A PNEUMATIC BALLOON ACTUATED CANTILEVER BEAM WITH TACTILE FEEDBACK FOR USE IN MINIMALLY INVASIVE SURGERY

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There is a need for a versatile system with integration between micro-technologies and sensing techniques to retrieve information feedback about the physical parameters of an object in the emerging areas of minimally invasive surgery. These methods have been applied to a pneumatic balloon actuated cantilever beam sensor in order to design a micro-scale gripping device and to further develop upon the existing need for sensory feedback. The pneumatic actuation produces displacement together with a large force by a deformation of the beam under a pressure supply. When actuated the gripper rig is able to grasp objects. The force exerted on the object is measured by the pressure of the air in the balloon and used to control the driving system of the gripper. Neural networks that are able to predict contact of the object, object position, size and stiffness have been constructed, this could help surgeons to detect tissue properties in minimally invasive surgical procedures. The results from the gripper proved extremely accurate in their predictions, they were able to predict object position within 98.6% accuracy and object diameter within 90% accuracy, also the gripper is able to discriminate between four different examples of object stiffness. The results from the large gripper and further analysis have been used to make recommendations for the design of the gripper on the micro-scale.

Keywords: Tactile, Gripper, Minimally invasive surgery, Micro-scale, Neural Network.

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In the name of Allah, the Entirely Merciful, the Especially Merciful.

All praise is to Allah, Lord of the sky's and the earth.

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Glossary of terms

L : actual beam length

E: Elastic modulus

I: Moment of inertia

θ: Deflection angle

y : Small deflection

x: Length of the plate

F : Applied Force on the cantilever

ANN : Artificial Neural Network

DOF: Degree Of Freedom

MIS: Minimally Invasive Surgery

Chapter 1

1.0 Introduction

This thesis describes the research on the performance of a new surgical microgripper with tactile sensing that relies on the distributive deformation of a consistent substrate to retrieve information feedback about the physical parameters of an object for instance: position, diameter and stiffness. This chapter introduces the aims, objectives, definitions, the need for micro-grippers with tactile feedback in microsurgical applications, and concludes with details on the structure of the thesis. The work includes design, theoretical, and experimental analysis of a large gripper integrated with distributive tactile sensors.

Aims:

This work aims to increase the understanding of the performance of gripping systems and distributive tactile sensing in order to extend the application in the emerging areas of microsurgery. The studies investigate the application of parameters and the distributive tactile sensing method for distributive tactile sensing methods for micro-grippers for minimally invasive surgery.

Objectives:

1- Comprehensive review of the literature to identify the technical and functional capabilities required.
2- Develop the experimental gripping test rig in a large scale.
3- Construct and commission a gripping test system integrating the system elements to judge the feasibility.
4- Examine the performance in retrieving information that can allude to object properties as might be required in a surgical task.

1.1 Background

This research is concerned with developing a gripping test rig which allows surgeons to guide the instrument to access sites which are difficult to reach and to perform gripping on the tissue. It is a master-slave system (figure 1.1). The slave robot is in contact with the patient and follows the instruction of the master robot. In this way the slave robot performs the actual operation of the surgeon. The reaction of the tissue is sensed by sensors and relays perception feedback. This leads to a test rig to evaluate the application of a novel method for retrieving tactile sensory feedback from which relevant information could be derived also discriminating the nature of the contact. The areas of research:

- Gripping systems
- Tactile Sensing
- Microsurgery application
- Data interpretation
- Measurement
- Microsensors

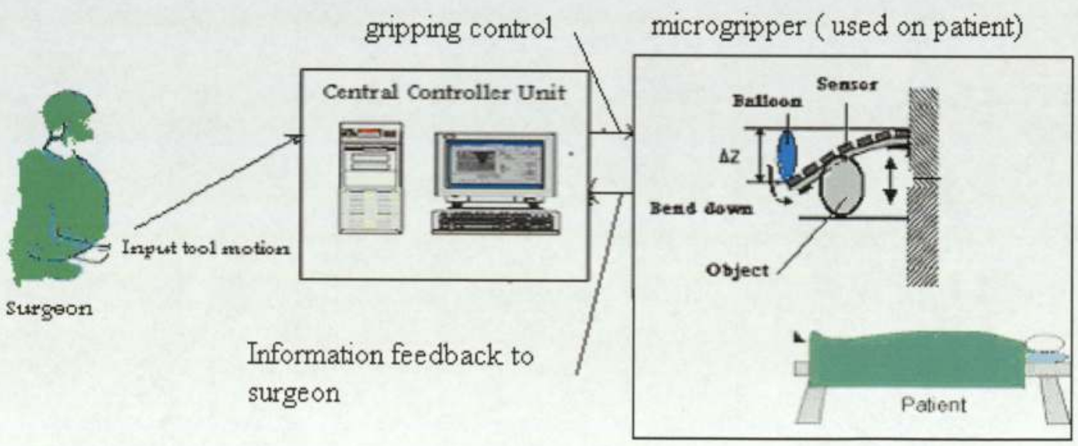

Figure 1.1: Overview of the microsurgical system.

1.2 Designing the experimental gripping test rig.

There is a need for a versatile grasping system with integration between sensors and grippers, suited to sterile and magnetic scanning environments and available at low cost. The successful grasping still needs the assistance of tactile sensors, which not only sense contact forces but also sense the geometry of an object, to establish feedback that allows the planning and control of the grasp.

1.2.1 Tactile Sensor

Tactile sensation is generated by means of changes in displacement in reference to the surface. Tactile sensing systems have utilized multiple sensing elements to provide information of contact in a map like form. The resolution of the tactile sensors depends on the number of sensing elements used. Tactile sensors can play a major role in retrieving information about tissue in unstructured environments. Tactile sensors are used for measuring contact parameters and also they can provide information about object properties through physical contact between the system and the object. They can measure the distribution of forces in the sensory area. Slip is also related to tactile sensing which is the measurement of the movement of the object in reference to the sensor.

Tactile information helps the surgeon to use palpation (is a method of examination in which the examiner feels an object to determine its size, shape, firmness, or location) as in open surgery. This is necessary to find invisible structures (e.g. blood vessels below fat layer). The feedback information gives the surgeon direct access to the forces at the operating area and therefore increases the quality of the operation.

A distributive tactile sensing technique is used in this research in order to retrieve information about the physical properties of an object. A distributive tactile sensing (Brett and Stone, 1997)[1] able to retrieve large volumes of data with many connections but the data interpretation process can be computationally intensive. The distributive tactile sensing technique uses a tactile sensor with some similarities to the human touch and it's better suited for discrimination.

1.2.2 Microsurgery applications

There is a need for a flexible gripper in minimally invasive surgical operations including laparoscopy, thoracoscopy, arthroscopy, ophthalmic micro-surgery etc. For the application of microsurgery such as cell manipulations and tissue manipulations, it is important for surgeons to develop very accurate tools and adapted procedures. There is a need for versatile instruments with intelligent systems (sensors) that allows the surgeon to perform surgical procedure with accuracy and safety. Flexible grippers integrated with tactile sensing is important in MIS (Minimally Invasive Surgery) in order for the surgeon to locate arteries and tumours hidden in the tissue. Also, softness of the tissue cannot be judged during the operation using ordinary instruments. In other words, to perform the MIS more effectively, the surgeon should be able to detect the tissue, sensing the pressure of blood vessels and ducts during the procedure. This ability is very important during manipulation tasks such as the grasping of the internal organs, gentle load transfer during lifting, suturing and removing tissues. The need to feel the tissue and its softness is particularly important during an operation. Gripping applications in microsurgery would include:

- Estimating tissue hardness.
- Locating blood vessels
- Manipulating soft tissue.
- Sensing the contact forces between the gripper and the object.

1.2.3 Micro sensors

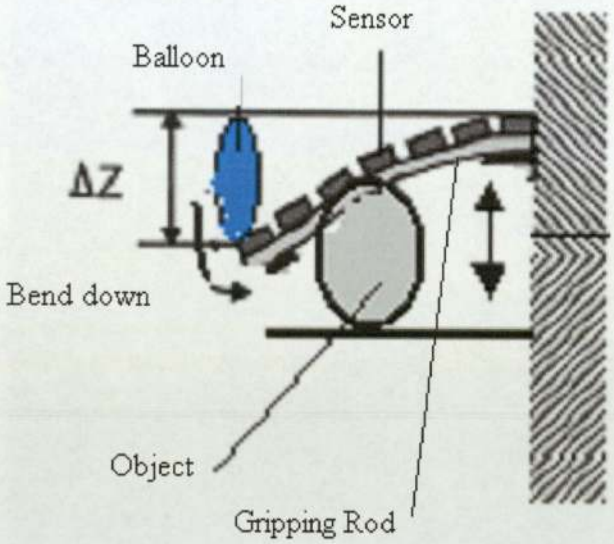

Figure 1.2: Experimental gripping rig with distributive tactile sensing.

The gripper rig (figure 1.2) uses micro sensor techniques which can improve and give new functionalities to the surgeons allowing them to perform operations in better conditions. The gripper is instrumented with strain gauges. The strain gauges measure compression and tension on the gripper. Strain gauge transducers are used as they are a proven means of investigating the actuator behaviour. The designed assembly consists of four micro strain gauge sensors, which are positioned on one face of a prototype gripper.

1.2.4 Measurement

Strain gauge sensors measure strain. Strain is a function of the bending angle of the beam. An indication of strain could equally be made by measuring the radius of the curvature of the bending angle. Sets of load, strain data are to be collected from the instrumented actuator. The sensors need to be able to measure the applied force, and to retrieve information on the object diameter, position and the cantilever displacement by measuring the stress and deformation of the tactile sensor. From the results of the force-deformation test, it is possible to find the objects force-displacement characteristics. From the force-displacement characteristics it will be possible to identify different test objects.

1.2.5 Stable Grasp

End effectors performing the function of grasping should account for the variations in shape, size, and flexibility of the object. For equilibrium in grasping it will be necessary for the gripping device to hold and maintain the position and orientation of each object during manipulation, and to ensure that there is no possibility of motion as a result of acceleration or deceleration forces acting on the object. An added complication could be the weight variation in the object.

1.2.6 Data Interpretation

For the purpose of data interpretation a computational intelligent output tool may used. One of the most powerful tools is the neural network. An Artificial Neural Network (ANN) processes information in a way that is inspired by the way biological nervous systems, such as the brain, process information. It is composed of a large number of highly interconnected processing elements such as neurons working in unison to solve specific problems. The ANN learns through training. An ANN is configured for a specific application, such as pattern recognition or data classification, through a learning process. Learning in biological systems involves adjustments to the synaptic connections that exist between the neurons.

1.2.7 The Need for a Tactile Gripper

The concept of providing tactile feedback for an endoscope and laparoscope presents an ongoing challenge. In minimal access procedures a common process that would benefit from tactile information is the control of contact against the surface of the lumen whilst carrying out navigation and palpation diagnosis. For example, during endoscope navigation a range of tactile feedback information such as the sense of the point of contact of the gripper, the discrimination between hard and soft contact, and the identification of edges, should allow the clinician to achieve greater control and better perception of position targets as compared with current methods. Similarly, diagnostic methods would benefit by adding in palpation to existing use of ultrasound imaging. In all such cases the key requirement relevant to the current research is the need to use the outer structure of the gripper as a means of providing tactile sensory feedback, something that current grippers don't have.

1.3 Structure of the thesis

The thesis is divided into 3 further chapters as follows:

Chapter 2 In Chapter 2 the relevant literature is discussed on surgical robotics systems in minimally invasive surgery and microsurgery, investigating the need for tactile sensing for actuation in microsurgery and micro-technology in gripping. These discussions provide the setting on which this research is based.

Chapter 3 The minimum design requirements for a gripping rig system are discussed. These are followed with the design idea for the micro-gripper, design specifications, gripping tests, device limitations, the relationship between the large scale and the micro gripper and displacement tests.

Chapter 4 A distributive tactile sensor is integrated with the gripper. Experiments to evaluate the gripper performance in discriminating between different objects types in diameter, position and stiffness are reported. The experimental protocol was designed to examine the neural network ability in discrimination of objects according to their position, size and stiffness. The work concludes with principal contributions, recommendations and future work.

Chapter 2

2.0 Literature Review

2.1 Robotics in minimally invasive surgery

Advancements in robotics have led to significant improvement in robot-assisted surgery. The use of these robotic systems has improved precision, stability, and surgeon dexterity. Minimally invasive procedures use remotely controlled robots that allow the surgeon to work inside the patient's body.

2.2 Minimally invasive surgery

Traditional surgery requires an incision large enough for the surgeon to see directly and place his or her fingers and instruments directly into the target operating site. Most often, the damage done to skin, muscle, connective tissue, and bone to reach the region of interest causes much greater injury then the procedure itself. This results in more pain to the patient, longer recovery times, and complications due to surgical trauma. The accelerating trend is toward Minimally Invasive Surgery (MIS).Over the past decade; several surgical specialties have been rapidly transformed by minimally invasive surgery. (MIS) is the practice of performing surgery through small incisions or "ports" using specialized surgical instruments in order to reduce the size of incisions required to access the internal tissues during surgery. During conventional "open" surgery, a significant trauma is created at the incision site, which is the reason for much of the post operational pain and discomfort. Therefore it is argued that procedures performed using MIS techniques have reduced bleeding, discomfort, patient recovery time and cost. However, MIS is technically more difficult for the surgeon. Surgeons must train extensively due to the lack of advanced tools and instruments for performing MIS.

Perhaps the most common form of MIS is laparoscopy, which is minimally invasive surgery within the abdominal cavity. A rapidly emerging field is MIS cardiac surgery for coronary artery bypass graft surgery. During laparoscopy, a patient's abdomen is insufflated with CO_2, and cannulae (essentially metal tubes) with pneumatic check valves are passed through small (approximately 1-2 cm) incisions to provide entry ports for laparoscopic surgical instruments. The instruments include an endoscope for viewing the surgical site, and tools such as a needle driver, graspers, scissors, clamps, staplers, and electrocauteries. The instruments differ from conventional instruments in that the working end is separated from its handle by an approximately 30cm long, 4-13 mm diameter shaft. As shown in (Figure 2.1), the needle driver instrument is used to hold the needle and drive it through the tissue while suturing.

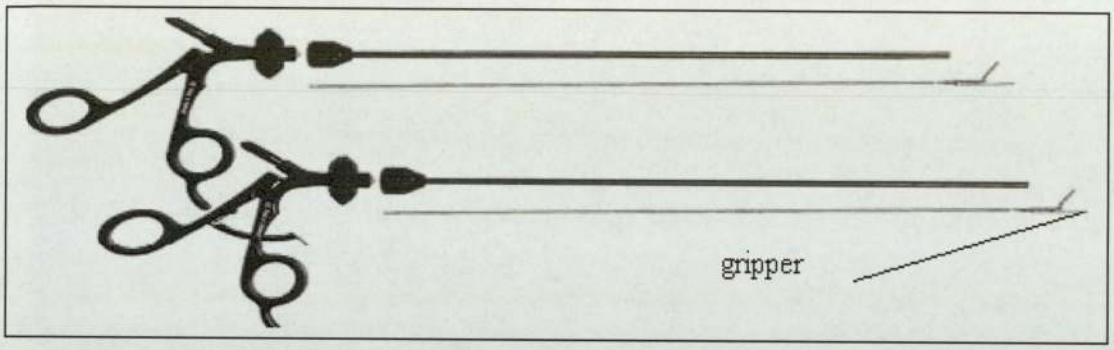

Figure 2.1: Needle driver for minimally invasive surgery.

The surgeon passes these instruments through the canula and manipulates them inside the abdomen by sliding them in and out, rotating them about their long axis and pivoting them about centres of rotation defined roughly by their incision site in the abdominal wall. Typically a one-degree-of-freedom device (gripper, scissors, etc.) can be actuated with a handle via a tension rod running the length of the instrument. The surgeon monitors the procedure by means of a television monitor which displays the abdominal worksite image provided by the laparoscopic camera.

2.3 Microsurgery

In microsurgery the technology allows the surgeon to have a better view and more accurate control of motion and forces. (Taylor et al., 1999)[2] Microsurgical applications like tumour removal can be done more accurately without damaging surrounding tissues. The small scale forces and motions used in microsurgery applications, cannot be achieved with a normal hand held surgical tool In microsurgery forces produced by the surgeon on the master are scaled down and reproduced at the slave side. Likewise, forces and motions encountered by the slave are scaled up and reflected to the surgeon.

There are several disadvantages to the current MIS technology.

1-Visualization of the surgical site is reduced. The operating site is viewed on an upright, two dimensional video monitor placed somewhere in the operating room. The surgeon is deprived of three-dimensional depth cues and must learn the appropriate geometric transformations to properly correlate hand motions to the tool tip motions.

2-The surgeon's ability to orient the instrument tip is reduced. The incision point/ cannula restricts the motions of the instrument from six degree of freedom to four. As a result, the surgeon can no longer approach tissue from an arbitrary angle and is often forced to use secondary instruments to manipulate the tissue in order to access it properly or to use additional incision sites. Suturing becomes particularly difficult.

3-The surgeon's ability to feel the instrument, tissues interaction is nearly eliminated. The instruments are somewhat constrained from rotating and sliding within the cannula due to sliding friction from the air seal, and the body wall constraints pivoting motions of the instrument shaft. The mechanical advantage designed into MIS instruments reduces the ability to feel grasping / cutting forces at the handle. Specialized mechanical designs and sensing technologies are needed to maximize dexterity under these access constraints.

2.4 Haptic Perception

Haptic is derived from the Greek term, hapsis meaning 'to grasp' or 'hold'. Haptic *(technical)* relating to the sense of touch.(Oxford English Dictionary , 2004)[3]. The haptic system is responsible for the perception of geometric properties, such as shape, dimensions and proportions of objects handled. As well as manipulations such as grasping, squeezing and lifting. The haptic system will give information on the weight and consistency of an object.

Touch is one of the five human senses. It is difficult to describe touch in terms of physical properties. It includes many physical parameters like contact, position, size, shape, hardness, force, etc. When touch is used to determine the physical properties of an object, one speaks about tactile sensing. (Lee and Nicholls, 1999)[4] define a tactile sensor as a device or system that can measure a given property of an object or contact event through physical contact between the sensor and the object. Tactile sensation is important in surgery, because soft tissues cannot always be identified by use of vision.

With the help of the softness, viscosity and elasticity information, the tissues can be distinguished and determined. Haptic perception concerns about combining tactile information. Haptics is defined as the science of applying tactile sensation and control to interact with the environment (Bholot , 1999)[5]

2.5 Surgical Robotics Systems

The robotics system for surgery is one element of a larger system designed to assist a surgeon in carrying out a surgical procedure that may include everything from preoperative planning to presurgical plans. The advantages of using robots in surgery is precision and accuracy. The combination of 3-D imaging data and surgical sensors, for example, allows robots to accurately guide instruments to pathological structures deep within the body. Another important difference is that specialized manipulator designs allow robots to work through incisions that are much smaller than would be required for human hands, or to work at small scales, where hand tremor poses fundamental limitations.

Impressive dexterous hands have been built in the past. Dextrous hands have been developed to perform laboratory research on grasping and finger manipulation for different applications like: underwater applications, and surgical grippers. There are different types available now. The following presents an overview of the state of the art (MIS) actuation systems developed at research institutes and companies.

Intuitive Surgical Inc manufactures the da Vinci Surgical system. The da Vinci Surgical System consists of an ergonomically designed surgeon's console, a patient-side cart with four interactive robotic arms, a stereo endoscope viewing system and proprietary endo wrist instruments. During the surgical operation, the surgeon's hand movements are scaled, filtered and seamlessly translated into precise movements of the instruments. The surgeon's console and the da Vinci Surgical system with four robotic arms are shown in the (Figure 2.2). The first two arms of the da Vinci

Surgical system represent the surgeon's left and right hands which hold the EndoWrist instruments. A third arm positions the endoscope, allowing the surgeon to easily change, move, zoom and rotate his or her field of vision from the console. The optional fourth arm extends the surgical capabilities by enabling the surgeon to add a third EndoWrist instrument and to perform additional tasks like applying counter traction and following running sutures. The surgical instruments for the da Vinci surgical system are 8mm in diameter. These instruments have 6 DOF (degree of freedom) at the instrument tip (Figure 2.2). The wrist design technology is based on a tendon driven mechanism. The motors required for actuating the instrument tip are placed outside the patient's body (Figure 2.3) similar to the design of the Zeus Robotic Surgical system (Intuitive Surgical Inc, 2006)[6].

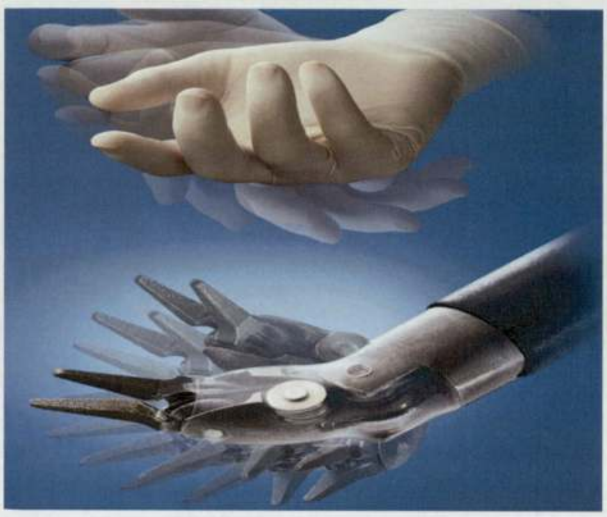

Figure 2.2: Da Vinci EndoWrist & Surgeon Hand.[6]

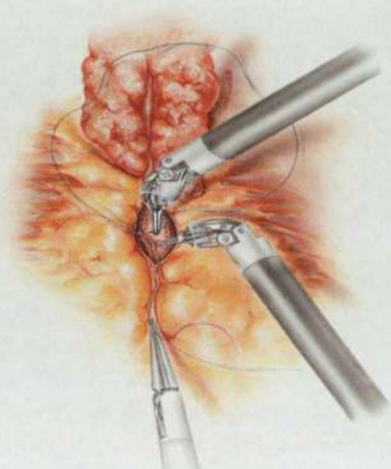

Figure 2.3: 6 DOF surgical gripper. [6]

(Dario, 2000) [7] demonstrates a mechatronic tool for orthopedic joint, especially knee surgery applications (Figure 2.4). They develop a sensor that is able to sense contact on the whole surface of the tip. The mechatronic arthroscopy tool gives the surgeon the option of servo controlling the steering mechanism. The surgeon controls the tip motion by means of a lever, instrumented with an internal potentiometer, also located in the handle. The arthroscopy geometry is a cylinder with an external diameter of 4mm and a total length of 350mm. The 25mm long distal section of the arthroscopy tool is steerable, the range of bending angle of this steerable tip is between 0° and 110°. The embedded control unit can also communicate with the computer assisted arthroscopy tool through a suitable interface. Although this tool provides more information compared to traditional arthroscopy surgery tools, no information about the contact object can be retrieved, such as its shape and stiffness.

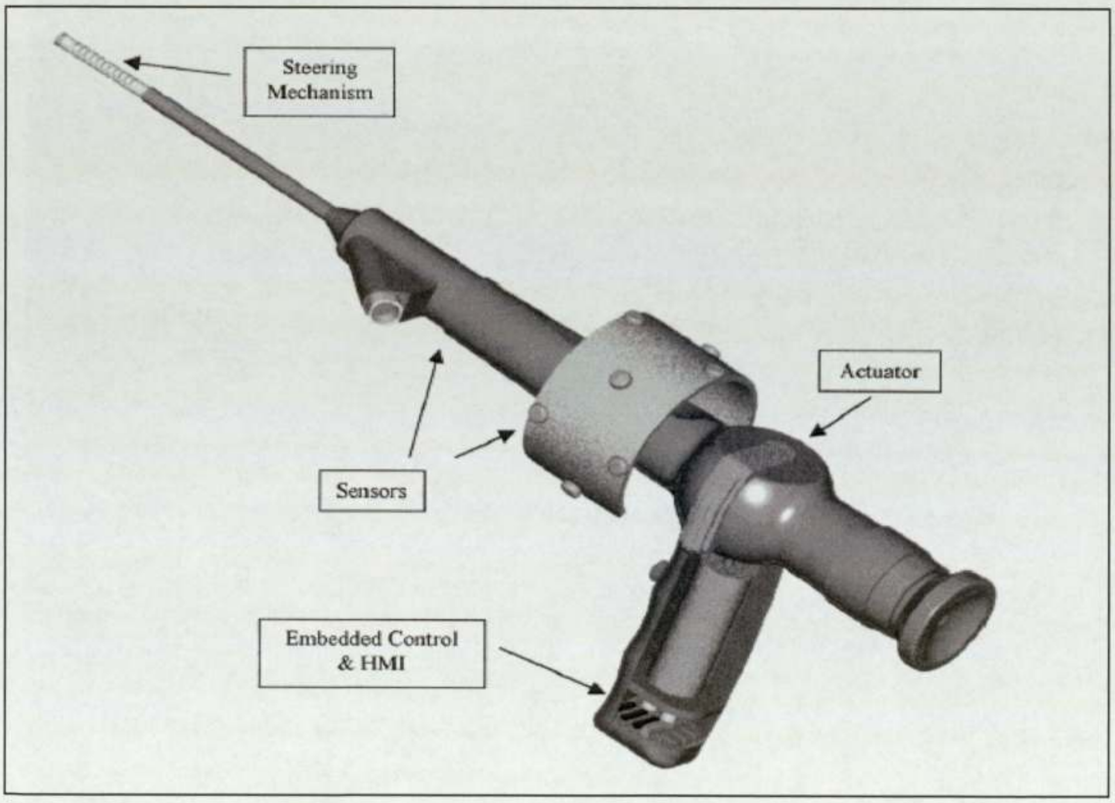

Figure 2.4: A Mechatronic tool for arthroscopy.(Dario,2000) [7].

An interesting but unconventional example of a gripping device employing a single tactile sensor are hydraulic forceps with force feedback for use in minimally invasive surgery by (Lazeroms et al., 1996)[8]. A pressure sensor is used to measure liquid pressure in the forceps which are constructed from rubber tubes of different stiffness (Figure 2.5). The device can be used for control purposes as part of a master slave system allowing tele-manipulation. The sensing part uses pressure transducer sensors. The force exerted on the tissue is measured by the pressure of the water in the tube and this is used to control the driving system of the forceps. The displacement is measured by a potentiometer. The difference between the pressure for the loaded and unloaded conditions at a certain displacement is a measure of the force exerted by the object on the tubes. Using a computer system, the force exerted on the tissue can be limited to a certain amount by a control algorithm. The force exerted on the gripper is introduced to the master manipulator by two electromotors on the joints of the finger. With this instrument the operator can drive the gripper, while directly feeling the force exerted on the object. The motors introduce a force on the finger which is related to the force exerted on the gripper. However, it does not retrieve any information about the tissue the forceps are in contact with.

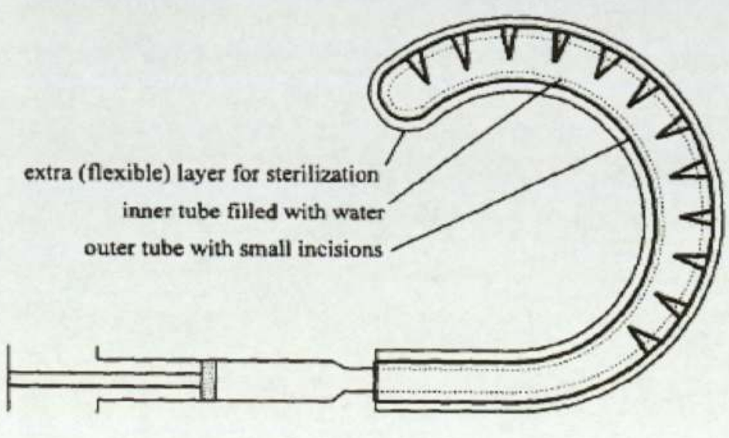

Figure 2.5, Hydraulic Forceps (M.Lazeroms 1996)[8] .

2.6 How distributive tactile sensing can evaluate gripping.

Tactile sensing systems can evaluate gripping systems in a variety of ways. The complexity of tactile sensors ranges from single to multiple point devices as shown in figure 2.6 .

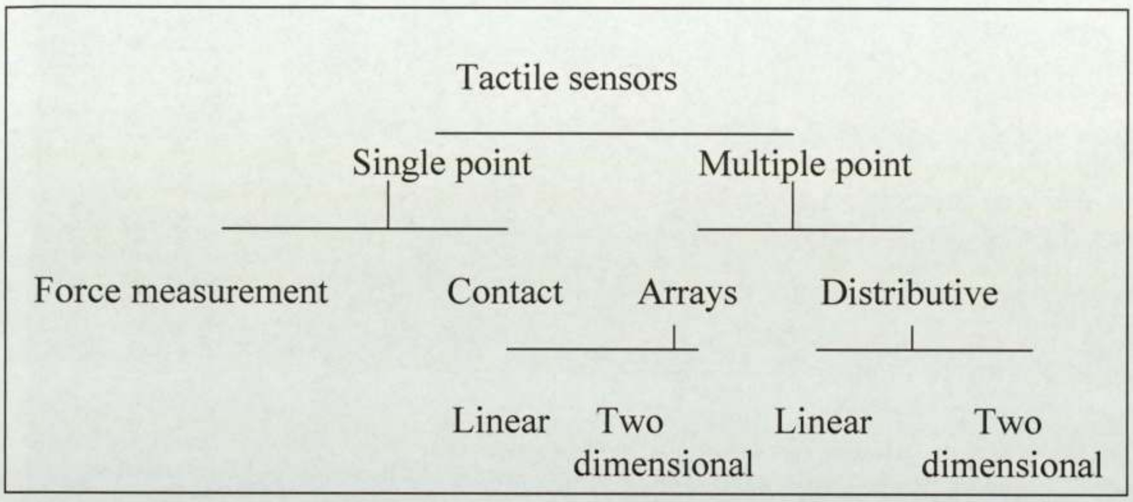

Figure 2.6: Types of tactile sensors.

An alternative to the conventional array sensor is the distributive approach. It relies on the coupling effect between the contact and the surface. While the sensor arrangement of most array devices ensures that the measurements between sensing elements are decoupled as far as possible, the deformation of a common surface in response to an applied load forms a unique characteristic of the distributive approach. The coupling effect between sensory information enables a distributive tactile sensor to use previous knowledge of the surface behaviour under contact to identify the contact type. Distributive sensors are appropriate for discriminating between different contact types rather than deriving exact measurements. A schematic diagram of distributive tactile sensing is illustrated in figure 2.7.

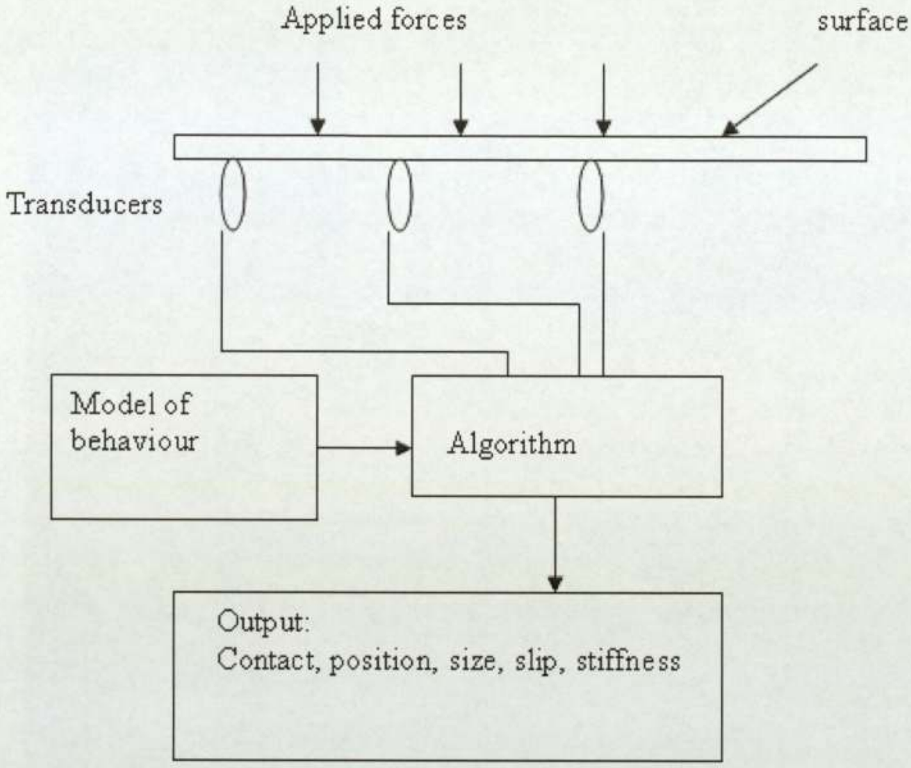

Figure 2.7: Schematic diagram of distributive tactile sensing.

Single point devices are used to measure contact on a single axis or on multiple axes. Single point sensors are limited in use in tactile devices, because of the limitation of information obtained from such sensors. It can be used to detect contact. One example of a single tactile sensor would be the hydraulic forceps with force feedback for use in minimally invasive surgery by (Lazeroms et al., 1996)[8].

In the case of multiple point sensing systems there are two options : array sensors or a distributive approach. Both types of multi sensor systems can be applied to single or multi axis systems. Arrays can be used to measure a discrete pressure distribution at the sensing element between the substrate and the contacting object. These can also be used to measure contacting shape.

This method requires further processing of data as it is of complex construction and requires many connections that need to be sampled by a computer. The distributive approach offers the potential for fewer sensing elements, mechanically efficient construction and minimal processing of sensory data as the method uses process discrimination to estimate the state of contact. For invasive surgical applications this is very important.

2.6.1 Multiple point sensing

Multiple point sensing is widely in use in many tactile sensing devices. A multiple point sensor can be either an array or a distributive type. Array sensors can be used in measuring shape as well as detecting other contacting parameters. As discussed earlier in order to ensure sufficient resolution a large number of sensing elements are needed in an array which leads to a complex construction. In contrast distributive sensors require fewer sensing elements and are of a more simple construction.

2.6.2 Array sensors

Tactile sensing devices with array sensors are multiple sensing points arranged in a single axis or multi dimensional axes. In most cases, the sensing elements are integrated with the contacting surface and the resolution of such devices depends on the number of sensing elements, as they respond to contact independently. Often few sensing points at and around contact points are influenced by contact. The most common type of array sensors are 2 D surfaces, which have been used for recognition of 2D shapes, detection of 3D profiles and slip detection for example. In many cases, array tactile sensors are made from a silicon integrated circuit coupled with a Polyvinylidene Fluoride (PVDF) film. There are several different types available now. The following section presents an overview of the tactile array sensors used in surgical robotics.

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2.6.3 Grippers and manipulators with tactile array sensing

(Dargahi, 1999)[9] demonstrates a micromachined piezoelectric tactile sensor for an endoscopic grasper . They developed a sensor that is able to sense the magnitude and position of an applied force. The sensor consists of three layers. The top layer is made of micromachined silicon with a rigid tooth like structure similar to the present day endoscopic grasper. The bottom layer is made of flat Plexiglass serving as a substrate. Packaged between the plexiglass and the silicon is a patterned Polyvinylidene Fluoride (PVDF) film. The sensor exhibits high sensitivity, a large dynamic range, and a high signal-to-noise ratio.

A new type of tactile sensor has been proposed that can detect both the contact force and hardness of an object (Shikida et al , 2003)[10](Figure 2.8). It consists of a diaphragm with a mesa structure, a piezo- resistive displacement sensor on the diaphragm, and a chamber for pneumatic actuation. An array of these sensors can detect the two dimensional contact force distribution and hardness distribution information and the surface texture of the contact object. The sensor element is

6.0mm high x 6.0mm long x 0.4mm wide, and it has a displacement sensor element of piezo-resistance at the periphery of the diaphragm structure. The authors confirmed the characteristics of the device by using pneumatic actuation.

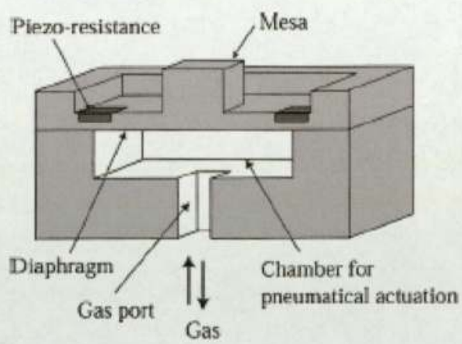
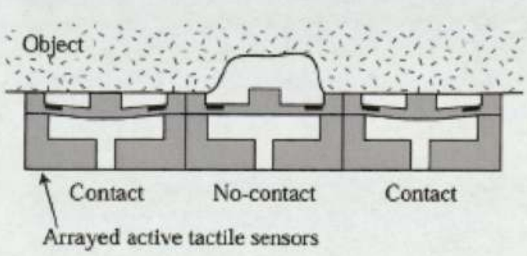


Figure 2.8: Structure of the tactile sensor.[10]

The hardness distribution of the object is determined by measuring the relationship between the displacement of the actuation force and the mesa elements (figures 2.9 (a)) and (2.9 (b)).



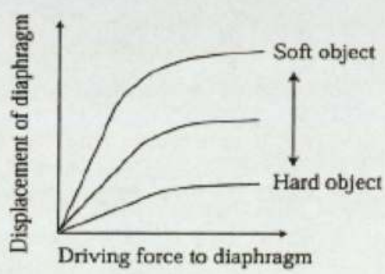


Figure 2.9 (a): Detecting hardness distribution.[10] Figure 2.9 (b): Detection principles.[10]

(Najarian et al. , 2006)[11] demonstrated a novel method of measuring the stiffness of sensed objects with applications for biomedical robotic systems. They have developed a sensor that is able to detect the presence or absence of a grasped tissue. An array of sensors is used. The sensor has two separate parts, which enables it to resolve the stiffness of a biological tissue into two components, the component detected by the hard central part and the component detected by the soft peripheral part of the sensor. The combination of these two components results in a novel procedure for the measurement of tissue compliance. The design prototype has the potential of being miniaturized and hence it could be used in various endoscopic surgeries, such as arthroscopic or laparoscopic surgeries.

(Provancher, 2003)[12] demonstrates a tactile array sensor for measuring local object geometry (Figure 2.10), using an artificial skin developed for robotic hands. The sensor is pressure sensitive and able to comply with irregular surfaces. The sensor (Figure 2.11) is constructed using strain gauge arrays that are bonded to single-sided custom-fabricated polyamide flex circuits. The pattern is created using standard contact print photo-imaging techniques.

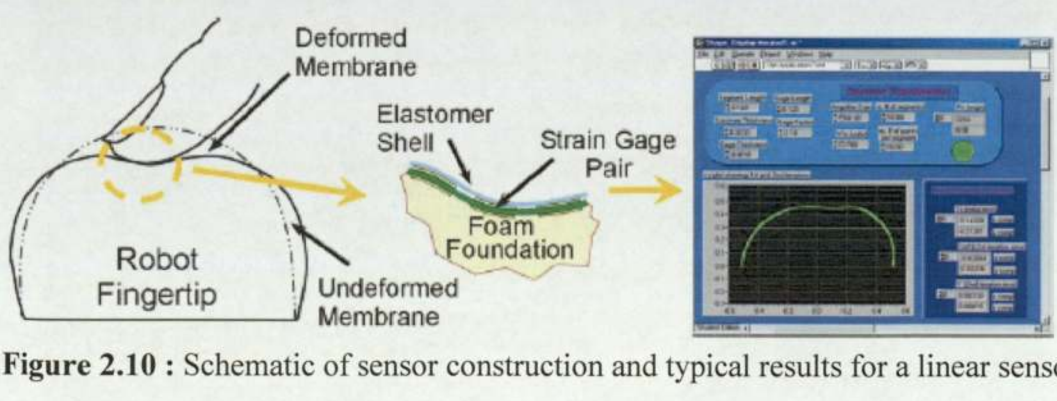


Figure 2.10 : Schematic of sensor construction and typical results for a linear sensor prototype.[12]

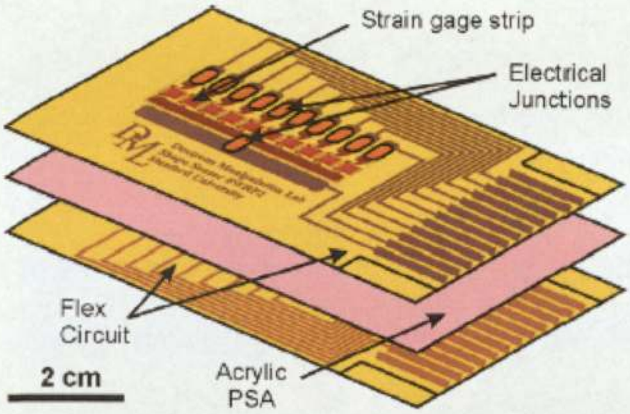


Figure 2.11: Sensor array construction.[12]

2.7 Micro-Technology In Gripping

Microgrippers find their application in micromanipulations of cells and tissues in microsurgery. As they work in direct contact with the cells and tissues, microgrippers must be useable in a biological environment and in conductive solutions.Electrostatic, electromagnetic, thermal and piezoelectric actuation is used to fabricate accurate grippers for micro/nanomanipulations.

Micromachining methods permit the production of very precise structures. Impressive microgrippers have been built. There are different types available now. The following represents an overview of the state of the art of microgripper actuation systems developed at research institutes and companies around the world.
A micro-finger articulation by pneumatic balloons has been developed by (Lu and Kim, 2003)[13]. This micro-finger is made from bulk silicon film and monolithic integration to minimize leakage. Each finger is measured to exert over 0.15mN at 8.27

bar. The micro hand in figure (2.12) is a device that closes by actuation and opens as a result of the stiffness. Its grasping force can be controlled by the actuation pressure.

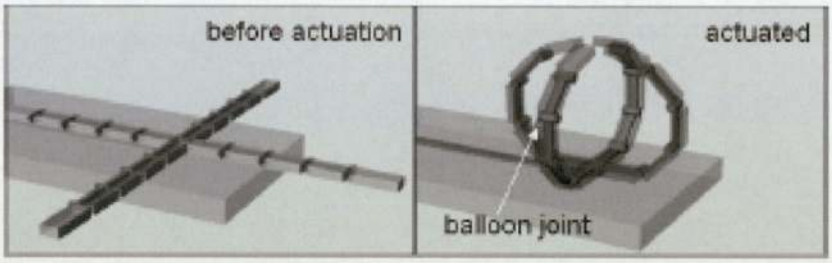


Figure 2.12: Articulate fingers closed by inflating balloon.[13]

The device consists of articulated micro-fingers, monolithically joined by balloons and made by silicon batch processing. Each finger is a functional element featuring bulk silicon blocks connected by pneumatic ballon joints. Once the ballon joints are actuated, the silicon blocks will rotate out of plane and the micro hand closes. This provides a strong finger structure and allows control of the grasping with the actuation pressure. The tip of each micro-finger rotates out of plan about 40 degrees. The response of the micro-finger actuation follows the control signal of the pneumatic valve, but the gripper does not have any tactile sensing feedback. Aeronautics and Medical Robotics ,Toulouse have developed plastic forceps using microtechnology techniques (Van Meer, 2004)[14]. There 8 mm plastic forceps are shown in figure 2.13. The aim of this design is to evaluate two points: the difficulties of the wire integration in an articulated instrument and the method to reduce the end effectors costs. The model has got 3 degrees of freedom, 6 mechanical cables activate it and 10 electrical cables are connected to the jaws for the lights and sensors.

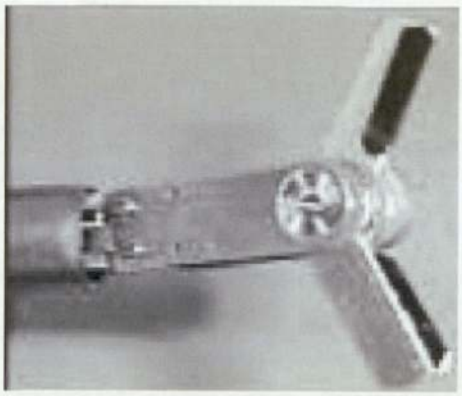


Figure 2.13: Articulated tool with light emitters and straingauges, LAAS/CNRS.[14]

(Menciassi. et al., 2000)[15] demonstrate a microgripper for measuring tissue properties in microsurgery (Figure 2.14). They microfabricated the microgripper and instrumented it with semiconductor strain-gauges to develop a force sensor. They have demonstrated that the tool can discriminate, both qualitatively and quantitatively, tiny skin samples based on their different elastic properties.

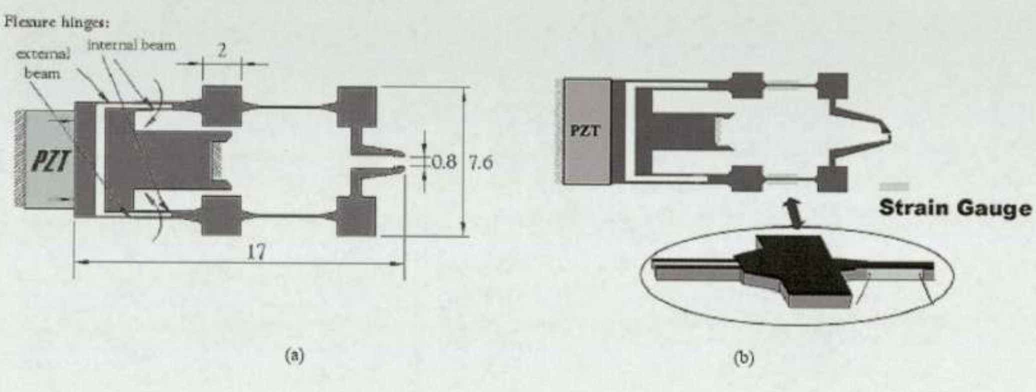


Figure 2.14: (a) Microgripper design (dimensions in mm). (b) Scheme of the microgripper showing the location of the strain gauge sensors.[15]

The system comprises the following components: a microfabricated instrumented probe which can produce controllable force-displacement cycles on soft tissues and measure force generated by pulsating flow in microvessels; a three-degree of freedom motorized manipulator which moves the microgripper; a fiber optic microscope (50–200X) with monitor which allows the operator to visualize the sample and the microgripper position; a PC-based control unit; and a haptic interface which provides force feedback to the operator.

The disadvantages of arrays are of that they are complex construction and involve many sensing points, which are costly and difficult to apply in limited sizes. In contrast to the array type sensor, the coupling between sensing elements induced by an applied load on a common surface is the fundamental requirement for a distributive sensor. With the same number of sensing elements, a distributive tactile sensor normally has a greater spatial resolution. A distributive system is potentially of a non-complex construction, low cost, fast response and redundancy can be incorporated in to the design. There is no need for the sensing element to be in contact with the object, which is a benefit in the difficult environment. The distributive tactile sensing technique relies heavily on the nature of the response of the surface to loading, which means the system discriminates rather than measures. The work described in later chapters of the thesis forms a basis to extend the application of distributive tactile sensing in gripping systems.

Chapter 3

3.0 A Pneumatically Actuated Cantilever Beam Sensor

3.1 Introduction

One of the most important needs in the emerging area of micro-technology is manipulation. Micro-scales require special ways to design grasping devices. An approach involving a pneumatically actuated cantilever beam has been used to design an experimental gripping test rig integrated with tactile sensing to retrieve information about the physical properties of an object. When actuated the beam will deform to grasp objects of different sizes. The gripper rig will be designed, analysed, manufactured and tested on a large scale.

There are many requirements for the gripping rig. The most crucial requirements are that the device can be manufactured on the micro-scale, the ability to grip a variety of objects with different sizes and the ability to retrieve information about the physical properties of the object. The most important engineering specification is actuation pressure and the maximum force applied.

The large gripper rig was successful in gripping a variety of object shapes and sizes. A model of the cantilever deflection was created and compared to the experiment results. The cantilever beam was integrated with a distributive tactile sensor in order to retrieve information about the physical properties of the object.

3.2 System Requirement

Following are a list of the gripper requirements:

1- The gripper must have sensory feedback which can not only sense the contact forces but also sense the physical properties of an object, such as: contact, position and size of object, This information can then be used to provide tactile feedback to the operating surgeon.
2- Pneumatic actuation for large scale, hydraulic actuation for micro scale (which is more suitable to a medical environment).
3- The gripper must be able to pick-up and hold objects without dropping them.
4- Force reflection in order to be able to sense the gripping forces applied to object.
5- The gripper must be able to grasp objects that vary in size and shape.

6- The gripper must be well suited to the surgical environment it may encounter for example: sterile, magnetic scanning, minimal/ restricted access, all at a low cost.
7- The gripper must be able to generate the appropriate actuation force.
8- The gripper must hold objects without damaging or permanently deformating them.
9- The gripper should be able to produce both vertical displacement and horizontal motion of the tip to pick-up and hold objects of varying sizes.

3.3 System Design

The following list of engineering specifications was developed:

1- Displacement: displacement of the tip of the cantilever from its starting position to its final position is 20mm.
2- Actuation pressure: a reasonable actuation pressure range for the pneumatically actuated gripper is 2 bar.
3- Finger length: Cantilever beam length for the large scale is 14cm.
4- Distance between the two plates of the gripper rig: Based on the size of the objects the distance between the two plates will be 7 cm, the distance between the cantilever and the plate is designed to be flexible and easy to adjust for different object sizes. If the distance between the two plates is larger than that of the object being grasped, the object will be released easily.

5- Maximum Force Applied: the maximum amount of force that can be applied will depend on the type of object being grasped. Based on the research and experiments the value of 0.1N will be accepted.

3.4 Design Description

The design can be divided into six subsystems. They are the pressure valve, pressure lines, fittings, base, cantilever beam and the pneumatic balloon as shown in Figure (3.1).

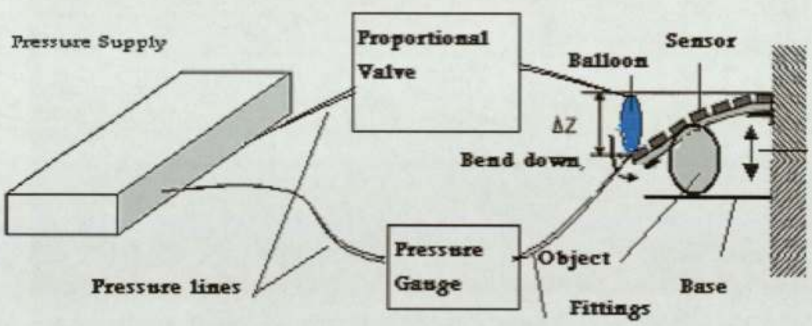


Figure 3.1: Working principle of the gripper

The cantilever beam sensor deforms nonlinearly when actuated. The pressure lines transport pressurized air to actuate the device. The fittings are the link between the pressure line and the pneumatic balloon. The base holds the pneumatic balloon and the cantilever beam sensor

3.4.1 Base

The base must hold the pneumatic balloon and the cantilever beam sensor in order to produce an appropriate gripping action (Figure 3.2). It must be rigid so that it will not deflect when the cantilever beam is actuated and affect the sensor reading and gripping action. Also, the base need to be rigid to support the weight of the object inside the gripper. Here, the base is constructed out of Plexiglas in order to demonstrate the gripper. It contains two Plexiglas plates, the distance between the two plates, can be adjusted easily for different object sizes also the height of the beam can be adjusted.

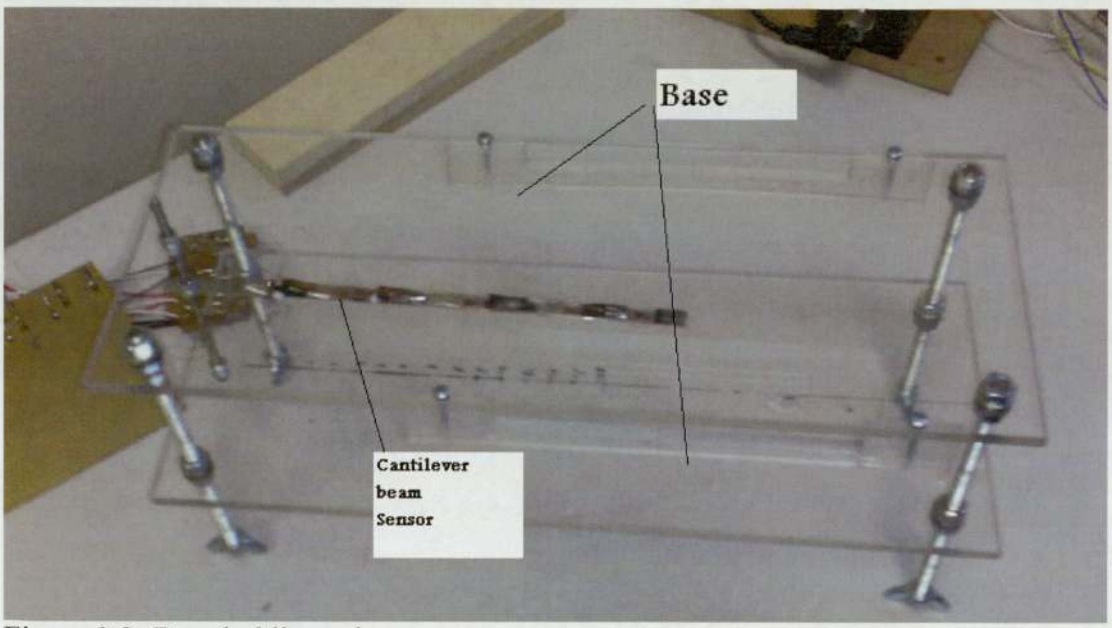


Figure 3.2: Base holding gripper.

3.4.2 Pressure Gauge

The pressure gauge will have to be very accurate and able to measure small amount of pressure in order to effectively control the gripping force and prevent any damage to the object. A very accurate electronic pressure gauge will require a range of 0-0.41bar.

3.4.3 Pressure Valve

The gripper is actuated pneumatically from a supply pressure of 5.71 bar. In these experiments, each actuator was controlled using a Norgren VP50 proportional control valve (Appendix 1) which has a linear pressure gain over the range 0 to 3 bar (Figure 3.3). By changing the control signal to the valve from (0 to 1 V), consistent changes can be maintained. The slope of the input voltage against pressure is linear. The pressure gain of the valve can be adjusted.

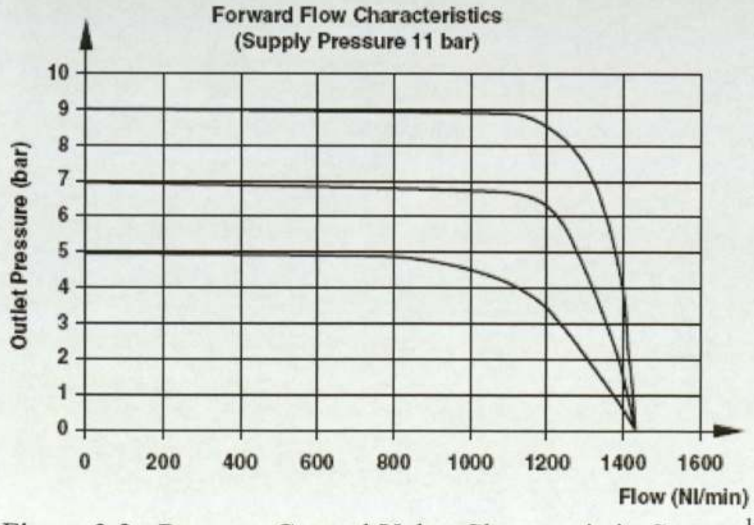


Figure 3.3: Pressure Control Valve Characteristic Curves.[16]

3.5 Relationship between the large gripper and the smaller gripper

The large gripper rig is able to validate certain aspects of the goals. However, given the large difference in scale between the two devices, some issues relating to the small gripper cannot be addressed by the large one, for example the material in the large gripper will be different to the micro-scale design. Likewise, the difference in actuation will be taken into account in the micro scale size. As such the large gripper will be used to:

- Verify the performance of the sensors and measure the distribution of forces on its surface
- Identify the actuation mechanism
- Perform grip-and-hold
- Demonstrate control the grip-and-hold operation.
- Enable the strain data to be interpreted.
- Allow the behaviour of the gripper to be simulated.
- Calculate the shape of the actuated gripper from a known pressure.

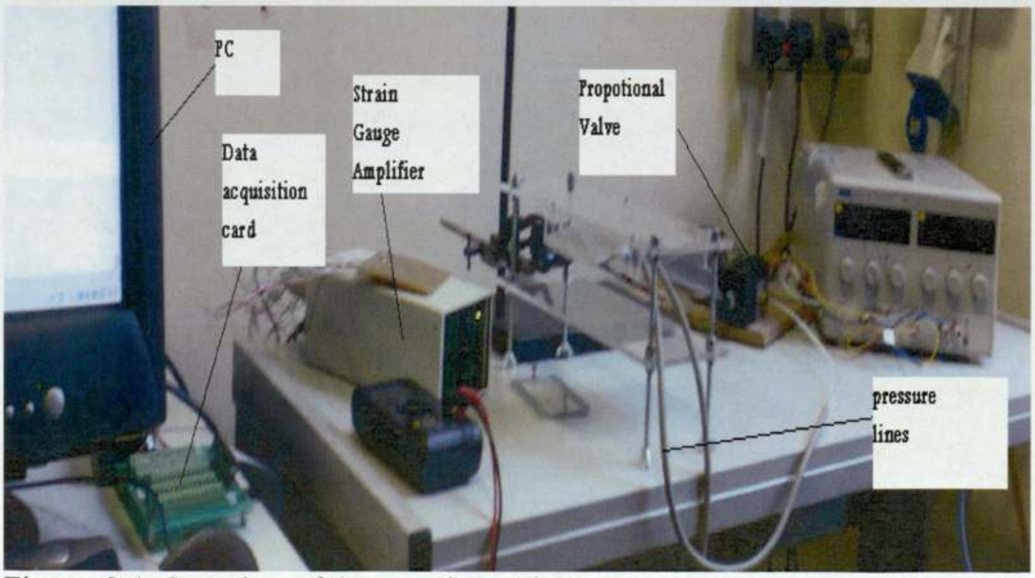


Figure 3.4: Overview of the experimental setup

3.5.1 Limitations

Due to manufacturing issues the cantilever beam sensor with pneumatic balloon actuation was preferred over the first prototype gripper (figure 3.5).

The experiment was performed on a 3D System using a Viper SLA 250 rapid prototyping machine. The Viper SLA system using the High Resolution (HR) mode can provide a laser beam diameter of just 3 mm with a minimum feature size of just 7mm.

Due to material limitations of the resin, building the micro-scale pneumatic fingers was unsuccessful using the 3D Viper prototype machine, resulting in the micro-finger being unable to withstand the application of a 0.14 bar actuation inflation pressure. It was decided that was little scope for building the gripper using resin material.

Figure 3.5: First Prototype gripper.

3.6 Gripping Experiments

3.6.1 Gripping Test

The aim of this experiment to verify that the gripper was able to hold various objects of different diameters. The gripper was tested using various object diameters as shown in figure (3.6).

Figure 3.6: Objects with varying diameters and weights.

The gripper succeeded in grasping different object sizes for object diameters from 25-60mm (Figure 3.7).

Figure 3.7: The gripper holding and maintaining grip on different object sizes.

3.6.2 Displacement Test

The aim of this experiment was to measure the distance that the tip of the cantilever beam travelled for different cantilever beam sizes. Apiece of paper was taped to the base of the gripper. An initial mark at the beam tip was made for the horizontal position. This point was called the origin and the following beam tip marks were measured from this point. The placement of the beam tip was marked for the same amount of pressure, as shown in figures (3.8) and figure (3.9).

Figure 3.8: Displacement for 3 cm long beam.

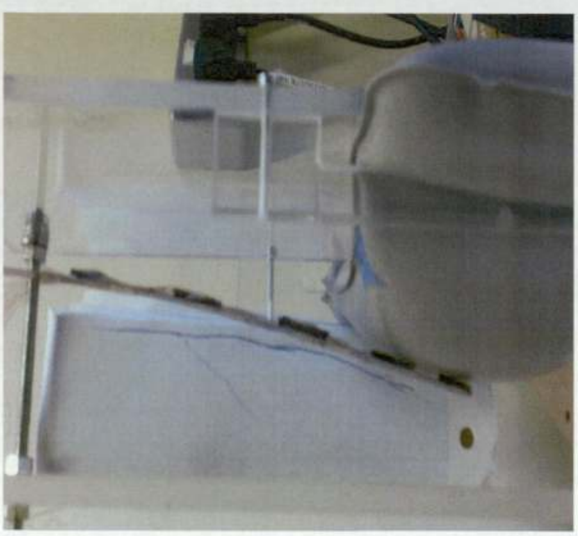


Figure 3.9: Displacement for 14cm long beam.

The location displacement measurements are shown below in Table 3.1.

Pressure (psi)	Cantilever beam length (mm)	Displacement(mm)
2	18	24
2	10	26
2	7	27
2	3	30

Table 3.1:Cantilever beam displacement measurements for different sizes.

3.6.3 Pressure and vertical displacement Test

The aim of this experiment to measure the pressure readings in order to achieve the same tip displacement for different cantilever beam sizes

Pressure (psi)	Cantilever beam length (mm)	Displacement (mm)
6	4	24
5	6	24
4	8	24
3	14	24
2	18	24

Table 3.2: Relation between pressure and vertical displacement of the cantilever beam tip.

3.6.4 Force Scaling

The gripper was able to provide adequate force to lift different sizes of objects. If the gripper were to be scaled down it would need to be able to provide enough force to lift small object weights in surgical applications. The force exerted on the object is measured by the pressure of the air in the balloon and this is used to control the driving system of the gripper. A very high accuracy electronic pressure transducer is used to determine the amount of pressure inside the balloon. The pressure transducer is able to measure pressure to a very high accuracy. To convert the pressure measurement into a feedback force, the unloaded pressure-displacement diagram of the cantilever beam must be measured. From this measurement a function can be derived, which is used to calculate the actual force.

3.6.5 Failure

To make sure that the material of the air bag would be able to withstand the required amount of pressure before leaking or braking, the balloon was tested to the maximum pressure before leaking which was 0.41 bar. The design was determined to be adequately safe.

3.7 Engineering Design Parameters

3.7.1 Deflection

A model for the cantilever beam deflection was used to explore the deflection of the cantilever beam and to determine if the cantilever would be able to bend enough to grip objects.

3.7.2 Beam Theory

The bending theory is reported in most structural mechanics texts, for example (Gere, 2000)[17]. The deflection y at position x in response to an applied force F at the free end of the beam is given in equation (3.1). The beam has length l (figure 3.10). The beam model undergoes only small rotations when the beam is loaded, resulting in very flat deflection curves with extremely small curvatures. Thus, small deflection ($\cos\theta \approx 1$ when θ is small) is assumed. Where x is the distance along the beam.

$$y(x) = \frac{Fx^2(3l - x)}{6EI} \quad (3.1)$$

$$y(l) = \frac{Fl^3}{3EI} \quad (3.2)$$

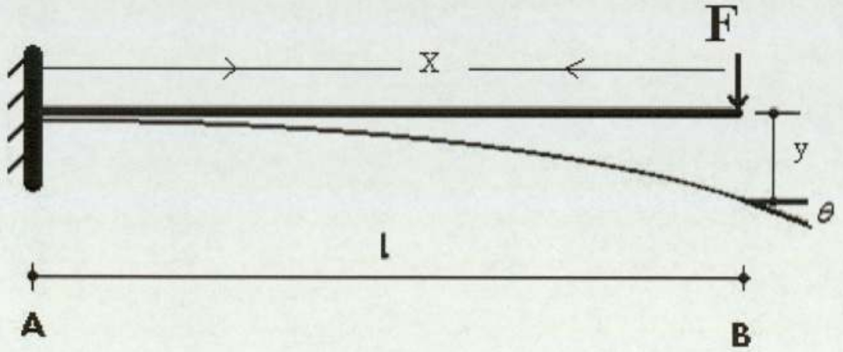


Figure 3.10: Deflection of a beam under load.

Where E is the Young's Modulus and I is the second moment of inertia. For equation (3.2) the following assumptions apply:

(a) The beam is straight or nearly so, (b) the beam is of a homogeneous material that has the same modulus of elasticity in tension and compression, (c) the cross sectional area remains planar and is uniform, (d) the applied load will not cause permanent deformation and (e) deflections are small in respect to length. Shear stress may contribute to the error.

3.7.3 Verification of the model

To test the validity of the model, the deflection of the cantilever beam from the model was compared to values obtained through experimentation. Figure 3.11 presents an example comparison of the deflections derived from the model and experimental measurement when a 0.3 N load applied at the tip of the 19cm long beam.

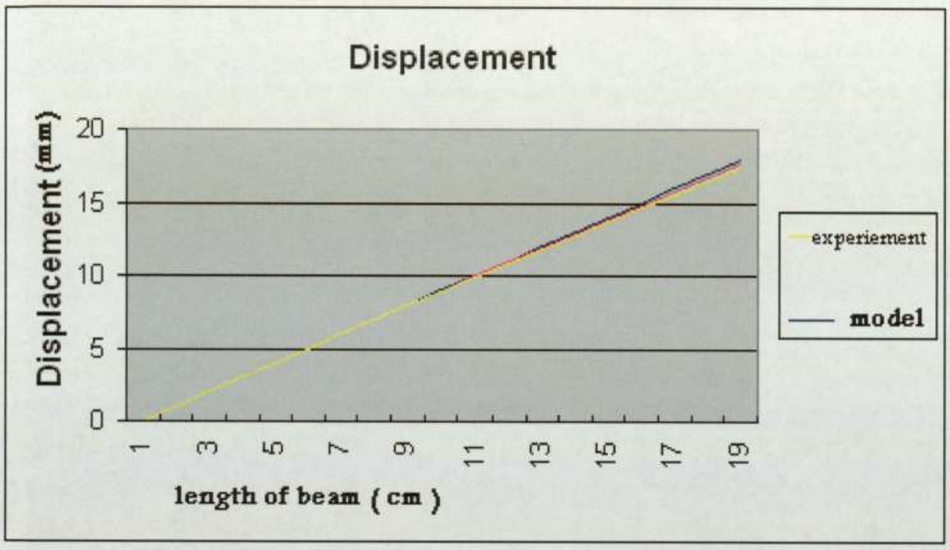


Figure 3.11: Example of comparison between deflections derived from the model and experimental measurement.

Results are summarized in the table below:

	Model	Experiment
Pressure (bar)	Δy(mm)	Δy(mm)
0.03	1	12
0.07	20	21
0.1	25	22
0.14	27	24

Table 3.3: Model and experimental results for vertical displacement of the 19cm long beam.

3.8 Actuation

The actuator enables the gripper to conform to the optimum shape required, and by integrating a tactile sensing technique this will allow automatic control of the gripper configuration with respect to the material. This then enables the device to react and control the deformation of the object actuators which can be characterized by five key design parameters: force, size, displacement, stiffness and frequency. Actuators with high displacement provide low force and vice versa.

For the wide variety of existing applications and actuators, some means of matching the requirements of an application to the performance characteristics of an actuator is desirable. The maximum force and maximum displacement are not achieved at the same time. The maximum force is measured when there is zero displacement. The maximum displacement is measured when there is no load in resistance. Actuator selection is based on the entire motion characteristics (force displacement curves) rather than single-point designs.

There are different possible actuation techniques for the gripper, these include thermal actuation, pneumatic actuation, electrical actuation, hydraulic actuation and cable actuation. The classification tree below show different type of possible actuation for the gripper.

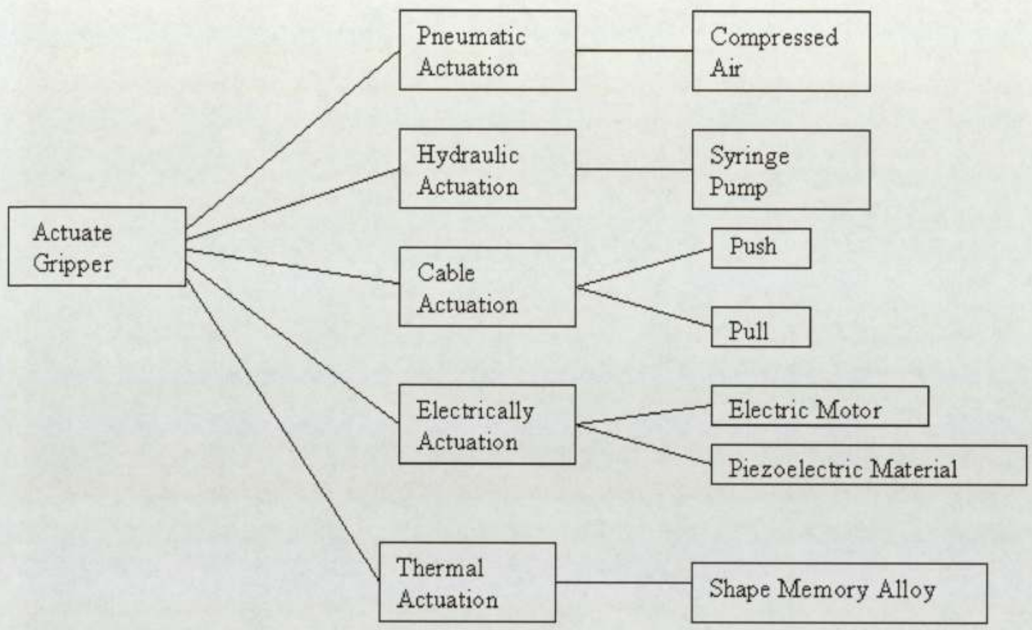


Figure 3.12: Classification tree of actuating gripper.

(Brett and Stone,1995)[18] demonstrate a flexible pneumatic actuator for gripping soft irregular shaped objects. A bellowed tube forms an air tight chamber with a strip of steel present along one side. This tube is then pressurised pneumatically. One example of cable actuation (Slack, 2005)[19] demonstrates a cable actuated flexible digit with tactile feedback.

3.9 Ultimate Goals

The ultimate goal would be a microsurgical gripper that deforms to grasp an object and has appropriate stiffness to withstand the reaction forces present upon gripping the object. The gripper must be able to apply 0.1N force with large displacement. The gripper has to fit through a 1.5 cm diameter incision. Once inside the body, it has to expand to securely hold tissue. The gripper must be able to meet versatility and safety constraints. The human tissue has an estimated average mass of 1-100g. Also the gripper must be able to securely hold and grasp tissue, with a safety factor.

3.10 Distributive Tactile Sensing

The distributive tactile sensing technique uses tactile sensors with some similarities to the human touch and it is thus more able to discriminate. Distributive tactile sensing is able to retrieve large volumes of data with many connections but the data interpretation process can be computationally intensive. (Brett and Stone, 1997)[20]

3.10.1 Strain Gauges sensors

Strain gauges are measuring elements that convert applied force, pressure, tension, etc., into an electrical signal. A strain gauge is a resistive elastic sensor whose resistance is a function of applied strain. Many types of strain gauges depend on the electrical resistance to strain. These types include: piezoresistive, semiconductor, carbon-resistive, bonded metallic wire, and foil gauges. The resistance of an electrically conductive material changes with dimensional changes that take place when the conductor is deformed elastically. When such a material is stretched, the conductors become longer and narrower, which causes an increase in resistance. Strain can be by definition tensile or compressive. The measuring grid of the strain gauge is embedded between two layers of plastic strip. It consists of a thin metal foil which is electrically conductive. Typically the grid is wound from wires with 15-25 μm diameter (Hoffmann, 1992)[21]. As the grid is distorted due to an applied force, or temperature, the electrical resistance of the gauge is altered. This is due to the change in cross sectional area of the gauge. This change is proportional to the resistance of the wire per unit length.

A Wheatstone bridge then converts this change in resistance to an absolute voltage. The resulting value is linearly related to strain by a constant called the gauge factor. Capacitance devices, which depend on geometric features, can also be used to measure strain. Specification for the strain gauge can be found in appendix (2).

Strain gauges are usually bonded to the object where displacement is to measured using cyanoacrylate. As the strain is applied to the gauge, the shape of the cross sectional area of the material distorts, changing the area. The resistance of this material is inversely proportional to the cross sectional area (Morris, 1993)[22]. The relationship between a given value of strain ε and the change in resistance R is expressed as the gauge factor (*GF*):

$$GaugeFactor\ (GF) = \frac{\delta R}{\delta \varepsilon} \qquad (3.3)$$

Strain gauges are chosen as the preferred sensing element type due to their abundance, low cost and the availability of amplification equipment. They are generally robust once they are bonded to the surface of the object whose displacement is to be measured.

To measure the strain requires accurate measurement of very small changes in resistance. To measure such small changes in resistance, strain gauges are always used in a bridge configuration with a voltage excitation source. The general Wheatstone Bridge, illustrated below, consists of four resistive arms with an excitation voltage, V_{EX}, that is applied across the bridge.

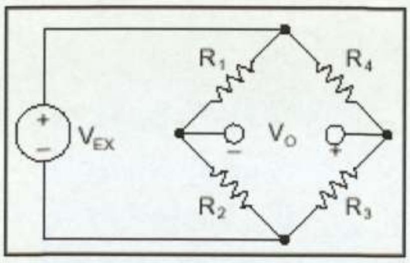


Figure 3.13: Wheatstone Bridge

The output voltage of the bridge, V_O, will be equal to:

$$V_o = [\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2}] \times V_{EX} \qquad (3.4)$$

From this equation, it is apparent that when $R_1/R_2 = R_4/R_3$, the voltage output V_O will be zero. Under these conditions, the bridge is said to be balanced. Any change in resistance in any arm of the bridge will result in a nonzero output voltage.

3.10.2 Sensor Installation

The half bridge configuration (figure 3.14) was used in the experimental system because the half-bridge configuration reduces thermal effects, strain gauge amplifier restrictions and leads to a doubling of the sensitivity of the bridge. R1 and R2 are equal, and are set within the strain gauge amplifier. R3, is the strain resistance value of the strain gauge. R4 is a high accuracy resistor (RC). The value of RC should be equal to the strain gauge resistance ($120\,\Omega$). The output voltage of the half-bridge circuit is linear and approximately doubles the output of the quarter-bridge circuit.

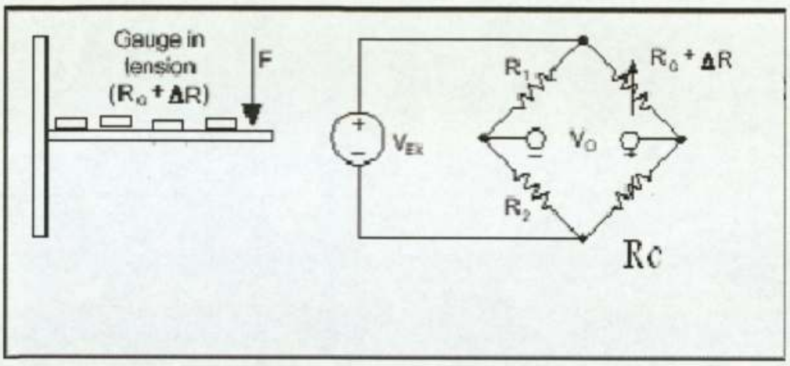


Figure 3.14: Half-Bridge Circuit.

The experiment consists of one piece of spring steel 10mm wide, 19cm long and 0.38 mm thick, which is supported at one end. The sensor element locations are at 30 mm, 70mm, 110mm and 170 mm from the root of the beam (Figure 3.15)

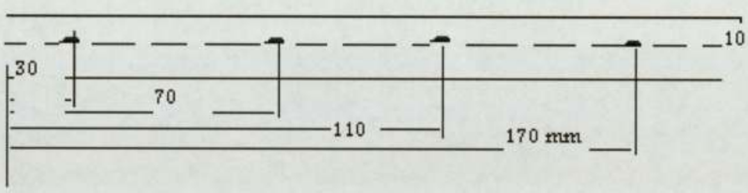


Figure 3.15: Layout of sensing elements on beam.

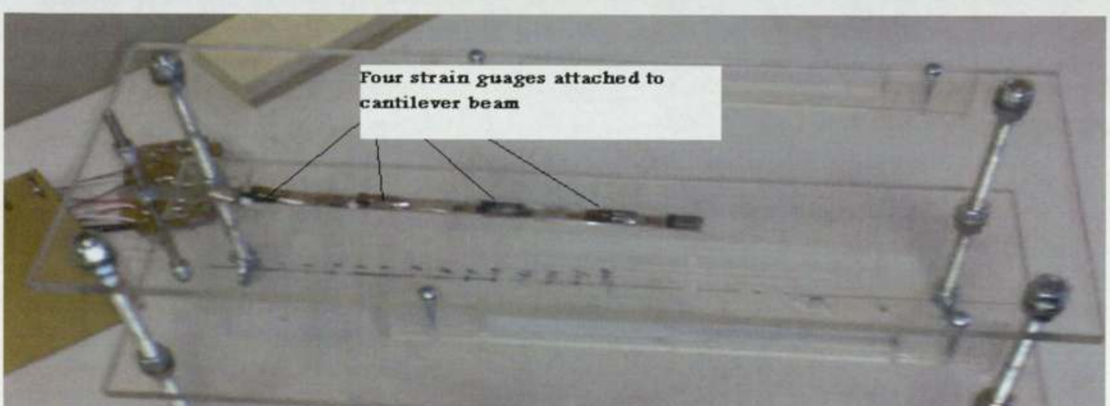


Figure 3.16: Four strain gauges attached to cantilever beam.

3.10.3 Strain Gauge Amplifier

The strain gauge readings due to deflection of the cantilever beam must be converted to a voltage in order to feed it to the neural network. The strain gauge amplifier converts the resistance change to a voltage and amplifies the signal. The strain gauge readings must be amplified sufficiently so that they can be read by the data acquisition card. The signals are adjusted by the strain gauge amplifier.

The strain gauge readings are amplified using four Fylde FE-356 strain gauge amplifier channels. The amplification is set to 10,000. The resistance conversion is performed with the half bridge configuration. Specification for the strain gauge amplifier can be found in appendix (3).

3.10.4 Data Collection

The gripper base is divided into 14 positions, numbered from 0 (the root of the beam) to 14 (the tip of the beam). Objects can be placed at 14 chosen positions along the gripper. Table 3.5 shows the position and object size combinations for the experiment.

Position of object from the root of the gripper	**Object diameter (mm)**
1	30,35,36,38,39,43,44,50,53
2	30,35,36,38,39,43,44,50,53
3	30,35,36,38,39,43,44,50,53,64
4	25,30,35,36,38,39,43,44,50,53,64
5	25,30,35,36,38,39,43,44,50,53,64
6	25,30,35,36,38,39,43,44,50,53,64
7	25,30,35,36,38,39,43,44,50,53,64
8	25,30,35,36,38,39,43,44,50,53,64
9	25,30,35,36,38,39,43,44,50,53,64
10	25,30,35,36,38,39,43,44,50,53,64
11	25,30,35,36,38,39,43,44,50,53,64
12	35,36,38,39,43,44,50
13	25,30,35,36,38,39,43,44,50,53,64
14	25,30,35,36,38,39,43,44,50,53,64

Table 3.4: Position and object size combination for the experiment

3.10.5 Data Acquisition

The data was acquired using a Computer Board PCI-DAC 1602/16 data acquisition board with a MatLab data acquisition tool box. Specification for the data acquisition can be found in appendix (4).

Chapter 4

A Contact Sensitive Gripper

4.1 Introduction

This chapter aims to evaluate the gripper performance in discriminating between different objects in diameter, position and stiffness. The experimental protocol was designed to examine the ability of a neural network to discriminate objects according to their position, diameter and stiffness.

4.1.1 Taxonomy of gripping contact

In this system, four classes of contact were introduced. This classification takes into account surface deformation under pressure (figure 4.1). Examination of these needs shows that the gripping can be categorised into several simple characteristics:

- Contact versus not contact
- Position of Contact Object
- Size of Contact Object
- Stiffness of Contact Object

The gripping system is made from a number of neural networks, each represents a certain type of information. The higher level on the program is the supervisory system which monitors the outputs and controls the decision making.

The processing power of the system can be concentrated into basic information that, when combined togther can be used to produce a better understanding of the object inside the gripper. The information feedback to the surgeon needs to be focused on the critical parameters aiding better performance in surgery (Tam.B, 2005)[23].

In reality, the taxonomy of gripping is based on a hybrid parallel and cascaded neural network architecture. For example, the most usefual data collected from a strain gauge transducer is that of contact versus non contact. It would not be useful to discriminate a position or object size when there is no contact.

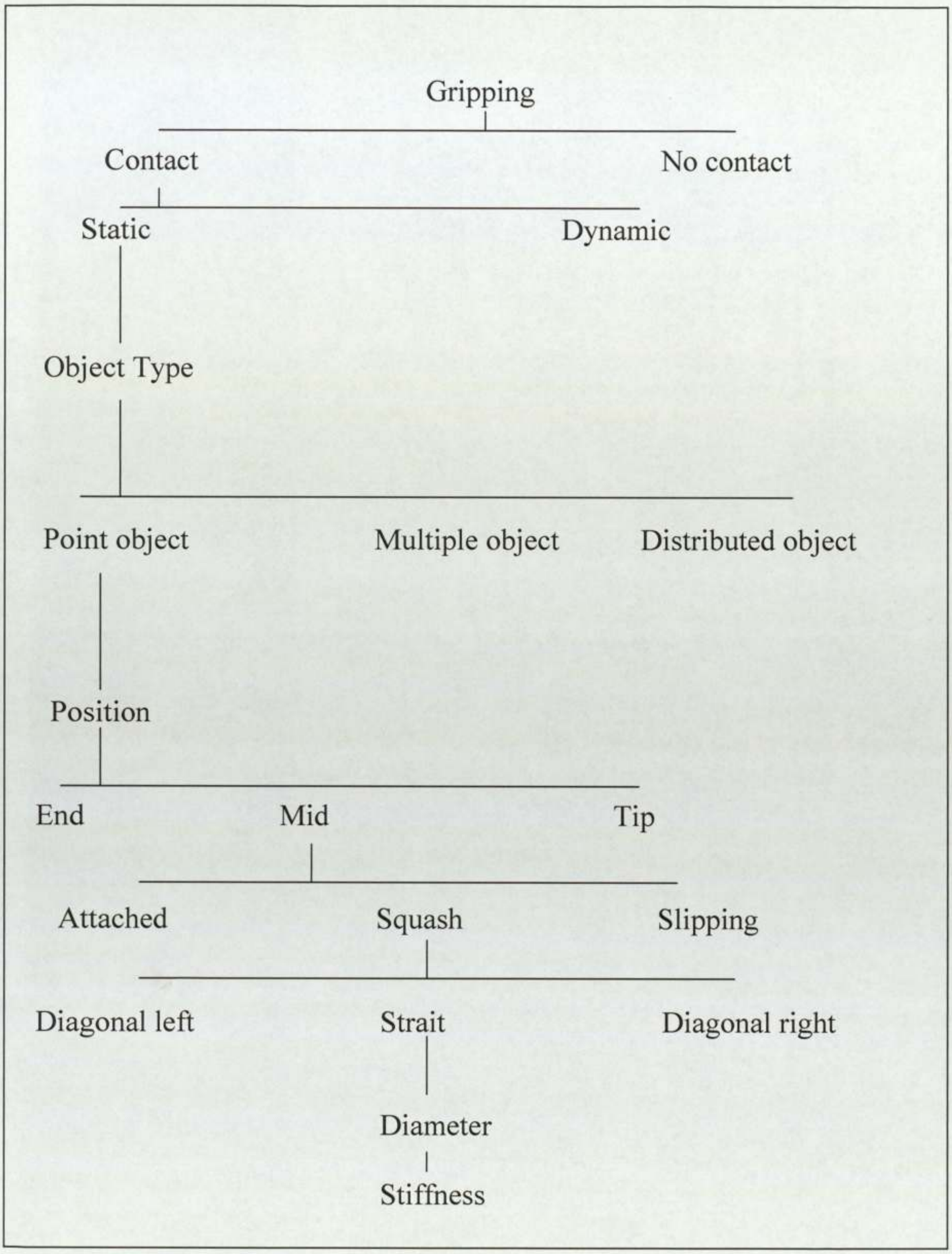


Figure 4.1: Gripping Taxonomy

4.1.2 Neural Networks

Neural networks provide a unique computing architecture which can provide an effective approach for a broad spectrum of applications. Neural networks can be applied to translate images into keywords. It is composed of a large number of highly interconnected processing elements (neurons) working in unison to solve specific problems (figure 4.2). ANNs , like people, learn through training. An ANN is configured for a specific application, such as pattern recognition or data classification. Automatic classification (or discrimination) is one of application of neural networks that has specific features.

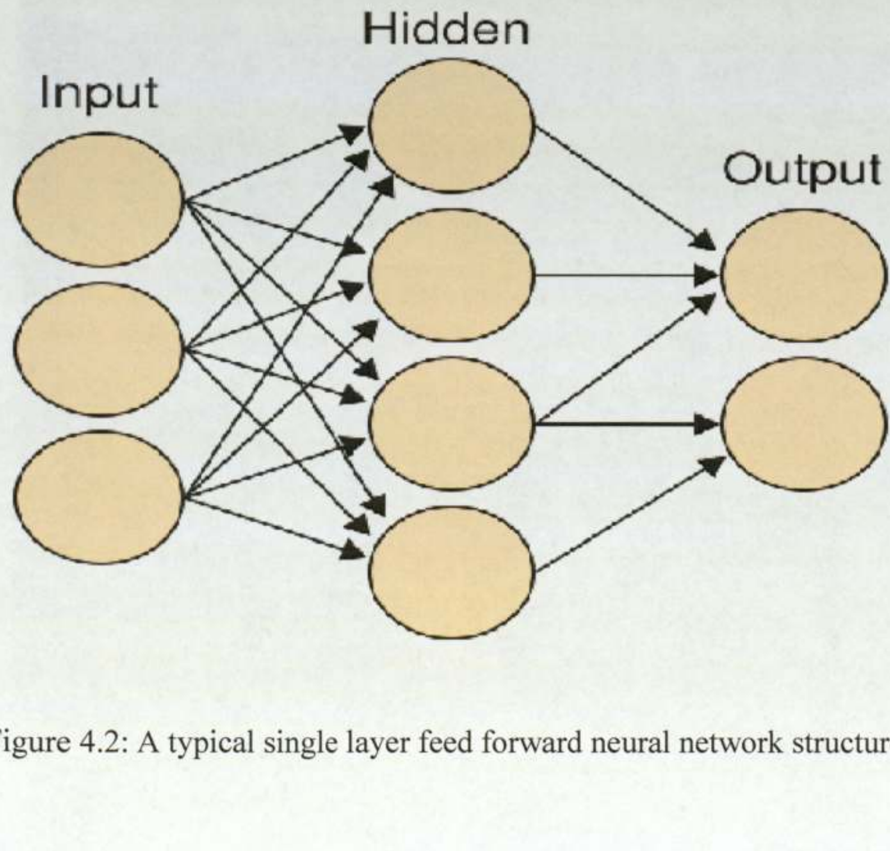


Figure 4.2: A typical single layer feed forward neural network structure.

The neural network used for these experiments was based around the neural network tool box in MatLab. Various types of neural networks can be employed, but for the following experiments, a single layer feed- forward neural network as in Figure 4.2 was employed. Single layer use statistical techniques of linear regression and generalised linear models which consist of a linear combination of input variables where the coefficients are the parameters of the model followed by an activation function. The activation function used depends on the type of data being modelled. There are four standard steps in using a neural network (Figure 4.3).

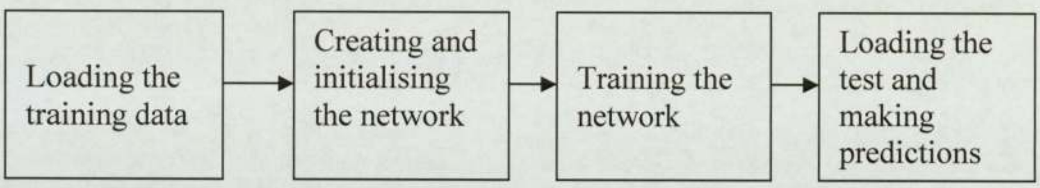


Figure 4.3: Standard steps for implementing a neural network

The information intended to be extracted from the sensors included:

1- Presence of contact
2- Object position
3- Object diameter
4- Object stiffness

4.1.3 Neural Network Strategies

There are strategies that can be applied to neural networks to achieve predicted outputs. A combined neural network, a parallel neural network; and a cascaded neural network. Cascade networks start learning with only one neuron, and during learning the algorithm automatically adds and trains new neurons creating a multi-layer structure. The number of hidden neurons, that is the complexity of the network, increases step-by-step while the training error decreases. As a result, the training algorithm grows the neural network of a near optimal complexity which can generalise well. A parallel ANN has potential benefits for numerous applications. Applications with large training or data sets could process those at a substantial speed increase, while other applications could utilize multiple networks simultaneously to ensure accuracy of any output. A parallel neural network (Figure 4.4) was used in this project

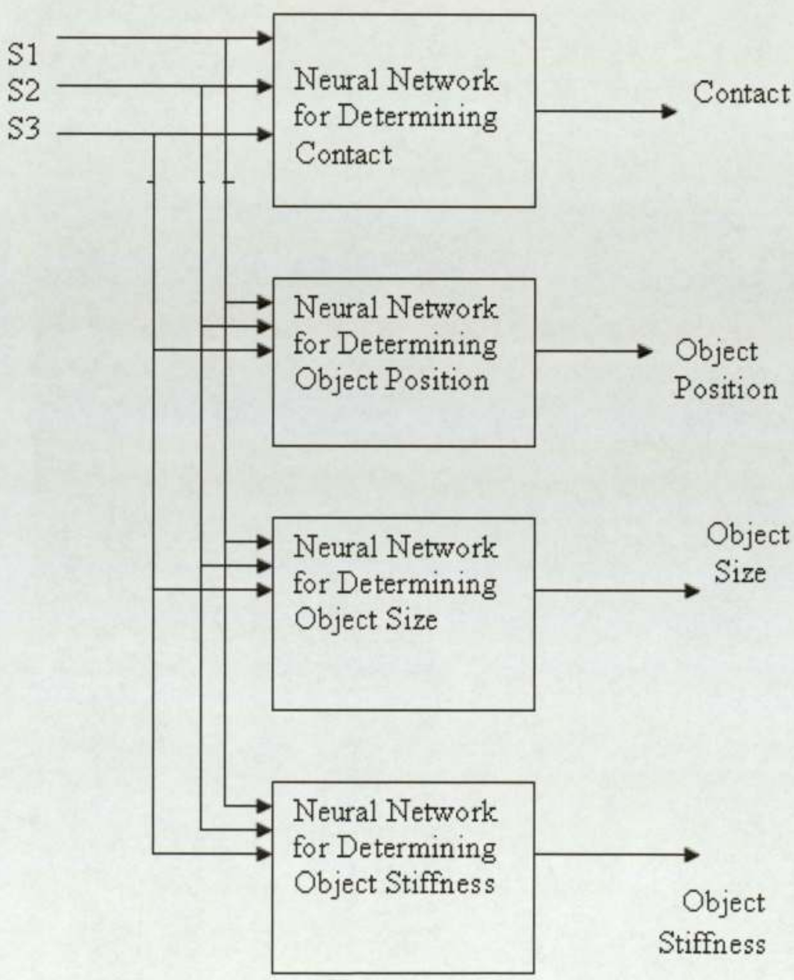


Figure 4.4: A Parallel Neural Network using four networks to predict four output parameters where S denotes the sensor input channel number

4.2 The Experiments

The experiments evaluate the cantilever beam sensor. The first phase of the experiments was to detect object position and object diameter. Finally, object stiffness was considered in order to discriminate between hard and soft objects.

4.2.1 The Performance Evaluation Rig

To examine the performance of the cantilever beam sensor, an experimental rig was designed and built to provide gripping contact conditions based on the taxonomy of gripping.

Static experiments were performed to simulate conditions of gripping contact. The experimental evaluation of the performance of the cantilever beam sensor to detect tactile information requires loading the gripper with different sized objects at different positions with different physical parameters.

The cantilever beam sensor had pneumatic balloon actuation and had a base made from clear Perspex for visibility. It was designed to be functional and capable of holding different objects at different positions for a wide range of object diameters from 10mm diameter to 70 mm. Figure (4.5) shows the evaluation gripping contact rig.

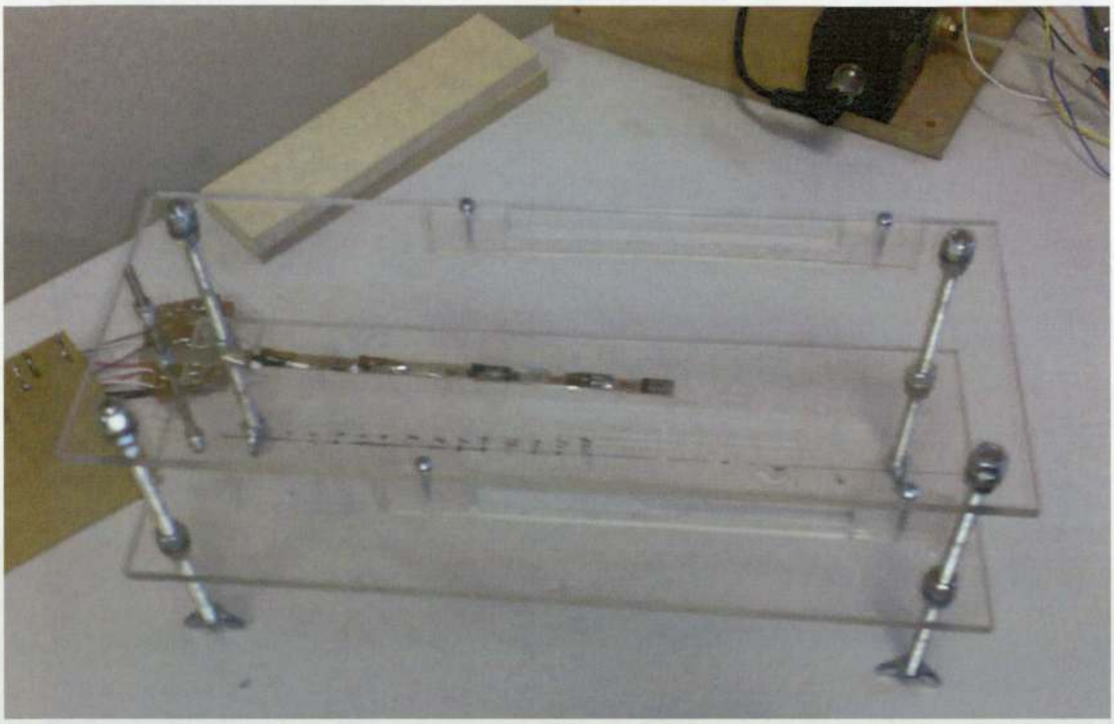


Figure 4.5: A Cantilever beam sensor.

The special purpose balloon was designed to be capable of controlling the grasping with an actuation pressure. The gripper was measured to exert over 70mN at 0.14 bar. The gripper is a device that closes by actuation. Its grasping force can be controlled by the actuation pressure. Once the balloons are actuated, the cantilever beam sensor will rotate out of plane around the object. This provides a strong finger structure and allows it to control the grasping with the actuation pressure. The cantilever beam sensor was placed on a holder to enable the beam to be adjusted for different object sizes. The tip of the gripper rotates out of plan about 20 degrees. The response of the gripper actuation follows the control signal of the pneumatic valve.

Data acquisition is set to collect 30 samples per second. Attached to the cantilever beam with four strain gauges is a Fylde six channel strain gauge amplifier. Data from the amplifier is acquired using computer boards PCI-DAS 1602/16 data acquisition board and recorded using Matlab.

The cantilever beam is 180 mm in axial length and the sensors were placed at 30mm, 70mm, 110mm and 170mm from the root of the cantilever and were connected to the amplifiers and data acquisition equipment. Actuation of the gripping rig was controlled using a Norgren VP50 (0-1Bar) proportional pressure control valve, the range of the actuation pressure by using air balloon was from 0-0.14 bar.

The cantilever beam sensor was subject to a pressure of 0.14 bar being applied in a perpendicular direction at the tip of the beam and the strain recorded. The strain sensory data corresponding to the cantilever was recorded using the data acquisition equipment.

Each contact was repeated 3 times to check for repeatability of results.
A Neural Network was produced for this application for data interpretation. The type of neural network used for these experiments was in a classification mode.

4.3 Evaluating fundamental gripping contact characteristics.

The experiments carried out in this section were to evaluate the gripper and discriminate:

- Contact and non contact
- Object position
- Object size
- Object stiffness

4.3.1 Contact detection

In this experiment, contact and non contact is evaluated for the gripping rig when it is loaded with a single object. Contact is useful for object detection. Detection contact is important to define the characteristics of gripping. It is very clear that there is a difference in the data output of the cantilever beam sensor when contact is present compared to when there is not. There is no benefit from a neural network used to discriminate a position, diameter or stiffness magnitudes when there is no contact present.

Method for Evaluating Contact and Non Contact

1. The cantilever beam sensor is actuated by pneumatic balloons to a pressure of 0.14 bar which is applied in a direction perpendicular to the tip of the beam. The strain is then recorded.
2. The gripper is subjected to a load with objects at different positions and with different sizes. The strain is then recorded.
3. The strain sensory data corresponding to the gripper is recorded by the data acquisition equipment for both cases when the gripper is loaded with objects and without loads.
4. Each loading position is repeated three times for repeatability of the results.
5. The Neural Network used for these experiments is in a classification mode.

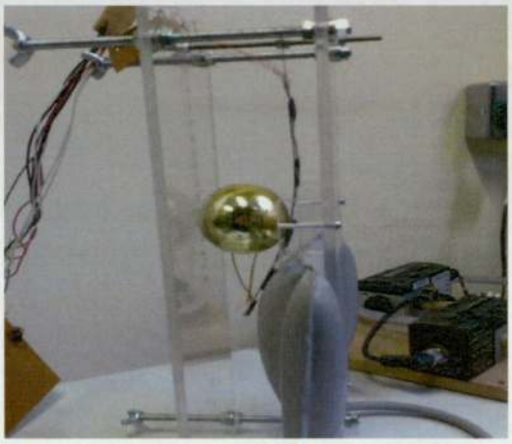


Figure 4.6: The gripper in gripping action of hard object

Results for contact of objects

The neural network used for the contact experiment has 4 inputs and 2 class outputs and contain 16 hidden nodes. Figure 4.7 displays the results of the contact / non contact experiements.

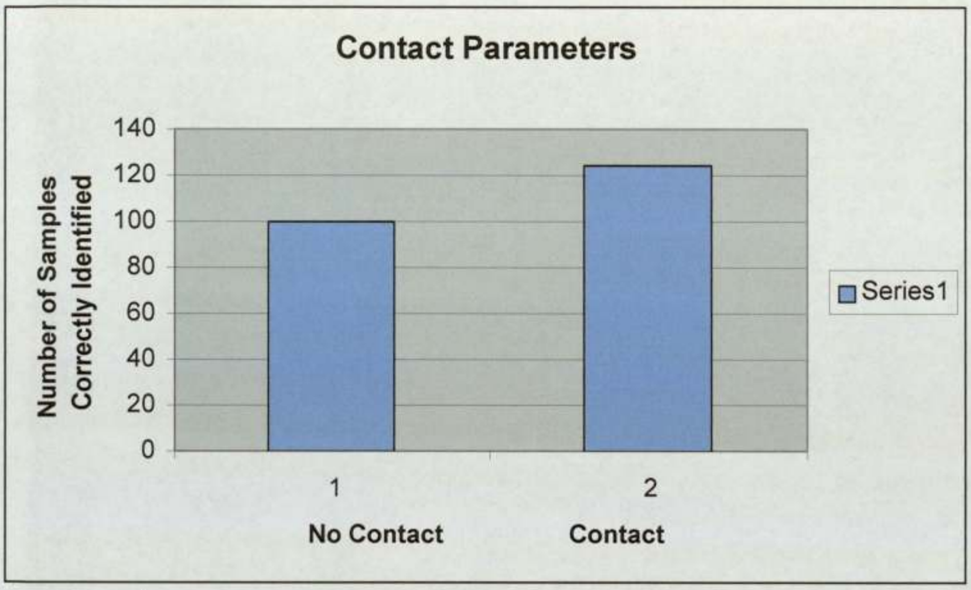


Figure 4.7: Chart showing contact and non contact of objects correctly identified

Real / Predicted	No Contact	Contact
No Contact	100	0
Contact	0	124

Table 4.1: This table shows that the neural network has been trained and can classify the contact and non-contact.

Table (4.1) show a matrix of 224 samples of data, All classification were correctly identified using a classification type neural network. This type of neural network will output results of only contact or non contact, with the output number closer to 0 indicating a non contact and closer to a value of 1 for contact.

The results indicate that the gripping contact rig is able to identify the occurrence of contact. The detection of contact plays a major role in all tactile systems and this is a good starting point for contact characterisation in the gripping taxonomy.

4.3.2 Object Position

In this experiment the position of the object was detected. The aim of this experiment is to determine the performance of the gripper in the evaluation of the object position.

Method for position testing

1- The large gripper was actuated by the pneumatic balloons to a pressure of 0.14 bar being applied in perpendicular direction of the tip of the beam and the strain recorded.

2- The gripper is subjected to a load with the objects at different positions. From the root of the gripper. The steps incremented were by 10mm each time. This will yield positions P1 to P14.

3- The strain sensory data corresponding to the gripper is recorded to from the data acquisition equipment for both cases when the gripper loaded with objects and without loads.

4- Each object position is repeated three times for repeatability of results.

5- The Neural Network used for these experiments is as a continuous model.

As explained previously, twelve different objects were positioned along the length of the gripper rig. These objects were categorized as : 25, 30, 33, 35, 36, 37, 38, 39, 44, 50, 53, 64mm diameter. Each object is positioned along the gripper rig in fourteen different positions, position 1 is considered to be at the root of the beam. Each of the positions, are 1cm apart from one another.

Results of position experiements.

The Neural Network used for the position experiments was a 4 inputs 2 class output neural network. Contained 16 hidden nodes. Figure (4.8) displays the neural network predicted position of the object for different objects. Testing the neural network for static contact points shows that the gripper is able to predict the object position to within 0.2mm of the actual contact position. This equates to a percentage error of 1.4% over the full range.

The result of the training of the neural network is compared against the experimental test data. The two data sets were plotted against each other as shown in figure 4.8 . The red points are the actual test points, whereas the blue are the predicted data from the neural network.

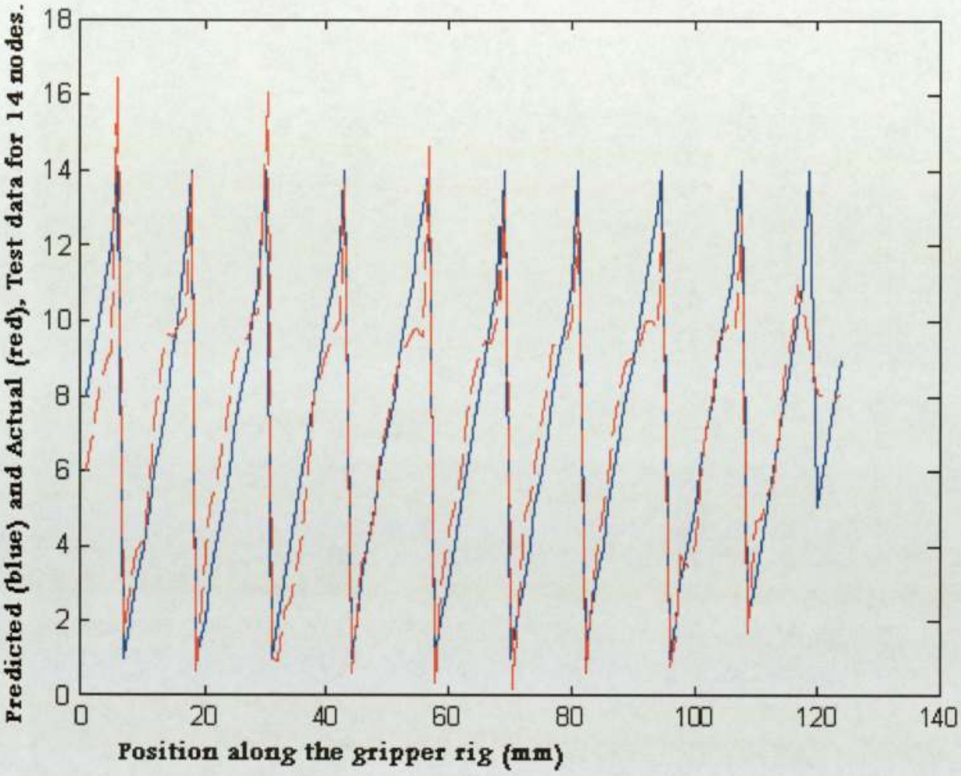


Figure 4.8: A graph showing the neural network predicted position of the object (blue) plotted against the actual position (red) of 140 samples of data.

The percentage error between the actual and the predicted generally lies under 5%.

$$\text{Percentage Error} = \frac{real - predicted}{real} \times 100\%$$

4.3.3 Object diameter testing

In this experiment, the diameter of the object is detected. The aim of this experiment is to determine the performance of the gripper in the evaluation of the object diameter. The gripper is able to discriminate the diameter of an object by sensing strain at multiple points. The device changes its shape to the shape of the contact object.

Method for retrieving Object diameter

1-Determine the diameter of the grasped object at different positions.

2-The large gripper actuated by pneumatic balloons to a pressure of 2psi being applied in perpendicular direction at the tip of the beam and the strain recorded.

3- The gripper is subjected to a load using one of 12 objects. The objects vary in diameter from 25 to 60 mm. Inputs were obtained by placing a sample object into the gripper.

4-The strain in the beam due to a gripping action was measured across the beam using four strain gauge sensors.

5-Each object size was repeated three times for each position to check for repeatability of results.

6- A neural network was used as the interpretation algorithm to discriminate the diameter of a grasped object. Voltage differences between gripping and releasing actions were derived and used as inputs.

As explained previously, twelve different objects sizes were positioned along the length of the gripper rig. These objects were categorized as: 25, 30, 33, 35, 36, 37 38, 39, 44, 50, 53, 64mm size. Each object is positioned along the gripper rig in fourteen different positions, position 1 is considered to be at the root of the beam. Each of the positions, are 1cm apart from one another.

Results of object diameter detection

The neural network used for this experiment is a 4 input 2 class output neural network with 16 hidden nodes. Figure 4.9 displays the neural network predicted diameter of the object (blue) plotted against the actual size of the object (red) for 140 samples. Testing the neural network shows that the gripper is able to predict the object diameter to within 3mm of the actual diameter. This equates to a percentage error of 10% over the full range.

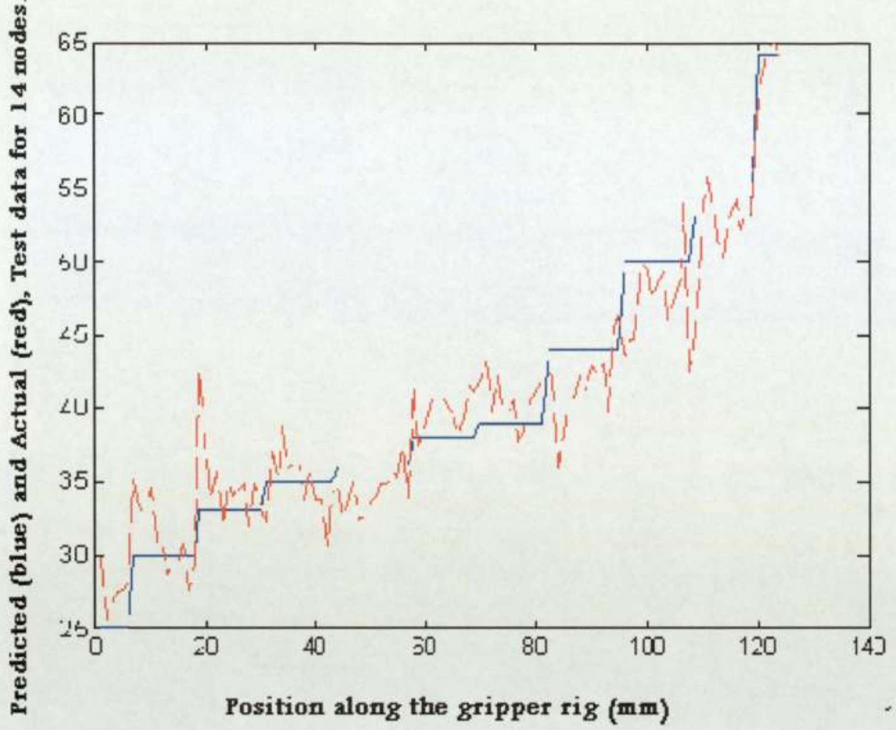


Figure 4.9: A graph showing neural network predicted the diameter of the object (blue) plotted against the actual diameter of the object (red) for 140 samples of data..

The result of the training of the neural network is compared against the experimental test output data. The two data sets were plotted against each other as shown in Figure 4.9. The red points are the actual test points, whereas the blue are the predicted data from the neural network.

The percentage error between the actual and the predicted values generally lies under 10% with the exception of a few, thus indicating good matching of the two data sets.

Testing the Neural network

It is now possible to validate the efficiency of the neural network using the test data. A 4 input 2 output classification network using 16 hidden nodes is able to predict four discrete contact ranges to a high degree of accuracy as shown below.

Real		Predicted	
Diameter(mm)	Position (mm)	Diameter (mm)	Position (mm)
50	9.5	54.6	9.6
50	10.5	54.9	9.7
50	8.5	47.6	8.7
40	8.5	43.6	8.8

Table 4.2 This table shows that the neural network has been tested and can discriminate four discrete contact position and size ranges.

It has been shown that the neural network can predict accurately position and diameter of objects along the gripper rig.

4.3.4 Characteristics of Gripping Contact

The aim of this experiment is to determine the ability of the gripper to actually discriminate the softness of four objects and the ability to rank the objects according to their stiffness. A hard object in this project means strong and un-deformable like a rock compared to a soft object such as a piece of sponge.

Methods for evaluating contact stiffness.

1- To detect object stiffness, four objects with the same diameter (50mm) and shape were used. Three of them were attached to a specimen of soft expanded polystyrene foam. The foam specimen dimensions were 40mm x 20mm with a height of 15mm attached to object one, a height 30 mm attached to object two and a height of 45 mm attached to object three.

2- The gripper was actuated by pneumatic balloons to a pressure of 0.14 bar being applied in perpendicular direction at the tip of the beam and the strain recorded.

3- The gripper is subjected to a load with objects at position 10.

4- The strain sensory data corresponding to the gripper is recorded to by the data acquisition equipment for all of the cases when the gripper was loaded with objects.

5- Each case was repeated three times for repeatability of results.

6- The neural network was used as an interpretation algorithm to discriminate the stiffness of a grasped object.

Results

The Neural Network was used to discriminate the object stiffness. A 4 input, 3 output classification network using 56 hidden nodes was able to predict three discrete contact stiffness ranges to a high degree of accuracy.

Real/Predicted	Hard	Soft1	Soft2	Soft3
Hard	124	0	0	0
Soft1	0	3	0	0
Soft2	0	0	3	0
Soft3	0	0	0	3

Table 4.3: This table shows that the neural network has been trained and can predict three discrete contact stiffness ranges.

Figure 4.10: The gripper in gripping action of a soft object (soft-2).

Table 4.3 shows a matrix of 133 samples of data, All classification were correctly identified using a classification type neural network. This type of neural network was able to predict four discrete contact stiffness in the ranges of hard, soft1, soft2, soft3 (figure 4.11).

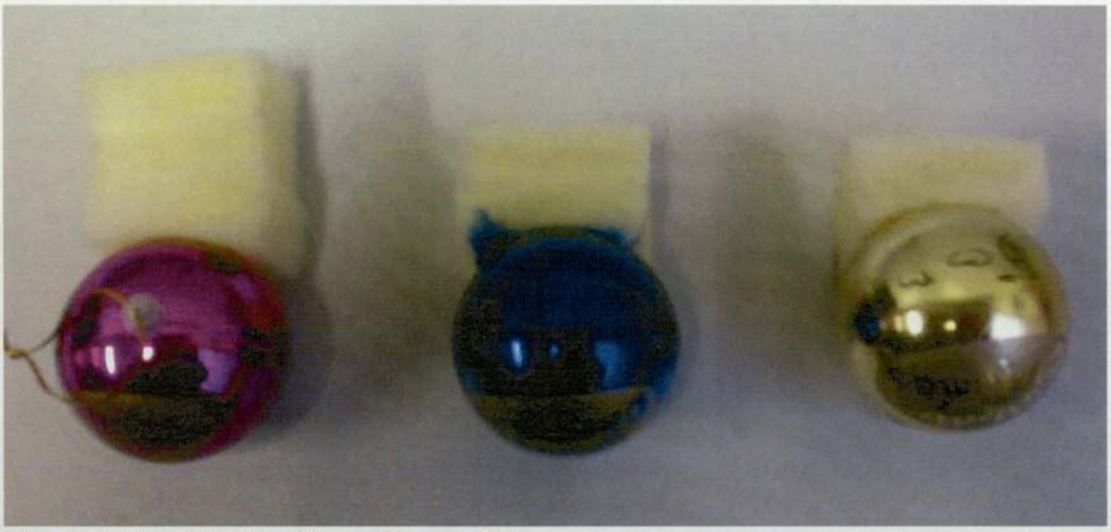


Figure 4.11: objects soft1, soft2 or soft3

The results show that the gripper rig is able to discriminate between four different object stiffnesses.

4.4 Conclusion and Future Work

This thesis has presented the design, and implementation of a pneumatic balloon actuated gripper with novel tactile feedback. A literature review of microsurgical robotics was presented (Chapter 2), followed by the design of the physical system (Chapter 3). The device was designed to mimic a three section pneumatic balloon actuated cantilever beam sensor capable of grasping and holding various type of objects. Strain gauges were used for tactile feedback to retrieve information about the physical properties of the object.

The gripper was successful in gripping a variety of object sizes. A model of the gripper deflection was created, and compared to the large gripper experimentation results. The results from the gripper validate the model.

The gripper with tactile sensing has four sensing elements. By applying the distributive tactile sensing method on the gripper and by using neural network techniques in classified gripping the resolution achieved is higher than the number of transducers employed.

The gripper with four sensing elements is able to detect contact of an object using a neural network with high accuracy. These neural networks predicted object position to 98.6% accuracy and object size to 90% accuracy. The results show that the gripper is able to discriminate between four different object stiffnesses.

The next step is to scale down the size of the gripper to a smaller size in order to compare the performance of the large gripper to the micro-scale. For the micro-scale gripper a pneumatic balloon will be applied to actuate the cantilever beam sensor. The pneumatic balloon actuator will be fabricated on the cantilever beam sensor. The cantilever beam sensor bends as a result of inflation of the pneumatic balloon. The pneumatic balloon was successful in producing displacement with a large force by a deformation of the flexible structure under an applied pressure.

The studies described in this thesis have explored and discovered effective means of implementing neural networks into hardware for the purpose of developing a gripper with a tactile sensing system. The system lead to a smart tactile gripper which has been able to retrieve information about the size, position and stiffness of the object. The main benefit of the technique is high performance. The technique has also shown many features which will make useful applications in the biomedical field.
The essence of the sensing technology explored in this thesis is distributive tactile sensing, a type of sensing which is unique in terms of the way the sensors are constructed and the topology of the sensory processing. This research has demonstrated that only a minimal number of sensing elements is required for high accuracy. This technique thus offers the possibility of a less complicated system, particularly in terms of fabricating the sensory elements. it is also more robust and has a low cost of construction.

The sensory processing involved in distributive tactile sensing is usually in the form of an interpretation algorithm, used to directly interpret the pattern of signals from the sensory elements into contact information. A clearly effective method used in this research was a supervised neural network.

References

[1] Brett, P. N., Stone,R.S.W (1997). "A technique for measuring contact force distribution in minimally invasive surgical procedures." Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine **211(4)**: 309-316..

[2] Russell Taylor, Aaron Barnes, Rajesh Kumar(1999)A Steady-Hand Robotic System for Microsurgical Augmentation, Submitted for consideration MICCAI99: the Second International Conference on Medical Image, Computing and Computer-Assisted Intervention, Cambridge, England, September 19-22, 1999.

[3] The Concise Oxford English Dictionary. Ed. Catherine Soanes and Angus Stevenson. Oxford University Press, 2004. Oxford Reference Online. Oxford University Press. Aston University, march2005 <http://www.oxfordreference.com/views/ENTRY.html?subview=Main&entry=t23.e25055>O[accessed 29/03/05]

[4] Lee, M.H., Nicholls, H.R., Tactile sensing for mechatronics-a state of the art survey, Mechatronics (9), 1999, pages 1-31.

[5] Bholat, O.S., Haluck, R.S., Murray, W.B., Gorman, P.J., Krummel, T.M., Tactile Feed-back Is Present During Minimally Invasive Surgery, Journal of American College of Surgeons, 1999, volume 189, pages 349-355.

[6] http://www.intuitivesurgical.com/index.aspx

[7] Paolo Dario, Member, IEEE, Maria Chiarra Carrozza, IEEE transaction on information technology in biomedicine, Vol.4,No 1, March 2000.

[8] Lazeroms, A. L. H., etc (1996). "a hydraulic forceps with force feed back for use in minimally invasive surgery". Mechatronics **6**(4): 437-446.

[9] Dargahi, J., Payandeh, S., Parameswaran, M. (1999), "A micromachined piezoelectric teeth-like laparoscopic tactile sensor: theory, fabrication, and experiments", Proceedings of IEEE International Conference on Robotics and Automation, Detroit, MI, pp.299-340.

[10] Shikida, M., Shimizu, T., Sato, K., Itoigawa, K. (2003), "Active tactile sensor for detecting contact force and hardness of an object", *Sensors and Actuators A: Physical*, Vol. 103 No.1-2, pp.213-8.

[11] Siamak Najarian , Javad Dargahi , Xiang Zhi Zheng.(2006)," A novel method in measuring the stiffness of sensed objects with applications for biomedical robotic systems". The international journal of medical robotics,2006,2:p84-90.

[12]R. Provancher," On Tactile sensing and display" PhD thesis, Stanford university,2003.

[13] Y. Lu, and C. Kim,"Micro-finger articulation by pneumatic parylene Balloons"The 12th Inetrnational Engineering Conference on Solid State Sensors, Actuators and Microsystems, Boston , June 8-12 ,2003 ,pp276-279

[14] F. Van Meer and D. Steve, 2004," microtecnology applications for medical instrument",Cellular and Molecular Biology (3), 301-308, 2004 Cell. Mol.

[15] Arianna Menciassi,, Anna Eisinberg, Maria Chiara Carrozza, and Paolo Dario, Force Sensing Microinstrument for Measuring TissueProperties and Pulse in Microsurgery", IEEE/ASME TRANSACTIONS ON MECHATRONICS, VOL. 8, NO. 1, MARCH 2003.

[16] http://store.norgren.com/UK/en-GB/cat3/skuVP5002BJ411H00.html.

[17] Gere. James .M., 2002,"Mechanics of Materials,fifth edition, Nelson Thornes ltd.

[18] Brett, P. N., Stone,R.S.W (1995). "A flexible pneumatic actuator for gripping soft irregular shaped objects" Proceedings of the Institution of Electrical Engineers,IEE Colloquium on ' Innovation Actuators for Mechatronics Systems',volume170,p.13.

[19] Slack.Paul, Master thesis "Cable Actuated Flexible Digit Design",Aston University.2005

[20] Peter N. Brett , 'The Performance of a 1-D Distributive Tactile Sensing System for Detecting the Position, Weight, and Width of a Contacting Load', IEEE tranactions on intstrumentation and measurement, vol.51, no 2, Aprill 2002.

[21] K Hoffmann,"The Strain Gauge; a Universal Tool of the Experimental Stress Analysis", McGraw Hill, Singapore, 1992.

[22] Morris,A.S. (1993) Principals of Measurement and Instrumentation, Prentice Hall: Europe

[23] Tam.B., PhD thesis," A Touch Sensitive Digit",2005,Aston University,UK.

Appendix 1

Data sheet for VP50 Norgren Proportional Pressure Control Valve

Technical specification

Medium: compressed air filtered to 50 micron
Operation:Proportional, direct acting air pilot spool

Supply pressure: 14 bar max.
Supply Sensitivity: Better than 0,75% span output change per bar supply
Flow capacity: 1200 Nl/min max.
Response time: < 80 ms (from 10-90% of output pressure into a 0.1 litre load)
Air consumption: < 5 l/min
Port size: G1/4; manifold versions on request
Total error: Max. error < ±1% of span (independent error includes the combined
effect of non-linearity, hysteresis, deadzone and repeatability)
Operating temperature: -5°C to +50°C
Temperature effect: Typically better than 0,03% of span/°C for span and zero over

Degree of protection: IP 65 in normal operation
Vibration immunity: < 3% output shift for 3 g 10-2000 Hz
Mounting position: Any screw mounting
Material:
Weight: approx. 800 g

Appendix 2

Data sheet for 2mm Strain Gauges

Technical Specification

Gauge length : 2 mm

Measurable Strain : 3 to 4 % Max

Gauge Resistance : 120 Ohms +/- 0.5 %

Gauge Factor : 2.00

Material : Foil

Linear Expansion : Mild steel

Temperature range: -30 C to + 180 C

Measurable Strain : 3 to 4 % Max

Appendix 3 Data Sheet for Strain Amplifiers

Type : Fylde Strain Gauge Amplifiers

Online data sheet:

Fylde Technical Manual for Strain Module Type Micro Analog 2 - FE-MM4

http://www.fylde.com/microan2_MM4.htm

Accessed 1/2/2006

System Specification

Maximum 4 channel analogue instrumentation system
Up to 2 dual channel cards in any combination. Auto Zero function is included in FE-MM4 if specified when ordering. (Specify part number FE-MM4-AZ)
10 to 36 V DC supply (Max current 0.5 A).
Inputs 2 x 7 pin Tuchel. Output 1 x 15 way D sockets. Adaptors available for both input and output connectors.
Dimensions 74(H) x 60(W) x 228(D)
Environment 0°C to 40°C, 0 to 80 % R.H. non condensing.
IP rating : IP53
Transducer Excitation : +2.5 V , +5 V , +10 V (factory set +/- 2.5 mV).
Powers up to 4 bridge type transducers of 120 ohm at 2.5 V or 5 V and 350 ohm at +5 V or +10 V. 170 mA at +5V or +2.5 V and 130 mA at +10 V
Noise and Ripple of Transducer Excitation < 5 mV pk-pk (bandwidth 50 kHz)

Appendix 4:

16-Bit High Performance Analog and Digital, I/O Boards PCI-1602

Type : National Instrument , 16-Bit, I/O Boards PCI-1602

Online data sheet:

http://www.omega.com/DAS/pdf/OME-PCI-1602.pdf

Accessed 25/8/2006

System Specifications:

16 Digital Input/16 Digital Output Channels

Programmable Low Gain: 0.5, 1, 2, 4, 8

Internal/External Trigger

Two 12-Bit Independent

Programmable DAC

2 MHz Throughput per Channel (max)

2.7 M Word/High Speed Data Transfer Rate