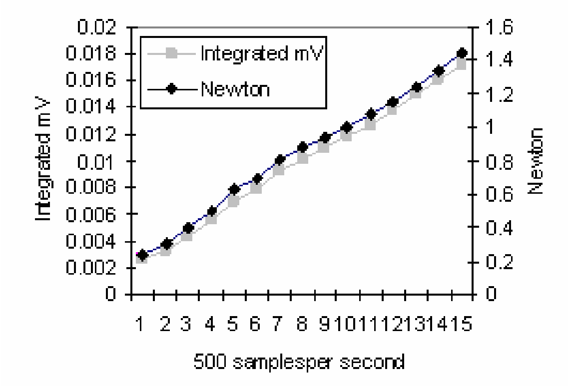


Fig.5. Integrated output in millivolts versus force applied.

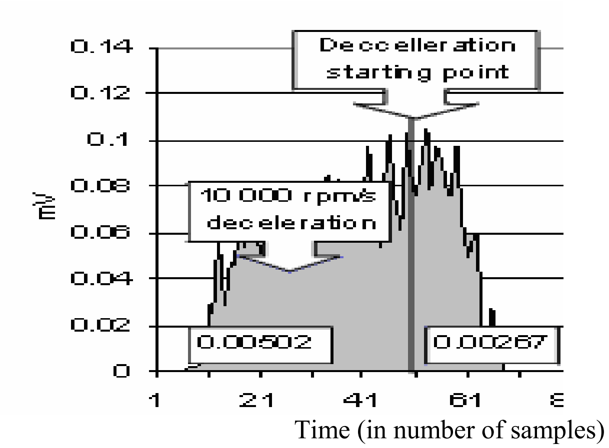


Fig.6 Deceleration process of Gripper

VI FORCE CONTROL

The system as developed makes provision for software control of the maximum force that is to be exerted on an object. When gripping an object, the sensor's output is monitored and the movement of the gripper is stopped when the correct, final pressure is exerted.

However, unfortunately the final pressure will not equal the requested value exactly. This is because the gripper has a finite deceleration action after the requested millivolt integral has been met and the motor is disconnected from the power source. Fig. 6 shows this effect with a set final integrated value of 0.005. However, due to the finite, non-zero deceleration time of the motor a final value of 0.00769 (0.00502+0.00267) resulted. As can be expected, with the gripper motor programmed for a particular speed, this error will decrease in relative terms with higher set values of force. Obviously, a slower operating speed for the motor will result in less overshoot.

Infinite deceleration and instant system response would have been ideal, giving near perfect results. However, with the finite deceleration value for a set motor- and, thus, gripper–speed, a close to perfect result can be obtained by using error correction through adaptation of the software. The difference between a fixed, set gripper force at a specified speed and corresponding measurements can be seen in Fig. 7. Readings in this figure show clearly recurring results and a constant deviation from the requested value. The discrepancy is primarily due to deceleration.

With this expectancy of predictable results, combined with good linearity, the preferred force value can be offset by an amount equal to the mean error. This should create a situation where the preferred and actual values are much closer together – with an improved minimum force that can be exerted on a particularly fragile object. From Fig. 7 it appears that an offset value of 0.002mV would ensure a fair correction voltage for most applications.

Keeping this correction in mind, it is possible to modify the software so as to ensure a very good approximation of the ideal, specified gripping force. Fig. 8 shows a set of calculated output gripping forces with a correction value of 0.0019mV.

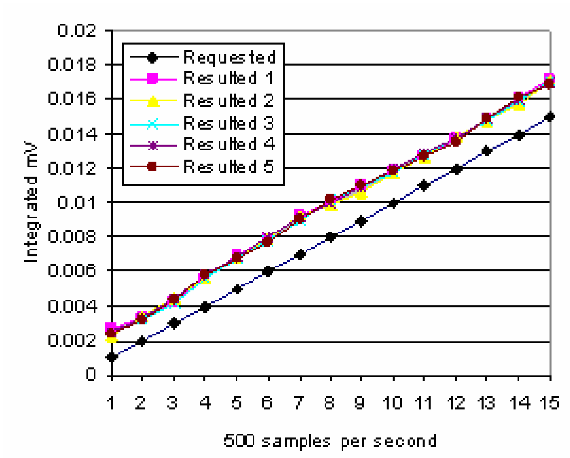


Fig.7. Requested versus measured force.

From sample nine upward the force intensity appears to deviate negatively relative to the desired value. This is due to the plasticity of the finger. Typical plasticity characteristics of gripper fingers are shown in Fig. 9.

Initially the gripper stops according to the correct force, but then the finger's deformation enters its plasticity region, reducing the actual force that the finger is applying to the object. According to the output of the sensor, an initial result will gradually reduce until it stabilizes – as shown in Fig. 10.

The initial result equals the programmed gripping force. As the finger starts to deform plastically the force on the strain gauge starts to decrease, hence the deviation towards higher forces.

VII CONCLUSION

Force applied by the gripper of a robot can be accurately determined using a piezoelectric film if the impact velocity and deceleration characteristics are known.

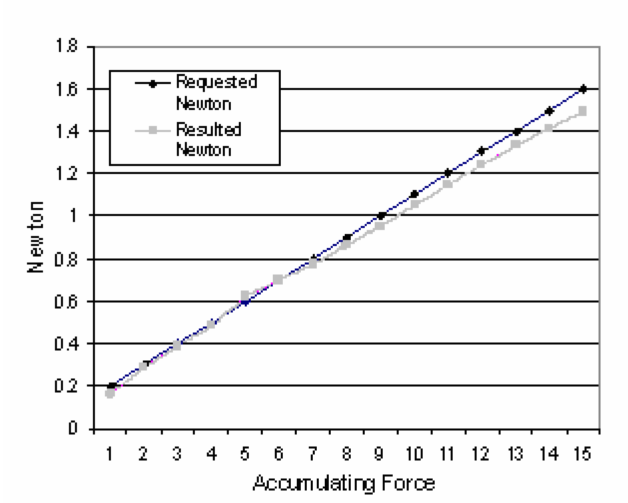


Fig.8. Newton compared with its results

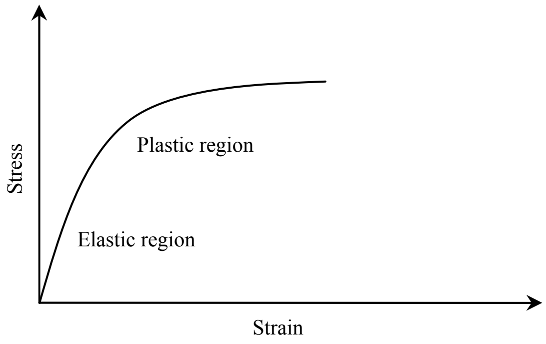


Fig.9. Plasticity Characteristics of the gripper's fingers

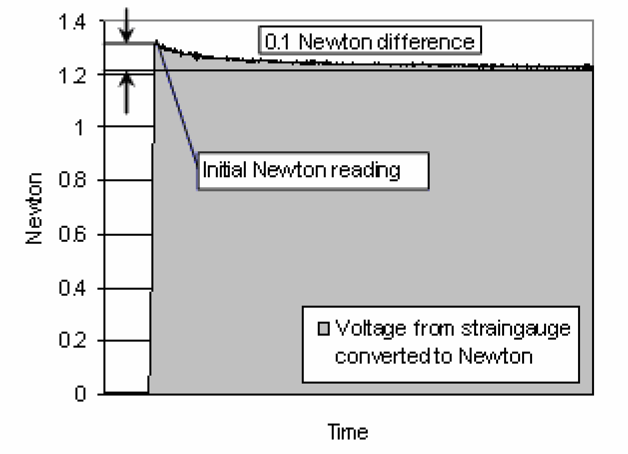


Fig.10. Finger losing tension while moving into its plastic deformation region

In this application the impact velocity, deceleration, contact surface and contact area remained the same. Thus, the software could be adapted to correct for the error caused by the non-zero deceleration time of the gripper motor assembly.

Reducing the initial requested force will increase the minimum controllable force – enabling accurate handling of extremely fragile components. Measured requested and resultant forces stray from linearity towards higher forces. Gripper finger plasticity is responsible for this phenomenon.

Initial impact provides the requested force, hence stopping the gripper from closing further. This force then imposes tension in the finger, bending the finger into its plastic region so that the force on the piezoelectric film decreases from the initial value. This plastic strain can be prevented by using a material with more elasticity. Using the gripper finger's deformation curve the software can be adapted to compensate for this plasticity as well.

Compared to three dimensional analysis, object handling using dynamic fingertip force sensing is a much cheaper and more accurate solution.

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Any opinion, findings and conclusions or recommendations expressed in this material are those of the authors and therefore the NRF does not accept liability in regard thereto.

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